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Neuroanatomical Characteristics and Speech Perception in Noise in Older Adults

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Abstract

Objectives—Previous research has attributed older adult's difficulty with perceiving speech in noise to peripheral hearing loss. Recent studies have suggested a more complex picture, however, and implicate the central nervous system in sensation and sensory deficits. This study examines the relationship between the neuroanatomical structure of cognitive regions and the ability to perceive speech in noise in older adults. In particular, the neuroanatomical characteristics of the left ventral and dorsal prefrontal cortex are considered relative to standard measures of hearing in noise.

Design—The participants were fifteen older and fourteen younger right-handed native speakers of American English who had no neurological deficits and scored better than normal on standardized cognitive tests. We measured the participants' peripheral hearing ability as well as their ability to perceive speech in noise using standardized tests. Anatomical magnetic resonance images were taken and analyzed to extract regional volumes and thicknesses of several key neuroanatomical structures.

Results—The results showed that younger adults had better hearing sensitivity and better speech perception in noise ability than older adults. For the older adults only, the volume of the left pars triangularis and the cortical thickness of the left superior frontal gyrus were significant predictors of performance on the speech-in-noise test.

Discussion—These findings suggest that, in addition to peripheral structures, the central nervous system also contributes to the ability to perceive speech in noise. In older adults, a decline in the volume and cortical thickness of the prefrontal cortex (PFC) during aging can therefore be a factor in a declining ability to perceive speech in a naturalistic environment. Our study shows a link between anatomy of PFC and speech perception in older adults. These findings are consistent with the decline-compensation hypothesis, which states that a decline in sensory processing due to cognitive aging can be accompanied by an increase in the recruitment of more general cognitive areas as a means of compensation. We found that a larger PFC volume may compensate for declining peripheral hearing. Clinically, recognizing the contribution of the cerebral cortex expands treatment possibilities for hearing loss in older adults beyond peripheral hearing aids to include strategies for improving cognitive function. We conclude by considering several

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mechanisms by which the PFC may facilitate speech perception in noise including inhibitory control, attention, cross-modal compensation, and phonological working memory, though no definitive conclusion can be drawn.

Keywords

speech perception; prefrontal cortex; cortical anatomy; hearing loss

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INTRODUCTION

In the present study, we examine the relationship between cortical anatomy and the ability to perceive speech in noise in older adults. Speech perception in the real world does not occur in a pristine acoustic environment, but rather in the presence of interfering background noise. For older adults, the presence of background noise makes speech perception particularly challenging (e.g., Cooper & Gates, 1991; Helfer & Freyman, 2008; Walton, Simon and Frisina, 2002). While the older adults do show peripheral hearing loss and this certainly contributes to problems with hearing in noise, peripheral loss does not explain the entirety of their problems. For example, multiple studies have found that even in idealized laboratory conditions, hearing aid users appear to derive only a few dB of signal-to-noise ratio (SNR) benefit, even when the best available technologies such as directional microphones are used (see Bentler, 2005 for a review).

In light of these findings, recent behavioral and neurological studies have begun to examine contributions of the central nervous system (e.g., see Frisina et al., 2001 for a series of experiments in humans and animals; see Gordon-Salant et al., 2010 for recent reviews). Behaviorally, recent findings suggest that given the same level of audibility of the signal, cognitive factors such as attention, working memory, and speed of processing contribute significantly to both speech perception in quiet and in noise (see Humes, 2007 for a review). For example, Humes et al. (2002) found that portions of the variance in speech recognition in noise can be accounted for by non-peripheral factors including cognitive functions (measured by various subtests of the WAIS-R). Lunner (2003) found 30–40% of the variance in speech recognition in noise to be explained by reading span. In hearing aid users, Foo et al. (2007) found reading span to be correlated with speech recognition in noise. Gatehouse et al. (2003, 2006) and Lunner and Sundewall-Thoren (2007) found visual letter monitoring (resembling the n-back working memory task) to be predictive of hearing aid users' success in adjusting hearing aid settings when listening to speech in noise.

These behavioral studies corroborate with recent neuroimaging studies. For example, Harris et al. (2009) found an association between activation of the anterior cingulate cortex and recognition of low-pass filtered words in older adults. In Wong et al. (2009), younger and older adults participated in an fMRI experiment in which they identified single words in quiet and in two multi-talker babble noise conditions (SNR 20 and −5 dB), following the paradigm of an earlier fMRI study (Wong et al., 2008a). Behaviorally, older adults performed significantly worse in the −5 dB SNR condition but not in the other two conditions, supporting previous work that showed that older adults suffer greater effects due to noise. In terms of hemodynamic responses, we found decreased activation in the sensory areas, including the superior temporal region (STR), which was accompanied by increased activation in cognitive brain regions, including the prefrontal cortex (PFC) and precuneus in the older adults. Crucially, increased activation in these cognitive brain regions was positively correlated with their ability to perceive speech in noise in our older adults. This positive relationship suggests that in order to reduce further degradation in speech perception performance (or to achieve performance levels of healthy young adults), some older adults successfully recruit PFC.

Taken together, these behavioral and neurophysiological studies suggest that hearing in noise depends on both sensation *and* cognition (e.g., Humes, 2002; Frisina & Frisina, 1997; see Akeroyd, 2008 for a recent review). Furthermore, these findings are consistent with the *decline-compensation hypothesis* (see Li & Lindenberger, 2002 for an alternative hypothesis), which states that cognitive aging and a decline in sensory processing reflected in a decline in the activation of sensory cortical areas is accompanied by an increase in the recruitment of more general cognitive areas (e.g., PFC) as a means of compensation. To qualify PFC or other cognitive-related brain activation as compensatory, a critical aspect of this hypothesis is that it specifically predicts a positive relationship between PFC activation and behavioral performance within older adults. Ample evidence in other domains supports this hypothesis (e.g., Grady et al., 1994; Cabeza et al., 2004).

In the present study, we investigate the possible link between the anatomical characteristics of cognitive brain regions and speech perception in noise abilities in older adults. Much evidence exists supporting a positive relationship between volumes of cognitive brain regions and cognitive brain functions measured behaviorally. For example, it has been found that positive correlations exist between PFC volume and executive function (Gunning-Dixon & Raz, 2003), working memory (Salat, et al., 2002), and attention (Brickman et al., 2006; Filipek et al., 1997; Knudsen, 2007; Kramer et al., 2007; Zimmerman & Aloia, 2006). Memory performance has also been shown to be correlated with hippocampal volume (see Van Petten, 2004 for a review). However, it is not known whether anatomical characteristics of cognitive brain regions, such as PFC volume, are linked to sensory functions such as speech perception in noise.

In particular, we focused on the anatomical characteristics of cognitive and sensory cortical regions and their relationship to listeners' speech perception in noise ability. We selected seven regions bilaterally, including regions of cognitive significance (e.g. those related to working memory and attention) in the dorsal and ventral aspects of PFC (caudal middle frontal gyrus, rostral middle frontal gyrus, superior frontal gyrus, pars opercularis, and pars triangularis) and the precuneus, as well as the auditory cortex (superior temporal region). The dorsal and ventral aspects of PFC encompass a large region of the cerebral cortex and their cognitive involvement is broad. Although it remains a matter of debate, the PFC can be viewed as responsible for response and semantic selection (Nagel et al., 2008), comparisons and monitoring of sensory inputs (Petrides & Pandya, 1994), goal-oriented and maintenance processes (Miller & Cohen, 2001) and selection and organization (Blumenfeld & Ranganath, 2007). In consideration of PFC structures, it is important to consider both dorsal and ventral aspects. The regions we selected were also found to be significant contributors to speech perception in noise in our previous fMRI study (Wong et al., 2009).

MATERIALS AND METHODS

Subjects

Subjects were 15 older (mean age = 67.1 years; age range = 62–75; 7 females) and 14 younger (mean age = 21.1 years; age range = 18–27; 9 females) adult native speakers of American English who reported no neurological deficits. All subjects were right-handed as assessed by the Edinburgh Handedness Inventory (Oldfield, 1971). The cognitive abilities of all but one subject were assessed using the Woodcock-Johnson Tests of Cognitive Abilities-3 (Brief Intellectual Ability index was obtained) (Woodcock & Johnson, 2001). The remaining subject was not available for a lengthy cognitive assessment and therefore the Mini-Mental State Examination (MMSE) (Folstein, Folstein, & McHugh, 1975) was used as a screener. All subjects scored better than the normal limit for their age; the subject who performed the MMSE scored 30 out of a possible 30 points. Of the fifteen older and fourteen younger subjects, twelve of the subjects in each group also participated in our previous study examining the cortical mechanisms of speech perception in noise (Wong et al., 2009).

Peripheral Hearing

Subjects' peripheral hearing ability was screened using a Maico MI 26 audiometer and TDH 39 headphones. All subjects passed a hearing screening at 25 dB HL between 250 and 4000 Hz, the frequency range relevant for speech perception (e.g., Turner et. al., 1998). A more detailed assessment was also conducted using a custom tracking procedure in 2-dB steps. The stimuli were presented through custom insert earphones that were calibrated in a Bruel and Kjaer 4157 (IEC 711) ear simulator using a Bruel and Kjaer 4134 1/2″ microphone. Subjects controlled the attenuation of the signal generator using a computer mouse. They were instructed to hold the mouse down as long as the signal was audible. Depressing the mouse reduced the level of the signal in the ear. The level decreased in 2-dB steps until the signal was no longer audible, prompting the subject to release the mouse. The midpoints of six such reversals were averaged to compute hearing threshold (in dB SPL) at a particular frequency. All subjects had hearing thresholds within limits of normal sensitivity established in the laboratory using this custom system. Tympanometry was also normal for all subjects.

Speech in Noise Testing

Subjects' ability to perceive speech in noise was assessed using the QuickSIN test (Etymotic Research, 2001; Killion et al., 2004). The first four lists of the QuickSIN test were presented to each subject in counter-balanced order. The target sentences and the background babble were simultaneously presented to both ears using insert earphones with the target material at 70 dB SPL. The level of the masker was varied in 5-dB steps to achieve SNR ratios between 25 and 0 dB with each sentence within each list. The number of words repeated correctly at each SNR was averaged across the four lists for each subject. This method of analysis was chosen over the traditional derivation of SNR loss (based on the total number of correctly repeated words) as we intended to use SNR as a factor in our analyses.

MRI Acquisition & Data Analysis

Anatomical MR images were acquired at the Center for Advanced MRI in the Department of Radiology at Northwestern University using a Siemens 3T Trio scanner. A high resolution, T1-weighted 3D volume was acquired (MP-RAGE; TR/TE = 2300 msec/3.36 msec; flip angle = 9 degrees; TI = 900 ms; matrix size = 256 × 256; FOV = 22 cm; slice thickness = 1 mm; axial acquisition).

Data analysis was performed using the FreeSurfer image analysis suite, following published methods employed by others (e.g. Tartaglia et al., 2009) and in our previous research (e.g. Wong et al., 2008b). These methods are described in detail in previous publications (Dale et al., 1999; Dale and Sereno, 1993; Fischl and Dale, 2000; Fischl et al., 2001; Fischl et al., 2002; Fischl et al., 2004a; Fischl et al., 1999a; Fischl et al., 1999b; Fischl et al., 2004b; Han et al., 2006; Jovicich et al., 2006; Segonne et al., 2004), and include the removal of all non-brain structures from the T1 scans based on a combination of watershed algorithms and deformable surface models, transformation to a common standard stereotaxic atlas, segmentation of brain tissues into grey and white matters, intensity normalization, and automated topology correction. After generating these cortical models, further surface-based analysis involved registration to a spherical atlas based on cortical folding patterns, and parcellation of the cerebral cortex into anatomical regions utilizing the structural information of brain gyral and sulcal folding (Desikan et al., 2006). This parcellation provides region-specific anatomical measures of grey matter volume (henceforth "raw volume") and mean cortical thickness (henceforth "thickness"), and has been demonstrated to be comparable in accuracy to manual techniques (Kuperberg et al., 2003; Salat et al., 2004). To reduce the impact of inter-subject variation, we further calculated normalized grey matter volumes for each cortical region as the regional volume fraction of total hemispheric cortical grey matter (henceforth "fractional hemispheric volume").

RESULTS

Group Differences in Pure-tone Thresholds and Speech Perception in Noise

Mean hearing thresholds for each frequency are presented in Figure 1. A group × ear × frequency repeated measures ANOVA showed a main effect of group [F(1, 21) = 5.026, p = .036]. This main effect of group suggests that although older subjects scored within normal limits for the frequencies important for speech perception, their overall peripheral hearing sensitivity was still lower than that of the younger subjects. We also found a main effect of frequency [F(7, 15) = 4.656, p = .006], with poorer thresholds for higher frequencies for both groups. A significant frequency × group interaction was also found [F(7, 15) = 3.54, p = .019], suggesting that the two groups differed more in higher frequencies. There was no main effect of ear (left vs. right), nor any other significant interactions.

Figure 2 shows subject performance for each SNR condition (number of words correctly recalled). A group × SNR condition repeated measures ANOVA revealed a main effect of group [F(1, 27) = 8.388, p = .007], a main effect of SNR condition [F(5, 23) = 887.746, p < .001], and a significant interaction [F(1, 27) = 4.108, p = .008]. Post-hoc t-tests revealed that the only SNR condition that showed a significant group difference after Bonferroni correction (p < .0083 is required to reach significance for the 6 tests performed) was the SNR 0 dB condition [t(27) = 3.621, p = .001]. No significant group difference was found for the SNR 5 dB condition [t(27) = 1.954, p = .061] nor for any other conditions.

Group Differences in Neuroanatomy

To gain a broad understanding of group differences in neuroanatomical structures, we performed a series of one-way ANOVAs on the areas of interest. Raw volume, fractional hemispheric volume, and thickness were all considered. Figure 3 shows the results with significant differences highlighted. As the goal here is to highlight general differences, uncorrected p values are shown. Generally speaking, older adults showed significantly lower raw volumes than younger adults across all cortical areas of interest. The observation that group differences were not observed for fractional hemispheric volume (with the exception of left pars orbitalis) suggests that the significant differences in raw volume were driven by overall cortical atrophy in older adults rather than targeted atrophy in specific areas of interest. Group differences in thickness were also found across areas of interest, with reduced thickness in older adults.

Neuroanatomy and Speech Perception in Noise

We performed stepwise multiple linear regression analyses[1] (entrance criterion, α = .05; exit criterion, α = .10) using bilateral anatomical measures of caudal middle frontal gyrus, pars opercularis, pars triangularis, rostral middle frontal gyrus, superior frontal gyrus (covering

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[1] Because no definitive relationship has been established between the α level used for stepwise regression and the Type-I error rate (see e.g. Pope & Webster, 1972), there is no gold standard for the choice of the entrance and exit criteria; however, the analyst must seek to balance both the Type-I and Type-II error rates. Considerable variability in the choice of selection criteria thus exists in the literature (Montgomery & Peck, 1982), with accepted α levels ranging anywhere from .05 to .25 (Kennedy & Bancroft, 1971). Often the entrance and exit criteria are held equal, though a larger α value may be employed for the exit criterion in order to more conservatively retain previously identified predictors in the model (Draper & Smith, 1998). We additionally replicated the statistical analyses for both subject groups using α = .05 for both entrance and exit criteria, and arrived at identical models for all neuroanatomical measures considered.

dorsal and ventral aspects of PFC), precuneus, and superior temporal region (auditory cortex) as predictors of speech perception in noise ability in the least favorable condition on the QuickSIN (0 dB SNR condition). Not only did these regions contribute significantly to speech perception in noise in our previous fMRI study (Wong et al., 2009), but they are also putative cognitive brain regions associated with executive functions, working memory, and attention (e.g., Blumenfeld & Ranganath, 2007). The 0 dB SNR condition was selected because it was the only condition that showed significant group differences. Separate regression models were assessed for raw volume, fractional hemispheric volume, and thickness.

For the older adults subject data, we found only one significant model for both raw volume and fractional hemispheric volume, with volume of left pars triangularis being the sole significant predictor [raw volume: $R^2 = .297$, $F(1,13) = 5.497$, $p = .036$; fractional hemispheric volume: $R^2 = .361$, $F(1,13) = 7.333$, $p = .018$]. Figure 4 (left panels) demonstrates the relationship between fractional hemispheric volume of left pars triangularis and QuickSIN performance. For cortical thickness, only one significant model was found, with thickness of left superior frontal gyrus being the sole significant predictor [$R^2 = .473$, $F(1,13) = 11.683$, $p = .005$] (Figure 4, right panels).[2,3] As seen in Figure 4, the significant correlations linking task performance to left pars triangularis remained after normalizing for total hemispheric volume, implying that the relationship between this cognitive brain region and speech perception in noise abilities in older adults was not related to overall cortical volume. Furthermore, total cortical volume was not correlated with performance in either the 0 dB [Pearson's $r = .008$, $p = .905$] or the 5 dB [Pearson's $r = -.034$, $p = .977$] SNR conditions.

It is also worth mentioning that some of our findings are unrelated to age. We found no significant correlation between the age of the older adults subjects and raw volume of left pars triangularis [Pearson's $r = .006$, $p = .983$], fractional hemispheric volume of left pars triangularis [Pearson's $r = .060$, $p = .833$], or QuickSIN performance (0 dB SNR condition) [Pearson's $r = -.166$, $p = .553$]. However, there was a marginal significant correlation between age and thickness of superior frontal gyrus [Pearson's $r = -.514$, $p = .050$]. (All p values reported were not corrected for multiple comparisons.) In addition, the appendix contains correlational matrices showing colinearity statistics for age, performance on the QuickSIN 0 dB SNR condition and all neuroanatomical measures of interest for the older adults listeners.

The results above indicate that regions of the prefrontal cortex (especially the left pars triangularis, and also the left superior frontal gyrus) are associated with success in perceiving speech in noise in the most difficult listening condition (0 dB SNR), the only Quick SIN condition in which our older and younger subjects differed at a statistically significant level. To further examine the relationship between speech perception in noise and anatomy of the prefrontal cortex, we conducted additional correlational analyses between older adults' performance in the 5 dB SNR condition and anatomical measures of left pars triangularis and superior frontal gyrus. For both raw volume and fractional hemispheric volume, we found a significant positive correlation in the left pars triangularis [raw volume: Pearson's $r = .650$, $p = .009$; fractional hemispheric volume: Pearson's $r = .602$, $p = .018$]. No significant results were found for the superior frontal gyrus [raw volume: Pearson's r =

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[2] It is important to note that step-wise multiple linear regression represents one of the more conservative statistical methods. It is possible that other anatomical variables were predictive of speech perception in noise performance but failed to enter into the model because they were highly correlated with those that did enter into the model (e.g., left pars triangularis and left superior frontal gyrus).

[3] We also performed a correlational analysis to test for a relationship between left superior frontal gyrus (L SF) thickness and accuracy (% correct) on the QuickSIN 0 dB SNR condition, including total brain volume as a control variable. The results remained significant [partial correlation = .704, p = .005].

−.056, p = .844; fractional hemispheric volume: r = −.379, p = .164; thickness: r = −.001, p = .997]. These results are displayed graphically in Figure 5.

For younger adults, we also performed regression analyses on raw volume, fractional hemispheric volume, and thickness, using the same neuroanatomical areas as predictors for QuickSIN performance (0 and 5 dB SNR conditions), and using the same entrance and exit criteria. No significant regression models were found for any neuroanatomical measures. That is, no neuroanatomical measures were predictive of QuickSIN performance.

High Frequency Pure-tone Thresholds and Speech Perception in Noise

Because high-frequency Pure-tone thresholds have been linked to speech perception in noise performance (Plomp, 1986; Nilsson et al., 1994), we performed additional regression analyses using the two highest frequencies we measured (6000 and 8000 Hz) bilaterally as predictors for QuickSIN 0 dB SNR condition). Using a step-wise multiple regression method, we found no significant model for either the older or younger subject groups. However, it is worth pointing out that relatively speaking, even our older subjects have good hearing thresholds and speech perception in noise abilities. Previous studies that found a relation between pure-tone thresholds and speech perception have focused on populations with hearing loss.

DISCUSSION

This study presents evidence for a relationship between the cortical neuroanatomy of cognitive brain regions and spoken word processing in the older adults. Although recent studies have found associations between neuroanatomical measures and speech recognition (e.g., Harris et al., 2009; Eckert et al., 2008), they focused on degraded (low-pass filtered) speech rather than speech embedded in noise, and they did not focus on anatomy of cognitive brain regions. Our study focused on the relationship between PFC anatomy and the ability to identify sentences in noise: the larger or thicker the PFC (considering both “raw” and normalized measures), the better the ability to perceive speech in noise in older (but not younger) adults. Along with other studies that show a correlation between PFC activation and hearing in noise performance (e.g. Wong et al., 2009), these findings underscore the importance of cognitive-association areas when peripheral and central auditory areas are insufficient to process speech in older adults. That is, when the peripheral and central hearing system is taxed (in our case, poorer puretone thresholds and speech perception in noise functions), a larger and more active PFC can facilitate hearing in noise. One conceivable way to interpret these results is through the decline-compensation hypothesis, which suggests that an increase in the recruitment of more general cognitive areas (e.g., PFC) serves to compensate for the decline in sensory processing often found in older adults.

Our results complement decades of research on the peripheral contributions to speech perception in noise (for a review, see Gordon-Salant, 2005) and argue that complex auditory functions are not encapsulated but rather dependent and can be facilitated by higher-order cognition functions. Although the contribution of PFC to cognitive functions has been studied extensively (Knudsen, 2007; Miller & Cohen, 2001), the precise manner in which it may facilitate speech perception in noise and compensate for decreased sensory activation is not clear. Several possible accounts are worth mentioning, including inhibitory control, attention, cross-modal compensation, and phonological working memory.

It is possible that the PFC is exerting inhibitory control, particularly of working memory contents (Hasher & Zacks, 1988) as well as of posterior association and sensory cortices. A larger and more active PFC can more successfully inhibit irrelevant information from the peripheral system, facilitating identification. Evidence for this approach comes from findings that older adults make more indirect semantic associations and remember disconfirmed or inappropriate information relative to younger adults (Zacks et al., 2000). A confirmation of this hypothesis for this study would in part be based on whether the particular areas of the PFC are inhibitory regions or not, and evidence suggests that the left ventral PFC does indeed inhibit verbal working memory (Jonides et al., 2000). Thus, the PFC may be inhibiting competing words during lexical access (Sharp et al., 2004) and a larger (or thicker) PFC may be more successful in inhibiting possible incorrect answers. Alternatively, a larger PFC may be better at blocking the noise itself, inhibiting its acoustic signal from affecting word identification.

An alternative account is based on the role of PFC in attention. Aging is accompanied by a reduction in the amount of attentional resources leading to poor performance on cognitively demanding tasks (Craik, 1986). This is supported by evidence that attentional limits imposed upon younger adults result in performance similar to older adults (Anderson et al., 1998), though the applicability of this hypothesis to the auditory domain is yet to be assessed.

At least two speech-specific possibilities exist for the involvement of PFC in speech perception, and while an account of cross-modal compensatory PFC activation may be useful given the similar pattern of activation found in vision, there may also be speech-specific processes at work. First, most theories of speech perception incorporate the motor system in addition to the auditory system to varying degrees in the network of regions responsible for sound recognition (see Fadiga & Craighero, 2006, Liberman & Mattingly, 1985 for arguments for a significant role; Hickok & Poeppel, 2007 for a limited role). For example, Fadiga and Craighero suggest that listeners understand speakers by virtue of having their articulatory gestures activated by acoustic sounds. Greater dorsal PFC activation may therefore compensate for a degraded acoustic signal in interpreting the acoustic signal as gestures.

Finally, the PFC’s role in speech perception in noise could be as a locus of working phonological memory (Cowan, 1995). Frankish (1996) suggests a crucial role of working memory in the processing of complex strings of sounds, particularly those that are long, based on Baddeley’s (1986) hypothesis of a phonological processing loop. This loop involves entering acoustic information into a store that is then mediated by a central executive process based in the frontal lobe. In this model, speech understanding fails when information decays from the phonological store before it can be subsequently accessed and processed. A larger working memory (i.e. a larger PFC) can ameliorate this situation for both long words or sentences as well as for difficult words that may take longer to process.

Although we attribute our results to a decline-compensation mechanism within the framework of age-related brain atrophy, it is conceivable that such a mechanism is not restricted to older adults but rather to many populations that show decline in sensory domains. For example, it may be the case that younger subjects who have deficits in auditory perception would show the same link between PFC anatomy and task performance as did the older subjects in this study. Importantly, however, we found that young adults with normal hearing did not show this pattern, suggesting that when there is no decline in peripheral hearing, these cognitive regions do not play the same role.

Future research is needed to clarify the role of the PFC in speech perception in noise. It is worth pointing out that neuroanatomical anomalies can sometimes be associated with communicative disorders, which can be partially remediated through behavioral training. For example, phonologically-based treatment can result in behavioral gain, as well as activation of under-activated areas in the left posterior temporal regions of normal readers (e.g., Shaywitz et al., 2004; Simos et al., 2002). Therefore, it is plausible that in certain cases of neuroanatomical anomalies, remediation techniques can alleviate the behavioral deficit. In the case of hearing in noise, this remediation may be facilitated by understanding the role of higher-order cognitive processing. Other future research directions may include investigations of populations of subjects with peripheral hearing impairments and potential gender differences.

Speech communication in the real world is not trivial. Chief among the obstacles facing older adults is the perception of speech in noise. Several studies have found that the frontal lobe shows the fastest rate of age-related atrophy (Pfefferbaum et al., 1998; Raz et al., 2005; Resnick et al., 2003); thus understanding its role in the processing of speech in noise becomes crucial. This study provides evidence that a larger (or thicker) PFC is associated with more successful speech perception in noise in older adults. This contributes to a growing body of converging evidence that seeks to explain hearing in noise problems not constrained to the auditory domain, but rather reflecting the complementary interaction of auditory and cognitive systems.

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APPENDIX: CORRELATIONAL MATRICES*

*A reference key containing the abbreviations used in this appendix can be found in the legend for Figure 3.

Raw Volume

df = 13	Age	QSIN 0 dB	L CMF	R CMF	L IF(po)	R IF(po)	L IF(pt)	R IF(pt)	L PCUN	R PCUN	L RMF	R
Age		r = −.166 p = .553	r = .047 p = .868	r = −.057 p = .840	r = .214 p = .444	r = .214 p = .445	r = .006 p = .983	r = .281 p = .311	r = .175 p = .533	r = −.219 p = .433	r = −.310 p = .261	r = 24 = .
QSIN0 dB	r = −.166 p = .553		r = .032 p = .910	r = .276 p = .320	r = .161 p = .566	r = .121 p = .667	r = .545 p = .036	r = .170 p = .545	r = .215 p = .441	r = .034 p = .904	r = .179 p = .523	r = p = 91
L CMF	r = .047 p = .868	r = .032 p = .910		r = .475 p = .073	r = .529 p = .042	r = .365 p = .181	r = .139 p = .621	r = .513 p = .050	r = .597 p = .019	r = .765 p = .001	r = .384 p = .157	r = p = 11
R CMF	r = −.057 p = .840	r = .276 p = .320	r = .475 p = .073		r = .633 p = .011	r = .431 p = .109	r = .438 p = .103	r = .338 p = .218	r = .690 p = .004	r = .541 p = .037	r = .363 p = .184	r = 04 = .
L IF(po)	r = .214 p = .444	r = .161 p = .566	r = .529 p = .042	r = .633 p = .011		r = .497 p = .060	r = .361 p = .186	r = .332 p = .227	r = .675 p = .006	r = .421 p = .118	r = .275 p = .321	r = p = 75

df = 13	Age	QSIN 0 dB	L CMF	R CMF	L IF(po)	R IF(po)	L IF(pt)	R IF(pt)	L PCUN	R PCUN	L RMF	R
R IF(po)	r = .214 p = .445	r = .121 p = .667	r = .365 p = .181	r = .431 p = .109	r = .497 p = .060		r = .334 p = .223	r = .204 p = .467	r = .339 p = .217	r = .137 p = .625	r = .413 p = .126	r = p = 54
L IF(pt)	r = .006 p = .983	r = .545 p = .036	r = .139 p = .621	r = .438 p = .103	r = .361 p = .186	r = .334 p = .223		r = .434 p = .106	r = .535 p = .040	r = .200 p = .475	r = .712 p = .003	r = p = 28
R IF(pt)	r = .281 p = .311	r = .170 p = .545	r = .513 p = .050	r = .338 p = .218	r = .332 p = .227	r = .204 p = .467	r = .434 p = .106		r = .398 p = .141	r = .557 p = .031	r = .318 p = .248	r = p = 47
L PCUN	r = .175 p = .533	r = .215 p = .441	r = .597 p = .019	r = .690 p = .004	r = .675 p = .006	r = .339 p = .217	r = .535 p = .040	r = .398 p = .141		r = .659 p = .008	r = .487 p = .066	r = p = 39
R PCUN	r = −.219 p = .433	r = .034 p = .904	r = .765 p = .001	r = .541 p = .037	r = .421 p = .118	r = .137 p = .625	r = .200 p = .475	r = .557 p = .031	r = .659 p = .008		r = .526 p = .044	r = p = 06
L RMF	r = −.310 p = .261	r = .179 p = .523	r = .384 p = .157	r = .363 p = .184	r = .275 p = .321	r = .413 p = .126	r = .712 p = .003	r = .318 p = .248	r = .487 p = .066	r = .526 p = .044		r = p < 00
R RMF	r = −.243 p = .383	r = .029 p = .919	r = .425 p = .114	r = −.048 p = .865	r = .089 p = .751	r = .171 p = .541	r = .296 p = .284	r = .201 p = .473	r = .236 p = .398	r = .485 p = .067	r = .791 p < .001	
L SF	r = −.150 p = .594	r = −.081 p = .774	r = .479 p = .071	r = .391 p = .149	r = .174 p = .536	r = .252 p = .364	r = .395 p = .145	r = .529 p = .043	r = .422 p = .117	r = .617 p = .014	r = .555 p = .032	r = p = 19
R SF	r = −.228 p = .414	r = .050 p = .861	r = .418 p = .121	r = .424 p = .116	r = .186 p = .506	r = −.148 p = .599	r = .440 p = .101	r = .448 p = .094	r = .549 p = .034	r = .601 p = .018	r = .411 p = .128	r = p = 50
L ST	r = .098 p = .728	r = .028 p = .921	r = .235 p = .400	r = .469 p = .078	r = .226 p = .418	r = .251 p = .366	r = .321 p = .244	r = .239 p = .390	r = .713 p = .003	r = .434 p = .106	r = .366 p = .179	r = p = 68
R ST	r = −.093 p = .742	r = .225 p = .419	r = .596 p = .019	r = .751 p = .001	r = .506 p = .054	r = .437 p = .103	r = .528 p = .043	r = .522 p = .046	r = .838 p < .001	r = .706 p = .003	r = .585 p = .022	r = p = 34

Fractional Hemispheric Volume

df = 13	Age	QSIN0 dB	L CMF	R CMF	L IF(po)	R IF(po)	L IF(pt)	R IF(pt)	L PCUN	R PCUN	L RMF	R
Age		r = −.166 p = .553	r = .183 p = .514	r = .062 p = .826	r = .342 p = .212	r = .357 p = .191	r = .060 p = .833	r = .443 p = .098	r = .391 p = .149	r = −.114 p = .686	r = −.329 p = .231	r = 14 = .
QSIN 0 dB	r = −.166 p = .553		r = .018 p = .949	r = .261 p = .348	r = .121 p = .669	r = .131 p = .642	r = .601 p = .018	r = .219 p = .432	r = .210 p = .453	r = −.003 p = .991	r = .218 p = .435	r = p = 90
L CMF	r = .183 p = .514	r = .018 p = .949		r = .054 p = .849	r = .134 p = .634	r = .027 p = .923	r = −.407 p = .132	r = .174 p = .535	r = .138 p = .625	r = .492 p = .063	r = −.463 p = .082	r = 09 = .
R CMF	r = .062 p = .826	r = .261 p = .348	r = .054 p = .849		r = .389 p = .152	r = .186 p = .507	r = .127 p = .652	r = .042 p = .882	r = .367 p = .178	r = .064 p = .820	r = −.318 p = .249	r = 68 = .
L IF(po)	r = .342 p = .212	r = .121 p = .669	r = .134 p = .634	r = .389 p = .152		r = .346 p = .206	r = .044 p = .875	r = .020 p = .942	r = .375 p = .168	r = −.105 p = .710	r = −.372 p = .172	r = 33 = .
R IF(po)	r = .357 p = .191	r = .131 p = .642	r = .027 p = .923	r = .186 p = .507	r = .346 p = .206		r = .175 p = .534	r = .011 p = .970	r = −.029 p = .919	r = −.542 p = .037	r = .054 p = .848	r = 13 = .
L IF(pt)	r = .060 p = .833	r = .601 p = .018	r = −.407 p = .132	r = .127 p = .652	r = .044 p = .875	r = .175 p = .534		r = .283 p = .307	r = .212 p = .448	r = −.444 p = .097	r = .627 p = .012	r = p = 59
R IF(pt)	r = .443 p = .098	r = .219 p = .432	r = .174 p = .535	r = .042 p = .882	r = .020 p = .942	r = .011 p = .970	r = .283 p = .307		r = .003 p = .993	r = .257 p = .355	r = −.175 p = .533	r = 13 = .
L PCUN	r = .391 p = .149	r = .210 p = .453	r = .138 p = .625	r = .367 p = .178	r = .375 p = .168	r = −.029 p = .919	r = .212 p = .448	r = .003 p = .993		r = .177 p = .529	r = −.181 p = .518	r = 28 = .
R PCUN	r = −.114 p = .686	r = −.003 p = .991	r = .492 p = .063	r = .064 p = .820	r = −.105 p = .710	r = −.542 p = .037	r = −.444 p = .097	r = .257 p = .355	r = .177 p = .529		r = −.431 p = .109	r = 15 = .
L RMF	r = −.329 p = .231	r = .218 p = .435	r = −.463 p = .082	r = −.318 p = .249	r = −.372 p = .172	r = .054 p = .848	r = .627 p = .012	r = −.175 p = .533	r = −.181 p = .518	r = −.431 p = .109		r = p = 00
R RMF	r = −.140 p	r = .033 p = .906	r = −.098 p = .728	r = −.687 p = .005	r = −.334 p = .224	r = −.137 p = .627	r = .148 p = .599	r = −.130 p = .644	r = −.288 p = .298	r = −.155 p = .582	r = .707 p = .003	

df = 13	Age	QSIN0 dB	L CMF	R CMF	L IF(po)	R IF(po)	L IF(pt)	R IF(pt)	L PCUN	R PCUN	L RMF	R
	= .618											
L SF	r = −.061 p = .829	r = −.174 p = .536	r = −.279 p = .314	r = −.305 p = .269	r = −.571 p = .026	r = −.232 p = .405	r = .116 p = .682	r = .068 p = .811	r = −.298 p = .280	r = −.250 p = .369	r = .102 p = .717	r = 00 = .
R SF	r = −.048 p = .866	r = −.022 p = .938	r = −.163 p = .560	r = −.030 p = .914	r = −.223 p = .425	r = −.549 p = .034	r = .247 p = .375	r = .094 p = .740	r = .161 p = .566	r = −.064 p = .820	r = −.038 p = .894	r = 18 = .
L ST	r = .195 p = .487	r = −.032 p = .909	r = −.191 p = .495	r = .124 p = .659	r = −.179 p = .524	r = −.020 p = .942	r = .135 p = .630	r = −.062 p = .827	r = .579 p = .024	r = −.016 p = .954	r = .118 p = .675	r = 04 = .
R ST	r = .107 p = .704	r = .310 p = .260	r = .031 p = .913	r = .553 p = .032	r = .109 p = .699	r = .131 p = .643	r = .316 p = .252	r = .227 p = .415	r = .624 p = .013	r = .032 p = .909	r = −.104 p = .711	r = 43 = .

Thickness

df = 13	Age	QSIN0 dB	L CMF	R CMF	L IF(po)	R IF(po)	L IF(pt)	R IF(pt)	L PCUN	R PCUN	L RMF	R
Age		r = −.166 p = .553	r = −.432 p = .107	r = −.459 p = .085	r = −.392 p = .148	r = −.122 p = .665	r = −.183 p = .515	r = −.434 p = .106	r = −.289 p = .296	r = −.226 p = .417	r = −.360 p = .188	r = 37 = .
QSIN 0 dB	r = −.166 p = .553		r = .520 p = .047	r = .463 p = .083	r = .482 p = .069	r = .328 p = .232	r = .522 p = .046	r = .581 p = .023	r = .587 p = .022	r = .365 p = .182	r = .438 p = .103	r = p = 05
L CMF	r = −.432 p = .107	r = .520 p = .047		r = .633 p = .011	r = .759 p = .001	r = .747 p = .001	r = .568 p = .027	r = .700 p = .004	r = .566 p = .028	r = .637 p = .011	r = .702 p = .004	r = p = 16
R CMF	r = −.459 p = .085	r = .463 p = .083	r = .633 p = .011		r = .562 p = .029	r = .648 p = .009	r = .388 p = .153	r = .658 p = .008	r = .342 p = .212	r = .479 p = .071	r = .408 p = .131	r = p = 00
L IF(po)	r = −.392 p = .148	r = .482 p = .069	r = .759 p = .001	r = .562 p = .029		r = .470 p = .077	r = .635 p = .011	r = .690 p = .004	r = .744 p = .001	r = .834 p < .001	r = .714 p = .003	r = p = 27
R IF(po)	r = −.122 p	r = .328 p = .232	r = .747 p = .001	r = .648 p = .009	r = .470 p = .077		r = .364 p = .183	r = .500 p = .058	r = .204 p = .467	r = .400 p = .140	r = .547 p = .035	r = p = 15

df = 13	Age	QSIN0 dB	L CMF	R CMF	L IF(po)	R IF(po)	L IF(pt)	R IF(pt)	L PCUN	R PCUN	L RMF	R
	= .665											
L IF(pt)	r = −.183 p = .515	r = .522 p = .046	r = .568 p = .027	r = .388 p = .153	r = .635 p = .011	r = .364 p = .183		r = .441 p = .100	r = .708 p = .003	r = .519 p = .048	r = .872 p < .001	r = p = 11
R IF(pt)	r = −.434 p = .106	r = .581 p = .023	r = .700 p = .004	r = .658 p = .008	r = .690 p = .004	r = .500 p = .058	r = .441 p = .100		r = .745 p = .001	r = .746 p = .001	r = .606 p = .017	r = p = 00
L PCUN	r = −.289 p = .296	r = .587 p = .022	r = .566 p = .028	r = .342 p = .212	r = .744 p = .001	r = .204 p = .467	r = .708 p = .003	r = .745 p = .001		r = .807 p < .001	r = .683 p = .005	r = p = 04
R PCUN	r = −.226 p = .417	r = .365 p = .182	r = .637 p = .011	r = .479 p = .071	r = .834 p < .001	r = .400 p = .140	r = .519 p = .048	r = .746 p = .001	r = .807 p < .001		r = .587 p = .022	r = p = 11
L RMF	r = −.360 p = .188	r = .438 p = .103	r = .702 p = .004	r = .408 p = .131	r = .714 p = .003	r = .547 p = .035	r = .872 p < .001	r = .606 p = .017	r = .683 p = .005	r = .587 p = .022		r = p = 10
R RMF	r = −.379 p = .164	r = .506 p = .054	r = .378 p = .165	r = .744 p = .001	r = .300 p = .277	r = .385 p = .157	r = .429 p = .111	r = .729 p = .002	r = .535 p = .040	r = .429 p = .111	r = .430 p = .109	
L SF	r = −.514 p = .050	r = .688 p = .005	r = .760 p = .001	r = .719 p = .003	r = .654 p = .008	r = .592 p = .020	r = .668 p = .007	r = .813 p < .001	r = .744 p = .001	r = .546 p = .035	r = .733 p = .002	r = p = 00
R SF	r = −.322 p = .242	r = .471 p = .076	r = .455 p = .088	r = .815 p < .001	r = .305 p = .269	r = .527 p = .044	r = .439 p = .102	r = .677 p = .006	r = .444 p = .097	r = .403 p = .137	r = .438 p = .102	r = p < 00
L ST	r = −.018 p = .948	r = .572 p = .026	r = .592 p = .020	r = .459 p = .085	r = .462 p = .083	r = .251 p = .367	r = .365 p = .180	r = .456 p = .087	r = .383 p = .159	r = .382 p = .161	r = .272 p = .327	r = p = 30
R ST	r = −.098 p = .728	r = .459 p = .085	r = .630 p = .012	r = .399 p = .141	r = .379 p = .163	r = .241 p = .386	r = .268 p = .335	r = .396 p = .144	r = .324 p = .239	r = .352 p = .198	r = .208 p = .456	r = p = 43

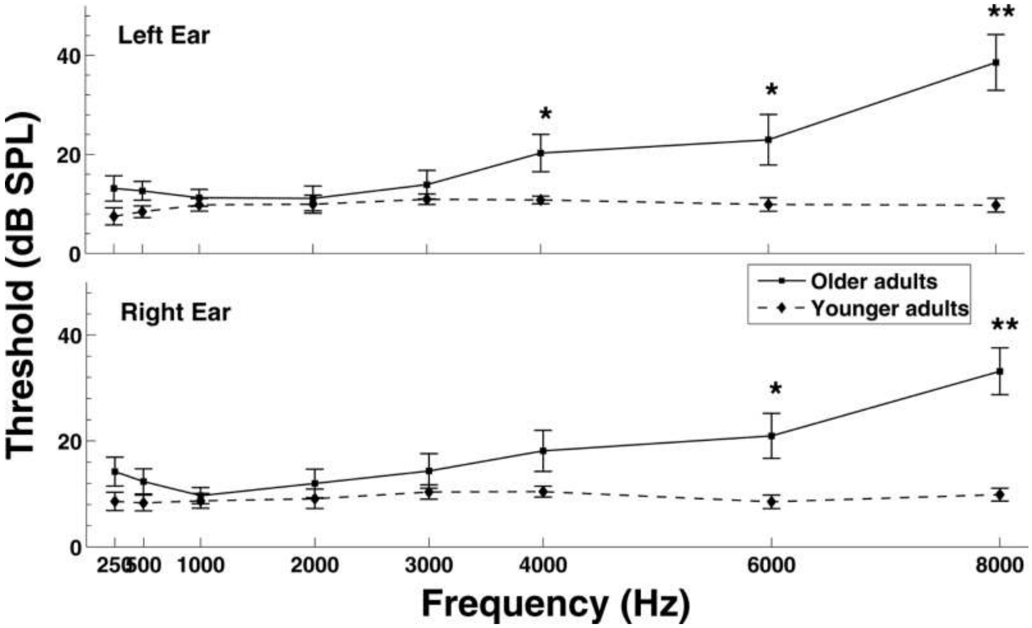

Figure 1.

Subjects' mean hearing thresholds in dB HL. Error bars indicate standard error of the mean. *p < .05 **p < .001

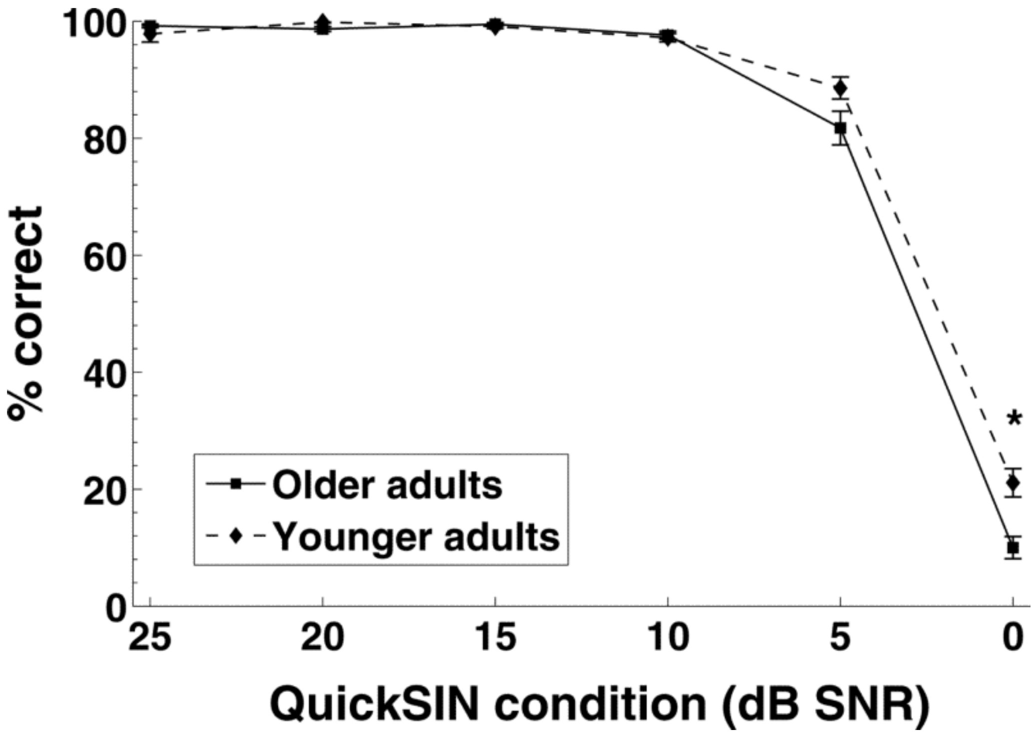

Figure 2.

Subjects' mean QuickSIN performance for all conditions tested. Error bars indicate standard error of the mean. The only QuickSIN condition that showed a significant group difference after Bonferroni correction was the 0 dB SNR condition. *p = .001

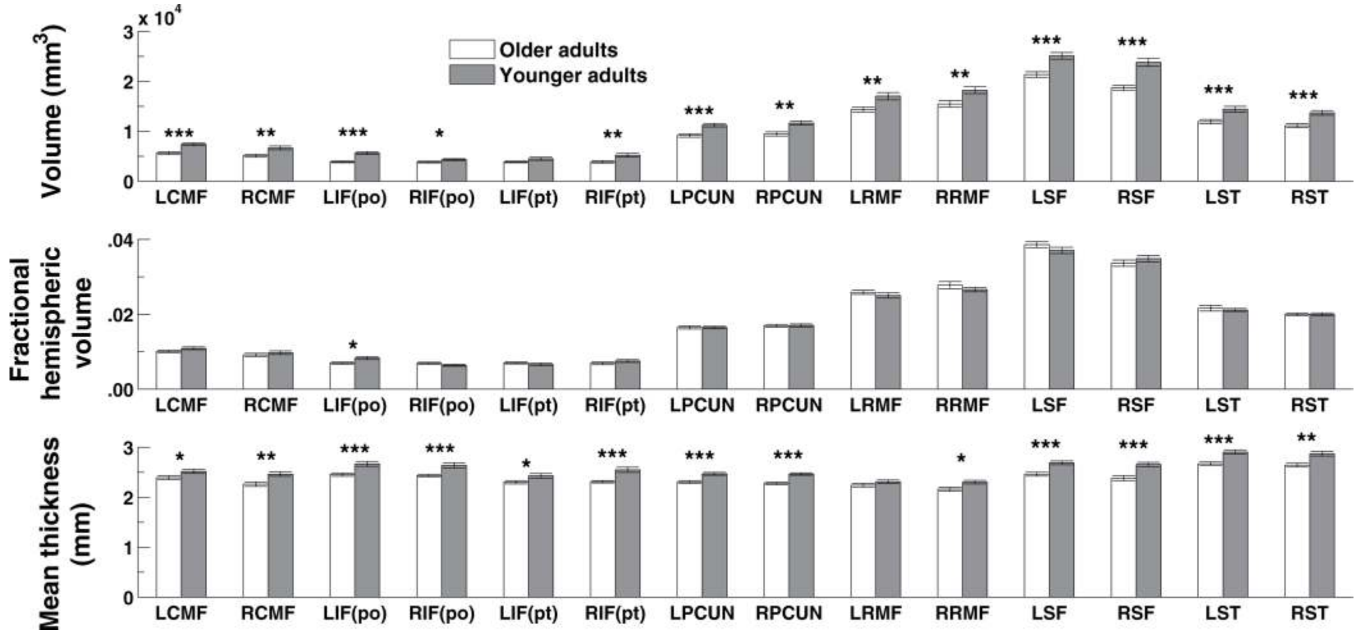

Figure 3.

Average raw cortical volume (top panel), fractional hemispheric volume (middle panel), and cortical thickness (bottom panel) for areas of interest in all subjects. Error bars indicate standard error of the mean. *p < .05 **p<.01 ***p<.001. Abbreviations used:

Left/Right hemispheres	L/R
Caudal Middle Frontal	CMF
Inferior Frontal	IF
Pars opercularis (Area 44)	po
Pars triangularis (Area 45)	pt
Precuneus	PCUN
Rostral Middle Frontal	RMF
Superior Frontal	SF
Superior Temporal	ST

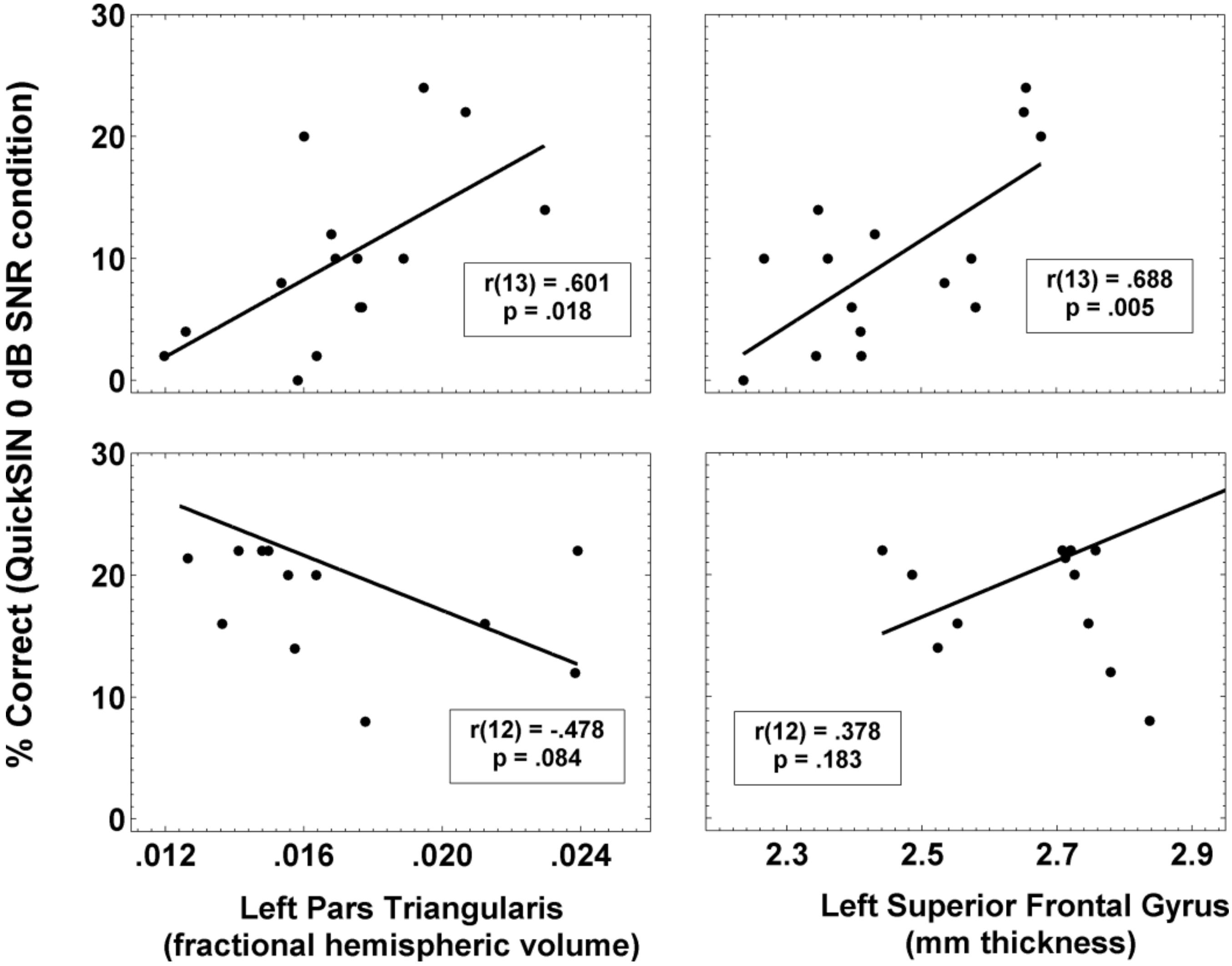

Figure 4.

Scatterplots demonstrating relationships between QuickSIN (0 dB SNR condition) performance and fractional hemispheric volume of left pars triangularis (left panels) and left superior frontal gyrus thickness (right panels). Top and bottom panels show results for older and younger subjects, respectively. (r: Zero order Pearson's correlation)

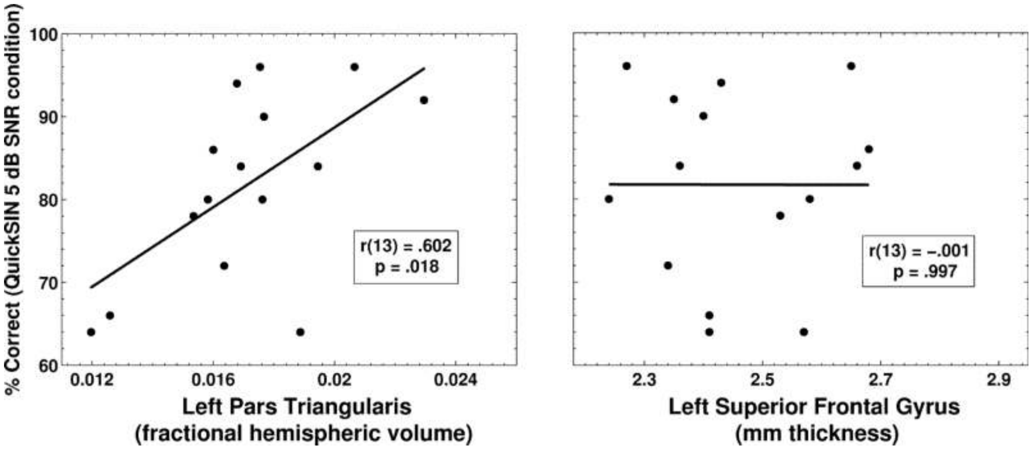

Figure 5.

Scatterplots demonstrating relationships between QuickSIN (5 dB SNR condition) performance and fractional hemispheric volume of left pars triangularis (left panel) and left superior frontal gyrus thickness (right panel) in older adults subjects. (r: Zero order Pearson's correlation)