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Cingulo-opercular activity affects incidental memory encoding for speech in noise

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ABSTRACT

Correctly understood speech in difficult listening conditions is often difficult to remember. A long-standing hypothesis for this observation is that the engagement of cognitive resources to aid speech understanding can limit resources available for memory encoding. This hypothesis is consistent with evidence that speech presented in difficult conditions typically elicits greater activity throughout cingulo-opercular regions of frontal cortex that are proposed to optimize task performance through adaptive control of behavior and tonic attention. However, successful memory encoding of items for delayed recognition memory tasks is consistently associated with increased cingulo-opercular activity when perceptual difficulty is minimized. The current study used a delayed recognition memory task to test competing predictions that memory encoding for words is enhanced or limited by the engagement of cingulo-opercular activity during challenging listening conditions. An fMRI experiment was conducted with twenty healthy adult participants who performed a word identification in noise task that was immediately followed by a delayed recognition memory task. Consistent with previous findings, word identification trials in the poorer signal-to-noise ratio condition were associated with increased cingulo-opercular activity and poorer recognition memory scores on average. However, cingulo-opercular activity decreased for correctly identified words in noise that were not recognized in the delayed memory test. These results suggest that memory encoding in difficult listening conditions is poorer when elevated cingulo-opercular activity is not sustained. Although increased attention to speech when presented in difficult conditions may detract from more active forms of memory maintenance (e.g., sub-vocal rehearsal), we conclude that task performance monitoring and/or elevated tonic attention supports incidental memory encoding in challenging listening conditions.

Introduction

Poor recall of words occurs in difficult listening conditions, such as in background noise, even when those words were understood (Murphy et al., 2000; Pichora-Fuller et al., 1995; Rabbitt, 1968; Ward et al., 2016). One explanation for poor recall of speech in noise is that attention is diverted away from memory encoding to help extract the speech signal from noise, at least for serial recall tasks (Heinrich et al., 2008; Rabbitt, 1991, 1968; Tun et al., 2009; Wild et al., 2012). For example, increased cingulo-opercular cortex activity is frequently observed during speech identification tasks (Eckert et al., 2009; Erb and Obleser, 2013; Harris et al., 2009; Vaden et al., 2013). The limited neural resource hypothesis would predict that this attention-related activity results in poorer memory encoding in challenging listening conditions. However, elevated cingulo-opercular activity is consistently associated with successful recall when memory encoding occurs in less perceptually demanding conditions (Kim, 2011; Spaniol et al., 2009). We examined the extent to which the engagement of cingulo-opercular cortex during a word identification in noise task was associated with relatively better or worse recognition memory.[1]

Cingulo-opercular activity is pronounced during word identification in noise tasks (Eckert et al., 2009; Harris et al., 2009; Erb and Obleser, 2013; Wild et al., 2012; see meta-analyses and reviews: Adank, 2012; Eckert et al., 2016). These anatomically distinct cingulo-opercular regions are differentially sensitive to errors and response uncertainty (mid-cingulate; Ullsperger and von Cramon, 2004), response selection

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[1] To limit terminology confusion, word identification refers to understanding aurally presented words and recognition memory refers to familiarity-memory for an item after a delay of minutes or longer between presentation and memory test.

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demands (left inferior frontal gyrus; Thompson-Schill et al., 1997; Goghari and Macdonald, 2005; Moss et al., 2005), autonomic responses (insula; Cechetto, 2014), and inhibition (right inferior frontal gyrus; Aron et al., 2003; Aron, 2007; Hughes et al., 2013). Together, these diverse functions could be integrated to provide adaptive control, which consists of performance monitoring and flexible modifications of attention and behavior.

An adaptive control framework for cingulo-opercular function is supported by evidence of consistently elevated cingulo-opercular activity across varied perceptual and response demands of different tasks (Dosenbach et al., 2006). Activity increases following response errors and uncertainty, when the benefit from adaptive control (Shenhav et al., 2013) is not restricted by conditions that result in particularly poor or good performance (Eckert et al., 2016; Poldrack et al., 2001; Zekveld et al., 2006). Consistent with this framework, elevated cingulo-opercular activity has been associated with subsequent improvements in task performance (Botvinick et al., 2004; Carter et al., 2000, 1998; Eichele et al., 2008; Kerns et al., 2004; Sheth et al., 2012), including word identification in noise (Vaden et al., 2015, 2013). Complementing the premise that cingulo-opercular functions optimize task performance, attentional lapses that occur with lower cingulo-opercular activity have been associated with a subsequent increase in the likelihood of response errors (Eichele et al., 2008; Weissman et al., 2006).

Cingulo-opercular engagement during memory encoding has also been consistently linked to successful recognition memory in neuroimaging studies (see two large-scale meta-analyses: Kim, 2011; Spaniol et al., 2009). Specifically, cingulo-opercular activity has been shown to increase during the encoding phase for items that were correctly remembered in delayed recognition memory tests. Together with observations that lateral prefrontal cortex lesions impair associative memory and limit the use of common memory strategies, these findings support the proposal that prefrontal cortices engage attention control to enhance processing of task-relevant information and memory formation (Blumenfeld and Ranganath, 2007).

The existing evidence on memory encoding and memory for speech in noise sets up competing predictions for the role of attention, as reflected in cingulo-opercular activity. On the one hand, cingulo-opercular activity during encoding has been linked to both 1) correct word identification in noise on a trial-by-trial basis (Vaden et al., 2013) and 2) successful memory encoding of items in recognition memory tasks, albeit in the absence of perceptual difficulty manipulations (Kim, 2011; Spaniol et al., 2009). Taken together, this evidence predicts that increased cingulo-opercular activity benefits memory encoding for correctly identified words in noise through changes in tonic attention and behavior that support speech understanding. On the other hand, observations that listening to speech in noise results in both 1) elevated cingulo-opercular activity (Eckert et al., 2009; Harris et al., 2009; Erb and Obleser, 2013; Wild et al., 2012) and 2) poorer serial recall (Heinrich et al., 2008; Rabbitt, 1991, 1968; Tun et al., 2009) could also indicate that increased attention required to aid speech understanding limits the resources available for memory encoding. Under this view, increased cingulo-opercular activity for words identified in noise would be predicted to result in poorer memory encoding.

To date, there is no direct evidence that increased attention-related cingulo-opercular activity accounts for poorer memory for speech in noise. Moreover, there is extensive neuroimaging evidence from delayed recognition memory studies supporting the opposite conclusion. We predicted that elevated cingulo-opercular activity during correct word identification in noise improves memory encoding, resulting in better delayed recognition memory task performance. Because cortical attention systems are often engaged variably across trials despite consistent task demand, this prediction also means that failures to engage or maintain attention (i.e., lapses in cingulo-opercular activity) could result in poorer memory encoding.

Materials and methods

During two consecutive fMRI runs, participants performed a word identification in noise task (Task 1: 25 m 48 s) that was immediately followed by a delayed recognition memory task (Task 2: 21 m 30 s). Neuroimaging data from Task 1 were analyzed to examine changes in activity during the word identification in noise task (i.e., during memory encoding) that were associated with delayed recognition memory. Although neuroimaging data from Task 2 was not a focus of the current study, the Task 2 memory hits or misses were used in the functional imaging analyses of Task 1 words that were correctly identified.

Results from the signal-to-noise ratio (SNR) conditions during word identification (Task 1) were previously reported in Vaden et al. (2013). The neural memory encoding effects during Task 1 and delayed recognition memory results (Task 2) are the focus of the current study, and have not been reported previously. Additional details about the Task 2 method and results are presented in the Supplementary materials.

Participants

Twenty healthy, young adults (10 females, average age = 29.8 ± 5.9 years) with normal hearing participated in the current study. They were recruited as part of a larger study on age-related changes in hearing and communication. The final sample included 20 participants, after excluding participants older than 41 years and one participant with noted movement in the scanner and related artifacts (e.g. ghosting). Pure-tone thresholds were measured with a Madsen OB922 audiometer and TDH-39 headphones (American National Standards Institute, 2004, 2010). Each participant had mean pure-tone thresholds < 12 dB HL from 500 to 2000 Hz (better ear), with less than 7 dB difference between right and left ears. All participants demonstrated normal immittance measures. The participants were all native English speakers, with an average of 16.4 ± 2.2 years of education (M ± SD). Handedness preference scores of 70.3 ± 48.0 indicated that the sample was largely right-handed (possible range = −100, strongly left-handed, to 100, strongly right-handed; Oldfield, 1971). 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 (MUSC), and experiments were conducted in accordance with the Declaration of Helsinki.

Experimental design

Task 1: Word identification in noise

For Task 1, each participant was instructed to listen to a single monosyllabic word presented in multitalker babble and repeat the word out loud, or say "nope" if they could not recognize the word. The word recordings from a male talker were originally prepared by Dirks et al. (2001), and the multitalker babble recordings were from Kalikow et al. (1977). Each trial had an 8.6 s inter-trial interval (ITI), which was the length of time between consecutive scans in the sparse fMRI acquisition sequence. A word was presented 3.1 s into each trial during the relatively quiet period following the scanner offset. This design allowed for greater control over the SNR for the calibrated speech and babble stimuli than if the stimuli were presented in scanner noise. Words were presented through piezoelectric headphones (Sensimetrics) at 85 or 92 dB SPL with continuous babble presented at 82 dB SPL, which resulted in a +3 dB or +10 dB SNR. Words were presented in the same SNR for 4–6 consecutive trials, with a total of 60 words in each SNR across Task 1. Participant responses were recorded using an MRI-compatible microphone (Resonance Technology, Inc.), during an interval (4.1–6.1 s) cued by a crosshair that changed colors