# Distinct prefrontal networks for semantic integration and articulatory planning

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**Abstract:**

**The spatiotemporal neural dynamics in frontal cortex underlying speech production remain poorly understood. Growing evidence has implicated the posterior MFG as critical for language alongside inferior frontal gyrus (IFG). We leveraged a battery of language production tasks within a cohort of 24 neurosurgical patients undergoing electrocorticographic monitoring. Focusing on high gamma broadband (70-150 Hz), we employed an unsupervised clustering approach to reveal two new networks in frontal cortex with differentiated articulatory and semantic specificity. The articulatory cluster, centered in IFG and precentral cortices, showed comparable activity prior to speech onset across all tasks. The semantic cluster, centered on the border of IFG and MFG, showed strong task-selectivity prior to articulation with significantly greater activity for tasks requiring semantic access. Neural covariance across time locked to perception in the semantic cluster highly correlated with the semantic embeddings of the changing auditory stimuli. Our results suggest two distinct language production components distributed across frontal cortices, a preparatory motor-related component agnostic to task, and a component recruited specifically as semantic integration is required.**

**Keywords: speech production; speech perception; intracranial EEG;**

## Introduction

The ability to produce language is a uniquely human function. Traditionally, studies have shown that production critically depends on frontal and temporal cortex activity to retrieve, plan, and execute speech utterances (Hickok, 2012). For example, the inferior frontal gyrus (IFG) for speech preparation (Flinker et al., 2015), superior temporal gyrus (STG) for auditory perception (Mesgarani et al., 2014), and sensorimotor cortex for speech production (Bouchard et al., 2013). Growing evidence has implicated the posterior MFG (area 55b) and dorsal precentral gyrus as critical for speech integration and auditory feedback (Haller et al, 2018; Chang, 2020; Ozker, 2022). Several cognitive models provide estimates for the spatiotemporal dynamics of language perception and production (Hickok and Poeppel, 2007). However, the timing and extent of cortical activation for each region in the language system, as well as the nature of the neural representations remain unknown. We hypothesized that articulatory preparation, lexical retrieval, and semantic integration may not be localized to one region but rather may be distributed in nature.

## Methods

We employed a battery of five functional language tasks which prompt the subject to produce the same 50 words through distinct routes of word retrieval: picture naming, word reading, auditory naming, auditory word repetition, and auditory sentence completion. Words were randomly interspersed within the block. We obtained direct cortical ECoG recordings in a cohort of 24 neurosurgical patients undergoing treatment for refractory epilepsy. Neuronal activity from both regular and high-density arrays were collected and epoched locked to stimulus or speech onset. We focused on high gamma (70 ~ 150 Hz) spectral responses shown to correlate with the spiking rate of underlying neuronal populations. 936 active electrodes were selected with sustained activity for over 100ms compared to baseline during speech perception, planning, and production (t-test $p < 0.05$). We then employed analyses based on specific regions of interest, unsupervised clustering of the data as well as Representational Similarity Analysis (RSA) in order to investigate which regions are recruited and when stimulus identity is encoded.

## Results

### High gamma shows prototypical speech planning and articulatory responses

We reported the spatiotemporal dynamics across peri-sylvian cortices locked to language perception and articulation. A region of interest analysis provided unique profiles of task-related neural recruitment per region during perception and production across all significant electrodes. Based on anatomy, STG showed robust activity for the three auditory tasks locked to perception, as well as articulation for all the tasks locked to articulation. Occipital regions and fusiform areas showed activity for two visual tasks locked to perception. Pre- and post- central gyri were activated locked to articulation onsets. Electrodes in IFG and MFG showed activity prior to articulation, which was significantly higher as the semantic load increased. (Figure 1)

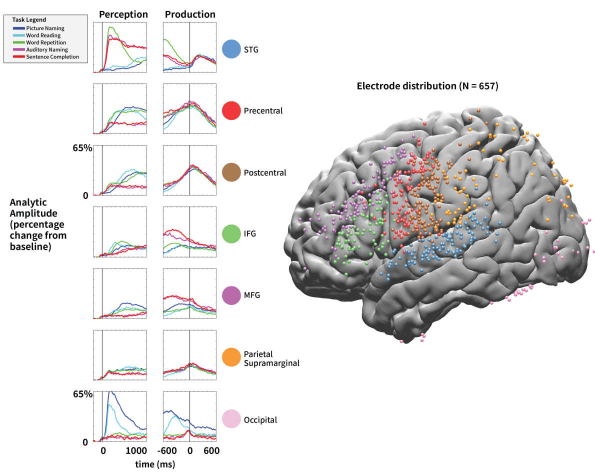


Figure 1. Region of interest analysis. Left: high gamma analytical amplitude for tasks across regions. Right: electrode distribution on MNI space.

### Unsupervised clustering analysis revealed two frontal networks for articulatory planning and semantic integration

We found specific enhancement in IFG and MFG related to semantic load (t-test between semantic vs. non-semantic tasks, $p < 0.001$). Non-negative matrix factorization revealed two new networks in frontal cortex with differentiated articulatory and semantic specificity. These clusters were distributed across cortical regions and differed in responses from a strictly anatomical segmentation. One cluster of electrodes, centered in IFG and precentral cortices, showed comparable activity prior to speech onset across all tasks. The second cluster, centered on the

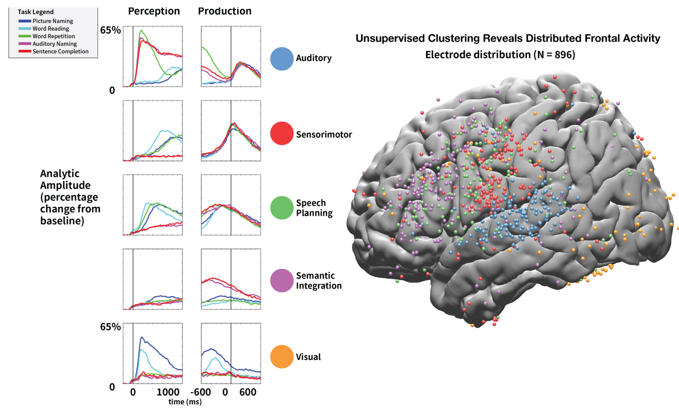


Figure 2. Clusters revealed from unsupervised clustering approach.

border of IFG and MFG, showed strong task-selectivity prior to articulation with significantly greater (t-test, $p<0.001$) activity for tasks requiring semantic access (figure 2).

In order to investigate the nature of these two clusters, we performed representational similarity analysis across the auditory naming and sentence completion tasks. Neural covariance across time locked to perception in the semantic cluster highly correlated with the semantic embeddings of the changing auditory stimuli (based on the last 3 layers of a deep neural network GPT-2 model (Radford et al., 2019), spearman correlation $p<0.001$ rho= 0.53, 0.27, respectively for each task) which quickly diminished as speech production onset approached. The articulatory cluster, however, was strongly correlated with phonetic information rather than semantic embeddings prior to speech onset across tasks.

## Conclusion

Traditionally, the inferior frontal gyrus has been implicated in various aspects of language processing including articulatory, syntactic and semantic processes, our results suggest two distinct networks, not bounded to IFG, are critical for speech planning and semantic integration. The two language production networks are distributed across frontal cortices, one is related to speech motor preparation agnostic to task, and the other is recruited specifically as semantic integration is required.

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