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Original Article

Preserved Gray Matter Volume in the Left Superior Temporal Gyrus Underpins Speech-in-Noise Processing in Middle-Aged Adults

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BACKGROUND: Neuroanatomical evidence suggests that behavioral speech-in-noise (SiN) perception and the underlying cortical structural network are altered by aging, and these aging-induced changes could be initiated during middle age. However, the mechanism behind the relationship between auditory performance and neural substrates of speech perception in middle-aged individuals remains unclear. In this study, we measured the structural volumes of selected neuroanatomical regions involved in speech and hearing processing to establish their association with speech perception ability in middle-aged adults.

METHODS: Sentence perception in quiet and noisy conditions was behaviorally measured in 2 different age groups: young (20-39 years old) and middle-aged (40-59-year-old) adults. Anatomical magnetic resonance images were taken to assess the gray matter volume of specific parcellated brain areas associated with speech perception. The relationships between these and behavioral auditory performance with age were determined.

RESULTS: The middle-aged adults showed poorer speech perception in both quiet and noisy conditions than the young adults. Neuroanatomical data revealed that the normalized gray matter volume in the left superior temporal gyrus, which is closely related to acoustic and phonological processing, is associated with behavioral SiN perception in the middle-aged group. In addition, the normalized gray matter volumes in multiple cortical areas seem to decrease with age.

CONCLUSION: The results indicate that SiN perception in middle-aged adults is closely related to the brain region responsible for lower-level speech processing, which involves the detection and phonemic representation of speech. Nonetheless, the higher-order cortex may also contribute to age-induced changes in auditory performance.

KEYWORDS: Middle-aged, gray matter volume, aging, speech-in-noise perception

INTRODUCTION

In everyday listening situations, hearing is accomplished in the presence of some degree of background noise. For young people, hearing is well maintained, even in a noisy environment. However, the ability to perceive speech-in-noise (SiN) significantly declines with age due to damage to both the peripheral and central auditory systems.[1] The age-induced changes in the systems can alter the sensitivity to sound, which is more pronounced for speech understanding in adverse listening conditions.[2] Previous research has shown that difficulty in SiN perception is not simply due to poorer hearing ability.[3] Neural functions such as central auditory processing[4] and cognitive involvement[5] decline as a consequence of aging, which contributes to the difficulty of SiN perception. In addition, hearing problems can be attributed to or misdiagnosed as cognitive decline due to difficulties in remembering or understanding speech.[6] Consequently, older adults experience greater difficulty understanding SiN than young adults.[7]

The findings reported in the previous literature suggest that there is a reciprocal interaction between brain function and hearing performance with age. The results of a large cohort study infer that hearing loss is independently associated with decreased cognitive ability, which can lead to dementia.[8] Even though the evidence from population-based studies suggests hearing-associated

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cognitive decline, the neural mechanism underlying the causal relationship between cognitive functioning and hearing is still unknown. To understand this mechanism, it has been suggested that the neuroanatomical structures in the cognition and hearing-associated regions are related to the auditory performance of the elderly when listening to SiN. For example, cortical functional changes in the elderly involving the neural activities in the anterior cingulate cortex, lateral prefrontal cortex, and inferior frontal gyrus alter with age, and the activities in those areas are correlated with the ability to perceive SiN.[9,10] These findings suggest that aging influences not only the memory-related structural changes but also the brain functionality involved in SiN perception. Wong and colleagues[11] examined neuroanatomical structural changes as a function of age and their relationships to behavioral SiN perception. They reported that SiN perception was significantly lower in the elderly compared to young adults and that performance was associated with the cortical volume and thickness of certain brain areas, including the left pars triangularis and the left superior frontal gyrus (SFG). Moreover, changes in Heschl's gyrus and the superior temporal gyrus (STG) (areas pertaining to auditory function) are closely associated with SiN perception in the elderly.[9]

Most previous studies examining the relationship between behavioral performance and aging-related structural changes have focused on elderly people over the age of 65. However, neurological evidence such as decreased gray matter volume (GMV) in the temporal lobe[12] and atrophy in the white matter[13] supports the notion that cortical structural changes have already been initiated between the ages of 20 and 50 years old. In addition to the structural changes, brain functional changes in middle-aged individuals have also been found. Grady and colleagues[14] reported that middle-aged adults showed decreased performance in a memory-related task and that decreased behavioral performance is correlated with reduced neural activities in the dorsal lateral prefrontal cortex and the medial frontal cortex.

Determining how a listener extracts speech sounds from noise is of considerable importance for understanding speech. Although the hearing sensitivity of middle-aged people is in the normal range, they may have a decreased ability to perceive SiN. There is ample evidence showing that middle-aged adults have poorer auditory performance than young adults.[15,16] Reduced temporal processing ability has been attributed to decreased speech perception and delayed reaction times when listening SiN,[17] thereby providing evidence that substantial neural changes occur during middle age. Given that research on middle-aged individuals offers a unique opportunity to explore gradual changes in both the functional and structural mechanisms during transitioning into old age, understanding the relationships between neuroanatomical characteristics and the behavioral performance of middle-aged people could help in determining the trajectory of aural rehabilitation programs for the elderly.

Our aim in the present study was to examine the association between neural correlates and auditory performance in middle-aged individuals. We hypothesized that brain structure measured via structural brain imaging is related to auditory performance and that the relationship between them varies in young and middle-aged adults.

MAIN POINTS

- There is a reciprocal relationship between brain function and hearing performance with age.
- Speech-in-noise perception is related to brain functionality concerning semantic processing and the lower levels of auditory processing in young and middle-aged adults, respectively.
- Neurostructural changes in multiple areas of the brain occur with aging.

MATERIAL AND METHODS

Subjects

Thirty-seven normal-hearing adults aged from 20 to 60 years old were divided into 2 age groups: young adults ($n=20$, 11 females, mean age: 29.1 ± 6.32 years, age range: 20-39 years old) and middle-aged adults ($n=17$, 8 females, mean age: 50.1 ± 6 years, age range: 40-60 years old). All of the participants were right-handed Korean native speakers. They reported no history of hypertension, diabetes, or any other medical diseases, as well as no neurologic or neuropsychiatric disorders. All of the experimental protocols and methods were approved by the guidelines and regulations and were performed in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki. Informed consent was obtained from all participants. Ethics committee approval was received by the Institutional Review Board of the Hallym University for this study (Approval No: 2018-02-019-002, Date: February 19, 2018).

Speech Performance Tests

Along with pure-tone audiometry, the Korean Hearing-In-Noise Test (K-HINT) has been used to measure speech reception thresholds in quiet (K-HINT_Q) and noisy conditions.[18] The target sentence stimulus was randomly selected from 12 lists of short sentences, and participants were instructed to repeat the sentence that they heard. The target sentences were delivered through a speaker located 1 meter in front of the listener, and 3 different background noise conditions were applied; noise front (K-HINT_F), noise left (K-HINT_L), and noise right (K-HINT_R). For each K-HINT testing condition, the reception threshold for sentences (RTS) was measured by using an adaptive technique with 4-dB steps to find the 50% correct performance level. Noise composite scores (K-HINT_C) were calculated using the following equation:

$$\text{K-HINT\_C} = [(\text{K-HINT\_F} \times 2) + \text{K-HINT\_L} + \text{K-HINT\_R}]/4.$$

Magnetic Resonance Image Acquisition and Analysis

Structural magnetic resonance (MR) scans were acquired by using a Philips Achieva 3.0 Tesla magnetic resonance scanner (Philips, Amsterdam). High-resolution T1-weighted images were acquired using the following protocol: TR = 20 ms, TE = 4.6 ms, flip angle = 30°, field of view = 230.0, matrix = 256 × 256, and 160 slices. Individual MR images were analyzed by using FreeSurfer v.5.1 (http://surfer.nmr.mgh.harvard.edu) following the methods in.[19] The 3D volume was obtained from the T1-weighted images through preprocessing steps such as motion correction, intensity normalization, and averaging of the T1-weighted images. The 3D volume was classified into 3 parts: white matter, gray matter, and cerebrospinal fluid segments.[19] The neocortex of the brain in the MR scans was automatically subdivided into 34 regions of interest (ROIs) in each hemisphere.[20]

In this study, we selected 12 ROI pairs related to auditory speech processing based on the previous literature.[11,21] The selected ROIs include the SFG, the pars opercularis, the pars triangularis, the transverse temporal gyrus, the STG, the banks of the superior temporal sulcus, the middle temporal gyrus (MTG), the inferior temporal gyrus (ITG), the superior parietal gyrus, the inferior parietal gyrus (IPG), the supramarginal gyrus, and the insula in bilateral hemispheres. To reduce the impact of intersubject variability, we performed a normalization procedure to correct for differences in brain size among the participants. The GMV of each cortical region obtained from an individual was divided by the total cortical GMV to yield the normalized GMV (nGMV = volume of the ROI/total hemispheric volume).

Statistical Analysis

Statistical analysis was performed using the Statistical Package for the Social Sciences Statistics software, version 12.0 (SPSS Inc.; Chicago, IL, USA), and the R statistical package. Independent *t*-tests and Fisher's exact tests were used to test for differences in age and gender distribution in the groups. Differences in hearing threshold, K-HINT performance, and the nGMVs of the 12 ROI pairs between the groups were tested using repeated-measures ANOVA with Tukey's HSD test. Stepwise multiple linear regression, including the nGMVs and age as independent variables (entrance criterion, $a = 0.050$; removal criterion, $a = 0.100$), was performed on each group to identify the brain regions accounting for the behavioral performances. To be conservative, age was included in the regression model, as it was significantly related to the hearing threshold, behavioral performance, and the nGMVs of multiple cortical areas in the pooled dataset. In the middle-aged group, the hearing thresholds at 4 and 8 kHz were also used in the regression analysis to examine their relationship with behavioral performance. Pearson's product–moment correlation analyses were conducted on areas of significance to visualize the relationship.

RESULTS

Comparisons for the Hearing Performance Indicators by Group

Figure 1A shows a comparison of the hearing thresholds between the young and middle-aged groups. All of the subjects had normal-hearing sensitivity when measured using the 4-tone average method. The results of a repeated-measures ANOVA (the 2 groups × the 2 ear sides × 7 frequencies) revealed significant effects for group ($F(1) = 136.725$; $P < .001$), testing frequency ($F(6) = 10.622$; $P < .001$), and their interaction ($F(6) = 6.947$; $P < .001$) but not the ear side ($F(1) = 0.607$; $P = .436$). Tukey's honest significant difference test revealed significant group differences at frequencies of 4 and 8 kHz in both ears (Figure 1A). Regarding the RTS measured via the K-HINT test, group ($F(1) = 25.60$; $P < .001$), noisy conditions (K-HINT_Q vs. K-HINT_C; $F(1) = 1489.59$; $P < .001$), and their interaction ($F(1) = 10.69$; $P = .002$) were significant. The young adult group is significantly better at speech perception in quiet conditions ($P < .001$) but not in noisy conditions ($P = .588$) (Figure 1B).

Comparisons for Normalized Gray Matter Volume by Group

The effects of group and the side of the cortex on nGMV were tested for each ROI pair; the nGMVs for 3 ROI pairs were larger in the young adult group than the middle-aged group, while the hemispheric difference was significant for 7 ROI pairs (Figure 2).

Investigation of Potential Relationships Between Group and the Hearing Performance Indicators

The hearing thresholds for all frequencies tested in both ears were significantly related to age ($P < .05$), except for at 500 Hz in the right ear. Age was positively correlated to K-HINT performance in quiet conditions ($r = 0.593$; $P < .001$) and noisy conditions ($r = 0.606$; $P < .001$), indicating that speech perception in both decreases with age, especially in individuals aged between 20 and 60 years old. However, there were no significant effects on the hearing threshold and K-HINT performance according to age.

Although the hearing thresholds at all of the frequencies tested did not show any significant correlation with K-HINT performance in the young adult group, those for the middle-aged group at 4 kHz (the right ear: $r = 0.551$; $P = .022$; and the left ear: $r = 0.534$; $P = .027$) and 8 kHz (the right ear: $r = 0.553$; $P = .021$; and the left ear: $r = 0.511$; $P = .036$) were significantly associated. These results indicate that the higher the threshold, the lower the performance.

Relationships Involving the Normalized Gray Matter Volume and Korean Hearing-In-Noise Test Performance

Regression analysis was performed on the nGMVs of 12 brain areas involved in auditory and language processing to examine whether nGMV changes in any of these parcellated cortical areas can be used as a predictor for the behavioral performances of the 2 groups. For the young adult group, the K-HINT performances in noisy conditions were significantly related to the nGMVs of 5 brain areas: the bilateral ITG, the left MTG, the right pars opercularis, and the left insula (Table 1). The nGMV of the right ITG was negatively related to the RTS

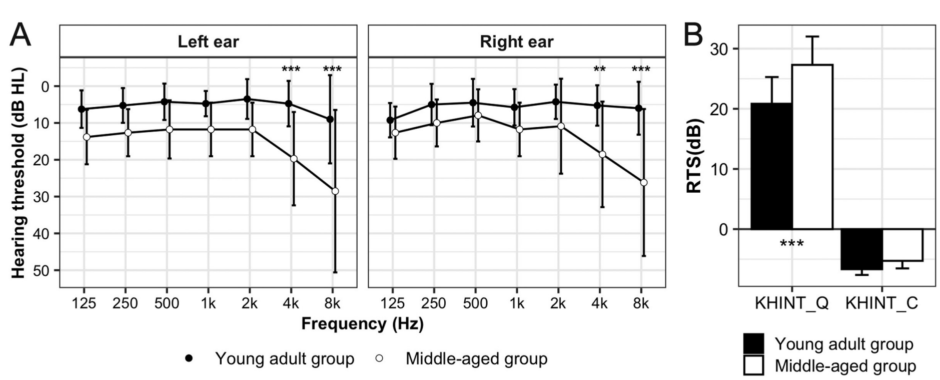

Figure 1. A. The hearing threshold (the mean ± SD) and B. the Korean Hearing-In-Noise Test (K-HINT) performances under quiet (K-HINT-Q) and noisy (K-HINT-C) conditions of the young and middle-aged adult groups. RTS, the reception threshold for sentences.

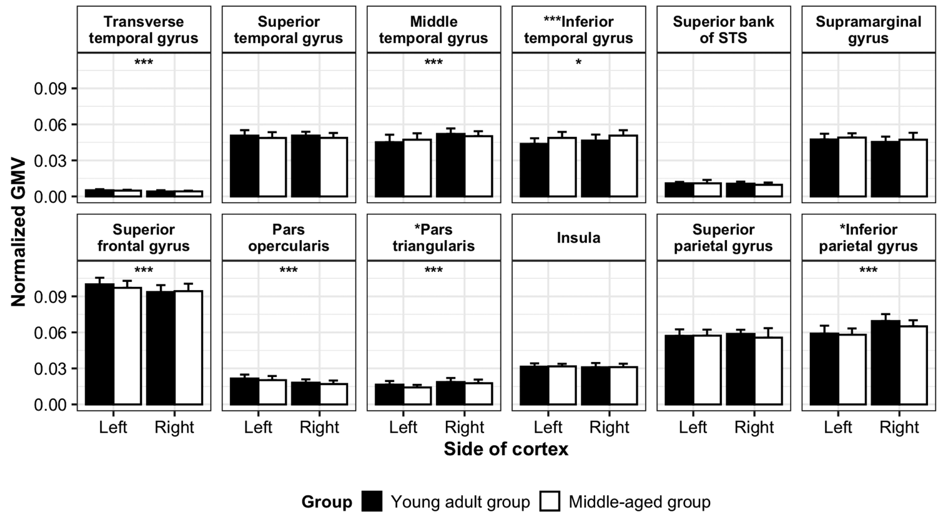

Figure 2. Normalized gray matter volumes (GMVs) of the 12 ROI pairs for the young and middle-aged adult groups. Significant group differences are marked in front of the name of the region and the hemispheric difference in the plot areas (*$P < .05$; ***$P < .001$). The bars denote 1 SD.

for the K-HINT test, which indicates that young adults with greater GMVs of these areas had better speech perception performance ($P < .001$), while the larger nGMV of the left MTG was associated with a higher threshold in the K-HINT test ($P < .001$). However, no relationship between the K-HINT score and the nGMVs was found in the quiet listening conditions. For the middle-aged group, the nGMV of the left STG was significantly associated with speech perception in both quiet ($P = .011$) and noisy ($P = .001$) conditions.

Figure 3 depicts the region of the left STG in an MR image of the brain and significant correlations between the RTS for K-HINT in quiet (K-HINT_Q) and noisy (K-HINT_C) conditions and the nGMV of the left STG of middle-aged individuals. The regression results reveal that the nGMV of the left STG was significantly related to the thresholds for K-HINT in quiet ($r = 0.6$; $P = .011$) and noisy conditions ($r = 0.619$; $P = .008$).

Another regression analysis to investigate the possible association of nGMV with age revealed that there were significant inverse relationships between age and the nGMVs of 5 out of 24 ROIs: the right IPG ($r = -0.460$; $P = .004$), the right pars opercularis ($r = -0.330$; $P = .046$), the left pars opercularis ($r = -0.380$; $P = .020$), the left pars triangularis ($r = -0.426$; $P = .008$), and the left STG ($r = -0.404$; $P = .013$). These results indicate that the GMV of multiple cortical areas decreases with age.

DISCUSSION

The purpose of this study was to investigate possible relationships between behavioral auditory performance and the nGMVs of brain areas involved in hearing and language processing in 2 normal-hearing groups comprising young and middle-aged adults. The K-HINT in quiet and noisy listening conditions was used to assess speech perception ability. The neurostructural brain function was assessed by measuring the nGMVs of the ROIs. Our key finding is that speech perception in quiet and noisy conditions by the middle-aged group was poorer than by the young adult group. Meanwhile, the brain regions having a relationship with behavioral performance were different from those in the young adult group.

The results of the behavioral tests reveal that speech perception in noise becomes poorer with age, as assessed via K-HINT. This finding

Table 1. Predictors of Auditory Performance Using Stepwise Multiple Regression Analysis in Young Adults and Middle-aged Groups

Variables	Young Adult					Middle-Aged				
	Areas (nGMV)	B	Beta	T	Sig.	Areas (nGMV)	B	Beta	T	Sig.
K-HINT_Q						L STG	−588.289	−0.600	−2.903	.011
						Adjusted $R^2 = 0.317$	$F = 8.438$		$P = .011$	
K-HINT_C	R ITG	−138.269	−0.733	−6.063	<.001	L STG	−152.267	−0.584	−3.644	.003
	L MTG	89.598	0.589	5.237	<.001	R 4 kHz	0.045	0.51	3.184	.007
	L ITG	96.667	0.479	3.898	.002	Adjusted $R^2 = 0.591$	$F = 12.581$		$P = .001$	
	R pars opercularis	107.239	0.312	2.763	.015					
	L insula	90.508	0.264	2.300	.037					
	Adjusted $R^2 = 0.768$	$F = 13.580$		$P < .001$						

Excluded variables: age, other areas.
ITG, inferior temporal gyrus; K-HINT_C, Korean Hearing-In-Noise Test in Noise; K-HINT_Q, Korean Hearing-In-Noise Test in quiet; L, left; MTG, middle temporal gyrus; R, right; STG, superior temporal gyrus.

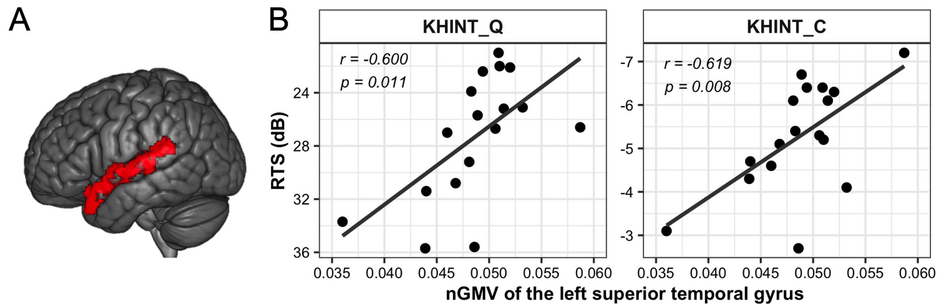

Figure 3. A. An magnetic resonance image of the brain showing the left superior temporal gyrus (STG) in red. B. Plots of reception threshold for sentences (RTS) vs. normalized gray matter volume (nGMV) for the left STG for quiet (left) and noisy (right) conditions using K-HINT (the Korean Hearing-In-Noise Test) conducted in quiet (K-HINT_Q) and noisy (K-HINT_C) condition.

of a deterioration in auditory skills with age is consistent with those from previous studies.[22] In elderly people, the RTS measured using noise bursts with varied frequency or amplitude modulation depths is higher and the distribution of the threshold is considerably wider than in younger people.[23] This decreased performance in behavioral tasks can be attributed more closely to age-induced physiological changes (such as temporal processing and binaural sensitivity) rather than presbycusis per se.[22] More importantly, decreased auditory performance in the elderly occurs even if their pure-tone thresholds are in the normal range.[24]

We found that K-HINT-based performance was lower in the middle-aged group than in the young adult group. Previous studies have suggested that age-induced changes in the auditory system begin in middle age. For instance, increased thresholds for a gap detection test and poor performance in gap-in-noise tests have been observed in middle-aged people compared to younger individuals.[25] In particular, middle-aged listeners are more susceptible to background noise since their speech recognition ability is significantly poorer in a noisy environment. Meanwhile, the auditory performance in noise could be affected differently by the type of background noise as well as the lexical characteristics of the speech. During SiN perception, the performance of middle-aged listeners is worse when the background noise comprises a competing speech masker and the target words are lexically complex compared to lexically simple sounds accompanied by pink noise.[16,25] In our study, speech-shaped noise was used as the background noise, while the sentences were comprised of lexically balanced items, including high and low predictability. Thus, we think that our test conditions could have contributed to the poor SiN perception by the middle-aged participants.

We found that the nGMV of the left STG was greater in the middle-aged participants, with better speech perception in both quiet and noisy conditions. Similarly, this has been previously demonstrated in young normal-hearing adults, with increased activation in the left STG in response to SiN that was not present in the elderly.[9,26] These results indicate that the brain's structural and functional characteristics in middle age are different from those in old age.[26] This could be related to the functionality of the STG contributing to precise phonological representation using successive acoustic and auditory information delivered through the peripheral auditory system.[27] Therefore, we assume that for young adults, efficient semantic processing is more critical for achieving good SiN perception than acoustic processing. In contrast, speech perception by middle-aged listeners is mainly determined by acoustic and phonological processing, which indicates the precedent stage of semantic processing. This could be partly due to the degeneration of neurons, including those in the superior temporal lobe, which is known to be initiated in middle age.[28]

Neurophysiologically, structural and functional changes caused by damage to hair cells and degeneration of spiral ganglion cells start at approximately 45 years of age.[28] Such changes in the peripheral auditory system could be the cause of high-frequency hearing loss in the middle-aged group, with decreased hearing sensitivity for the high-frequency range partly responsible for their poor auditory processing ability. However, decreased SiN performance was observed not only in those with an elevated threshold at 8 kHz but also in those with normal audiograms. This result supports the conception that auditory processing in middle age requires adequate bottom-up processing in the peripheral auditory system accompanied by top-down regulation at the higher level of the brain. Another explanation for the decline in auditory processing for SiN perception in middle age is the slow recovery rate of auditory neuron adaptation and/or age-related changes in cochlear nonlinearity.[29] This notion also implies that the deterioration in behavioral performance in middle age could be attributed to functional changes in the central auditory system rather than physiological issues in the peripheral system.

In the young adult group, more diverse areas involved in the auditory language network showed a significant structural relationship with SiN performance. We found that the nGMVs of 5 cortical areas (the bilateral ITG, the left MTG, the right pars opercularis, and the left insula) were associated with SiN perception in the young adult group. We assumed that this was because multiple brain areas become highly interconnected to form a functional network for accurate SiN perception. In particular, the right ITG was highly associated with SiN performance, which could be related to the role of the ITG in speech processing.[21,30,31] Subdivisions of the temporal lobe have different roles in speech processing according to their inter- and intraconnectivity with other parts of the brain. For example, the superior temporal lobe mainly processes phonemic aspects of speech, whereas the medial and inferior temporal lobes are more involved in the semantic processing of words and sentences, as well as understanding speech in background noise.[27] Hickok and Poeppel (2004) reported that spectral and phonetic aspects of speech are primarily processed in the superior temporal lobe and delivered to the inferior temporal lobe to accomplish conceptual representation of speech. Thus, the increased nGMV of the ITG in the young adult group suggests that activation in multiple brain areas involved in acoustic and semantic processing is required to enhance speech understanding in noise. The pars opercularis and insular cortex lying in the dorsal stream of the auditory language pathway are involved in both speech perception and production.[21] The results of previous neuroimaging studies indicate that the posterior ITG is associated with the semantic processing of language.[32] Increased brain activation in the ITG has also been observed when speech is not clear enough to process due to limited semantic information.[30] In addition, the MTG is responsible for semantic memory retrieval and for integrating semantic and syntactic information to complete verbal expression.[33] Meanwhile, in our study, the nGMV of the MTG in young adults was found to be related to SiN performance. Similarly, the outcomes from a recent study using functional near-infrared spectroscopy infer that activation in the MTG is associated with speech recognition in low-intelligibility conditions.[34] Given that K-HINT is used to examine the ability to recognize speech and the MTG is associated with comprehension rather than discrimination,[35] our findings reinforce the presumed roles of the MTG mentioned earlier.

Given the participation of middle-aged individuals in this study, it is conceivable that the estrogen hormone could have a potential influence on GMV. However, its impact is likely to be limited. First, within the middle-aged group, there are only 8 females out of 17 total, and it is possible that some of them were in the postmenopausal stage. Therefore, their influence on the results pertaining to gray matter volume should be minimal. Secondly, previous studies investigating gray matter volume changes as functions of age and sex have reported no significant alterations in the left temporal gyrus, which is associated with acoustic and phonological processing in our results.[36] Instead, the superior temporal gyrus has been proposed as one of the regions demonstrating the effects of sex hormone and age on brain volume in postmenopausal women.[37,38]

In the present study, we examined relationships between the nGMVs of various cortical areas related to speech processing and the auditory performance of young and middle-aged adults. The ability to perceive SiN was associated with regions in the brain related to semantic processing and lower levels of auditory processing of speech in young and middle-aged adults, respectively. Our results indicate that middle-aged people rely more on the detection of speech than semantic recognition to accomplish understanding. Further work is required to investigate whether auditory rehabilitation in middle age can change the brain functionality in the cortical regions associated with SiN perception identified in this study.

Ethics Committee Approval: This study was approved by Ethics Committee of Hallym University (Approval No: 2018-02-019, Date: February 19, 2018).

Informed Consent: Informed consent was obtained from the patients who agreed to take part in the study.

Peer-review: Externally peer-reviewed.

Author Contributions: Concept – H-J.L.; Design – H-J.L.; Supervision – H-J.L.; Resources – H-J.L.; Materials – J-H.K., G-K.P.; Data Collection and/or Processing – J-H.K.; Analysis and/or Interpretation – J-H.H., J-H.K., H-J.L.; Literature Search – J-H.H., J-H.K., G-K.P. H-J.L.; Writing Manuscript – J-H.H., H-J.L.; Critical Review – J-H.H., H-J.L.

Declaration of Interests: The authors have no conflict of interest to declare.

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