Published in final edited form as:

Exp Aging Res. 2016 ; 42(1): 67–82. doi:10.1080/0361073X.2016.1108784.

Cingulo-Opercular Function during Word Recognition in Noise for Older Adults with Hearing Loss

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Abstract

Background—Adaptive control, reflected by elevated activity in cingulo-opercular brain regions, optimizes performance in challenging tasks by monitoring outcomes and adjusting behavior. For example, cingulo-opercular function benefits trial-level word recognition in noise for normal hearing adults. Because auditory system deficits may limit the communicative benefit from adaptive control, we examined the extent to which cingulo-opercular engagement supports word recognition in noise for older adults with hearing loss (HL).

Methods—Participants were selected to form groups with Less HL ($N = 12$; $PTA = 19.2 \pm 4.8$ dB HL) and More HL ($N = 12$; mean pure tone thresholds, $PTA = 38.4 \pm 4.5$ dB HL, 0.25 to 8 kHz, both ears). A word recognition task was performed with words presented in multi-talker babble at +3 or +10 dB signal-to-noise ratios (SNRs) during a sparse acquisition fMRI experiment. The participants were middle-aged and older (ages: 64.1 ± 8.4 years) English speakers with no history of neurological or psychiatric diagnoses.

Results—Elevated cingulo-opercular activity occurred with increased likelihood of correct word recognition on the next trial ($t(23) = 3.28$, $p = 0.003$) and this association did not differ between hearing loss groups. During trials with word recognition errors, the More HL group exhibited higher Blood oxygen level-dependent (BOLD) contrast in occipital and parietal regions compared to the Less HL group. Across listeners, more pronounced cingulo-opercular activity during recognition errors was associated with better overall word recognition performance.

Conclusion—The trial-level word recognition benefit from cingulo-opercular activity was equivalent for both hearing loss groups. When speech audibility and performance levels are similar for older adults with mild to moderate hearing loss, cingulo-opercular adaptive control contributes to word recognition in noise.

Keywords

hearing loss; word recognition; adaptive control; attention

Introduction

Age-related hearing loss places considerable demands on the neural systems that support cognitive abilities such as processing speed, working memory, and inhibitory control that are required for successful communication in challenging listening conditions (Humes, Lee, & Coughlin, 2006; McCoy et al., 2005; Wingfield, Tun, & McCoy, 2005). With advancing age and hearing loss, older adults are thought to increasingly depend on controlled auditory processes during speech recognition in noise, as opposed to automatic processing of intelligible speech (Alain, McDonald, Ostroff, & Schneider, 2004; Getzmann, Wascher, & Falkenstein, 2015), particularly when information must be reconstructed from an acoustically degraded speech signal (McCoy et al., 2005; Rönnberg, Rudner, Lunner, & Zekveld, 2010; Wingfield et al., 2005). The current project was designed to characterize the impact of hearing loss on neural control systems that support speech recognition in noise (Erb & Obleser, 2013; Obleser, Wise, Dresner, & Scott, 2007; Wild et al., 2012).

The presentation of speech stimuli with reduced intelligibility during recognition tasks typically elicits a pronounced hemodynamic response within cingulo-opercular cortex (Eckert et al., 2009; Erb & Obleser, 2013; Obleser et al., 2007; Wild et al., 2012), which includes the bilateral dorsal paracingulate, frontal opercula, and anterior insula. This response is typically higher with increasing word recognition difficulty, at least as long as performance is not exceedingly low (Zekveld, Heslenfeld, Festen, & Schoonhoven, 2006). The relative difficulty of the task and the need to produce a behavioral response are both important for observing this activity.

Older adults frequently demonstrate increased cingulo-opercular activity during language and speech recognition tasks compared to younger adults, particularly for easier listening conditions (Eckert et al., 2008; Erb & Obleser, 2013; Harris, Dubno, Keren, Ahlstrom, & Eckert, 2009; Sharp, Scott, Mehta, & Wise, 2006). These findings support theories of perceptual and cognitive aging that propose older adults engage in controlled processing to a greater extent than younger adults by recruiting cortical and cognitive resources to enhance task performance (Decline Compensation Hypothesis: Wingfield & Grossman, 2006; Compensation-Related Utilization of Neural Circuits Hypothesis, CRUNCH: Reuter-Lorenz & Cappell, 2008). Indeed, older adults with better sentence comprehension exhibit increased frontal activity compared to older adults with relatively poorer comprehension (Peelle, Troiani, Wingfield, & Grossman, 2010; Wingfield & Grossman, 2006). Younger adults also exhibit elevated cingulo-opercular activity under task conditions that can challenge performance (Meinzer et al., 2012), suggesting that this is a normal response to task difficulty and errors.

Cingulo-opercular regions are thought to represent a system that regulates tonic alertness (Sadaghiani & D'Esposito, 2015) and facilitates adaptive control to optimize task performance by monitoring outcomes and initiating behavioral changes (Dosenbach et al., 2006). The dorsal cingulate exhibits increased neural activity when task conditions require greater control, such as when stimuli elicit information conflict or there is response uncertainty. This elevated activity appears to provide benefit by reducing response latencies on the next trial (Botvinick, Cohen, & Carter, 2004; Carter et al., 1998; Kerns et al., 2004;

Sheth et al., 2012). Thus, cingulo-opercular cortex appears to be important for performance monitoring and the implementation of adaptive control through transient adjustments of behavior or selective attention to improve performance.

Consistent with evidence of an adaptive control function for the cingulo-opercular cortex, increased cingulo-opercular activity has also been shown to precede correct word recognition in noise (Vaden et al., 2013; Vaden, Kuchinsky, Ahlstrom, Dubno, & Eckert, 2015). In a study of older adults with normal hearing, trial-level benefit from elevated cingulo-opercular activity was higher for older adults with better overall word recognition compared to older adults with poorer overall word recognition (Vaden et al., 2015). Older adults with a larger range of hearing loss have been shown to exhibit increased cingulo-opercular activity for easier conditions in a speech recognition task (Erb & Obleser, 2013), although it is not clear that this elevated activity occurred with performance benefit. These findings motivated the current study to characterize the impact of hearing loss on cingulo-opercular function for older adults during a speech recognition in noise task.

Declines in the central auditory system occur with peripheral hearing loss (Eckert, Cute, Vaden, Kuchinsky, & Dubno, 2012; Peelle, Troiani, Grossman, & Wingfield, 2011), which potentially impact performance even when signal levels provide sufficient speech audibility for people with and without hearing loss (Shinn-Cunningham & Best, 2008). The expected value of engaging adaptive control is predicted to decline (Shenhav, Botvinick, & Cohen, 2013) in cases where hearing-related deficits impose a ceiling on performance and thus the benefit from flexible adjustments in behavior and selective attention is limited. This change in the value of control may account for higher cingulo-opercular activity in easier task conditions when older adults with sensory declines perform challenging tasks (Reuter-Lorenz & Cappell, 2008), including speech recognition (Erb & Obleser, 2013). Cingulo-opercular cortex would still be predicted to respond robustly to errors and difficult task conditions in such cases (Harris et al., 2009; Meinzer et al., 2012; Sharp et al., 2006), but provide a limited word recognition benefit for people with hearing loss. Alternatively, cingulo-opercular engagement may predict word recognition to a similar extent for people with hearing loss, particularly when audibility and performance differences are limited. Hearing loss typically impacts speech audibility and therefore speech recognition task performance, which may confound central effects of sensory declines and poorer task performance, particularly in the error-responsive cingulo-opercular system. Thus, the goal of the current study was to compare the word recognition benefit from cingulo-opercular activity for older adults with mild to moderate hearing loss compared to performance-matched controls with better hearing.

Methods

Participants

The current study used a two group design to balance individual differences that could potentially vary with hearing loss among older adults. Twenty-four participants from a large-scale word recognition in noise experiment were selected for the current study on the basis of audiometric thresholds, age, and sex to form a group with relatively less hearing loss (Less HL; $N = 12$) and a group with more hearing loss (More HL; $N = 12$). The two groups

were selected with equivalent overall word recognition despite significant hearing loss differences (Table 1), to avoid conflating the effects of hearing loss on brain activity with the effects of more recognition errors. Incorrect word recognition drives a strong responses in the cingulo-opercular cortex that could increase Blood oxygen level-dependent (BOLD) variability for participants with more hearing loss, thereby reducing sensitivity to effects on subsequent word recognition. Moreover, we were interested in examining cingulo-opercular activity between hearing groups when the stimuli were audible to both groups. Balancing the groups for overall word recognition and the stimulus presentation methods described below substantially diminished the potential for audibility effects.

The participants were selected to include middle-aged to older adults (9 females; ages: 64.1 ± 8.4 years, mean $\pm$ sd; age range = 45.8 to 78.0 years). All twelve participants in the Less HL group and two in the More HL group were from a previously analyzed sample of 31 older adults (Vaden, Kuchinsky, Ahlstrom, Dubno, & Eckert, 2015). The participants were all native English speakers, had 15.8 ± 2.1 years of education, had no evidence of mild cognitive impairment with Mini Mental Status Examination test scores = 28.9 ± 0.8 out of 30 items (MMSE; Folstein, Robins, & Helzer, 1983; c.f. Tombaugh & McIntyre, 1992), and were largely right-handed (mean Edinburgh handedness score = 69.2 ± 53.9 ; Oldfield, 1971). The two groups did not significantly differ in age, handedness, sex, and MMSE scores (Table 1). None of the participants reported a history of neurological or psychiatric events. Informed consent was obtained in compliance with the Institutional Review Board at the Medical University of South Carolina, and experiments were conducted in accordance to the Declaration of Helsinki.

Audiometric assessment included the measurement of pure tone thresholds with a Madsen OB922 audiometer and TDH-39 headphones calibrated to American National Standards Institute standards (2010). Mean pure tone thresholds (PTA; 0.25 to 8 kHz tones, both ears) were significantly lower for the Less HL group than the More HL group (Table 1) with larger differences above 2 kHz (Figure 1). All participants had normal immittance measures and PTA differences of 10 dB HL or less between right and left ears.

Materials and Procedure

The materials and procedure are identical to those described in Vaden et al. (2013; 2015).

Stimuli and Apparatus—During each task trial, participants listened to a monosyllabic word that was presented to both ears in a continuous multi-talker babble at one of two signal-to-noise ratios (SNR; +3 or +10 dB SNR). Each of the 120 words had a consonant-vowel-consonant structure and were digitally recorded by a male talker (Dirks, Takayanagi, Moshfegh, Noffsinger, & Fausti, 2001). The multi-talker babble recording was from the Speech Perception in Noise test (Kalikow, Stevens, & Elliott, 1977) that consists of 12 talkers. Each word was presented at 85 or 92 dB SPL with the babble at 82 dB SPL using piezoelectric insert ear phones (Sensimetrics). Prior to the fMRI experiment session, presentation levels were calibrated in the scanner console room. The SNRs were further controlled by presenting words and babble during the relatively quiet intervals between scans for a sparse acquisition fMRI sequence with 8.6 sec between scan onsets. E-Prime

software (Version 2.0) was used to synchronize audio presentations, record participant responses from a microphone (Magnetic Resonance Technologies Inc.), and present task onset and response cues onto a screen that was viewed through a head coil-mounted periscope.

Design—A single scanning run (25 min 48 sec) was used to collect 180 functional volumes for a block design with two word recognition epochs (scanner repetition time, TR = 8.6 s; each block was 60 TRs; 8 min 36 s) that alternated between +3 and +10 dB SNR conditions for 4–6 consecutive trials (Figure 2A). There were two blocks during which only the babble was presented (15 TRs each; 2 min 9 sec). Silent rest blocks (10 TRs each; 1 min 26 sec) occurred at the beginning, middle, and end of the experiment, during which no words were presented and no task was performed.

Procedure—Participants were instructed to listen to each word presented in multi-talker babble and repeat the item exactly as they heard it. If the word was not recognized, participants were instructed to say “nope”. At the beginning of each trial (0 sec post-scanner onset), a white crosshair appeared onscreen. The scanner acquisition and associated noise had a duration of 1.6 sec. A word was presented at +3 or +10 dB SNR (3.1 sec). When the response interval started (4.1 sec), the crosshair changed from white to red, which indicated that the participant should respond. The crosshair then changed to white again when the response interval ended (6.1 sec) and remained onscreen until the onset of the next trial (8.6 sec). This trial timing was designed to reduce additive noise and speech masking from the preceding scan, and to reduce speech-related head movements during the following scan.

Scoring—Responses from each trial were scored as correct only when a word was repeated exactly as it was presented. During the fMRI experiment, two raters listened to and scored each response, with 94.2% agreement, and discrepancies were clarified by listening to recordings of participant responses. Across participants, 105 “nope” responses were scored as incorrect (3.6%), ranging from 0 to 17 responses per subject. A total of 71 missing or unintelligible responses were excluded from analyses (2.5%; 0 to 24 per subject).

Image acquisition—All of the MRI data were acquired with a Siemens 3T TIM Trio scanner that was equipped with a 32-channel head coil. Structural T1 images with 160 slices were collected with 1×1×1 mm voxels, 256×256 matrix, TR = 8.13 msec, TE = 3.7 msec, flip angle = 8°, slice thickness = 1.0 mm, and no slice gap. Functional T2*-weighted images with 36 slices were collected with 3×3×3 mm voxels, 64×64 matrix (FOV = 128×128) using a single shot gradient echo-planar imaging sequence, flip angle = 90°, TR = 8.6 sec, TE = 35 msec, TA = 1647 msec, transverse acquisition, slice thickness = 3.00 mm, sequential order, no slice gap, and GRAPPA-parallel imaging with acceleration factor = 2. Prior to the onset of the functional experiment, four dummy volumes were collected and discarded.

Preprocessing—Structural images from each participant were spatially transformed into a custom anatomical template and coordinate space for functional images, based on a sample of 31 middle-aged and older adults (Vaden et al., 2015) using the Advanced Normalization Tools (<http://stnava.github.io/ANTs>; ANTS version 1.9; Avants & Gee, 2004; Vaden, Gebregziabher, Kuchinsky, & Eckert, 2012). The functional image data from each

participant were motion-corrected, unwarped, co-registered to their structural image, and smoothed after spatial normalization (FWHM = 8mm) with Statistical Parametric Mapping software (SPM, version 8; www.fil.ion.ucl.ac.uk/spm). The global mean signal was regressed from the voxel time series using the Linear Model of the Global Signal method (Macey, Macey, Kumar, & Harper, 2004). Functional images that contained extreme values (5.0% of the total) were identified using an algorithm from Vaden, Muftuler, & Hickok (2010), which uses two methods to create a pair of binary nuisance regressors for SPM analyses. The first method tagged images with global intensity that exceeded 2.5 sd from the global time series mean. The second method counted voxels with intensity more than 2.5 sd from their respective voxel time series means, then tagged images with counts that exceeded 2.5 sd from the mean. Additional preprocessing steps were used for voxel-level analyses with R-statistics: 1) a high-pass filter (HPF; 1/128 Hz) then 2) multiple regression-based correction of voxel-level BOLD time series for high-pass filtered head motion vectors (Kuchinsky et al., 2012).

Task-related effects on BOLD contrast—Regression analyses were performed with SPM to test predictions that cingulo-opercular regions would exhibit increased activity during trials with incorrect compared to correct recognition, +3 dB SNR compared to +10 dB SNR, and across task trials compared to rest or babble presentations (Figure 2). The regression model specified BOLD contrast as the dependent variable for each trial (t), with the following event types and predictors: transitions between rest and task epochs to control for a large ventral attention response that typically occurs in these experiments (*TRANS*; Vaden et al., 2013), multi-talker babble presentations with no recognition task (*BABBLE*), trials with the word recognition task (*TASK*), SNR condition (*SNR*), correct or incorrect recognition (*COR*), nuisance regressors (NREG), and an error term. The model equation was expressed as: $BOLD_t = SNR_t + COR_t + TRANS_t + BABBLE_t + TASK_t + NREG_t + error$. Due to the sparse design, BOLD at trial t reflects activity changes following events during trial t (Figure 2C). The SPM analysis included a HPF (1/128 Hz) and did not use auto-regression correction, as longer TRs eliminate serial dependencies (Friston et al., 2002).

BOLD effects on subsequent word recognition—Associations between BOLD contrast and subsequent word recognition were tested with GLM-based logistic multiple regression analyses, using the R statistics software (version 3.0.1 with R-package: AnalyzeFMRI, version 1.1.16). The regression model specified correct or incorrect responses (*COR*) for each trial (t) as the dependent variable, with the following predictors: *BOLD* prior to the word presentation ($t-1$), *SNR* condition, $SNR \times BOLD$ interactions, and an error term, which was expressed: $COR_t = SNR_t + BOLD_{t-1} + SNR_t \times BOLD_{t-1} + error$. The BOLD contrast measured during trial $t-1$ reflects activity prior to the presentation of the word and SNR condition during trial t (Figure 2D). These analyses omitted BOLD values that were more than 3 sd from the voxel time series mean to limit the potential for motion or other spiking artifacts that could reduce statistical sensitivity. Furthermore, the analysis excluded trials immediately following a different SNR condition or rest (i.e., first trial of each block) and BOLD data were centered and scaled within SNR conditions to ensure that variability did not reflect participant or SNR-dependent differences (Vaden et al., 2013, 2015).

Group statistic maps—Voxel-level statistic maps were produced by performing Z-tests on standard estimates from the GLM analyses (i.e., Betas). Significant effects were defined for each group statistic map with an uncorrected voxel-level statistic threshold: $Z > 3.09$, $p_{UNC} = 0.001$ and family-wise error corrected cluster size threshold: $p_{FWE} < 0.01$ (Friston, Worsley, Frackowiak, Mazziotta, & Evans, 1994). The Montreal Neurological Institute (MNI) coordinates were obtained for peak voxel locations by applying transformations to statistic maps that were estimated by spatially warping the study-specific template into MNI template space using ANTS (Avants & Gee, 2004).

Group comparisons—Given previous findings linking cingulo-opercular activity to task performance and our focus on the impact of hearing loss, a region of interest analysis was performed to characterize differences between hearing loss groups. Participants from each hearing loss group were compared using pooled Betas within a cingulo-opercular mask. This approach limited the number of comparisons and increased statistical sensitivity across cingulo-opercular voxels that were previously shown to behave like a network (Vaden et al., 2013). The mask was based on significant adaptive control effects (voxel $p_{UNC} < 0.001$, cluster $p_{FWE} < 0.05$) from an independent sample of younger adults (Vaden et al., 2013).

Results

Word recognition

Mean word recognition was lower in the +3 dB SNR ($40.1 \pm 6.8\%$) compared to the +10 dB SNR condition ($70.1 \pm 7.7\%$; $t(23) = -15.80$, $p < 0.001$, $d = 3.22$). Mean word recognition was not lower with increasing age (+3 dB SNR: $r = -0.0008$, $p = 0.50$, $d = -0.0008$; +10 dB SNR: $r = -0.20$, $p = 0.18$, $d = -0.19$; or averaged across conditions: $r = -0.16$, $p = 0.23$, $d = -0.15$). Because the groups were equated for performance during subject selection, mean word recognition was not lower for the More HL group compared to the Less HL group for the +3 dB SNR condition ($t(22) = -0.55$, $p = 0.29$, $d = -0.11$), the +10 dB SNR condition ($t(22) = -0.84$, $p = 0.21$, $d = -0.17$), or averaged across conditions (Table 1). The number of correct, incorrect, missing, and “nope” responses did not differ between groups (all $|d| < 0.20$, $p > 0.33$). These results suggest that the babble presentation level, rather than the participants’ detection thresholds in quiet, was the limiting factor that determined speech audibility for the two groups.

Task-related activity

Whole brain results are presented in Table 2 and Figure 3A–C. A difference in BOLD contrast during trials with recognition errors (Incorrect > Correct) was the only significant HL group difference in voxel-level statistic results. During trials with recognition errors, the More HL group increased BOLD contrast in inferior occipital and parietal cortices, while the Less HL group decreased BOLD contrast in these regions (Figure 3B).

Predicting next trial performance

Whole brain statistics showed that correct word recognition was more likely when preceded by elevated BOLD contrast in the left anterior insula and frontal operculum, left precentral sulcus, and right parieto-occipital sulcus (Table 3, Figure 3D), and no significant effects of

hearing loss group. Betas pooled within the cingulo-opercular mask demonstrated an association between elevated BOLD contrast and subsequent word recognition ($t(23) = 3.28$, $p = 0.003$, $d = 0.67$). A direct comparison of those pooled cingulo-opercular mask betas did not show a significant hearing group difference ($t(22) = 1.65$, $p = 0.06$, $d = 0.34$; Figure 3E). In addition, PTA across all participants was not correlated with the cingulo-opercular pooled betas ($r = -0.21$, $p = 0.32$, $d = -0.21$).

Group comparisons

Within the cingulo-opercular mask, participants with better overall recognition demonstrated larger BOLD increases during error trials ($r = 0.50$, $p = 0.01$, $d = 0.56$; Figure 3F). This association was driven by the More HL group ($r = 0.83$, $p < 0.001$, $d = 0.95$) and was significantly stronger than for the Less HL group ($r = 0.19$, $p = 0.55$, $d = 0.13$; significant difference: Fisher Z-prime = 2.09, $p = 0.02$, $d = 0.46$). Thus, the cingulo-opercular cortex of the better performers from the More HL group was particularly sensitive to errors.

General Discussion

Cingulo-opercular activity predicted trial-level word recognition to a similar extent for older adults with more or less hearing loss, at least when speech stimuli were presented with similar audibility. These effects were modest for both groups, however, and were consistent with evidence that the word recognition benefit from cingulo-opercular activity is reduced for older adults compared to younger adults (Vaden et al., 2015). Adaptive control during word recognition, as defined by adjustments in performance following changes in cingulo-opercular activity, therefore appears to be more affected by age than by concomitant changes in the central auditory system function that may occur with hearing loss.

Numerous studies have shown that older adults with the best speech recognition are more likely to exhibit elevated frontal activity compared to those with poor performance (Erb & Obleser, 2013; Harris et al., 2009; Peelle et al., 2010; Vaden et al., 2015; Wingfield & Grossman, 2006). Participants in the current study exhibited elevated frontal activation during word recognition trials, particularly during trials with recognition errors. Error-related BOLD contrast in cingulo-opercular cortex was higher for the better performing participants. This effect appeared to be driven by a subset of the More HL cases who demonstrated better overall recognition. Our interpretation of this result is that better performing subjects were more sensitive to making an error and that there was more value in correct word recognition for these older adults.

We also observed that visual cortex exhibited increased activity when More HL cases made word recognition errors compared to Less HL cases. The Less HL cases were more likely to exhibit relatively suppressed visual cortex activity when making word recognition errors. A similar finding in the same visual cortex locations was observed among older adults compared to younger adults when participants listened to speech in noise (Kuchinsky et al., 2012). Older adults exhibited limited to no activity when speech was relatively intelligible, but visual cortex activity increased with decreasing word intelligibility. Younger adults seemed to suppress visual cortex activity when speech was relatively intelligible, and this suppression weakened with decreasing word intelligibility. These observations suggest that

visual cortex and the direction of attention is increasingly important as listening difficulty increases, particularly for older adults (Vaden et al., 2015). We hypothesize that older adults were directing attention to task-related visual cues that carried information about the timing of the next trial to enhance performance.

In previous studies, cingulo-opercular and visual cortex activity during word recognition predicted performance on the next trial (Vaden et al., 2013, 2015). The goal of this study was to examine the extent to which these effects differed between hearing groups. There were no significant hearing group differences, however, suggesting that people with moderate hearing loss can experience as much benefit from cingulo-opercular activity as people with better hearing thresholds, particularly when audibility and overall word recognition are controlled. The ability to engage or benefit from adaptive control is not limited by hearing declines as long as stimuli are sufficiently audible for participants to perform the task. Thus, older adults with hearing loss can benefit from cingulo-opercular function that is likely limited by normative age-related declines in cortical structure and function (Vaden et al., 2015).

One limitation of the current study and most hearing loss studies is the inclusion of cases with different types of age-related hearing loss or presbycusis (Dubno, Eckert, Lee, Matthews, & Schmiedt, 2013). People with high frequency hearing loss that is characteristic of sensory presbycusis may experience limited cingulo-opercular benefit because of structural declines in auditory cortex (Eckert et al., 2012), which would be expected to limit modulatory gain and benefit from attention systems during controlled auditory processing (Alain et al., 2004; Getzmann et al., 2015). Alternatively, people with low frequency hearing loss that is characteristic of metabolic presbycusis may experience limited cingulo-opercular benefit because of small vessel disease that appears to affect the inner ear and frontal cortex (Eckert et al., 2013), which could limit the use of attention systems (Eckert, 2011; Kennedy & Raz, 2009). A study of older listeners with metabolic, sensory, or neural presbycusis could explain when and why older adults will benefit from adaptive control in listening tasks. As in this study, we recommend balancing hearing groups for performance so that results can be interpreted in the context of hearing loss effects that are distinguishable from performance effects.

The current study provides preliminary evidence that older adults with mild to moderate hearing loss benefit to a similar degree from cingulo-opercular adaptive control. The engagement of cingulo-opercular adaptive control appears to facilitate communication in challenging listening conditions for older adults, at least when the speech stimuli are audible and performance differences are restricted. An important question stemming from these results is whether the engagement of control networks can explain why older adults experience more effortful listening and fatigue (Rudner, Lunner, Behrens, Thorén, & Rönnerberg, 2012; Wöstmann, Herrmann, Wilsch, & Obleser, 2015).

Acknowledgments

This work was supported (in part) by the National Institutes of Health / National Institute on Deafness and Other Communication Disorders (P50 DC 000422), MUSC Center for Biomedical Imaging, South Carolina Clinical and Translational Research (SCTR) Institute, NIH/NCRR (UL1 RR029882). This investigation was conducted in a

facility constructed with support from Research Facilities Improvement Program (C06 RR14516) from the National Center for Research Resources, National Institutes of Health. We also thank the participants for their involvement in this study.

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Figure 1. Mean pure tone thresholds across ears with standard error bars for the hearing loss groups. The Less HL group had a mild sloping hearing loss, while the More HL group had a mild to moderate sloping hearing loss that affected sensitivity for pure tones at 2 kHz and above.

Figure 2.

A) A block design was used to present rest trials, babble (B), and words in babble (W+B). Lower and higher blocks depict the +3 and +10 dB SNR, respectively. B) The BOLD response to conditions, as modelled by the GLM. C) Error effects were estimated by comparing BOLD after incorrect versus correct responses. D) Predictive activity compared the likelihood of correct responses after increased or decreased BOLD.

Figure 3.

A) The word recognition task trials elicited elevated BOLD contrast within temporal and frontal regions (red; Task > Rest). When trials that presented words in babble were contrasted with babble-only presentations, BOLD contrast increased in the left anterior insula and inferior frontal gyrus (green; Task > Babble). Overlapping effects are shown in motor cortex in yellow (green + red). Cingulo-opercular BOLD contrast increased during recognition error trials (blue; Incorrect > Correct Recognition). B) During trials with recognition errors, the More HL group increased BOLD contrast in inferior occipital and left superior parietal cortices while the Less HL group exhibited a relative decrease. C) BOLD contrast increased to a greater extent during trials in the +3 dB SNR compared to +10 dB SNR (red) in right anterior insula/frontal operculum and middle temporal cortices. BOLD

contrast decreased to a greater extent when +3 dB SNR trials were compared to +10 dB SNR trials throughout a default mode network distribution (blue). D) Voxel-level results where elevated BOLD contrast was associated with correct recognition on the next trial. E) Cingulo-opercular BOLD contrast within the mask region (red) was significantly related to next trial word recognition and this effect did not decline significantly with increasing hearing loss. F) Participants with better overall word recognition demonstrated the largest error-related cingulo-opercular activations within the same mask. Note: LH and RH indicate left and right hemispheres, respectively.

Table 1

Group Comparisons

Measure	Less HL	More HL	Difference
PTA (dB HL)	19.2 ± 4.8	38.4 ± 4.5	$t(22) = -10.13, p < 0.001, d = -2.07$
Percent correct word recognition	56.8 ± 5.4	54.4 ± 6.1	$t(22) = 1.00, p = 0.16, d = 0.20$
Age (years)	62.0 ± 4.9 [53.4, 71.3]	66.3 ± 10.7 [45.8, 78.0]	$t(22) = -1.25, p = 0.11, d = -0.26$
Sex	6 F, 6 M	3 F, 9 M	Fisher's exact test $p = 0.40$
MMSE	28.8 ± 0.8	29.0 ± 0.9	$t(22) = -0.76, p = 0.23, d = -0.16$
Edinburgh handedness	57.9 ± 58.3 [-70, 100]	80.4 ± 49.1 [-70, 100]	$t(22) = -1.02, p = 0.16, d = -0.21$
Years of Education	16.1 ± 2.1	15.6 ± 2.2	$t(22) = 0.57, p = 0.29, d = -0.12$

Note: PTA = Pure-tone Averages (mean ± standard deviation). Ranges appear in square brackets. Percent correct word recognition is averaged across SNR conditions. MMSE = Mini Mental Status Examination. Edinburgh handedness is measured on a scale of -100 to 100 where -100 is exclusively left-handed and 100 is exclusively right-handed.

Table 2

Word Recognition and SNR Effects on BOLD Contrast

Description of Contrast, Cluster Extent	Peak Z	# Voxels	Peak MNI
Task > Rest			
R. ant. to post. sup. temporal gyrus	6.64	670 **	63, -3, -1
L. ant. to post. sup. temporal gyrus, L. inf. precentral gyrus	6.48	706 **	-40, -26, 14
Brainstem, isthmus	4.64	113 **	3, -36, -7
L. ant. insula, L. inf. frontal gyrus	4.38	56 **	-37, 25, 3
R. medial temporal lobe	3.54	21 *	24, -23, -14
Task > Babble			
L. ant. insula, L. frontal operculum, L. inf. precentral gyrus	4.59	310 **	-30, 21, 10
R. ant. insula, L. frontal operculum	4.57	67 **	33, 21, 0
L. medial thalamus	3.53	31 *	-4, -27, 7
Incorrect > Correct Recognition (Errors)			
L. inf. frontal sulcus, L. precentral sulcus	4.61	169 **	-50, 5, 44
L. intraparietal sulcus	4.35	22 *	-37, -53, 49
L. ant. insula, L. inf. frontal gyrus	4.35	91 **	-31, 25, 0
L. dorsal paracingulate, L. supplementary motor area	4.25	111 **	-4, 11, 58
R. ant. insula, R. inf. frontal gyrus	3.81	74 **	46, 18, 5
Errors: More HL < Less HL			
L. sup. parietal lobule, L. intraparietal sulcus	3.93	24 *	13, -59, 5
L. collateral sulcus, L. lingual gyrus	3.88	25 *	-18, -68, -6
R. collateral sulcus, R. lingual gyrus	3.71	66 **	13, -79, 12
R. cuneus	3.57	22 *	-42, -47, 54
+3 > +10 dB SNR			
R. sup temporal sulcus	4.63	63 **	60, -29, -4
R. ant. insula	4.07	29 *	33, 21, 0
R. inf. frontal gyrus (pars orbitalis)	3.72	49 **	55, 27, 0
+10 > +3 dB SNR			
L. inf. parietal lobule	4.74	129 **	-33, -70, 25
R. ventromedial frontal cortex, ant. to post. cingulate, precuneus, L. sup. parietal lobule	4.65	929 **	24, 27, 33
L. ventromedial frontal cortex	4.33	87 **	-18, 38, 45
R. inf. parietal lobule	3.84	46 **	45, -74, 33
R. sup. parietal lobule	3.81	23 *	24, -44, 70

Note: Each reported result was significant using a combined voxel statistic threshold: $Z=3.09$, $p_{UNC}=0.001$, and cluster extent threshold: $p_{FWE}<0.01$. Asterisks denote the family-wise error corrected significance for each cluster: $p_{FWE}<0.01$, ** 0.001. MNI: Montreal Neurological Institute coordinates; L: left, R: right, otherwise bilateral; Ant: anterior, Post: posterior, Inf: inferior, Sup: superior.

Table 3

Effects of BOLD Contrast on Next Trial Word Recognition

Description of Contrast, Cluster Extent	Peak Z	# Voxels	Peak MNI
BOLD			
L. ant. insula, L. frontal operculum	4.77	35 *	−35, 22, 0
L. precentral sulcus	4.95	46 *	−43, 1, 45
R. parieto-occipital sulcus	4.05	36 *	11, −79, 38
BOLD × SNR			
R. rostral cingulate	5.12	36 *	6, 22, −12

Note: Statistic thresholds, asterisks, and abbreviations are identical to those in Table 2.