Elderly listeners with low intelligibility scores under reverberation show degraded subcortical representation of reverberant speech

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Research article

Elderly listeners with low intelligibility scores under reverberation show degraded subcortical representation of reverberant speech

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HIGHLIGHTS

- Auditory brainstem responses to anechoic and reverberant speech sounds were obtained from 28 elderly listeners (>62 y).
- Listeners with low word intelligibility of reverberant speech showed degraded encoding information of reverberant speech.
- The findings provide initial evidence of subcortical processing deficits in elderly listeners with difficulty in understanding reverberant speech.

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ABSTRACT

In order to elucidate why many elderly listeners have difficulty understanding speech under reverberation, we investigated the relationship between word intelligibility and auditory brainstem responses (ABRs) in 28 elderly listeners. We hypothesized that the elderly listeners with low word intelligibility scores under reverberation would show degraded subcortical encoding information of reverberant speech as expressed in their ABRs towards a reverberant /da/ syllable. The participants were divided into two groups (top and bottom performance groups) according to their word intelligibility scores for anechoic and reverberant words, and ABR characteristics between groups were compared. We found that correlation coefficients between responses to anechoic and reverberant /da/ were lower in the bottom performance group than in the top performance group. This result suggests that degraded neural representation toward information of reverberant speech may account for lower intelligibility of reverberant speech in elderly listeners.

1. Introduction

Reverberation and noise often exist in our daily listening environment. Many elderly listeners, even those with normal hearing, have difficulty understanding speech under reverberation and noise [1,2]. Degraded neural representation of acoustic sounds in elderly listeners is thought to be one of the factors underlying this difficulty understanding speech in such conditions, e.g., due to decreased neural inhibition [3], and temporal jitter [4].

In order to gain insight into the neural representation of speech sounds in noise, some studies have focused on the characteristics of auditory brainstem responses to speech (speech ABRs). The speech ABR is considered an objective indicator of speech processing in the brainstem, since it reflects speech-specific information, i.e., fundamental frequency and vowel formants [5,6]. Anderson et al. reported that the speech ABRs of elderly listeners with low speech-in-noise (SIN) perception had relatively small amplitudes in response to the fundamental frequency (F_0) of a speech stimulus, and lower correlations between responses in quiet and in noise compared to elderly listeners with high SIN perception [7]. These results indicate that elderly listeners' degraded neural representations of the morphology of a speech sound and its F_0 underlie difficulty understanding speech in noise.

Besides the ABR studies on speech perception in noise, however, few studies have concentrated on speech ABRs under reverberation. Reverberation is the continued movement of sound pressure waves as the result of repeated reflections after the initiating stimulus has stopped [8]. Reverberation, therefore, alters the acoustic waveform by smearing dynamic changes in the fine structure over time and reducing the "peakiness" of the waveform's temporal

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envelope [9]. The relation between speech and reverberation is different from that between speech and noise. Whereas speech and noise are generally thought of as arising from independent sources, speech and reverberation are strongly correlated, since the speech sounds themselves overlap with subsequent speech sounds. Therefore, the F_0 of speech, which is thought to be a cue to discriminate one speaker from other speakers and other sounds, might be useful for understanding speech under noise, but might be useless for understanding speech under reverberation.

Recently, we measured word intelligibility under reverberation and the ABRs to a non-reverberant syllable /da/ in elderly listeners. The measurements showed that word intelligibility under reverberation was related to the elderly listeners' ability to encode the temporal fine structure of speech, especially around the frequency of 500 Hz [10]. There was, however, no significant relationship between the elderly listeners' word intelligibility under reverberation and the amplitudes in the ABRs response to the F_0 of a non-reverberant speech stimulus. This result suggests that the factors affecting the difficulty understanding speech under reverberation might be different from those affecting the understanding of speech in noise as regards frequency bands in the speech signal. The effects of *actual* reverberation on speech ABRs in elderly listeners, however, have not been measured yet.

In this study, we measured the ABRs to an anechoic syllable /da/ and a reverberant syllable /da/ in elderly listeners. Furthermore, we assessed the intelligibility of the elderly listeners of words presented under reverberation. Our purpose was to investigate the effects of reverberation on the speech ABRs of the syllable /da/ and how the reverberant speech ABR characteristics would relate to the word intelligibility under reverberation. We hypothesized that the elderly listeners with low word intelligibility scores under reverberation would show degraded subcortical encoding information of reverberant speech.

2. Material and methods

2.1. Participants

Twenty-eight elderly females participated in this study [62–73 years; mean 67.2; standard deviation (SD) 3.7]. Two additional participants were recruited but were excluded from this study because of high artifact content in their electroencephalogram. It has been reported that the amplitudes of the speech ABRs for females are larger than for males [11]. Because we focused on the relationship between speech recognition and neural representation of speech sounds, we carried out the experiment only with a single, coherent participant group – females who showed robust ABR responses. Twenty-four of the 28 participants also participated in our previous study [10].

All participants had thresholds from 250 to 4000 Hz that were ≤30 dB HL, and thresholds at 8000 Hz of ≤50 dB HL at the right ear. The pure tone average differences between the left and right ear were ≤10 dB. All participants had normal click-evoked ABR latencies (wave V ≤ 6.1 ms), measured by a 100-μs click stimulus represented at 101.9 dB peSPL at a rate of 11.1/s). All participants gave written informed consent in accordance with the Institutional Review Board of Kyushu University.

2.2. Word intelligibility task

We obtained word intelligibility scores using the same procedure as in our previous study [10]. The words were four morae selected from Japanese familiarity-controlled word lists 2007 (FW07) [12]. The mora is a unit with which Japanese speakers segment speech streams [13]. We prepared words in four reverberant conditions with reverberation time (RT) of 0 s (anechoic), 0.5 s, 1.0 s and 1.5 s. The RT is defined as the time required for sound to decay sixty decibels from its initial sound level. Participants listened to twenty words per reverberant condition at the right ear. The word intelligibility score was the percentage of the test words for which all four morae were written down correctly.

2.3. Speech ABR measurement

2.3.1. Stimulus and presentation

We measured the speech ABRs in two condition, an anechoic condition (RT = 0 s) and a reverberant condition (RT = 0.5 s). A syllable /da/ with five formants was used to obtain the speech ABRs in the anechoic condition (the 'anechoic syllable'). The duration of the anechoic syllable /da/ was 170 ms, consisting of a formant transition period (0–50 ms) and a steady-state period (50–170 ms). The initial 10-ms in the formant transition period was an onset burst, which was centered at frequencies around F_4 (3300 Hz) and F_5 (3750 Hz). The formant transition period after the onset burst (10–50 ms) comprised of a linearly rising F_1 (400–720 Hz), a linearly falling F_2 (1700–1240 Hz) and F_3 (2580–2500 Hz), and a flat F_4 (3300 Hz) and F_5 (3750 Hz). During the steady-state period (50–170 ms), formant frequencies were held constant and consisted of F_1 (720 Hz), F_2 (1240 Hz), F_3 (2500 Hz), F_4 (3300 Hz) and F_5 (3750 Hz). The period after the onset burst period (10–170 ms) remained constant at the F_0 of 100 Hz. The reverberant syllable /da/ was created by convolving the anechoic syllable /da/ with an impulse response with an RT of 0.5 s as used in the word intelligibility task. The duration of the reverberant syllable was set at 170 ms, similar to the anechoic /da/, by removing the extended portion of the reverberation and by shaping the offset with a 20-ms fall time (cosine-curved). Following this, root-mean-squares of the anechoic and reverberant /da/ were set same. The anechoic and reverberant syllable /da/ are shown in Fig. 1.

An AV tachistoscope (IS-703, Iwatsu) delivered the syllables at random, with an inter-stimulus interval of 60 ms. Each stimulus with condensation and rarefaction polarities was presented 2000 times, making a total of 4000 times. The anechoic and reverberant syllable /da/ were presented at 70 dB SPL to the right ear through an amplifier (TA-DE 590, SONY) and a magnetically-shielded, inserted earphone (ER-3A, Etymotic Research).

2.3.2. Recording parameters

The speech ABRs were obtained using an electroencephalography apparatus (EEG 1200, NIHON KOHDEN) in continuous mode. Responses were obtained using Ag-AgCl disc electrodes from Cz referenced to the right earlobe, with the forehead as ground, were digitized at 10 kHz. Electrode impedances were maintained below 5 kΩ. The continuous recordings were filtered between 70 and 2000 Hz, and artifact rejected (±35 μV) with Matlab version 7.7 (The MathWorks, Inc.).

2.4. Data analysis

Two average responses were calculated for subsequent analyses, similar to earlier studies [5,10,14]. First, an equal number of responses to each polarity was added and divided by the total number of responses to minimize the influence of cochlear microphonic and stimulus artifacts on the response [15,16]. The average responses calculated with the addition method were called "ADD responses". Second, responses to the inverted stimulus were subtracted from an equal number of responses to the original stimulus and divided by the total number of responses. These average responses calculated with the subtraction method were called "SUB responses". It has been said that the ADD responses relate to the stimulus envelope, and the SUB responses to temporal fine struc-

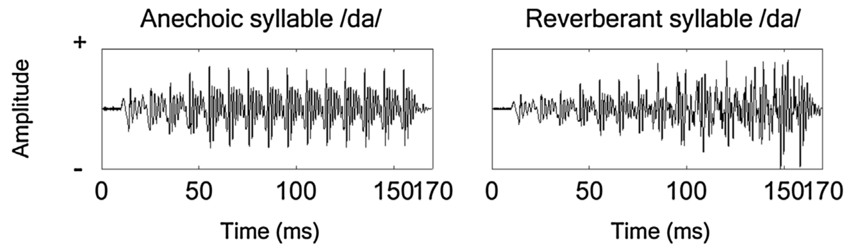

Fig. 1. Stimulus waveform for the anechoic and reverberant syllable /da/. The reverberant /da/was created by convolving the anechoic /da/ with an impulse response with an RT of 0.5 s.

ture [5,14]. The responses were computed with a time window from −40 to 190 ms relative to the stimulus onset at 0 ms, with baseline correction from −40 to 0 ms. All analyses were performed in the response-latency range from 5 to 170 ms.

We focused on the spectral composition of the responses associated with F_0 (100 Hz) and first formant frequency (F_1) information (400–720 Hz) of the speech stimulus. A discrete Fourier transform (DFT) was performed on each response. The frequency resolution of the DFT was increased to 2 Hz by performing zero-padding. The DFT amplitudes were averaged for 40-Hz-wide bins around each frequency. The DFT amplitudes associated with F_0 ($F_{0\text{-ADD}}$) were calculated at 100 Hz for ADD responses relating to the stimulus envelope. Averages of 40-Hz-wide bins surrounding 400, 500, 600 and 700 Hz for SUB responses ($F_{1\text{-SUB}}$), relating to the stimulus temporal fine structure, were calculated for the DFT amplitudes associated with F_1.

To investigate the effects of reverberation on the morphology of the response waveform, Pearson's correlation coefficients between the ADD responses to the anechoic syllable and reverberant syllable were calculated for each participant. Following the method reported by Anderson et al. [7], correlation coefficients were calculated by shifting the ADD response waveform to the reverberant syllable relative to the ADD response waveform to the anechoic syllable from −2 ms to +2 ms until a maximum correlation was achieved. We defined the maximum correlation as the anechoic-to-reverberant response correlation coefficient. Fisher's transformation was used to convert the anechoic-to-reverberant response correlation coefficients to z-scores for parametric statistical analyses.

2.5. Statistical analyses

Following the method reported by Anderson et al. [7], the participants were divided into two groups according to difference values in the word intelligibility scores (in rational arcsine units: RAUs) between the anechoic word condition (RT = 0 s) and the reverberant word condition (RT = 0.5 s). The average of the difference values was 29.90 (SD = 11.03). Fourteen participants who scored lower than the average (<29.90), and thus had relatively high intelligibility of words under reverberation, were assigned to the top performance group. The fourteen participants who scored higher than the average (>29.90), and thus had relatively low intelligibility of words under reverberation, were assigned to the bottom performance group.

All statistical analyses were conducted in SPSS software version 11.5J (SPSS Inc.). Student's *t*-test was performed to test significance between the top and bottom performance groups for age, hearing threshold, click-evoked ABR wave V latency and the word intelligibility score. A two-way, mixed-design analysis of variance (ANOVA) with group (repeated measures, 2 levels: top and bottom performance group) and speech (2 levels: anechoic and reverberant /da/) as main factors was conducted over the DFT amplitudes associated with F_0 and F_1. A one-way ANOVA was performed to test significance for the anechoic-to-reverberant response correlations.

3. Results

3.1. Age, hearing threshold, click-evoked ABR wave V latency and word intelligibility score

The means, SDs and p-values related to Student's *t*-test results for the two group comparisons (the top performance group and the bottom performance group) are shown in Table 1. The two groups did not differ statistically by age, hearing threshold (125–8000 Hz), click-evoked ABR wave V latency and the word intelligibility score for anechoic words (RT = 0 s). Since we, however, divided the two groups using the word intelligibility scores in the reverberant condition (RT = 0.5 s), the top performance group consequently showed significantly higher word intelligibility scores than the bottom performance group for the RT of 0.5 s.

3.2. Spectral analysis

Grand average brainstem responses to the anechoic and reverberant syllable /da/ and the spectrum of each response for both participant groups are shown in Fig. 2 (ADD responses) and Fig. 3 (SUB responses). The means, SDs and p-values related to the ANOVA for these group comparisons are shown in Table 2. The main effect of speech was significant for $F_{0\text{-ADD}}$ [$F_{(1,26)} = 21.973$, $p < 0.001$] and $F_{1\text{-SUB}}$ [$F_{(1,26)} = 9.745$, $p = 0.004$]. The main effect of group was significant for $F_{1\text{-SUB}}$ [$F_{(1,26)} = 4.811$, $p = 0.037$]. The group × speech interaction was not significant.

3.3. Anechoic-to-reverberant response correlations

As shown in Fig. 4A, the one-way ANOVA for the anechoic-to-reverberant response correlation coefficients showed that the correlation coefficients of the top performance group difference were significantly higher than those of the bottom performance group [$F_{(1,26)} = 4.873$, $p = 0.036$]. To remove the effect of group, Pearson's correlation coefficients between the difference values in the word intelligibility scores (RT = 0.5 s–RT = 0 s) and the anechoic-to-reverberant response correlation coefficients were calculated. As shown in Fig. 4B, the anechoic-to-reverberant response correlation coefficients significantly correlated with the difference values in the word intelligibility scores between the anechoic words and reverberant words ($r = 0.422$, $p = 0.025$).

4. Discussion & conclusions

We performed an experiment in which the ABRs to an anechoic and reverberant speech syllable /da/ were obtained from elderly listeners, who also judged their understanding of reverberant speech in a word intelligibility task. To our knowledge, this is the first

Table 1
Means, SDs and p-values related to Student's *t*-test results for the two group comparisons. Bold denotes significance at the 1% level.

	Top performance group (N = 14)	Bottom performance group (N = 14)	p-value (Student's *t*-test)
Age (years)	66.29 (3.89)	68.14 (3.35)	n.s. (0.188)
Hearing thresholds (dB HL)			
125 Hz	19.29 (6.75)	20.71 (7.03)	n.s. (0.588)
250 Hz	17.50 (6.43)	20.36 (7.46)	n.s. (0.288)
500 Hz	16.43 (6.91)	18.57 (7.45)	n.s. (0.437)
1 kHz	13.57 (6.63)	13.57 (6.33)	n.s. (1.000)
2 kHz	21.43 (6.02)	19.64 (5.36)	n.s. (0.415)
4 kHz	14.29 (7.81)	17.50 (6.43)	n.s. (0.245)
8 kHz	31.07 (12.89)	36.07 (11.12)	n.s. (0.282)
Pure tone average	16.43 (4.95)	17.32 (4.54)	n.s. (0.623)
Click-evoked ABR wave V latency (ms)	5.76 (0.23)	5.74 (0.27)	n.s. (0.822)
Word intelligibility score (RAUs)			
RT = 0 s	86.31 (6.06)	89.08 (3.45)	n.s. (0.149)
RT = 0.5 s	65.05 (6.82)	50.53 (9.40)	**<0.0001**

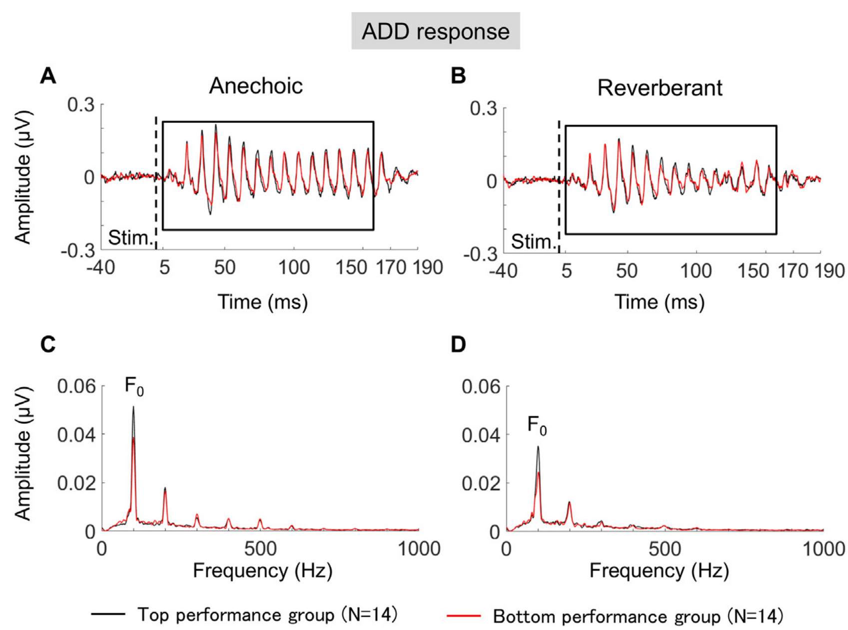

Fig. 2. A: Grand average ADD responses to anechoic /da/. B: Grand average ADD responses to reverberant /da/ (RT = 0.5 s). C: The discrete Fourier transform (DFT) was calculated from 5 to 170 ms for the ADD responses to anechoic /da/. D: The DFT was calculated from 5 to 170 ms for the ADD responses to reverberant /da/. The DFT amplitudes were calculated for 40-Hz-wide bins surrounding the frequency of the fundamental frequency (F_0).

Table 2
Means, SDs and p-values related to the ANOVA for two group comparisons. Asterisk p < 0.05, double asterisk p < 0.01 and triple asterisk p < 0.001.

	Top performance group (N = 14)		Bottom performance group (N = 14)		Main effect p value		Interaction
	Anechoic response	Reverberant response	Anechoic response	Reverberant response	Group	Speech	Group × Speech
DFT amplitude (μV)							
$F_{0\text{-ADD}}$	0.0171 (0.0054)	0.0147 (0.0049)	0.0138 (0.0046)	0.0116 (0.0038)	0.078	*** ***<0.001***	0.804
$F_{1\text{-SUB}}$	0.0016 (0.0004)	0.0015 (0.0004)	0.0013 (0.0003)	0.0012 (0.0003)	* ***0.037***	** ***0.004***	0.656

attempt to measure the ABRs to reverberant speech in elderly listeners.

We found that the speech ABR amplitudes for F_0 and F_1 significantly decreased due to reverberation. It has been reported that young listeners' speech ABR amplitudes for F_0 and F_1 of speech stimuli decreased due to reverberation as well [17], similar to our results. As mentioned, reverberation alters the acoustic waveform by smearing dynamic changes in the fine structure and reducing the "peakiness" of the waveform's temporal envelope [9]. Neural synchrony, therefore, degrades due to reverberation, which might result in decreased speech ABR amplitudes. Indeed, the top performance group showed a higher F_1 amplitude than the low performance group. This is consistent with our previous data [10] and indicates that the elderly listeners' speech recognition under reverberation depends on their ability to encode the temporal fine structure of speech.

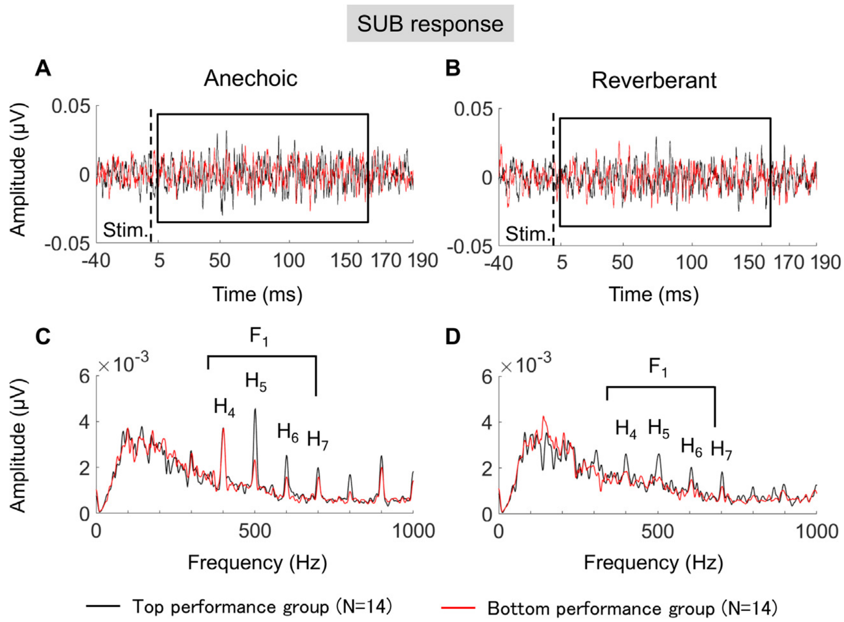

Fig. 3. A: Grand average SUB responses to anechoic /da/. B: Grand average SUB responses to reverberant /da/. C: The DFT for the SUB responses to anechoic /da/. D: The DFT for the SUB responses to reverberant/da/. Averages of 40-Hz-wide bins surrounding 400–700 Hz were calculated for the DFT amplitudes associated with first formant frequency (F_1).

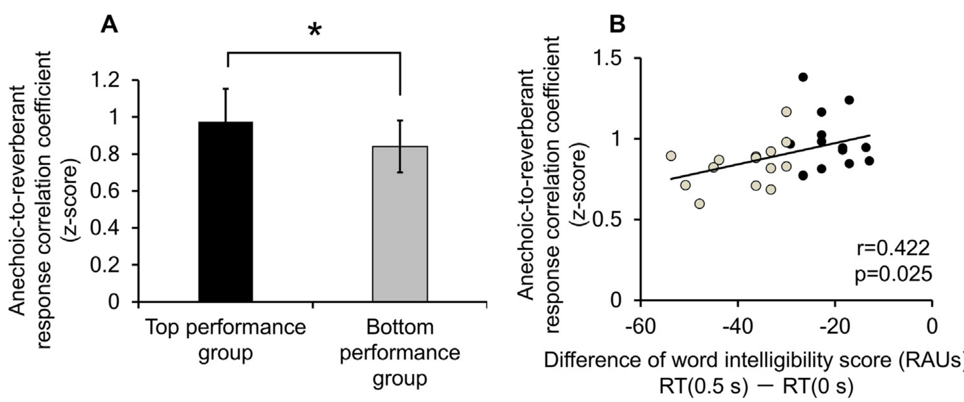

Fig. 4. A: Anechoic-to-reverberant response correlation coefficients means for the top and bottom performance groups. The one-way ANOVA showed that the anechoic-to-reverberant response correlation coefficients in the top performance group were higher than in the bottom performance group ($p < 0.05$). Error bars are standard deviations from the means. B: Anechoic-to-reverberant response correlation coefficients (black circles: top performance group, gray circles: bottom performance group) significantly correlated with the difference values in the word intelligibility scores between the anechoic words and reverberant words.

Our novel finding is that the anechoic-to-reverberant response correlation coefficients in the top performance group were higher than those in the bottom performance group. Moreover, the anechoic-to-reverberant response correlation coefficients related to the difference values in the word intelligibility scores. These results indicate that the tolerance for reverberation in morphology would contribute to the word intelligibility under reverberation. It is well-known that the temporal envelope cues of speech are important for speech perception, and several studies have reported that these cues alone are sufficient for the recognition of speech in the absence of spectral cues [18,19]. The ADD responses of the speech ABRs, used for calculating the anechoic-to-reverberant response correlation coefficients, are response components related to the stimulus envelope [5]. Therefore, the degraded neural representation to temporal envelope cues of speech under reverberation may have accounted for their lower word intelligibility of reverberant speech.

What may have affected the tolerance for reverberation in morphology? One of the reasons is thought to be the decline in gamma-aminobutyric acid (GABA) due to aging. GABA is an inhibitory neurotransmitter in the central nervous system and plays an important role in improvement of neural synchrony [20]. If there is a decline in GABA, the neural representation of speech, especially in noise or under reverberation, would degrade due to loss of neural synchrony. Caspray et al. [3] reported that GABA in aged-rats decreased relative to that in young rats in the inferior colliculus, which is thought to be a source of speech ABR [21]. Therefore, the tolerance for reverberation in morphology might depend on the amount of GABA in elderly listeners.

A limitation of the present study is that we only employed female listeners. Future research should confirm the findings with male participants. In addition, we should measure speech ABRs to two or more syllables under reverberation. To investigate the neural representation to consecutive syllables would shed more light on the subcortical processing of speech sounds actually used in daily life both by elderly listeners and young listeners with normal hearing.

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