JASA ARTICLE

The impact of reverberation on speech intelligibility and adaptation for people with unilateral hearing loss[a)]

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ABSTRACT:
Individuals with unilateral hearing loss (UHL) encounter difficulties in specific scenarios that may not be considered as unfavorable conditions for people with normal hearing. It is well known that reverberation degrades speech intelligibility for elderly and hearing-impaired populations. However, the impact of reverberation on individuals with UHL has been less investigated. In the current study, an experiment was conducted to investigate the impact of reverberation on speech intelligibility and spatial release from masking (SRM) and to assess the adaptation to a reverberant environment for individuals with UHL. For these purposes, data were measured in three groups of listeners, namely, those with binaurally stimulated normal hearing, monaurally stimulated normal hearing (MNH), and UHL. As a result, reverberation degraded speech intelligibility and SRM, with the greatest impact observed when the target sound was located on the impaired ear side for participants with UHL. However, the participants with long-standing UHL showed reduced effects of reverberation and informational masking compared to the MNH group, which simulated the listening situation immediately after the onset of UHL. These results indicated necessity of rehabilitation protocols, particularly immediately after the onset of UHL, to improve the quality of life for people with UHL. https://doi.org/10.1121/10.0036462

(Received 27 August 2024; revised 25 March 2025; accepted 2 April 2025; published online 21 April 2025)

[Editor: Pamela Souza] Pages: 3070–3086

I. INTRODUCTION

Sounds are usually heard under various conditions, including environments with the presence of noise and reverberation. Reverberation consists of many sound reflections from various room surfaces and objects that follow the direct sound from the sound source. Reverberation particularly affects our hearing in large rooms or venues that have a relatively long reverberation time. While early reflections (−50 ms after arriving of the direct sound) improve speech intelligibility (Bradley *et al.*, 2003), it is well known that late reverberation often degrades speech intelligibility (Knudsen, 1929; Nábělek *et al.*, 1989; Osawa *et al.*, 2021). Bolt and MacDonald (1949) summarized the mechanisms of reverberation as two points: (1) Reverberation alters the temporal structure of the original sound source, and (2) the "tail" of the current sound's reverberation masks the following sound. The impact of reverberation on speech intelligibility is much greater for elderly people and people with hearing loss (HL) (Harris and Reitz, 1985; Nábělek and Mason, 1981; Reinhart and Souza, 2018a). On the other hand, the overall impression of music is enhanced by reverberation, and preferences of room acoustics for music have been discussed (Kuhl, 1954; Lokki *et al.*, 2012; Prodi *et al.*, 2015). However, other studies have suggested that reverberation has a different effect on musical experiences for elderly and hearing-impaired populations (Reinhart and Souza, 2018b; Roy *et al.*, 2015; Tsuji and Arai, 2023).

HL encompasses a variety of conditions, including situations where one ear has good hearing while the other has impaired or no hearing. This type of HL is called unilateral hearing loss (UHL). According to the American Speech-Language-Hearing Association (ASHA), the degree of UHL can range from mild (26–40 dB HL) to very severe (91+ dB HL) (ASHA, 2024). UHL would be specifically referred to as single-sided deafness (SSD) when the side of the impaired ear exhibits profound HL. For pediatric UHL patients, it is reported that the main causes include cochlear nerve deficiency, congenital cytomegalovirus, and mumps, while sudden sensorineural HL and acoustic neuroma are common etiologies of UHL for adult patients (Usami *et al.*, 2017). The causes often remain unknown (van Beeck Calkoen *et al.*, 2019). It is estimated that 7.9%–13.3% of the population experiences UHL (Agrawal, 2008; Chia *et al.*, 2007). Harford and Barry (1965) discussed the difficulties of UHL, which can be summarized into three points: (1) hearing in noisy environments, (2) hearing on the side of the impaired ear, and (3) sound localization. The situations of individuals with UHL are characterized by the fact that the difficulties would arise in specific scenarios (Colletti *et al.*, 1988) that may not be considered as unfavorable conditions for people with normal hearing (NH).

It is well known that there are binaural advantages for those with NH and normal higher-order auditory processing (Avan *et al.*, 2015). Sounds often arrive at the two ears with

[a)]Part of this study was reported at the September 2023 Meeting of the Technical Committee on Speech Communication of the Acoustical Society of Japan, the 2023 Autumn Meeting of the Acoustical Society of Japan, and the 2024 Spring Meeting of the Acoustical Society of Japan.

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differences in timing (phase). Additionally, the head located between two ears creates a head shadow and one ear often falls in the shadow against arriving sounds. As a result, there are interaural time differences (ITDs) and interaural level differences (ILDs), as well as changes in the sound spectrum between the two ears due to the head-related transfer function (HRTF). ITDs are effective below about 1.5 kHz [at least for pure tones; e.g., Zwislocki and Feldman (1956)]. On the other hand, ILDs are significant at high frequencies [e.g., Feddersen *et al.* (1957)], where sounds have relatively short wavelength, resulting in less diffraction. Binaural advantages arise from these cues and hearing will be improved even in noisy environments, known as the cocktail party effect (Cherry, 1953). This improvement in hearing is particularly remarkable when the target sound is spatially separated from the competing masker, which is specifically referred to as spatial release from masking (SRM) (Bronkhorst and Plomp, 1988, 1992; Litovsky, 2012). The benefit of SRM is partially obtained by improving signal-to-noise ratio (SNR) at the ears due to the relative positions of the target and masker. This gain is crucial for hearing in relatively simple configurations (e.g., one target vs one masker) and/or when a simple noisy masker is present (i.e., under energetic masking). Similarly, it has been reported that individuals with UHL can also experience the benefit of SRM thorough SNR improvement (Rothpletz *et al.*, 2012). In contrast, binaural cues have a great role for the gain in SRM in more complex configurations (e.g., one target vs multiple masker) and/or in the presence of a semantically competitive masker (i.e., under informational masking) (Arbogast *et al.*, 2002, 2005; Corbin *et al.*, 2017, 2021; Hawley *et al.*, 2004; Marrone *et al.*, 2008).

The deficits of UHL are explained by the lack of binaural advantages as well as disadvantageous asymmetrical listening situations (Corbin *et al.*, 2021; Rothpletz *et al.*, 2012; Tsuji and Arai, 2023). In contrast to people with NH, the spatial separation is not always effective for individuals with UHL. For example, SRM in individuals with UHL is observed due to the increased SNR when the target is located on the side of the good hearing ear against the masker located in front. However, the amount of SRM would be reduced when target and masker positions are reversed, as the SNR decreases due to the head shadow effect. Moreover, previous studies reported that individuals with UHL showed significantly decreased speech intelligibility and SRM under informational masking conditions compared to individuals with NH (Corbin *et al.*, 2021; Marrone *et al.*, 2008; Rothpletz *et al.*, 2012).

Reverberation also affects the amount of SRM. Under reverberation, interaural information is smeared, which broadens auditory images (Blauert and Lindemann, 1986) and reduces the amount of SRM (Hui *et al.*, 2022; Kidd *et al.*, 2005; Marrone *et al.*, 2008). It is well known that binaural hearing can "squelch" the perceived reverberance (Koenig, 1950). This binaural squelch effect contributes to better speech intelligibility under reverberation (Lavandier and Culling, 2008; Nábělek and Robinson, 1982). The precedence effect ensures sound localization in reverberant environments for people with NH (Litovsky *et al.*, 1999). Additionally, their hearing is released to some degree from overlap-masking of the reverberation (Libbey and Rogers, 2004). On the other hand, elderly people and people with HL have difficulties in speech perception in reverberant environments due to the lack of these binaural advantages. In a part of our previous research (Tsuji and Arai, 2023), speech intelligibility and the amount of SRM were measured in a reverberant environment (with a reverberation time of about 1.6 s). As a result, it is suggested that speech intelligibility is particularly degraded immediately after the onset of UHL. However, participants with long-standing UHL showed better speech intelligibility and a better amount of SRM, suggesting adaptation to hearing under reverberation (Tsuji and Arai, 2023). Nevertheless, the effects of reverberation for individuals with UHL have been unclear, including the difference in the effects of energetic/informational masking as well as anechoic/reverberant environments.

In the current study, we carried out an experiment with two objectives: (1) to investigate the impact of reverberation on speech intelligibility and SRM and (2) to assess the adaptation to a reverberant environment for individuals with UHL. Additionally, correlations among various demographic factors and results were considered, including the degree of musical ability measured because its association with masked speech perception has been reported (Dumont *et al.*, 2017; Lo *et al.*, 2020; Slater *et al.*, 2015). The degree of musical ability was scored according to the Japanese version (Sadakata *et al.*, 2023) of the Goldsmiths Musical Sophistication Index (Gold-MSI) (Müllensiefen *et al.*, 2014). To accomplish our goal, measurements were conducted in simulated anechoic/reverberant environments as well as in the presence of energetic/informational masking for three hearing groups: (1) participants with NH presented with sound binaurally (BNH), (2) participants with NH presented with sound monaurally (MNH), and (3) participants with UHL. We assessed the impact of reverberation by comparing speech intelligibility and SRM of the UHL group measured in a reverberant environment to the effect measured in an anechoic environment. Furthermore, this impact would become more evident when compared to the results of the binaural group. Similarly, adaptation was evaluated by comparing speech intelligibility and SRM of the UHL group to those of the monaurally presented group with NH, which primarily differed in their experience with monaural hearing.

II. METHOD

A. Participants

There are three groups in our experiment, namely (1) the BNH group, (2) MNH group, and (3) UHL group. Twenty NH people participated in this study: 8 males and 12 females. Mean age at this experiment was 20.25 years [standard deviation (SD) = 1.68, range = 18–24 years]. The BNH group consisted of 10 participants of the 20 people with NH, and the MNH group consisted of the remaining 10 of them. For the MNH group, the ear to which the sound was presented was determined randomly (right ears = 5). The UHL group consisted of 16 participants with UHL: 5 males and 11 females. Mean age at this experiment was 39.31 years (SD = 13.66, range = 22–62 years). The participants were all native Japanese speakers.

All participants were measured in terms of their pure-tone audiometry using an audiometer (AA-79S; RION, Tokyo, Japan). The 20 participants with NH had a mean four-frequency pure-tone average (4fPTA; average hearing threshold levels at 0.5, 1, 2, and 4 kHz) of 5.41 dB HL (SD = 3.05, range = 0.00–11.25 dB HL). The 16 participants with UHL had mean 4fPTAs of 12.03 dB HL for their good ears (SD = 6.47, range = 3.75–23.75 dB HL) and 102.35 dB HL for their impaired ears (SD = 11.80, range = 76.25–110.00 dB HL). For the UHL group, seven had left-sided UHL and nine had right-sided UHL. Nine of the UHL participants had congenital losses, and seven had acquired UHL. In the current study, congenital UHL was defined as the absence of memory before the onset of UHL, as almost all of the nine participants were not diagnosed with UHL at birth and had unclear information about its onset. The mean duration of UHL was 27.38 years (SD = 14.83, range = 0.50–51.00 years). All participants with UHL did not use any types of hearing aids. Demographic factors of the participants with UHL are provided in Table I. Figure 1 also illustrates an audiogram of the impaired ears of the participants with UHL. UHL is defined following the ASHA criteria "Hearing is normal in one ear, but there is hearing loss in the other ear. The hearing loss can range from mild to very severe" (i.e., a mean 4fPTA of 26 or more dB HL in the impaired ear) (ASHA, 2024).

B. Binaural impulse responses

Binaural impulse responses were convolved to yield both anechoic and reverberant stimuli, as well as to add the directional cues to the target speech and masker. These binaural impulse responses were recorded in an anechoic chamber (Kayser *et al.*, 2009) and in an auditorium (Tsuji and Arai, 2023). In these studies, several recordings were collected at various relative angles between a sound source and a dummy head [for details, see Kayser *et al.* (2009) and Tsuji and Arai (2023)]. The binaural impulse responses, recorded with the sound source positioned in front (0°) and at ± 35° against the receiving point, all at the same height, were used in this study. The distance between the speaker and the dummy head was about 3.00 m for both anechoic and reverberant binaural impulse responses. The reverberation time of the binaural impulse responses in the auditorium was about 1.6 s [calculated in line with EN ISO 3382-1:2009 (2009)].

C. Stimuli

Measurements of speech reception thresholds (SRTs) were conducted using speech materials convolved with the binaural impulse responses. The target sentences were selected from the NTT Phonetically Balanced Sentence Speech Data (NTT Advanced Technology Corporation, 1997). A total of 250 Japanese sentences were selected, satisfying the criteria as follows: sentences (1) spoken by a male announcer, (2) at speech rates of 7.5–9.0 morae per second, and (3) having four or five phrases that include a main word or a main word with postpositional particle. Since many more sentences were required in this study, these criteria are slightly different compared to our previous study (Tsuji and Arai, 2023).

TABLE I. Demographic factors of participants with unilateral hearing loss.[a]

P#	Side of HL	Age (years)	Duration of HL (years)	Etiology	4fPTA (dB HL)		Gold-MSI score
					Better	Poor	
01	R	25	25.0	Microtia	3.75	77.50	99
02	R	38	38.0	Unknown	5.00	110.00	74
03	R	27	20.0	Mumps	12.50	110.00	72
04	R	28	28.0	Stapes hypoplasia	18.75	110.00	84
05	R	22	22.0	Mumps	10.00	97.50	66
06	L	33	33.0	Unknown	6.25	110.00	36
07	L	50	1.5	Sudden HL	5.00	76.25	95
08	L	62	0.5	Sudden HL	21.25	100.00	72
09	R	51	51.0	Unknown	13.75	110.00	75
10	L	58	25.0	Acoustic neuroma	23.75	110.00	61
11	R	27	15.0	Sudden HL	10.00	91.30	22
12	R	47	47.0	Unknown	22.50	110.00	58
13	L	48	48.0	Unknown	11.25	110.00	89
14	R	57	37.0	Unknown	12.50	95.00	41
15	L	27	27.0	Mumps	10.99	110.00	90
16	L	29	20.0	Sudden HL	6.25	110.00	56
Mean (SD)		39.3 (13.7)	27.4 (14.8)		12.03 (6.50)	102.35 (11.80)	68.1 (21.8)

[a]Note: P#, participant number; HL, hearing loss; 4fPTA, pure-tone average of hearing thresholds at 0.5, 1, 2, and 4 kHz; dB HL, decibel hearing level; Gold-MSI, Goldsmiths Musical Sophistication Index.

https://doi.org/10.1121/10.0036462

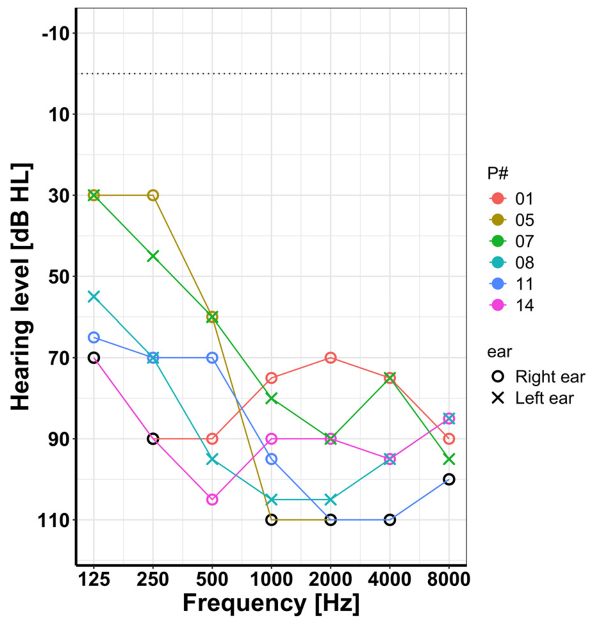

FIG. 1. The measurable audiograms of the impaired ears of participants with UHL. Those with unmeasurable audiograms are not included in this figure. Black bold symbols indicate there were no responses at the limits of the audiometer. P# indicates participant number, as shown in Table I, and other participants showed no responses for their impaired ear at the limits of the audiometer across all frequencies.

Specifically, in the current study, we included sentences that use a person's name, which was not used in our previous study. Twelve lists of 20 sentences and a list of 10 sentences were made from the selected 250 sentences, with keywords provided for each phrase in all sentences.

For the energetic masker, we used speech-shaped noise (SSN) modified in its spectral properties from white noise to match the long-term spectral properties of the 250 selected sentences using PRAAT (Boersma and Weenink, 2020). For the informational masker, we used two same-talker speech (TSS) that consisted of a male voice actor reading two different Japanese stories called *Akai rousoku to ningyo*, *Yodaka no hoshi*. This speech material was selected from Japanese Kamishibai and Audiobook Corpus (J-KAC) (Takamichi, 2021). Silent sections longer than 300 ms were manually trimmed to be less than 100 ms for TSS to decrease the gain in intelligibility of target speech due to dip listening following Corbin *et al*. (2021).

The target speech and masker (SSN/TSS) were convolved with binaural impulse responses at a sampling frequency of 48 kHz. These stimuli were normalized in terms of their root-mean-square (RMS) values and shaped with a cosine ramp to create 10 ms fade-in/fade-out. Stimuli were presented via headphones (HDA 300; Sennheiser, Wedemark, Germany) through a digital audio interface (Rubix24; Roland, Hamamatsu, Japan) at a sampling frequency of 48 kHz and 16-bit resolution.

D. Procedure

The procedure was approved by the Research Ethics Committee of Sophia University (2021-52). Informed consent was obtained from all participants. Participants were assessed in terms of their musical abilities using Gold-MSI before the experiment. The remaining procedures were conducted in a soundproof room as follows: (1) participants' demographic factors were collected using a questionnaire, (2) pure-tone audiometry was measured, and then (3) measurements of SRTs were conducted in anechoic and reverberant environments as well as with SSN and TSS.

We measured the SRTs using the one-up/one-down staircase procedure obtaining the 50.0% correct point on the psychometric function (Levitt, 1971). At the beginning of the SRT measurements, the target speech and masker were presented at sound pressure levels of 65 dB (A) and 75 dB (A) respectively, calibrated using a sound level meter (NA-28; RION) via an artificial ear (type 4153; Brüel&Kjaer, Naerum, Denmark). Participants were asked "Please repeat the sentence you heard." If they could correctly answer three or more keywords, the target and masker SNR were lowered by 2 dB (i.e., increased difficulty); if not, the SNR was raised by 2 dB (i.e., decreased difficulty). In several measurements, the step size for the first reversal was 6–14 dB SNR to reduce the number of trials. The sound pressure level of the target speech was manipulated with a maximum limit of 81 dB (A). If the target speech reached this maximum level, the sound pressure level of the masker was adjusted to decrease/increase the SNR. These trials continued until eight SNR reversals occurred. SRTs were defined as the arithmetic mean of the SNRs from the last six reversals. A custom MATLAB interface was used to present the stimuli and record the participants' answers and the SNRs of the presented stimuli. Practice sessions were provided for the participants to be familiar with their task using a list of ten sentences.

SSN and TSS were always convolved with the impulse response at 0° (i.e., the masker was presented in front of the participants, and the location was fixed under all hearing conditions). Changing the location of the target speech, SRTs were measured in three configuration conditions, namely (1) a co-located condition, where both target and masker were convolved with the impulse response at 0°, (2) an ipsilateral condition, where the target was convolved with the impulse response at ipsilateral ± 35° to the better-hearing/presented side of the ear for UHL/MNH, and (3) a contralateral condition, where the target was convolved with the impulse response at contralateral ± 35° to the impaired/non-presented side of the ear for UHL/MNH. For BNH, the left side (−35°) and right side (+35°) were selected for the ipsilateral condition and contralateral condition, respectively. The SRM values were obtained by subtracting the SRTs of ipsilateral/contralateral condition from the SRTs of the co-located condition.

The order of measurement was randomized with respect to the environments (anechoic/reverberant) and masker types (SSN/TSS), whereas the order of target locations was fixed at 0°, −35°, and +35°. Thus, the total of 12 measurements of SRTs were conducted using 12 different lists of 20 target sentences without repetition. The lists were randomized among participants.

III. RESULTS

A. Comparison of SRTs and the amount of SRM among three hearing conditions

We analyzed the data using R software (v.4.3.2) (R Core Team, 2022). Linear mixed-effect models by the *lme4* package (Bates *et al.*, 2015) were fitted with SRTs and SRM as dependent variables and each participant as a random variable. The groups (BNH, MNH, and UHL) were included as independent variables for the comparison among the three hearing conditions. The p values for the fixed effect were obtained using the *lmerTest* package (Kuznetsova *et al.*, 2017) and adjusted using the Bonferroni method for multiple comparisons. The estimated marginal means and 95% confidence intervals of SRTs were computed using the *emmeans* package (Lenth *et al.*, 2024).

Since masked speech intelligibility declines from middle age (50–60 years) onwards, even in individuals with NH (Goossens *et al.*, 2017), we excluded data from UHL participants aged 50 years or older when comparing them to the BNH and MNH groups. Additionally, we excluded a participant who had relatively better hearing thresholds at lower frequencies (P#05 in Table I and Fig. 1), as this participant showed different trends in the results (see the last paragraph in Sec. III C). Even after these exclusions, the Welch's t test found a significant difference in mean age between participants with NH and those with UHL ($p < 0.001$). The Welch's t test also found a significant difference between mean 4fPTA of participants with NH and mean 4fPTA in the better ear of those with UHL ($p < 0.05$).

The mean scores of the Gold-MSI were 74.80 (SD = 22.39, range = 44–108) for the BNH group, 63.10 (SD = 25.24, range = 30–99) for the MNH group, and 68.00 (SD = 24.90, range = 22–99) for the UHL group. There was no significant difference in the Gold-MSI score between the BNH, MNH, and UHL groups [one-way analysis of variance (ANOVA), F (2.00, 18.99) = 0.60, $p = 0.56$].

Figure 2(A) illustrates the results for the measurements of SRTs with SSN. Table II(a) also provides the estimated marginal means and 95% confidence intervals of SRTs and the amount of SRM. Lower SRTs represent better speech intelligibility, and higher SRMs indicate more benefit from the change of the target location away from the masker. For anechoic environment, there were significant differences in SRTs between BNH vs MNH [$\beta = -2.30$, standard error (s.e.) = 0.64, $t = -3.58$, $p < 0.01$] and MNH vs UHL ($\beta = 2.43$, s.e. = 0.64, $t = 3.78$, $p < 0.01$) under the co-located condition, significant differences in SRTs between BNH vs MNH ($\beta = -4.63$, s.e. = 1.13, $t = -4.11$, $p < 0.01$) and MNH vs UHL ($\beta = 3.03$, s.e. = 1.13, $t = 2.69$, $p < 0.05$) under the ipsilateral condition, and significant differences in SRTs among all hearing conditions (BNH vs MNH, $\beta = -9.50$, s.e. = 0.75, $t = -12.73$, $p < 0.001$; BNH vs UHL, $\beta = -6.53$, s.e. = 0.75, $t = -8.75$, $p < 0.001$; MNH vs UHL, $\beta = 2.97$, s.e. = 0.75, $t = 3.98$, $p < 0.01$) under the contralateral condition. There were significant differences in the amounts of SRM between BNH vs MNH ($\beta = 7.20$, s.e. = 1.15, $t = 6.24$, $p < 0.001$) and BNH vs UHL ($\beta = 6.66$, s.e. = 1.05, $t = 6.32$, $p < 0.001$) under the contralateral condition [Fig. 2(A), left panel). For the reverberant environment, there were significant differences in SRTs between BNH vs MNH ($\beta = -4.83$, s.e. = 1.06, $t = -4.55$, $p < 0.001$) and MNH vs UHL ($\beta = 3.87$, s.e. = 1.06, $t = 3.64$, $p < 0.01$) under the co-located condition, significant differences in SRTs between BNH vs MNH ($\beta = -7.37$, s.e. = 0.96, $t = -7.64$, $p < 0.001$) and MNH vs UHL ($\beta = 5.37$, s.e. = 0.96, $t = 5.57$, $p < 0.001$) under the ipsilateral condition, and significant differences in SRTs among all hearing conditions (BNH vs MNH, $\beta = -16.03$, s.e. = 1.46, $t = -10.98$, $p < 0.001$; BNH vs UHL, $\beta = -7.77$, s.e. = 1.46, $t = -5.32$, $p < 0.001$; MNH vs UHL, $\beta = 8.27$, s.e. = 1.46, $t = 5.66$, $p < 0.001$) under the contralateral condition. There were significant differences in the amounts of SRM between BNH vs MNH ($\beta = 11.20$, s.e. = 1.65, $t = 6.78$, $p < 0.001$) and MNH vs UHL ($\beta = 8.06$, s.e. = 1.51, $t = 5.34$, $p < 0.001$) under the contralateral condition [Fig. 2(A), right panel].

Figure 2(B) illustrates the results for the measurements of SRTs with TSS. Table II(b) also provides the estimated marginal means and 95% confidence intervals of SRTs and the amounts of SRM. For the anechoic environment, there were significant differences in SRTs between BNH vs MNH ($\beta = -2.97$, s.e. = 1.06, $t = -2.80$, $p < 0.05$) and MNH vs UHL ($\beta = 4.23$, s.e. = 1.06, $t = 4.00$, $p < 0.01$) under the co-located condition, significant differences in SRTs among all hearing conditions (BNH vs MNH, $\beta = -6.53$, s.e. = 1.14, $t = -5.74$, $p < 0.001$; BNH vs UHL, $\beta = -3.50$, s.e. = 1.14, $t = -3.08$, $p < 0.05$; MNH vs UHL, $\beta = 3.03$, s.e. = 1.14, $t = 2.67$, $p < 0.05$) under the ipsilateral condition, and significant differences in SRTs among all hearing conditions (BNH vs MNH, $\beta = -11.83$, s.e. = 0.99, $t = -11.93$, $p < 0.001$; BNH vs UHL, $\beta = -8.23$, s.e. = 0.99, $t = -8.30$, $p < 0.001$; MNH vs UHL, $\beta = 3.60$, s.e. = 0.99, $t = 3.63$, $p < 0.01$) under the contralateral condition. There were significant differences in the amounts of SRM between BNH vs MNH ($\beta = 3.57$, s.e. = 1.36, $t = 2.62$, $p < 0.05$) and BNH vs UHL ($\beta = 4.90$, s.e. = 1.24, $t = 3.95$, $p < 0.01$) under the ipsilateral condition and significant differences in the amounts of SRM between BNH vs MNH ($\beta = 8.87$, s.e. = 0.97, $t = 9.19$, $p < 0.001$) and BNH vs UHL ($\beta = 9.11$, s.e. = 0.88, $t = 10.35$, $p < 0.001$) under the contralateral condition [Fig. 2(B), left panel]. For the reverberant environment, there were significant differences in SRTs between BNH and MNH ($\beta = -5.70$, s.e. = 0.76, $t = -7.52$, $p < 0.001$) and MNH and UHL ($\beta = 4.63$, s.e. = 0.76, $t = 6.11$, $p < 0.001$) under the co-located condition, significant differences in SRTs among all hearing conditions (BNH vs MNH, $\beta = -7.30$, s.e. = 0.80, $t = -9.18$, $p < 0.001$; BNH vs UHL, $\beta = -2.27$, s.e. = 0.80, $t = -2.85$, $p < 0.05$; MNH vs UHL, $\beta = 5.03$, s.e. = 0.80, $t = 6.33$, $p < 0.001$) under the ipsilateral condition and significant

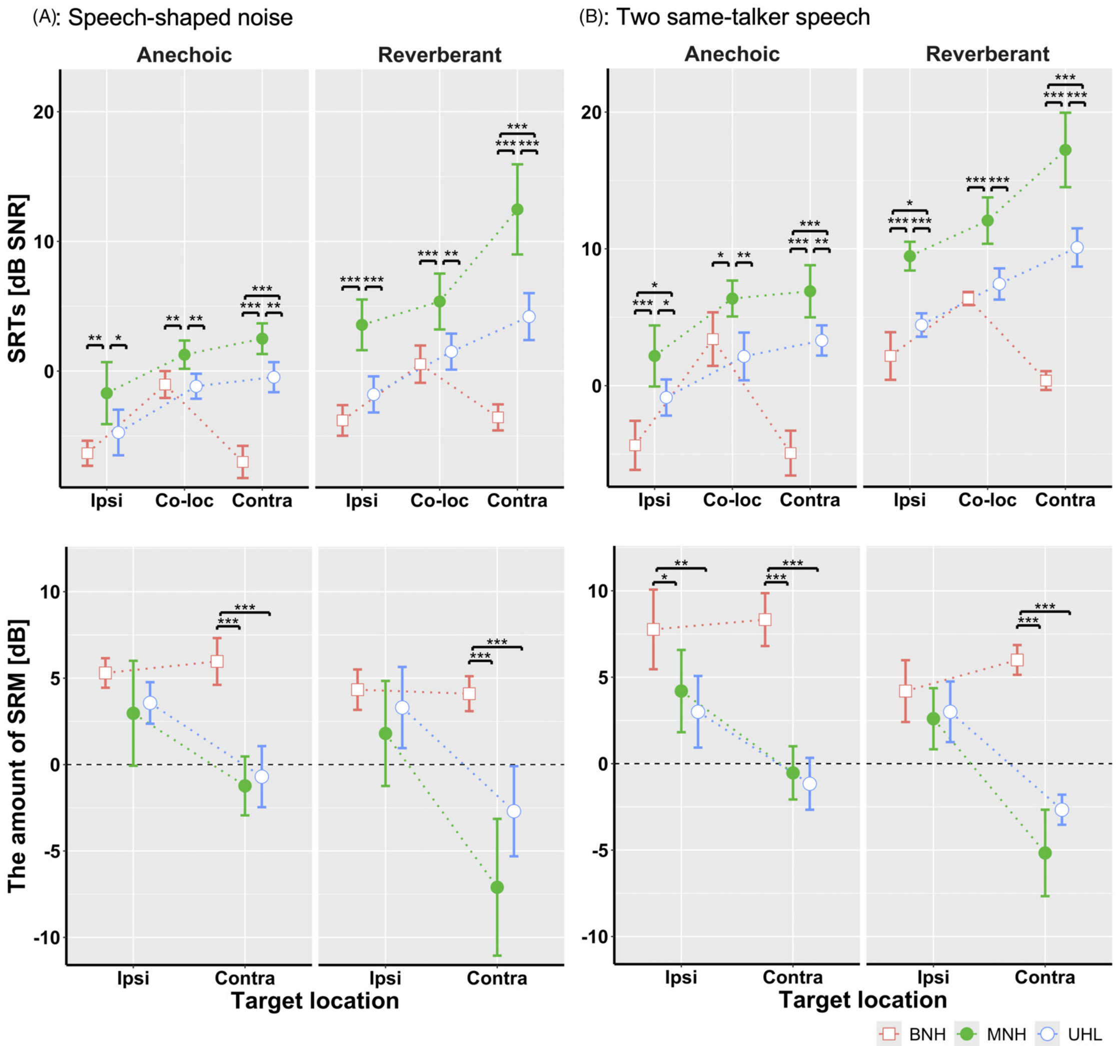

FIG. 2. Speech reception thresholds (SRTs; top row) and spatial release from masking (SRM; bottom row) measured with speech-shaped noise [(A), left column) and two same-talker speech [(B), right column]. Lower SRTs (top row) represent better speech intelligibility, and higher SRMs (bottom row) indicate more benefit from the change of the target location away from the masker. Measurements were conducted in anechoic and reverberant environments (left and right panels in each column). There were three configuration conditions: (1) the co-located target condition (Co-loc), (2) the ipsilateral target condition (Ipsi), and (3) the contralateral target condition (Contra). In addition, there were three hearing conditions: (1) binaural normal hearing (BNH; $n = 10$), (2) monaural normal hearing (MNH; $n = 10$), and (3) unilateral hearing loss (UHL; $n = 10$). For the BNH group, the target was located on the left under the ipsilateral condition and right under the contralateral condition (i.e., the BNH group always had an ipsilateral target signal for these conditions). Note that the data from UHL participants aged 50 years or older and a UHL participant who had relatively better hearing thresholds at lower frequencies are excluded for this comparison. Symbols and error bars indicate the mean and 95% confidence intervals, respectively, for each hearing condition, as described in the legend. ***, $p < 0.001$; **, $p < 0.01$; *, $p < 0.05$.

differences in SRTs among all hearing conditions (BNH vs MNH, $\beta = -16.87$, s.e. $= 1.13$, $t = -14.90$, $p < 0.001$; BNH vs UHL, $\beta = -9.73$, s.e. $= 1.13$, $t = -8.60$, $p < 0.001$; MNH vs UHL, $\beta = 7.13$, s.e. $= 1.13$, $t = 6.30$, $p < 0.001$) under the contralateral condition. There were significant differences in the amounts of SRM between BNH vs MNH ($\beta = 11.17$, s.e. $= 1.01$, $t = 11.04$, $p < 0.001$) and BNH vs UHL ($\beta = 8.98$, s.e. $= 0.92$, $t = 9.72$, $p < 0.001$) under the contralateral condition [Fig. 2(B), right panel].

B. The effect of reverberation on SRTs and the amount of SRM

For the analysis of each group, each masker type (SSN/TSS), the environments (reverberant/anechoic), target locations (ipsilateral/co-located/contralateral), and the Gold-MSI score were included as fixed independent variables of the linear mixed-effect models. Interactions between the masker type, environments, and target locations were included in the models. Table III provides the results from the regression models. Additionally, reverberation-induced degradation scores were calculated to compare the impact of reverberation across the three hearing conditions (Fig. 3). For SRTs, the scores were obtained by subtracting the SRTs in the anechoic environment from those in the reverberant environment. For SRM, they were calculated by subtracting the SRM in the reverberant environment from that in the anechoic environment. These scores were also included as fixed independent variables of the linear mixed-effect models.

TABLE II. The estimated marginal means (M) and 95% confidence intervals (CI) of speech reception thresholds (SRTs) and spatial release from masking (SRM) with (a) speech-shaped noise and (b) two same-talker speech.

Listening group	Conditions		SRT (M) (dB)	95% CI		SRM (M) (dB)
				Low	High	
(a) Speech-shaped noise						
BNH	Anechoic	Target on left side	−6.33	−7.97	−4.70	5.30
		Co-located	−1.03	−1.97	−0.10	
		Target on right side	−7.00	−8.08	−5.92	5.97
	Reverberant	Target on left side	−3.80	−5.20	−2.40	4.33
		Co-located	0.53	−1.01	2.07	
		Target on right side	−3.57	−5.68	−1.45	4.10
MNH	Anechoic	Ipsilateral	−1.70	−3.33	−0.07	2.97
		Co-located	1.27	0.33	2.20	
		Contralateral	2.50	1.42	3.58	−1.23
	Reverberant	Ipsilateral	3.57	2.17	4.97	1.80
		Co-located	5.37	3.83	6.91	
		Contralateral	12.47	10.35	14.58	−7.10
UHL	Anechoic	Ipsilateral	−4.73	−6.37	−3.10	3.56
		Co-located	−1.17	−2.10	−0.23	
		Contralateral	−0.47	−1.55	0.62	−0.70
	Reverberant	Ipsilateral	−1.80	−3.20	−0.40	3.30
		Co-located	1.50	−0.04	3.04	
		Contralateral	4.20	2.08	6.32	−2.70
(b) Two same-talker speech						
BNH	Anechoic	Target on left side	−4.37	−6.02	−2.72	7.77
		Co-located	3.40	1.86	4.94	
		Target on right side	−4.93	−6.37	−3.49	8.33
	Reverberant	Target on left side	2.17	1.01	3.32	4.20
		Co-located	6.37	5.27	7.47	
		Target on right side	0.37	−1.28	2.01	6.00
MNH	Anechoic	Ipsilateral	2.17	0.52	3.82	4.20
		Co-located	6.37	4.83	7.90	
		Contralateral	6.90	5.46	8.34	−0.53
	Reverberant	Ipsilateral	9.47	8.31	10.62	2.60
		Co-located	12.07	10.97	13.17	
		Contralateral	17.23	15.59	18.88	−5.16
UHL	Anechoic	Ipsilateral	−0.87	−2.52	0.79	3.00
		Co-located	2.13	0.60	3.67	
		Contralateral	3.30	1.86	4.74	−1.17
	Reverberant	Ipsilateral	4.43	3.28	5.59	3.00
		Co-located	7.43	6.33	8.53	
		Contralateral	10.10	8.46	11.74	−2.67

Linear mixed-effect models found that SRTs measured with SSN were significantly degraded by reverberation for the MNH group ($\beta = 4.10$, s.e. $= 0.61$, $t = 6.74$, $p < 0.0001$), while SRTs were less impaired for both the BNH and UHL groups (BNH, $\beta = 1.57$, s.e. $= 0.49$, $t = 3.19$, $p < 0.01$; UHL, $\beta = 2.60$, s.e. $= 0.45$, $t = 5.75$, $p < 0.0001$). However, there was no significant difference in reverberation-induced degradation scores of SRTs among three hearing groups under the co-located condition using SSN (Fig. 3, left panel of the top row). Linear mixed-effect models showed that SRTs measured with TTS were significantly higher for all hearing conditions (BNH, $\beta = 4.43$, s.e. $= 0.49$, $t = 9.04$, $p < 0.0001$; MNH, $\beta = 5.10$, s.e. $= 0.61$, $t = 8{,}38$, $p < 0.0001$; UHL, $\beta = 3.78$, s.e. $= 0.45$, $t = 8.36$, $p < 0.0001$). There were significant interactions between masker type and environment in all three groups (BNH, $\beta = 1.40$, s.e. $= 0.69$, $t = 2.02$, $p < 0.05$; MNH, $\beta = 1.60$, s.e. $= 0.86$, $t = 1.86$, $p = 0.06$; UHL, $\beta = 3.02$, s.e. $= 0.64$, $t = 4.73$, $p < 0.0001$; i.e., reverberation had a greater effect on SRTs in the presence of TSS compared to SSN). There was no significant difference in reverberation-induced degradation scores of SRTs among three hearing groups under the co-located condition using TSS (Fig. 3, right panel of the top row).

Linear mixed-effect models showed that SRTs were significantly improved by the change of the target location away from the masker (i.e., a significant benefit of SRM was estimated) for the BNH group (ipsilateral condition, $\beta = -5.30$, s.e. $= 0.49$, $t = -10.80$, $p < 0.0001$; contralateral

TABLE III. Results from linear mixed-effect regression models analyzing speech reception thresholds for each of the binaural normal hearing (BNH), monaural normal hearing (MNH), and unilateral hearing loss (UHL) groups.[a]

Listening group	Variable	β	s.e.	t value	p value
BNH	Intercept	−2.12	1.25	−1.70	0.12
	Configuration (left)	−5.30	0.49	−10.80	**<0.0001**
	Configuration (right)	−5.97	0.49	−12.16	**<0.0001**
	Environment (Rev)	1.57	0.49	3.19	**<0.01**
	Masker (TSS)	4.43	0.49	9.04	**<0.0001**
	Left:Rev	0.97	0.69	1.39	0.16
	Right:Rev	1.87	0.69	2.69	**<0.01**
	Left:TSS	−2.47	0.69	−3.56	**<0.001**
	Right:TSS	−2.37	0.69	−3.41	**<0.001**
	Rev:TSS	1.40	0.69	2.02	**<0.05**
	Left:Rev:TSS	2.60	0.98	2.65	**<0.01**
	Right:Rev:TSS	0.47	0.98	`0.48	0.63
	Gold-MSI score	0.01	0.02	0.94	0.38
MNH	Intercept	0.87	1.70	0.51	0.62
	Configuration (Ipsi)	−2.97	0.61	−4.87	**<0.0001**
	Configuration (Contra)	1.23	0.61	2.03	**<0.05**
	Environment (Rev)	4.10	0.61	6.74	**<0.0001**
	Masker (TSS)	5.10	0.61	8.38	**<0.0001**
	Ipsi:Rev	1.17	0.86	1.36	0.18
	Contra:Rev	5.87	0.86	6.81	**<0.0001**
	Ipsi:TSS	−1.23	0.86	−1.43	0.15
	Contra:TSS	−0.70	0.86	−0.81	0.42
	Rev:TSS	1.60	0.86	1.86	0.06
	Ipsi:Rev:TSS	0.43	1.22	0.36	0.72
	Contra:Rev:TSS	−1.23	1.22	−1.01	0.31
	Gold-MSI score	0.01	0.02	0.26	0.80
UHL	Intercept	1.08	1.31	0.82	0.42
	Configuration (Ipsi)	−3.73	0.45	−8.26	**<0.0001**
	Configuration (Contra)	1.18	0.45	2.61	**<0.01**
	Environment (Rev)	2.60	0.45	5.75	**<0.0001**
	Masker (TSS)	3.78	0.45	8.36	**<0.0001**
	Ipsi:Rev	1.07	0.64	1.67	0.10
	Contra:Rev	2.38	0.64	3.72	**<0.001**
	Ipsi:TSS	0.93	0.64	1.46	0.14
	Contra:TSS	−0.18	0.64	−0.28	0.78
	Rev:TSS	3.02	0.64	4.73	**<0.0001**
	Ipsi:Rev:TSS	−1.20	0.90	−1.33	0.18
	Contra:Rev:TSS	−0.29	0.90	−0.32	0.75
	Gold-MSI score	−0.03	0.02	−1.75	0.10

[a]Note: The reference conditions for comparisons regarding configuration, environment, and masker are co-located condition, anechoic environment, and speech-shaped noise, respectively. Colons indicate the interaction between the variables. Significant p values are shown in bold. Ipsi, ipsilateral condition; Contra, contralateral condition; Rev, reverberant environment; TSS, two same-talker speech; Gold-MSI, Goldsmiths Musical Sophistication Index.

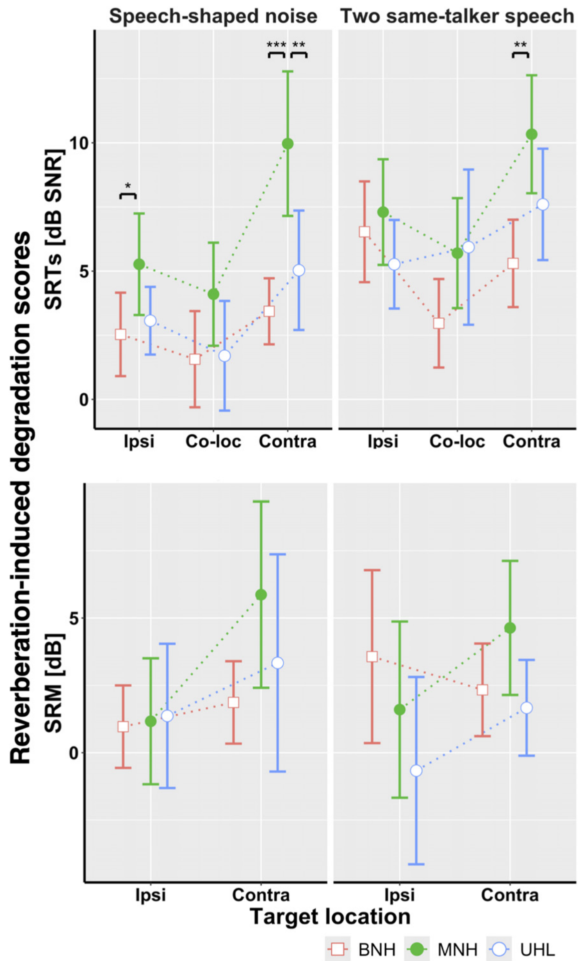

FIG. 3. The reverberation-induced degradation scores of speech reception thresholds (SRTs) and spatial release from masking (SRM). For SRTs, the scores were obtained by subtracting the SRTs in the anechoic environment from those in the reverberant environment (top row). For SRM, they were calculated by subtracting the SRM in the reverberant environment from that in the anechoic environment (bottom row). The left and right panels indicate these scores measured with speech-shaped noise and two same-talker speech, respectively. Higher scores represent a greater impact of reverberation on SRTs and SRM. There were three configuration conditions: (1) the co-located target condition (Co-loc), (2) the ipsilateral target condition (Ipsi), and (3) the contralateral target condition (Contra). In addition, there were three hearing conditions: (1) binaural normal hearing (BNH; $n = 10$), (2) monaural normal hearing (MNH; $n = 10$), and (3) unilateral hearing loss (UHL; $n = 10$). For the BNH group, the target was located on the left under the ipsilateral condition and right under the contralateral condition (i.e., the BNH group always had ipsilateral target signal for these conditions). Note that the data from UHL participants aged 50 years or older and a UHL participant who had relatively better hearing thresholds at lower frequencies are excluded for this comparison. Symbols and error bars indicate the mean and 95% confidence intervals, respectively, for each hearing condition, as described in the legend. ***, $p < 0.001$; **, $p < 0.01$; *, $p < 0.05$.

condition, $\beta = -5.97$, s.e. $= 0.49$, $t = -12.16$, $p < 0.0001$), with significant interactions between the configuration and masker type (ipsilateral/TSS condition, $\beta = -2.47$, s.e. $= 0.69$, $t = -3.56$, $p < 0.001$; contralateral/TSS condition, $\beta = -2.37$, s.e. $= 0.69$, $t = -3.41$, $p < 0.001$; i.e., the benefit of SRM was significantly greater in the presence of TSS). However, a smaller amount of SRM was estimated under the ipsilateral condition for both the MNH and UHL groups (MNH, $\beta = -2.97$, s.e. $= 0.61$, $t = -4.87$, $p < 0.0001$; UHL, $\beta = -3.73$, s.e. $= 0.45$, $t = -8.26$, $p < 0.0001$). Additionally, a negative amount of SRM was estimated for the contralateral condition for both the MNH and UHL groups (MNH, $\beta = 1.23$, s.e. $= 0.61$, $t = 2.03$, $p = < 0.05$; UHL, $\beta = 1.18$, s.e. $= 0.45$, $t = 2.61$, $p < 0.01$). For the MNH and UHL groups, there were no significant interactions between the configuration and masker type, in contrast to the BNH group.

Linear mixed-effect models found significant interactions between the configuration and environment, particularly for the contralateral condition of the MNH group ($\beta = 5.87$, s.e. $= 0.86$, $t = 6.81$, $p < 0.0001$; i.e., reverberation was estimated as a significant factor degrading the amount of SRM). There were significant differences in reverberation-induced degradation scores of SRTs between BNH vs MNH under the ipsilateral condition (using SSN, $\beta = -2.73$, s.e. $= 1.08$, $t = -2.53$, $p < 0.05$) and the contralateral condition (using SSN, $\beta = -6.53$, s.e. $= 1.34$, $t = -4.86$, $p < 0.001$; using TSS, $\beta = -5.03$, s.e. $= 1.42$, $t = -3.55$, $p < 0.01$) (Fig. 3, top row). On the other hand, although there was no significant difference, linear mixed-effect models found a better amount of SRM for the contralateral condition in the reverberant environment for the UHL group compared to the MNH group ($\beta = 2.38$, s.e. $= 0.64$, $t = 3.72$, $p < 0.001$) (see Sec. III A and Fig. 2). There were significant differences in reverberation-induced degradation scores of SRTs between MNH vs UHL under the contralateral condition (using SSN, $\beta = 4.74$, s.e. $= 1.23$, $t = 3.87$, $p < 0.01$) (Fig. 3, left panel of the top row). Linear mixed-effect models also found significant interaction among all the three factors for the BNH group (ipsilateral/reverberant/TSS condition, $\beta = 2.60$, s.e. $= 0.98$, $t = 2.65$, $p < 0.01$; i.e., the benefit of SRM in the presence of TSS was significantly degraded by reverberation). This interaction was not found for the MNH and UHL groups, in contrast to the BNH group. There was no significant difference in reverberation-induced degradation scores of SRM among the three hearing groups for both the ipsilateral and contralateral conditions (Fig. 3, bottom row).

C. Association between demographic factors and results

For analysis of the factors related to SRT and SRM, we included the extracted data from older participants of the UHL group (aged 50 years or older) and a UHL participant who had relatively better hearing thresholds at lower frequencies. In addition, the other demographic factors of the participants were included as fixed independent variables in the liner mixed-effect model and model fittings were carried out using the step function from the *lmerTest* package (Kuznetsova *et al.*, 2017).

For the BNH group, linear mixed-effect models found that only age was correlated with SRTs measured under the anechoic contralateral target condition with TSS ($\beta = -0.94$, s.e. $= 0.35$, $t = -2.66$, $p < 0.05$). For the MNH group, linear mixed-effect models also found that only age was correlated with SRTs measured under the reverberant ipsilateral target condition with TSS ($\beta = -0.75$, s.e. $= 0.26$, $t = -2.94$, $p < 0.01$). It was estimated that male participants in the MNH group showed significantly less SRM than female participants ($\beta = -3.17$, s.e. $= 1.19$, $t = -2.67$, $p < 0.05$). However, under the other conditions, neither age nor sex was correlated with SRTs and the amount of SRM. Similarly, other demographic factors, including the Gold-MSI score, showed no significant correlation with SRTs and the amounts of SRM for both the BNH and MNH groups.

On the other hand, linear mixed-effect models showed that Gold-MSI score, age, and side of HL were the main factors significantly correlated with SRTs and/or the amounts of SRM for the UHL group, particularly under the conditions using SSN. Table IV provides the results from the regression models after model fitting. Figures 4 and 5 show scatterplots, which were only and all the significant correlations. Figure 4 illustrates the SRTs and amount of SRM as a function of the Gold-MSI score. Figure 5 illustrates the SRTs and amounts of SRM as a function of the participants' age.

The linear mixed-effect models found significant negative correlations between the Gold-MSI score and SRTs measured with SSN, meaning that participants with higher musical ability tended to have better speech intelligibility. This was observed in the anechoic environment [ipsilateral condition, $\beta = -0.05$, s.e. $= 0.02$, $t = -2.58$, $p < 0.05$; Fig. 4(A)] and reverberant environment [ipsilateral condition, $\beta = -0.06$, s.e. $= 0.02$, $t = -2.76$, $p < 0.05$, Fig. 4(B); contralateral condition, $\beta = -0.06$, s.e. $= 0.02$, $t = -2.61$, $p < 0.05$, Fig. 4(C)] for the UHL group. Additionally, there was a significant positive correlation between the Gold-MSI score and the amount of SRM measured in the reverberant environment with SSN [contralateral condition, $\beta = 0.08$, s.e. $= 0.02$, $t = 3.26$, $p < 0.01$, Fig. 4(D)].

The linear mixed-effect models also found that there was a significant positive correlation between the participants' age and SRTs measured with SSN, indicating the participants with older age tended to show degraded speech intelligibility. This was observed in the reverberant environment [contralateral condition, $\beta = 0.12$, s.e. $= 0.04$, $t = 3.02$, $p < 0.05$; Fig. 5(A)]. Moreover, there was a significant negative correlation between the participants' age and the amount of SRM for that condition [$\beta = -0.15$, s.e. $= 0.04$, $t = -3.59$, $p < 0.01$; Fig. 5(B)].

The linear mixed-effect models showed that the participants with right-sided UHL tended to have significantly higher SRTs (i.e., degraded speech intelligibility) compared to those with left-sided UHL. This trend was found for the SRTs measured with SSN in the anechoic environment (co-located condition, $\beta = 1.44$, s.e. $= 0.66$, $t = 2.20$, $p < 0.05$; ipsilateral condition, $\beta = 1.73$, s.e. $= 0.80$, $t = 2.16$, $p < 0.05$) and reverberant environment (ipsilateral condition, $\beta = 2.25$, s.e. $= 0.99$, $t = 2.27$, $p < 0.05$). Additionally, the participants with right-sided UHL tended to have significantly lower SRM compared to those with left-sided UHL. This was observed for the measurements with TSS in the anechoic environment (ipsilateral condition, $\beta = -2.66$, s.e. $= 1.18$, $t = -2.25$, $p < 0.05$) and with SSN in the reverberant environment (contralateral condition, $\beta = -2.64$, s.e. $= 1.08$, $t = -2.44$, $p < 0.05$). On the other hand, an opposite trend was found for the measurements with TSS in the reverberant environment (contralateral condition, $\beta = 1.71$, s.e. $= 0.70$, $t = 2.46$, $p < 0.05$).

The linear mixed-effect models showed that the participants with congenital UHL had a significantly better amount of SRM compared to those with acquired UHL for

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TABLE IV. Results from linear mixed-effect regression models (after model fitting) analyzing speech reception thresholds (SRTs) and the amount of spatial release from masking (SRM) in (a) anechoic and (b) reverberant environments for the UHL group.[a]

Environment							
SSN or TSS	SRT or SRM	Configuration	Variable	β	s.e.	*t* value	*p* value
(a) Anechoic							
SSN	SRT	Co-located	Intercept	−0.16	1.20	−0.13	0.90
			Gold-MSI score	−0.02	0.02	−1.42	0.18
			Side of HL (right)	1.44	0.66	2.20	**<0.05**
		Ipsilateral	Intercept	−2.40	1.47	−1.64	0.13
			Gold-MSI score	−0.05	0.02	−2.58	**<0.05**
			Side of HL (right)	1.73	0.80	2.16	**<0.05**
	SRM	Ipsilateral	Intercept	2.73	1.18	2.32	**<0.05**
			Age	0.03	0.03	1.04	0.32
			Onset (congenital)	1.51	0.68	2.23	**<0.05**
TSS	SRT	Contralateral	Intercept	2.10	2.18	0.96	0.36
			Age	0.05	0.03	1.37	0.20
			Duration of HL	0.04	0.03	1.41	0.18
			Gold-MSI score	−0.02	0.02	−1.06	0.31
	SRM	Ipsilateral	Intercept	4.29	0.89	4.84	**<0.001**
			Side of HL (right)	−2.66	1.18	−2.25	**<0.05**
(b) Reverberant							
SSN	SRT	Ipsilateral	Intercept	2.15	1.81	1.18	0.26
			Gold-MSI score	−0.06	0.02	−2.76	**<0.05**
			Side of HL (right)	2.25	0.99	2.27	**<0.05**
		Contralateral	Intercept	2.91	2.76	1.05	0.31
			Sex (male)	1.98	1.09	1.82	0.10
			Age	0.12	0.04	3.02	**<0.05**
			Gold-MSI score	−0.06	0.02	−2.61	**<0.05**
			Side of HL (right)	1.85	0.99	1.86	0.09
	SRM	Contralateral	Intercept	2.31	3.02	0.77	0.46
			Age	−0.15	0.04	−3.59	**<0.01**
			Gold-MSI score	0.08	0.02	3.26	**<0.01**
			Side of HL	−2.64	1.08	−2.44	**<0.05**
TSS	SRT	Ipsilateral	Intercept	0.15	1.67	0.09	0.93
			Age	0.06	0.04	1.56	0.14
			Side of HL (right)	1.96	1.0.7	1.83	0.09
	SRM	Contralateral	Intercept	−7.63	3.25	−2.35	**<0.05**
			Age	−0.05	0.03	−1.75	0.11
			Side of HL (right)	1.71	0.70	2.46	**<0.05**
			Degree of HL	0.06	0.03	1.92	0.08

[a]Note: The reference conditions for comparisons regarding (1) side of HL, (2) onset, and (3) sex are (1) left, (2) acquired, and (3) female, respectively. Significant *p* values are shown in bold. SSN, speech-shaped noise; TSS, two same-talker speech; Gold-MSI, Goldsmiths Musical Sophistication Index; HL, hearing loss.

measurement using SSN in the anechoic environment ($\beta = 1.51$, s.e. $= 0.68$, $t = 2.23$, $p < 0.05$). However, the models did not show similar trends for the SRTs. Other demographic factors, including the degree of HL in the impaired ear, were neither selected as a result of model fitting nor significantly correlated with the results (Table IV).

On the other hand, the participant with relatively better hearing thresholds at low frequencies (30 dB HL at 125 and 250 Hz and 55 dB HL at 500 Hz, with no responses at higher remaining frequencies; P# 05 in Table I and Fig. 1) showed a better amount of SRM in the anechoic environment, even under the contralateral condition (with SSN, 6.33 dB/5.00 dB for the ipsilateral/contralateral condition; with TSS, 2.67 dB/1.67 dB for the ipsilateral/contralateral condition). However, this participant did not show the benefit of SRM under the contralateral condition in the reverberant environment measured with SSN (−1.67 dB/−5.00 dB for the ipsilateral/contralateral condition), while exhibiting a similar amount of SRM under the contralateral condition measured with TSS (11.3 dB/1.33 dB for the ipsilateral/contralateral condition) compared to the anechoic environment.

IV. DISCUSSION

A. Reverberation degraded speech intelligibility and its impact was greatest when the target sound was located on the impaired ear side for participants with UHL

One goal of this study was to investigate the impact of the reverberation on speech intelligibility and SRM for

https://doi.org/10.1121/10.0036462

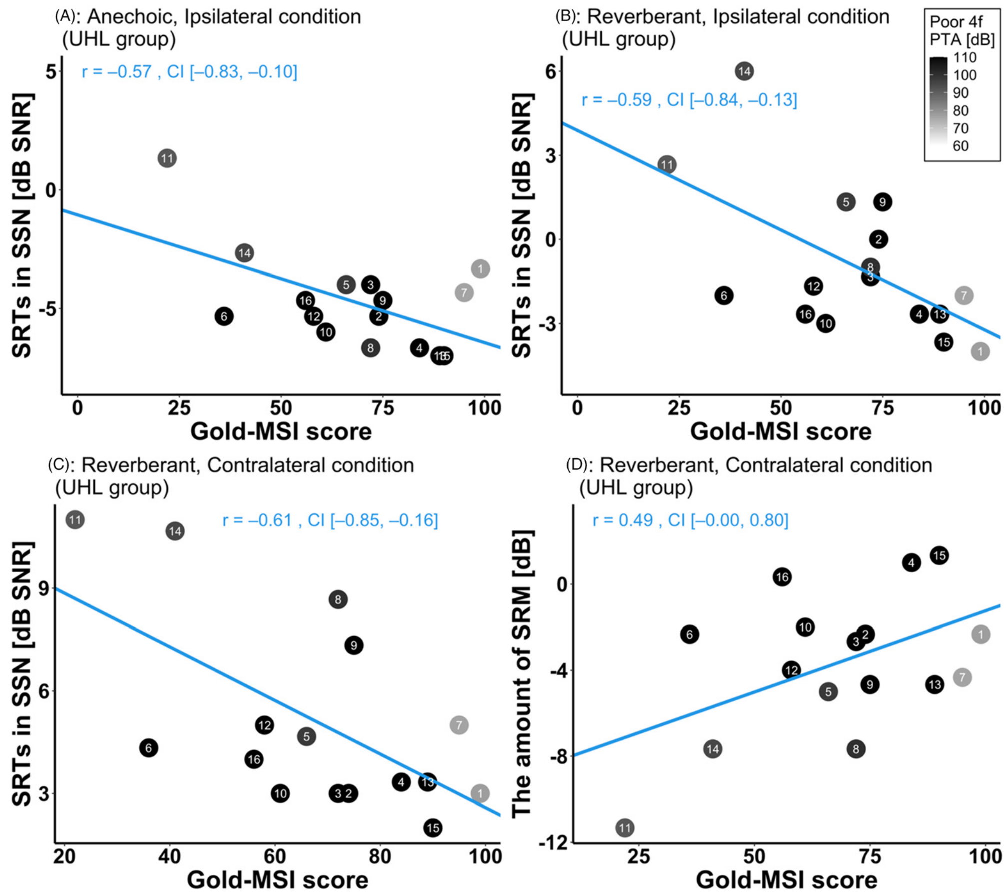

FIG. 4. Regression lines for the participant's Goldsmiths Musical Sophistication Index (Gold-MSI) scores of the UHL group on the speech reception thresholds (SRTs) and the amount of spatial release from masking (SRM) measured with speech-shaped noise (SSN). The correlation coefficients and 95% confidence intervals are also given. Each panel shows the correlation of the results measured under the following conditions: (A) anechoic environment, ipsilateral condition; (B) reverberant environment, ipsilateral condition; (C) reverberant environment, contralateral condition; and (D) reverberant environment, contralateral condition.

people with UHL. For this purpose, SRTs and the amounts of SRM measured in an anechoic environment were compared to those measured in a reverberant environment for the BNH, MNH, and UHL groups.

As expected from previous studies (Deroche *et al.*, 2017; Kidd *et al.*, 2005; Marrone *et al.*, 2008; Tsuji and Arai, 2023), participants demonstrated degraded speech intelligibility and amount of SRM in the reverberant

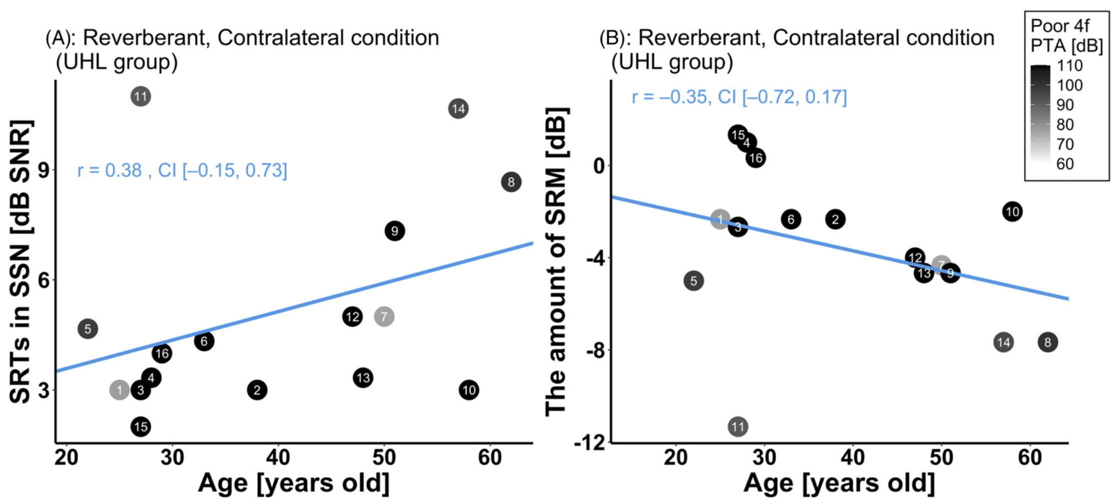

FIG. 5. Regression lines for the participant's age of the UHL group on the speech reception thresholds (SRTs) and the amount of spatial release from masking (SRM) measured with speech-shaped noise (SSN). The correlation coefficients and 95% confidence intervals are also given. Each panel shows the correlation of the results measured in the reverberant environment under the contralateral condition.

environment compared to the anechoic environment (Fig. 2, left panel vs right panel of each column; Fig. 3). The impact of reverberation was much larger for the MNH and UHL groups. On the other hand, the BNH group was less affected by reverberation (Fig. 2 and Table III). There were significant differences in reverberation-induced degradation scores of SRTs between the BNH and MNH groups for the ipsilateral target condition using SSN, as well as for all the contralateral conditions (Fig. 3, top row). The binaural squelch effect (Koenig, 1950; Lavandier and Culling, 2008; Nábělek and Robinson, 1982) and binaural release from overlap-masking (Libbey and Rogers, 2004) may explain this result.

In our previous research (Tsuji and Arai, 2023), SRTs and the amounts of SRM were measured only in a reverberant environment with SSN, and it did not include the contralateral target condition. For the UHL group, SRTs and the amounts of SRM measured in the current study were consistent with those reported under the same conditions (the reverberant co-located/ipsilateral target conditions) in our previous research (Tsuji and Arai, 2023). Additionally, compared to other conditions within the UHL group, the current study revealed that the impact of reverberation on the negative amount of SRM was greatest when the target sound was located on the impaired ear side, leading to degraded speech intelligibility (Fig. 2, right panels of each column). The impact of reverberation for elderly people and individuals with HL has been well known (Harris and Reitz, 1985; Nábělek and Mason, 1981; Reinhart and Souza, 2018a). In the current study, it was revealed that the reverberation has an impact on speech intelligibility for individuals with UHL as well as those populations.

Moreover, there was an interaction between reverberation and informational masking that led to degraded speech intelligibility and amount of SRM (Table III). For example, in the anechoic environment, higher SRTs caused by TSS were released by a larger amount of SRM for the BNH group, resulting in similar SRTs to those measured with SSN [Fig. 2, left columns in panel (A) vs panel (B)]. In the reverberant environment, however, the amount of SRM measured with TSS was decreased (this degradation was estimated significant in the reverberant/ipsilateral/TSS condition; Table III), leading to degraded SRTs compared to those measured with SSN for the BNH group [Fig. 2, right columns in panel (A) vs (B)], which was also demonstrated in a previous study (Deroche *et al.*, 2017). On the other hand, the MNH and UHL groups did not show this interaction (Table III), resulting in a similar pattern in the amount of SRM (Fig. 2, bottom row). As one of the factors for this result, the SRT ceiling effect due to positive SNR has been discussed (Arbogast *et al.*, 2005; Deroche *et al.*, 2017). For example, Best *et al.* (2012) compared the amounts of SRM measured for participants with NH to those measured for participants with HL. They used the coordinate response measure (CRM) speech identification test (Bolia *et al.*, 2000), which is similar to our methods in terms of obtaining SRTs by changing SNR of the target speech and masker, with two-talker speech as the informational masker and its time-reversed speech (i.e., removing semantic information from the speech) as the energetic masker. They found that participants with HL showed a decreased amount of SRM compared to those with NH, particularly under the two-talker speech (Best *et al.*, 2012). Regarding that result, Deroche *et al.* (2017) pointed out the SRT ceiling effect, meaning that the participants with HL may have been able to segregate the target speech from the competing masker using loudness as a salient cue when the SNR was positive, as suggested by Arbogast *et al.* (2005). Nevertheless, the results in the current study confirmed a degrading effect of informational masking on speech intelligibility for the UHL group [Fig. 2, panel (A) vs (B)], consistent with previous studies (Corbin *et al.*, 2021; Marrone *et al.*, 2008; Rothpletz *et al.*, 2012). These results gave evidence for a part of the difficulties in daily life encountered by individuals with UHL (Colletti *et al.*, 1988; Iwasaki *et al.*, 2013; Meehan *et al.*, 2017).

B. Our participants with long-standing UHL showed reduced effects of reverberation and informational masking compared to a listening group simulating the listening situation immediately after the onset of UHL

The other objective of the current study was to assess the adaptation for individuals with UHL. For this purpose, we compared SRTs and the amount of SRM measured for the UHL group to those measured for the MNH group, which simulated the listening situation immediately after the onset of UHL. The data from participants with UHL aged 50 years or older were excluded for this comparison, considering the effect of aging (Goossens *et al.*, 2017), so the MNH group data were compared to the younger participants with long-standing UHL (duration of HL of at least 15 years or longer; Table I). Even after this exclusion, significant differences in mean age and 4fPTA remained between the MNH and UHL groups, which would be expected to lead to poorer results in the UHL group.

As a result, however, the UHL group demonstrated significantly better speech intelligibility compared to the MNH group, resulting in similar SRTs to the BNH group for all co-located conditions and some ipsilateral conditions. For these conditions, there was no significant difference between the BNH group and the UHL group (Fig. 2, top row). In our previous research, which did not include the contralateral condition and was conducted only in a reverberant environment, the same results were observed (Tsuji and Arai, 2023). Additionally, the effect of configuration where the target was located contralaterally to the good-hearing/presented side was investigated in the current study. As a result, in the reverberant environment, the MNH group showed remarkable degradation in the amount of SRM for the contralateral condition, while the UHL group demonstrated less degradation in SRM, leading to significantly better speech intelligibility (Fig. 2 and Table III). This was not observed in the anechoic environment. There was a significant difference in reverberation-induced degradation scores of SRTs between the MNH and UHL groups for the contralateral condition with SSN (Fig. 3, top row). Moreover, the effect of informational masking was larger for the MNH group, while the UHL group showed some release from it in the anechoic environment [Fig. 2, panel (A) vs panel (B)]. The difference in performance between the UHL group and the MNH group decreased in the reverberant environment, probably due to the SRT ceiling effect caused by the too high SNR (see the last paragraph of Sec. IV A). Nevertheless, these results were consistent with previous studies, which have reported that individuals with long-standing UHL show adaptation in some aspects of hearing (Kim *et al.*, 2021; Litovsky *et al.*, 1997; Liu *et al.*, 2018; Tsuji and Arai, 2020, 2023).

For example, individuals with UHL could judge the direction of sound sources using HRTFs as a cue instead of ITDs and ILDs (Firszt *et al.*, 2015; Kim *et al.*, 2021). Kim *et al.* (2021) conducted research targeting sound localization using monaural level cues caused by HRTF for individuals with profound UHL (SSD). They found that the localization performance on the impaired ear side was improved with longer duration of SSD and younger age at SSD onset. Additionally, this improvement in localization on the impaired ear side was related to changes in the cortical structure, which are associated with auditory spatial processing for their participants with right-sided SSD (Kim *et al.*, 2021), as a kind of the cortical plasticity and reorganization observed in individuals with UHL (Propst *et al.*, 2010; Sharma *et al.*, 2016). Liu *et al.* (2018) found a significant positive correlation between the sound localization accuracy and duration of SSD. Although the difference was not statistically significant, the duration of SSD was also associated with lower SRTs (i.e., better speech intelligibility) (Liu *et al.*, 2018). It is well known that the precedence effect has a big role for hearing in reverberant environments (Litovsky *et al.*, 1999). While the precedence effect is often discussed as one of the binaural advantages, at least fusion of the direct sound and its reflection was observed under diotic and monaural conditions (Litovsky *et al.*, 1997; Litovsky *et al.*, 1999). For example, Litovsky *et al.* (1997) found that participants with SSD demonstrated a similar degree of fusion compared to participants with NH. However, this phenomenon is considered to be due to different processing from fusion in binaural hearing, and there would be adaptation to monaural processing for people with UHL (Litovsky *et al.*, 1999). Thus, it is suggested that the adaptation to some monaural cues could occur under reverberation, resulted in better speech intelligibility for individuals with UHL in the current study, consistent with our previous research (Tsuji and Arai, 2023).

On the other hand, it would likely be difficult to spatially distinguish the target and masker at $\pm 35°$ separation used in the current study, given the level of localization performance in individuals with UHL. For example, Firszt *et al.* (2015) showed mean RMS errors of about $30°-40°$ in individuals with SSD without any localization training. Bernstein *et al.* (2022) reported that mean localization errors were about $50°$ under more complex conditions with multiple sound sources, which is similar to the condition with TSS in our experiment. Additionally, Rothpletz *et al.* (2012) found no significant correlation between localization accuracy and SRTs at $\pm 90°$ separation. These findings suggest that localization ability would not be a contributing factor to SRM in the UHL and MNH groups in the current study. Instead, it is possible that improved monaural speech-in-noise or monaural selective attention contributed to the adaptation observed in the UHL group, rather than spatial hearing ability.

Regarding another aspect of hearing, Meehan *et al.* (2017) conducted a questionnaire survey mainly focused on musical appreciation targeting individuals with acquired SSD. As a result, their participants rated music as sounding more “unnatural,” “unpleasant,” and “indistinct” compared to before the onset of SSD. These changes led to degraded musical appreciation, such as less enjoyment of music (Meehan *et al.*, 2017). More recently, Tsuji and Arai (2020) conducted a questionnaire survey, which was similar to that of Meehan *et al.* (2017) but added the perspective of listeners immediately after the onset of UHL. As a result, it was revealed that the effect of UHL on music appreciation was serious immediately after the onset of UHL. However, some improvements in how music sounded were observed, resulting in recovery of music appreciation as experienced before the onset of UHL for some of the participants (Tsuji and Arai, 2020). This result was highly relevant to the adaptation to reverberation observed in the current study considering the importance of reverberation on music (Kuhl, 1954; Reinhart and Souza, 2018b).

C. Musical ability, age, and the side of HL were associated with speech intelligibility and amount of spatial release from masking

In the UHL group, there was a significant association that participants with higher Gold-MSI scores tended to have better speech intelligibility and a larger amount of SRM, particularly in the reverberant environment (Fig. 4 and Table IV). On the other hand, the Gold-MSI score was not correlated for the BNH and MNH groups. While there are many findings regarding the effectiveness of musical training on speech intelligibility, results have not been consistent both for individuals with NH (Madsen *et al.*, 2019; Meha-Bettison *et al.*, 2018; Slater *et al.*, 2015) and those with HL (Lo *et al.*, 2020; McKay, 2021). As part of a study conducted by Siedenburg *et al.* (2020), the contribution of musical training to SRTs was assessed for young participants with NH and old participants with HL using a subset of the Gold-MSI score, which is similar to our current study in terms of the using of the Gold-MSI score. As a result, there was no correlation between SRTs and musical training score (Siedenburg *et al.*, 2020), supporting a suggestion that the effect of musical training would appear only in purely auditory tasks but not in tasks related to speech processing (Madsen *et al.*, 2019). In the current study, a significant association of the Gold-MSI score was found only for SRTs measured with SSN, particularly in reverberant environment. In contrast, the Gold-MSI score was not significantly correlated to SRTs measured with TSS. Thus, results in the current study suggested that musical ability contributed to a part of hearing under reverberation, which might be related to fundamental auditory processing rather than speech processing.

There was also a significant association that older participants tended to show degraded SRTs and amounts of SRM under the reverberant contralateral condition (Fig. 5 and Table IV). This result is consistent with previous studies discussing the greater degrading effect of reverberation on speech intelligibility for an elderly population with both NH and HL compared to a young population with NH (Harris and Reitz, 1985; Nábělek and Mason, 1981; Reinhart and Souza, 2018a). For very small separations between the target and maskers, Srinivasan *et al.* (2016) found that a young NH group showed the benefit of SRM even at $\pm 2°$ separation, whereas an older NH group required relatively more separation of $\pm 6°$, suggesting that aging would be a predictive factor for SRM. For a much larger separation of $\pm 45°$, however, previous studies have shown that participants' age was not correlated with the amount of SRM, at least in non-reverberant environments, when using both headphones and loudspeakers for binaural presentation (Jakien *et al.*, 2017; Jakien and Gallun, 2018). In contrast, the results of the current study revealed an interaction between the effect of aging and reverberation in individuals with UHL, particularly under the contralateral target condition.

There was another significant trend that the participants with right-sided UHL tended to show poorer SRTs and a decreased amount of SRM compared to those with left-sided UHL (Table IV). Previous studies have not been consistent regarding the behavioral changes due to the difference of the UHL side. For example, Niedzielski *et al.* (2006) reported that children with right-sided UHL showed lower verbal ability compared to those with left-sided UHL. On the other hand, Lieu *et al.* (2010) found there was no significant difference between right- and left-sided UHL in the scores on the oral portion of the Oral and Written Language Scales. Beyond the behavioral changes, Kim *et al.* (2021) found that changes of the cortical structure were observed and associated with the localization performance only for the participants with right-sided SSD. Conversely, Han *et al.* (2023) reported that participants with left-sided SSD showed more prominent attentional modulation compared to those with right-sided SSD, suggesting that top-down attentional processing can differ, depending on the SSD side. These findings may explain the results of the current study.

Interestingly, for measurements in the anechoic environment with SSN, a larger positive amount of SRM was observed even under the contralateral condition for a participant with relatively good hearing at low frequencies in the HL ear. However, the amount of SRM under the contralateral condition turned negative for measurements in the reverberant environment with SSN, whereas a similar amount of SRM was observed with TSS (see the last paragraph of Sec. III C). This result might be associated with difficulties in understanding speech under reverberation for an elderly population, who typically have HL at high frequencies and relatively preserved hearing thresholds at low frequencies (Harris and Reitz, 1985; Nábělek and Mason, 1981; Reinhart and Souza, 2018a). It might be suggested that hearing thresholds at high frequencies have an important role to obtain SRM, particularly under reverberation. Further work should be conducted to determine the hearing mechanisms in reverberant environments for individuals with UHL.

D. Limitations

In the current study, an investigation of adaptation is obtained by the comparison between the MNH and UHL groups, realized by convolving binaural impulse responses of dummy head recording (generic HRTF) and presenting the sound monaurally via the headphones, which was similar to our previous research (Tsuji and Arai, 2023). However, while previous studies reported that the duration of UHL was correlated to behavioral results (Kim *et al.*, 2021; Liu *et al.*, 2018; Tsuji and Arai, 2023), the duration of UHL was not correlated with SRTs and the amounts of SRM in the current study. This discrepancy might be due to the use of generic HRTF, as participants with long-standing UHL may have developed monaural localization skills (Firszt *et al.*, 2015; Kim *et al.*, 2021), enhancing their spectral discrimination. Although there is a difference between acoustical cues provided by generic HRTF and HRTF of our own, previous research has often investigated SRM in virtual environments created from generic HRTF (Jakien *et al.*, 2017; Jakien and Gallun, 2018; Srinivasan *et al.*, 2016; Zenke and Rosen, 2022). Regarding the difference in presentation between headphones (i.e., generic HRTF) and loudspeakers (i.e., individualized HRTF), Jakien and Gallun (2018) reported that $\pm 45°$ separation of target and maskers was required with headphones to achieve the same amount of SRM as that obtained with $\pm 30°$ separation with loudspeaker presentation. On the other hand, Zenke and Rosen (2022) found no difference in the amount of SRM between individualized and generic HRTFs in children or adults for $\pm 90°$ separation of target and maskers, larger than that in the current study. They also suggested that spatial cue accuracy might play a more critical role at smaller separation angles (Zenke and Rosen, 2022). Given that our participants with UHL might be more sensitive to spectral cue errors due to enhanced monaural localization skills, further research should be conducted in the actual sound field.

Another limitation is the SRT ceiling effect when measuring SRTs under the influence of informational masking. This occurred because participants could obtain better SRTs by relying on loudness when the SNR was positive, as suggested by previous studies (Arbogast *et al.*, 2005; Deroche *et al.*, 2017). Experimental design should be considered to avoid the SRT ceiling effect for further research. Additionally, the MNH group was not sufficiently designed as a control group in the current study due to significant differences in mean age and 4fPTA between the MNH and UHL groups. Given the lower mean age and 4fPTA in the MNH group compared to the UHL group, poorer results would have been expected for the UHL group. However, the UHL group showed better SRTs and a greater amount of SRM, suggesting that the experience of monaural hearing may be crucial for speech intelligibility in reverberant environments. Further research should include a more rigorously controlled group to investigate the mechanisms underlying adaptation to reverberation.

It was revealed that individuals with UHL would experience difficulties in reverberant environments, particularly immediately after the onset of UHL, suggested by the results from the MNH group. To support people with UHL, many types of hearing devices have been discussed including hearing aids with contralateral routing of signals (CROS) (Harford and Barry, 1965), bone-anchored hearing aids (BAHAs) (Tjellstrom and Hakansson, 1995), and cochlear implantation (Van de Heyning *et al.*, 2008). These devices have demonstrated certain effectiveness in providing SRT benefits, particularly for mitigating the negative amount of SRM under the contralateral target conditions [e.g., Snapp *et al.* (2017)]. However, there are limitations of their effectiveness, high expense, and reservations regarding surgery (Siau *et al.*, 2015). For example, Snapp *et al.* (2017) reported that CROS hearing aids and BAHAs did not improve localization performance of participants with SSD. Körtje *et al.* (2022) investigated the effectiveness of cochlear implant for participants with SSD in a reverberant environment. As a result, it was found that the impact of reverberation on speech intelligibility was much greater for participants with SSD using a cochlear implant compared to the BNH group, indicating a limitation of cochlear implant under reverberation (Körtje *et al.*, 2022). On the other hand, for the sound localization in individuals with UHL, Firszt *et al.* (2015) found that the accuracy of localization could be improved by a localization training without any hearing devices, which emphasizes the necessity of considering of localization training within rehabilitation protocols. Similarly, rehabilitation protocols not only with hearing devices but also without hearing devices should be investigated to obtain earlier adaptation to reverberant environments for individuals with UHL.

V. CONCLUSION

In the current study, it was demonstrated that difficulties could occur in reverberant environments, particularly immediately after the onset of UHL, in addition to the difficulties of individuals with UHL that have been previously mentioned (Harford and Barry, 1965). On the other hand, our participants with long-standing UHL showed better performance in speech intelligibility and the amount of SRM than the MNH group. These results suggested adaptive contribution of some monaural cues under reverberation, which is consistent with our previous research (Tsuji and Arai, 2023). Thus, rehabilitation protocols should be considered to improve hearing for individuals with UHL, particularly immediately after the onset of UHL. Further research should investigate the effect of reverberation not only for better speech intelligibility but also for improved experience of music, which is more associated with reverberant environments to improve the quality of life for people with UHL.

ACKNOWLEDGMENTS

In this paper, we used the Japanese Kamishibai and Audiobook Corpus (J-KAC) provided by the Speech Resources Consortium, National Institute of Informatics. The contents of this study were included in a Ph.D. dissertation of the corresponding author (Tsuji, 2024). We would like to thank Ikuko Yairi, Kenji Kurakata, and Ryo Kawabata for their helpful comments on compiling the Ph.D. dissertation. We would also like to thank Associate Editor Pamela Souza and our anonymous reviewers for their helpful comments on an earlier version of the manuscript and our participants for their patience and time. This work was partly supported by the Japan Society for the Promotion of Science Grant-in-Aid for Scientific Research No. 24K23899.

AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Ethics Approval

This research was approved by the Research Ethics Committee of Sophia University (2021-52). Informed consent was obtained from all participants.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author on reasonable request.

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