The time-course of information processing within the language system

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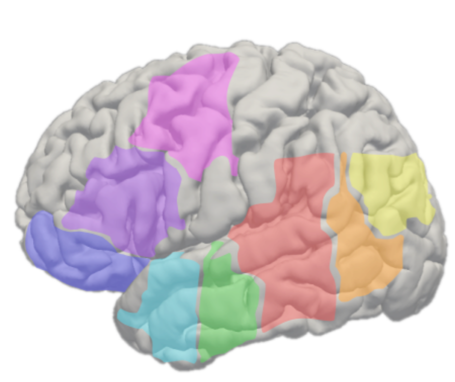
Summary

- Functional magnetic resonance imaging (fMRI) has revealed that a set of brain regions in the frontal and temporal cortices are selectively engaged during language tasks [1]. fMRI correlation analyses suggest that these regions form an integrated functional system (e.g., [2]).
- However, the time-course of linguistic processing – critical to eventually understanding the computations performed at different processing stages – has not yet been characterized for sentence-level comprehension.
- We here use electrocorticography (ECoG) to probe the temporal structure of language processing.
- We observed clear inter-regional differences in the latencies of responses to words during sentence comprehension. Given these latency differences, we can now begin to ask what information gets extracted from the linguistic signal at different processing stages.



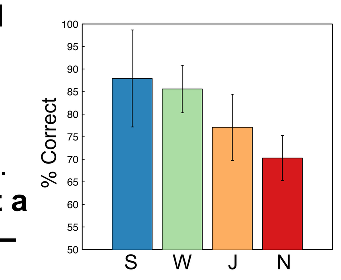
Methods

Participants

- We recorded activity from intracranial electrodes of seven subjects (5 female, ages 14-29) with intractable epilepsy.
- These subjects underwent temporary implantation of subdural electrode arrays at Albany Medical college to localize the epileptogenic zone(s).
- All subjects gave informed written consent to participate in the study, which was approved by the IRB of Albany Medical College.
- One subject was excluded from the main analysis due to difficulties performing the task, and another was excluded from analyses due to sparse electrode coverage.

Task

- Subjects read eight-item sentences, lists of scrambled words, jabberwocky sentences, and lists of scrambled nonwords, presented one item at a time.
- **Subjects S1 and S5 read at a rate of 450ms per item, S2 – S4 read at a rate of 700ms per item.**
- At the end of each sequence a probe item appeared and subjects responded with whether or not the probe appeared in the previous sequence.
- Each subject completed 10 runs of the experiment.



Signal Preprocessing

- Recordings were high-pass filtered to remove slow drifts in voltage.
- Noisy and ictal channels were removed.
- A common average was subtracted.
- **The signals were then band-pass filtered in the high-gamma band (70 – 170 Hz).** This signal is thought to track local neural processing and correlate with the BOLD signal in fMRI [4].
- The signal envelope was extracted.
- The envelope (high-gamma power) was low-pass filtered at 100 Hz and downsampled.
- Percent Signal Change (PSC) was calculated with respect to fixation.

EOI Selection

- Electrodes with noisy signals or ictal activity, as well as the ground and reference electrodes, were excluded from all analyses.
- **Sentences > nonwords electrodes**: We used a nonparametric randomization test to first correlate the mean signal from each ODD run trial with a condition label, and then randomize the condition labels.
- **Electrodes sensitive to word onsets**: We used a randomization test on the spectra from the mean of sentence trials to identify electrodes with significant peaks at a frequency of 1/word presentation rate.

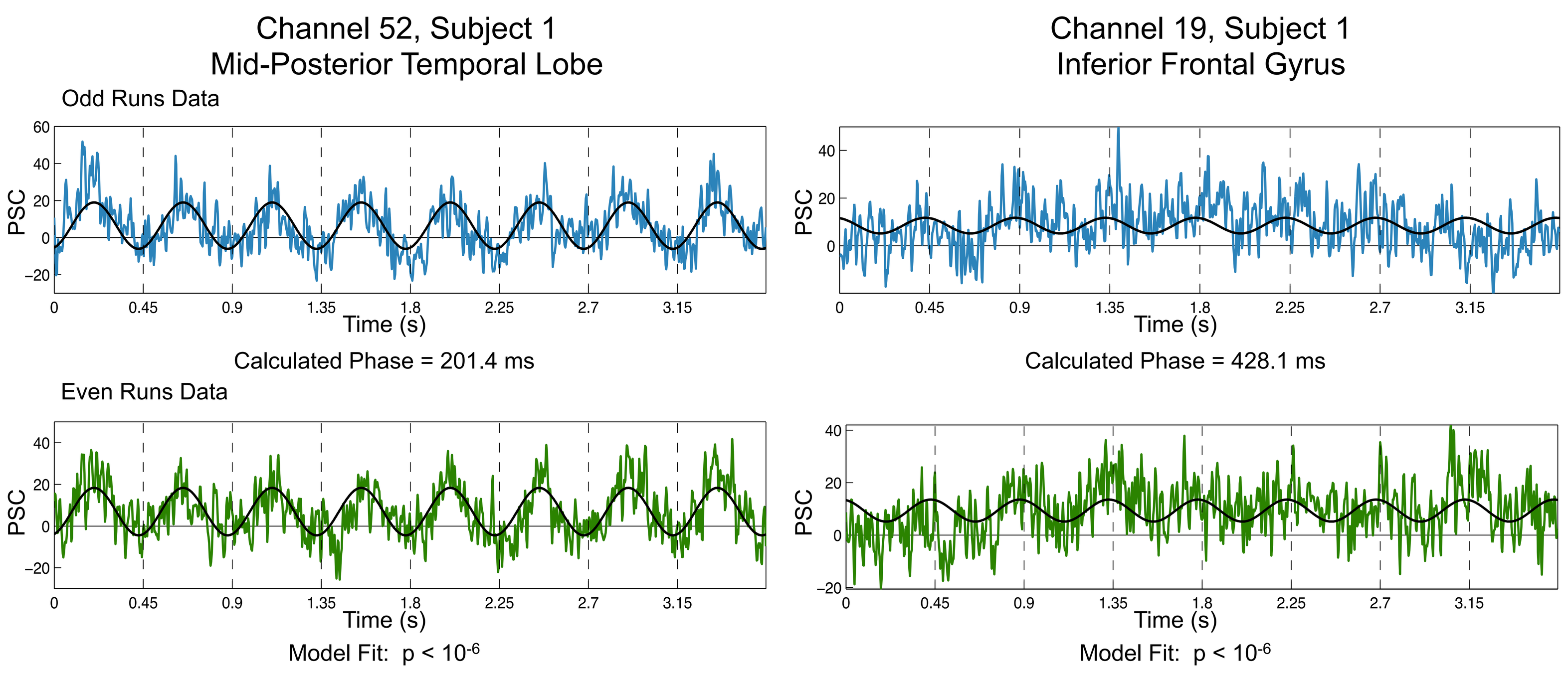
	Total Electrodes	Analyzed Electrodes	S>N Electrodes	S>N and S Modulated (i.e.,EOIs)
Subject 1	120	117	45 (0.38*)	31 (0.26**, 0.69***)
Subject 2	128	84	6 (0.07)	4 (0.05, 0.67)
Subject 3	112	84	11 (0.13)	9 (0.11, 0.82)
Subject 4	134	124	15 (0.12)	10 (0.08, 0.67)
Subject 5	98	87	15 (0.17)	10 (0.11, 0.67)

*proportion of *S>N* electrodes relative to analyzed electrodes
**proportion of *S>N AND S Modulated* electrodes relative to analyzed electrodes
***proportion of *S>N AND S Modulated* electrodes relative to *S>N* electrodes

Phase Analysis

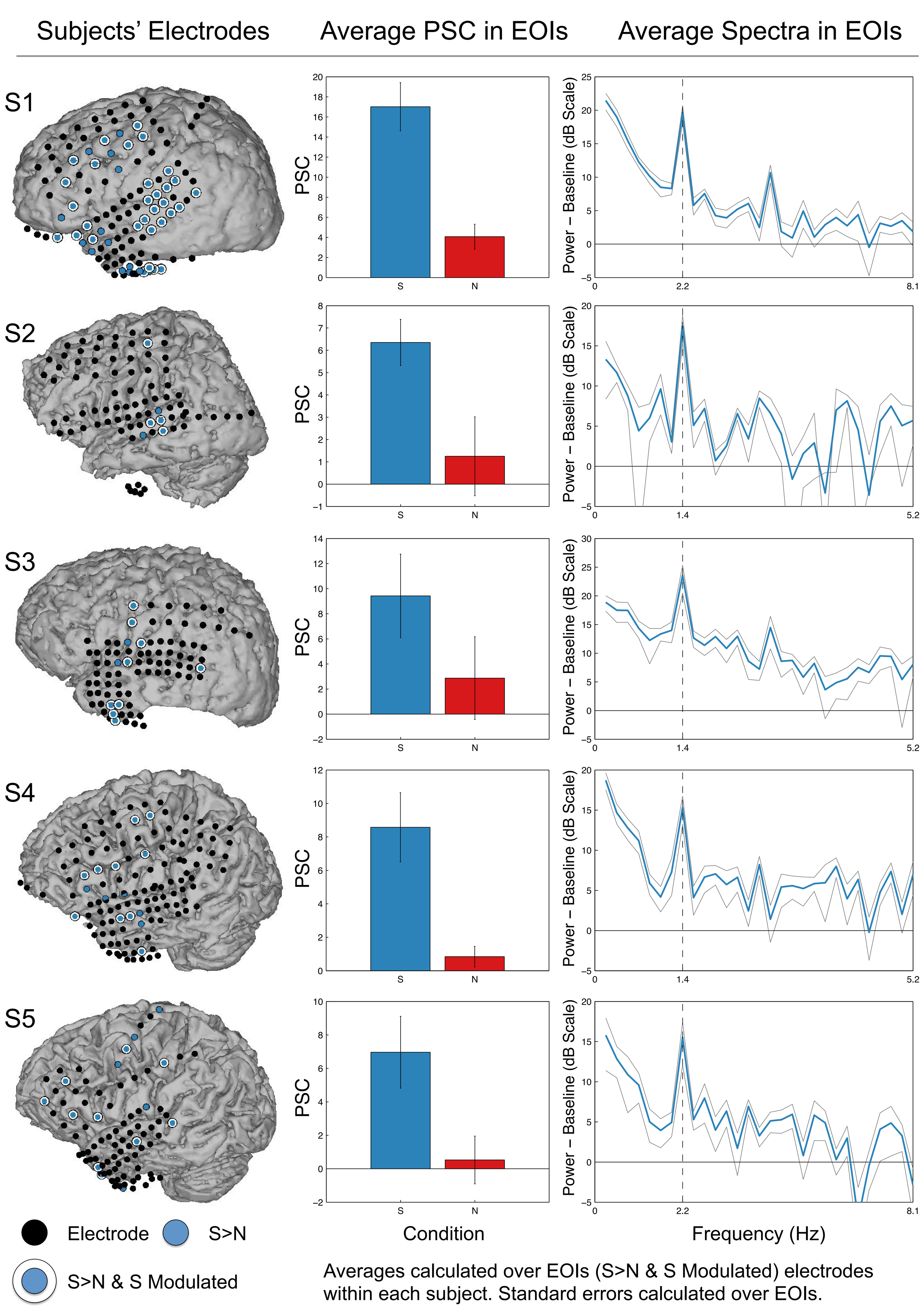
In channels exhibiting both significant S>N activation AND significant modulation at the frequency of word presentation during the sentences condition (defined in ODD runs only):

- We fit a linear model (to the ODD runs data) composed of a sine and cosine wave to estimate coefficients
  $$y = A*\sin(\omega t)+B*\cos(\omega t)$$
  $$\omega = 2\pi * 1/(\text{word presentation rate})$$
- Used those coefficients to calculate a phase angle for that channel
  $$\phi = \tan^{-1}(B/A)$$
- Converted the phase angle to a phase offset in milliseconds
- Applied a new cosine model the EVEN runs data to assess significance
  $$y = C*\cos(\omega t - \phi)$$
- This analysis requires that phase offsets occur within one period of the word presentation rate.



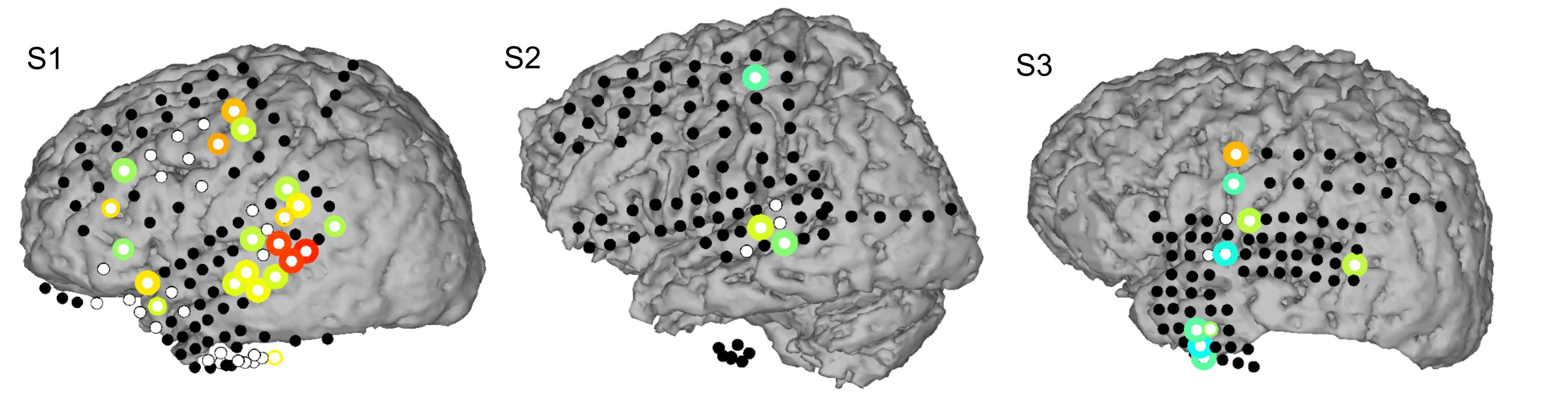
Results

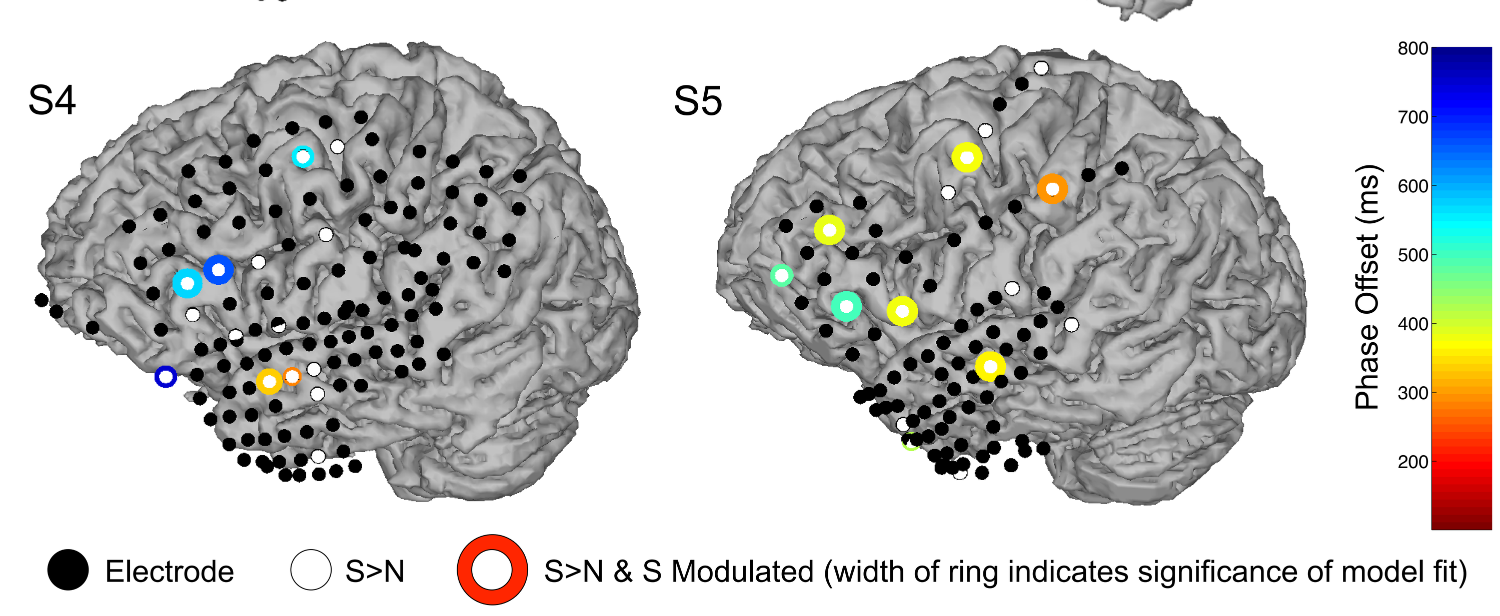
Electrodes Selected in ODD Runs Show Consistent Language Activation and Modulation by Word Presentation in EVEN Runs



Averages calculated over EOIs (S>N & S Modulated) electrodes within each subject. Standard errors calculated over EOIs.

Consistent Phase Delays Were Measured Across the Language System, Revealing Inter-Regional Latency Differences

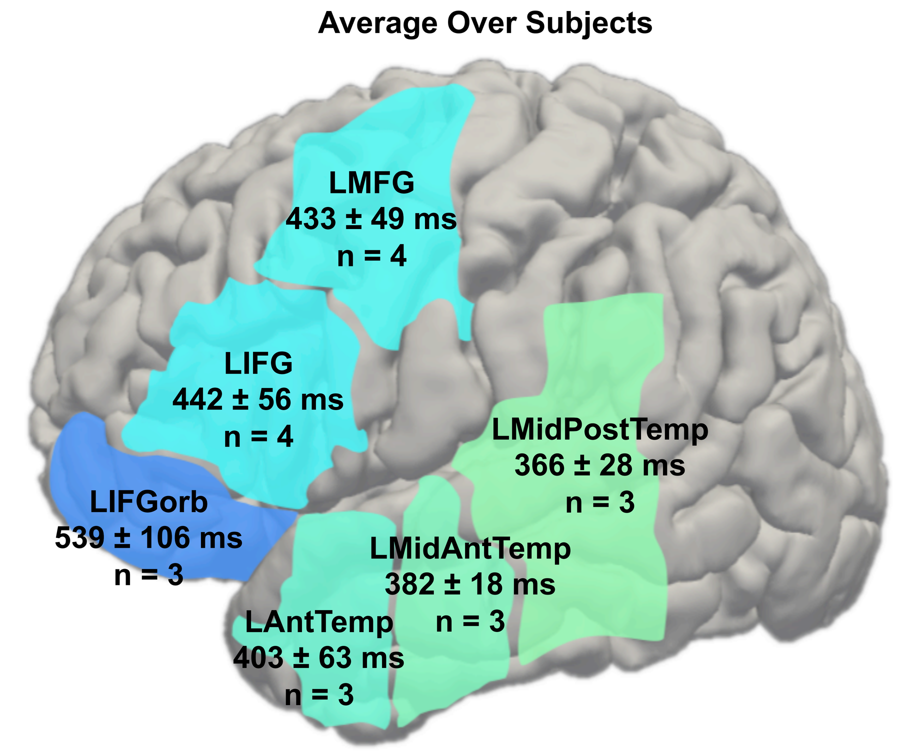




The width of the colored rings indicates the significance of the model fit in the test data (EVEN runs). The thickest rings correspond to $p < 10^{-6}$, while the thinnest rings correspond to the range $0.01 < p < 0.05$.

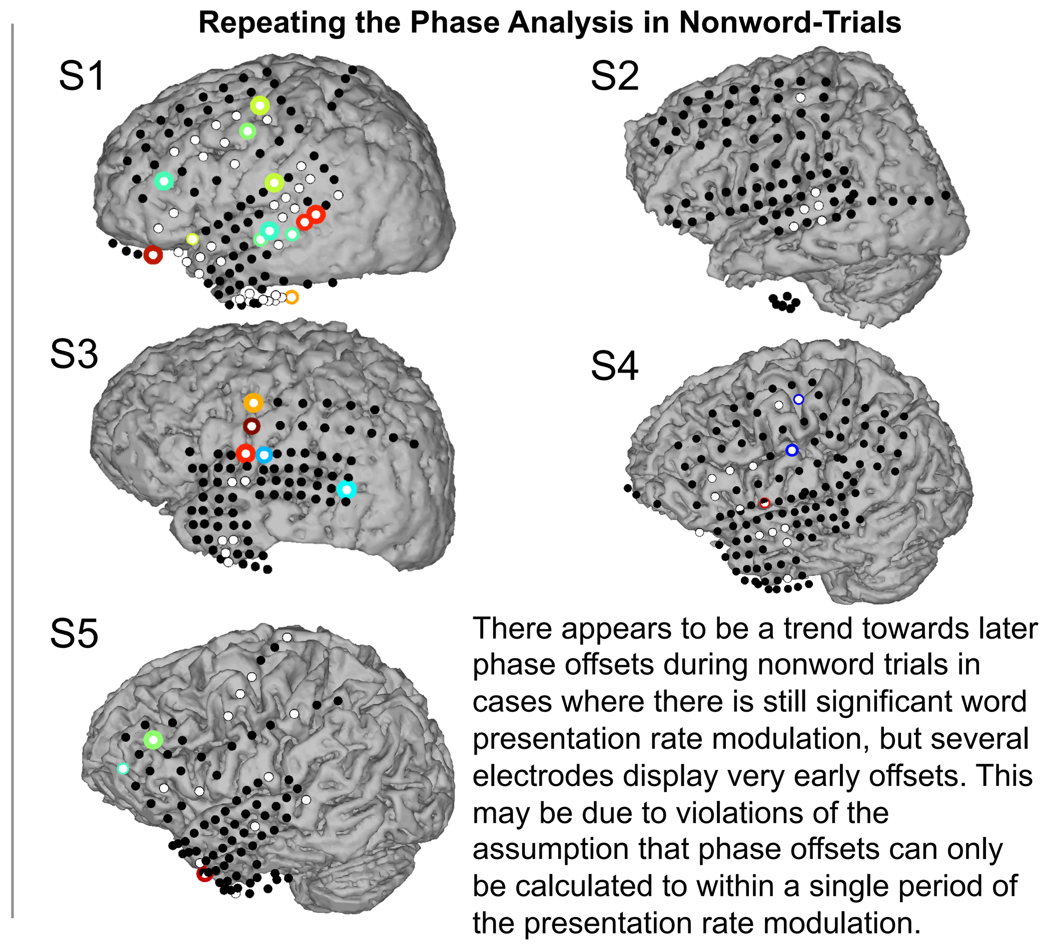
The mean of earliest phase offsets across subjects is 304 ± 30 ms. The mean of the latest phase offsets is 534 ± 55 ms. Results of a two-tailed paired T-test yield p = 0.012.

Average Over Subjects



Electrodes were localized by registering group-defined language "parcels" (see [3] for description) to individual subjects' anatomical MRIs.

Repeating the Phase Analysis in Nonword-Trials



There appears to be a trend towards later phase offsets during nonword trials in cases where there is still significant word presentation rate modulation, but several electrodes display very early offsets. This may be due to violations of the assumption that phase offsets can only be calculated to within a single period of the presentation rate modulation.

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References

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Funding

TLS was supported by the Boston University Graduate Program for Neuroscience as well as BU CompNet. This work was supported by the NIH (EB00856, EB006356 and EB018783), the US Army Research Office (W911NF-08-1-0216, W911NF-12-1-0109, W911NF-14-1-0440) and Fondazione Neurone. NK was supported by NEI grant EY13455 and NSF STC grant. EF was supported by NICHD award HD-057522.