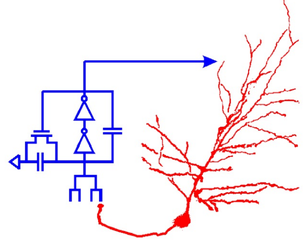

Computational
Sensorimotor
Systems Lab

The progression of neural speech representations through auditory cortex & beyond, from acoustics to semantics

Jonathan Z. Simon, I.M Dushyanthi Karunathilake, Christian Brodbeck,
Shohini Bhattasali, Philip Resnik, Joshua Kulasingham

University of Maryland
University of Connecticut
Linköping University

Acknowledgements

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Krishna Puvvada
Jonas Vanthornhout
Peng Zan

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NIDCD

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DARPA

University of Maryland

Outline

- Introduction
  - Neural representations of continuous speech
  - Primarily domain-specific cognition (for today)
  - Only younger normal-hearing listeners (for today)
- *Early & fast* cortical representation of continuous speech
- Cortical representations of speech *meaning*
- *Progression* of representations of continuous speech through cortex

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Cortical Representations of Continuous Speech

Continuous speech

- naturalistic
- redundant
- employs auditory cognition
- acoustically rich
- drives most auditory areas
- …
- but also complicated

If you happened to find yourself on the banks of the Ohio River on a particular afternoon in the spring of 1806—somewhere just to the north of Wheeling, West Virginia, say …

The Botany of Desire — Michael Pollan

Alfred the Great was a young man, three-and-twenty years of age, when he became king. Twice in his childhood, he had been taken to Rome, where the Saxon nobles were in the habit of going on journeys which they supposed to be religious; …

A Child's History of England — Charles Dickens

In the bosom of one of those spacious coves which indent the eastern shore of the Hudson, at that broad expansion of the river denominated by the ancient Dutch navigators …

The Legend of Sleepy Hollow — Washington Irving

He was an old man who fished alone in a skiff in the Gulf Stream and he had gone eighty-four days now without taking a fish. In the first forty days a boy had been with him. But after forty days without a fish …

The Old Man and the Sea — Ernest Hemingway

Cortical Representations of Continuous Speech

Temporal neural patterns ⇆ temporal patterns in speech

- Generalization of “Speech Tracking”
- Need high temporal precision, for fast temporal speech features

  - EEG (electroencephalography): *whole brain*
  - MEG (magnetoencephalography): *whole brain but with strong cortical bias*
  - ECoG (electrocorticography): *placed cortical surface electrodes*
  - single- and multi-unit recording methods: *placed depth electrodes*

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Cortical Representations of Continuous Speech

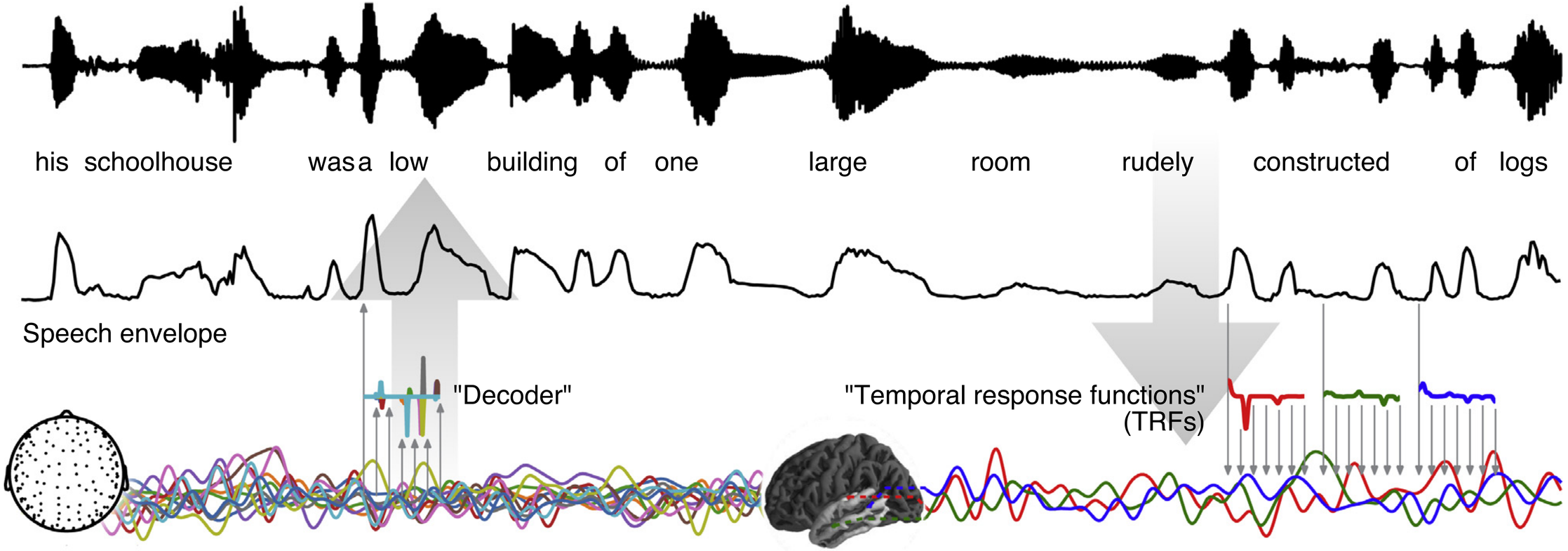
Neural Representations of Speech

- driven oscillations at pitch frequencies (mostly subcortical)
  - acoustic onset tracking
    - speech envelope rhythmic following
      - phoneme-based responses
        - phoneme-context-based responses
          - word-context-based responses
            - semantic structure rhythm following
- plus connections to **intelligibility/perception/behavior**

Brodbeck & Simon (2020) Continuous Speech Processing, Curr Op Physiol

Cortical Representations of Speech

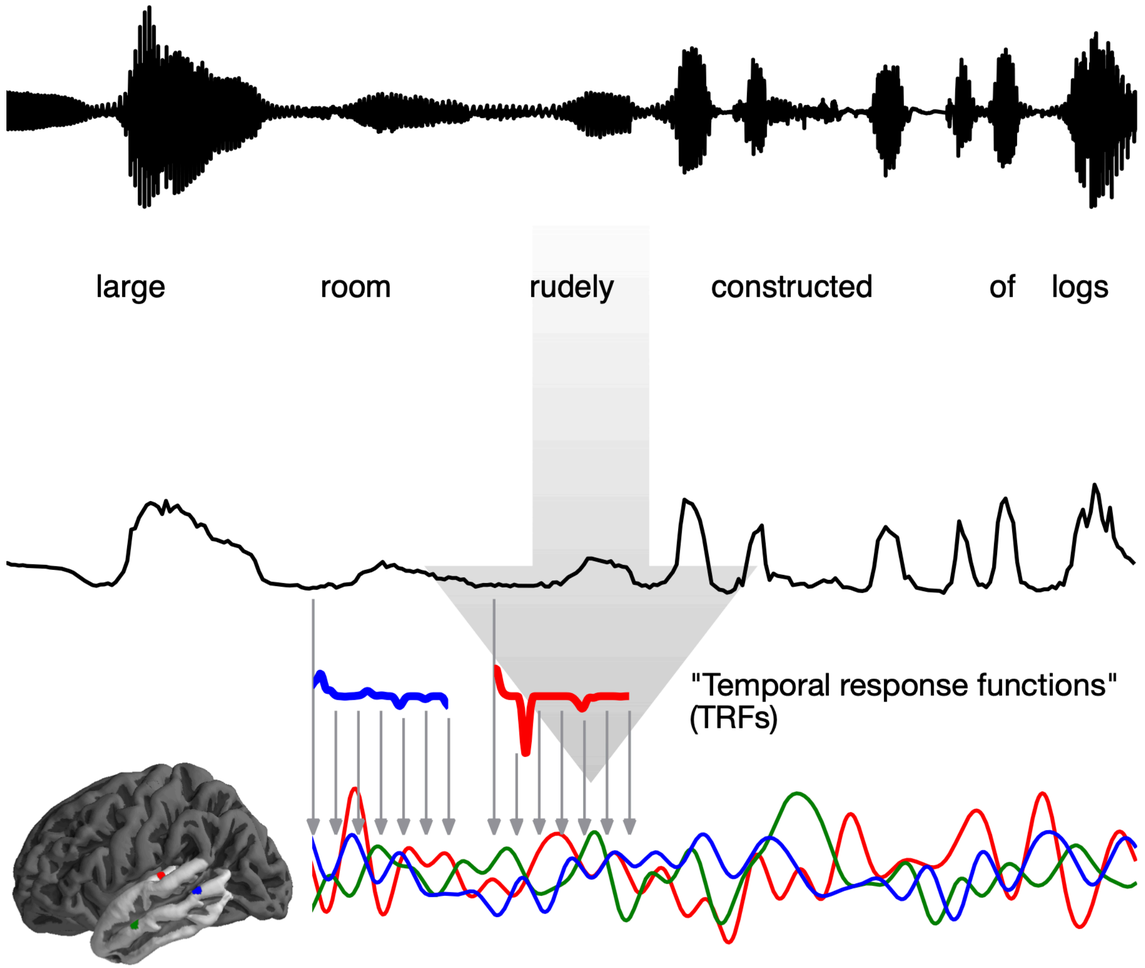
- Measure *time-locked* responses to temporal pattern of speech features (in humans)
- Any speech feature of interest: acoustic envelope, lexical, pitch, semantic, etc.
- Infer spatio-temporal neural origins of neural responses



Brodbeck & Simon (2020) Continuous Speech Processing, Curr Op Physiol

Cortical Representations: Encoding

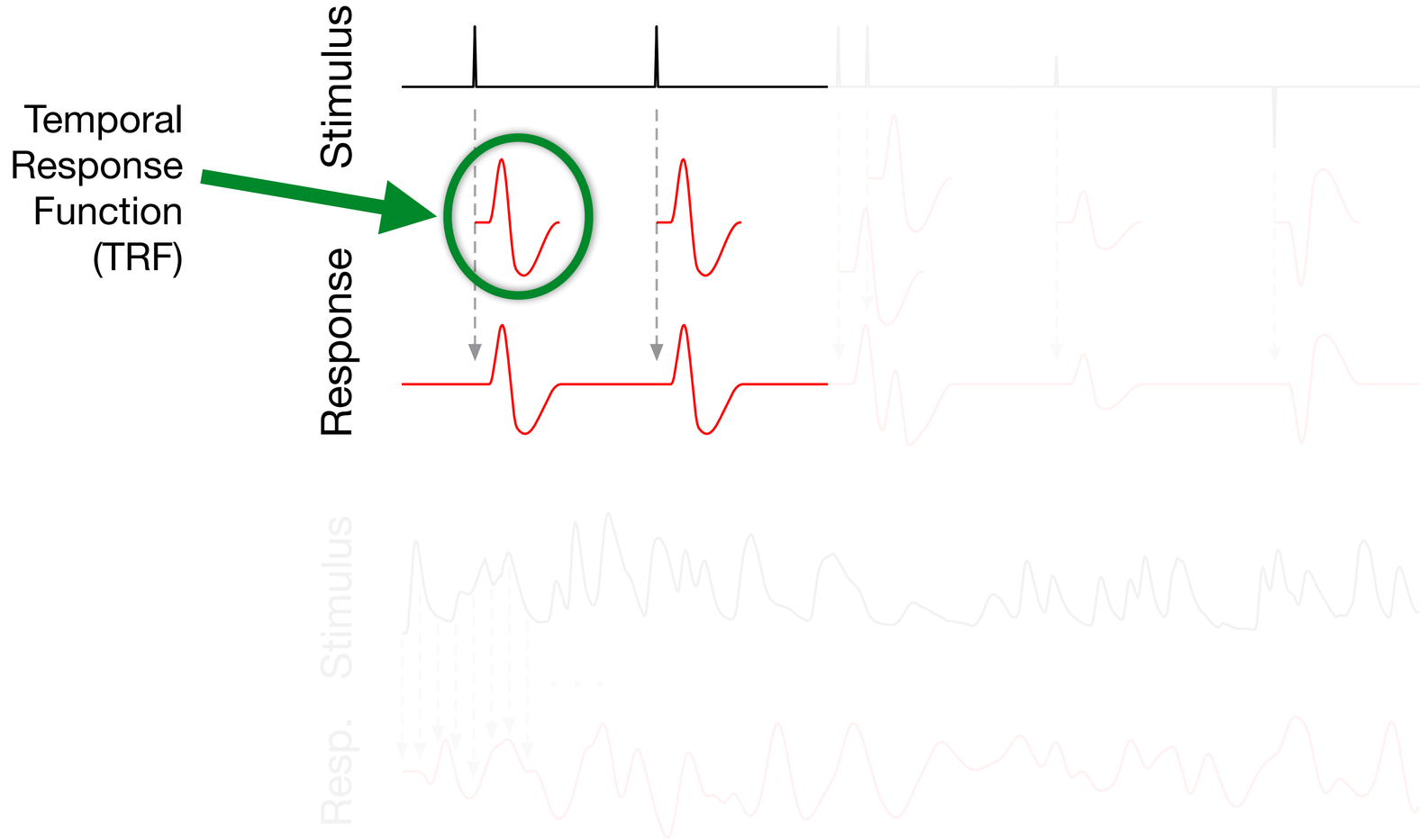
- Predicting future neural responses from present stimulus features,
  - wide variety of stimulus features
  - via Temporal Response Function (TRF)
- Why look at encoding? It *often* tells us more about the brain
  - TRF analogous to evoked response
  - peak amplitude ≈ processing intensity
  - peak latency ≈ source location
  - multiple TRFs simultaneously



Example: MEG Prediction of Voxel Responses

Brodbeck & Simon (2020) Continuous Speech Processing, Curr Op Physiol

Temporal Response Functions



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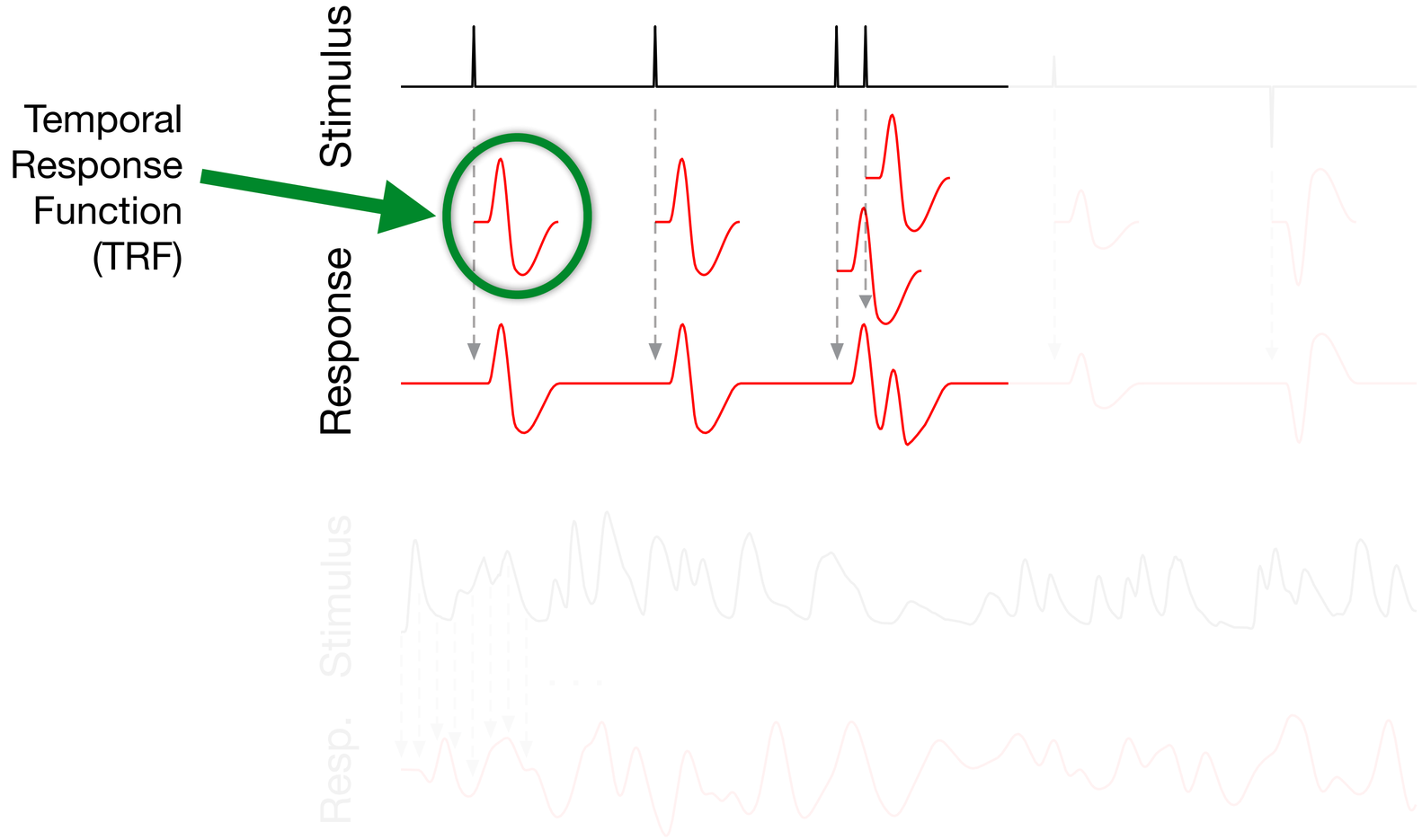

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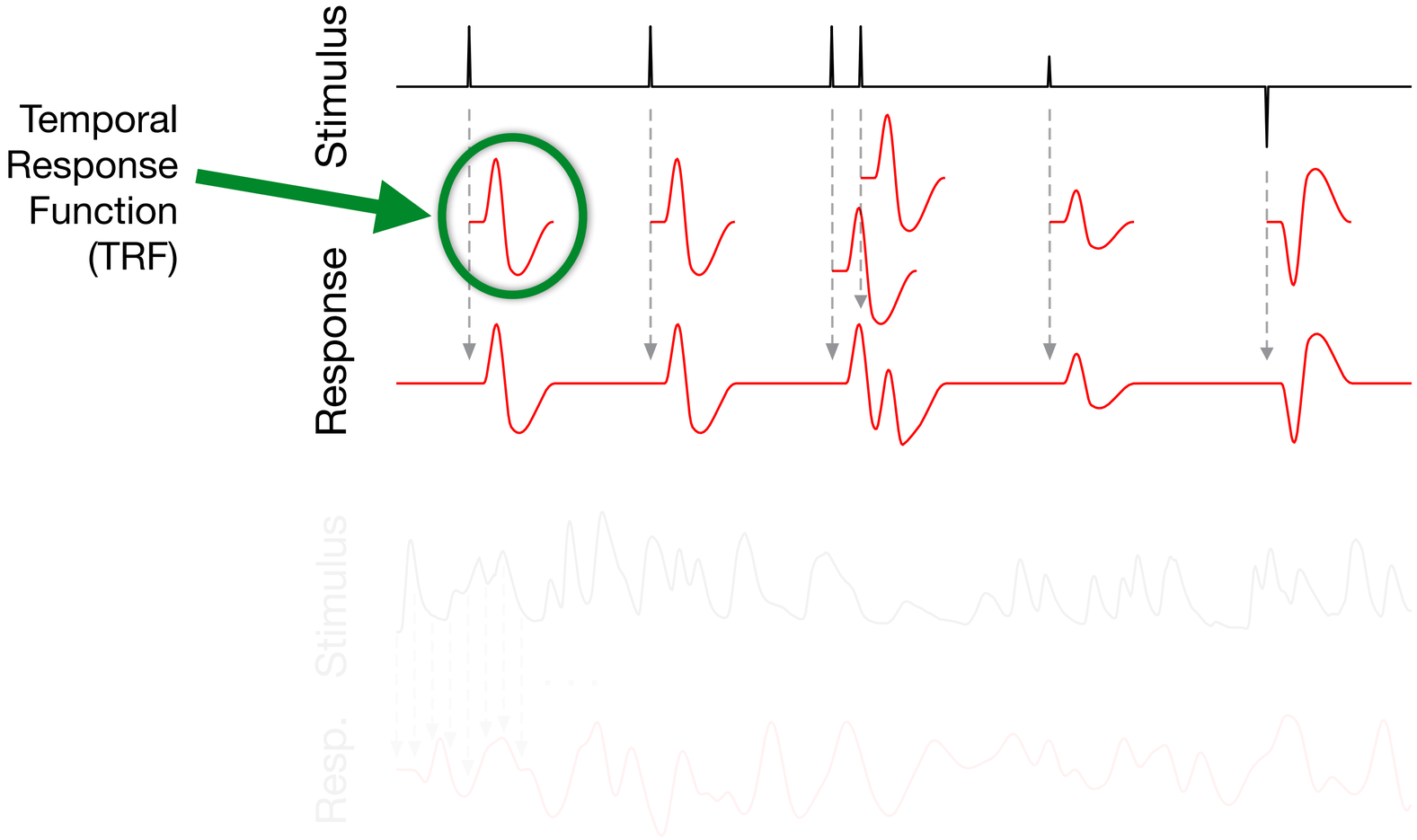

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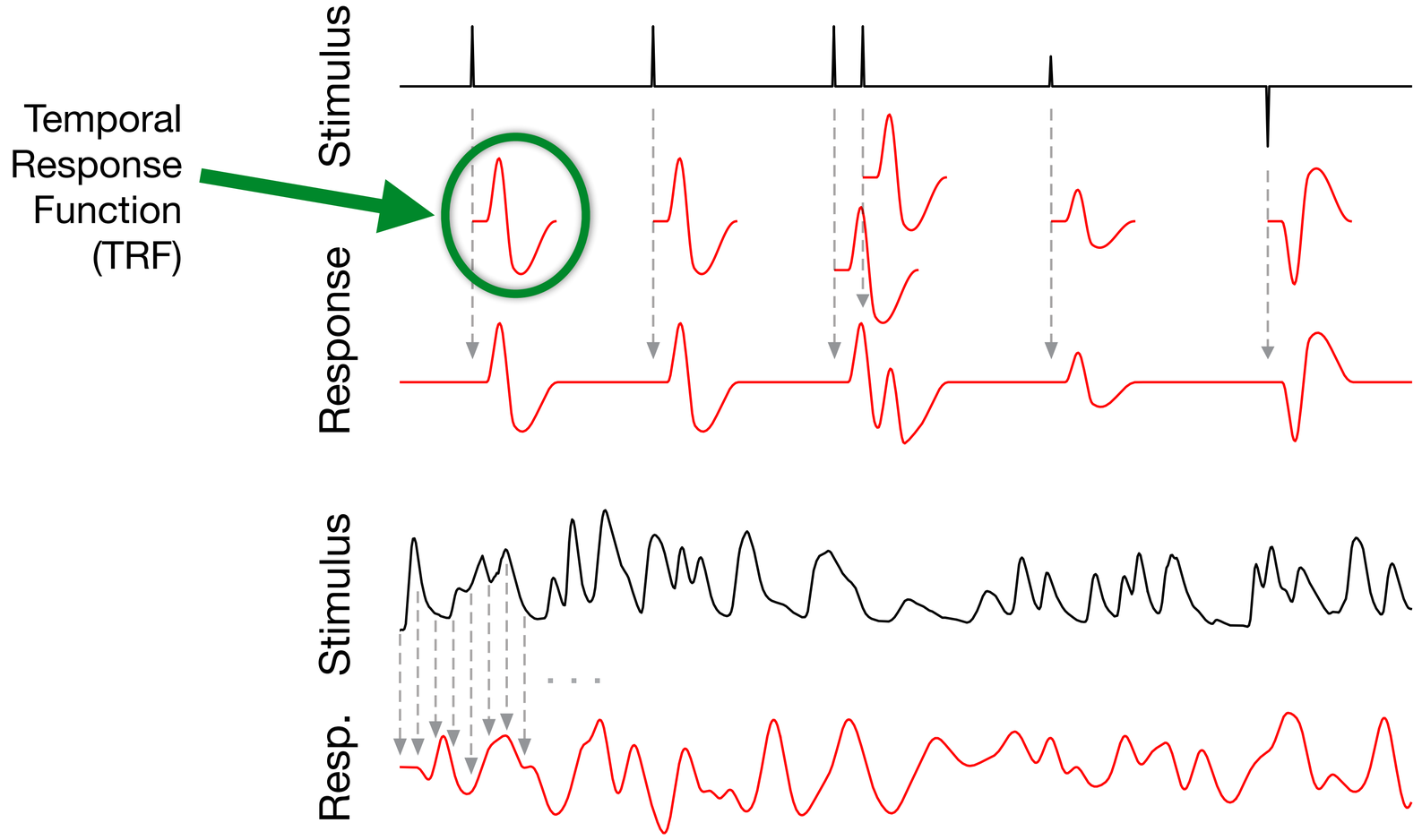
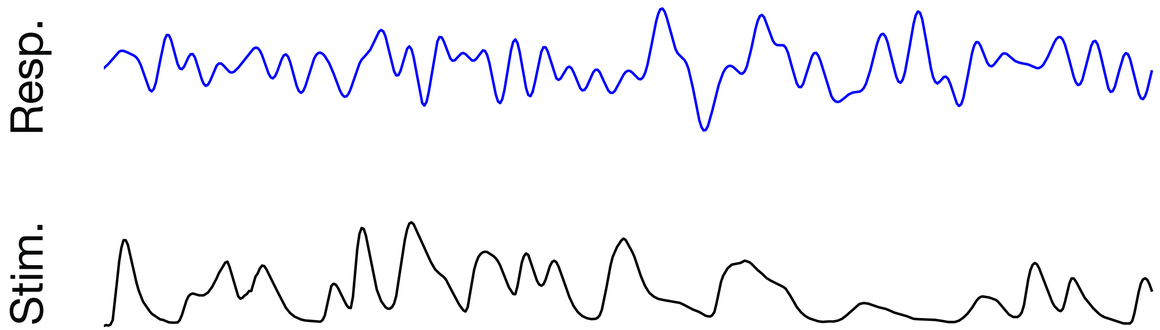


TRF Model Estimation & Fit

Temporal Response Function (TRF) estimation:

Stimulus and response are known; find the best TRF to produce the response from the stimulus:



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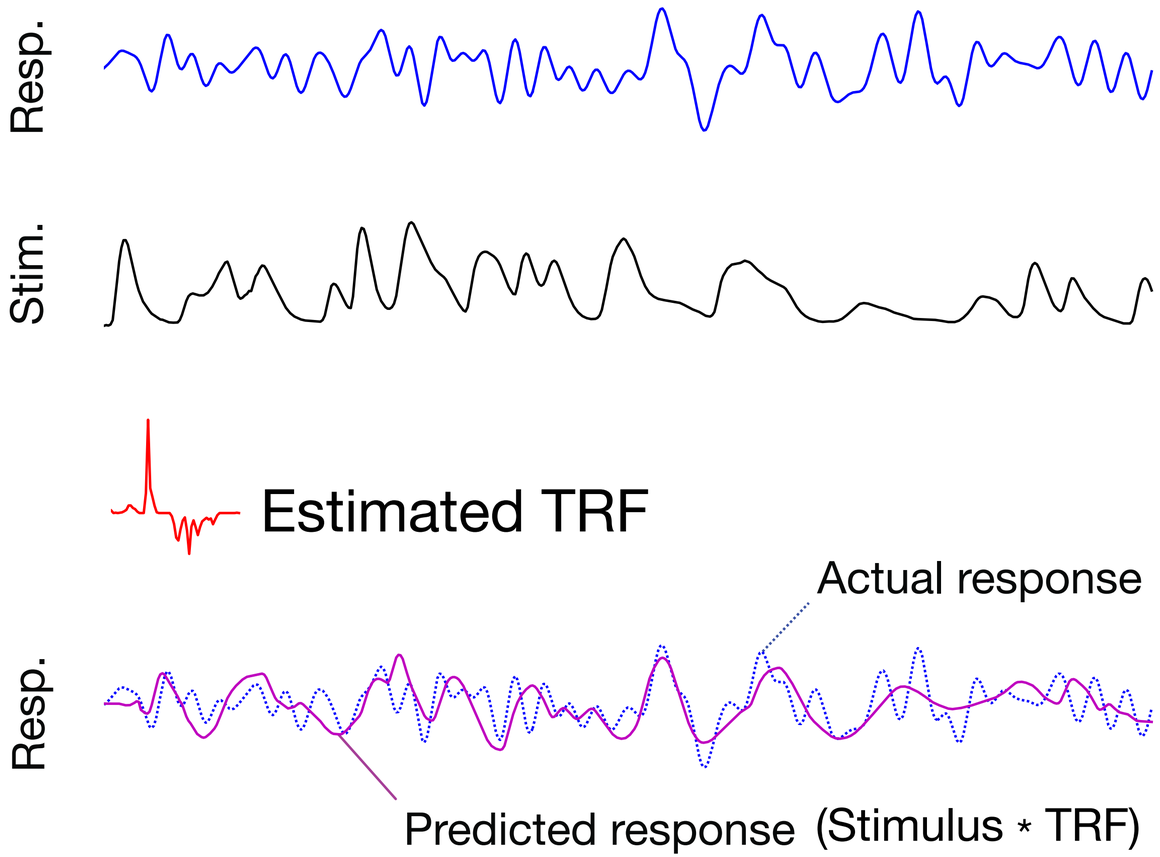

Simultaneous Temporal Response Functions

- TRFs predict neural response to speech
  - Analogous to evoked response
  - Peak amplitude ≈ processing intensity
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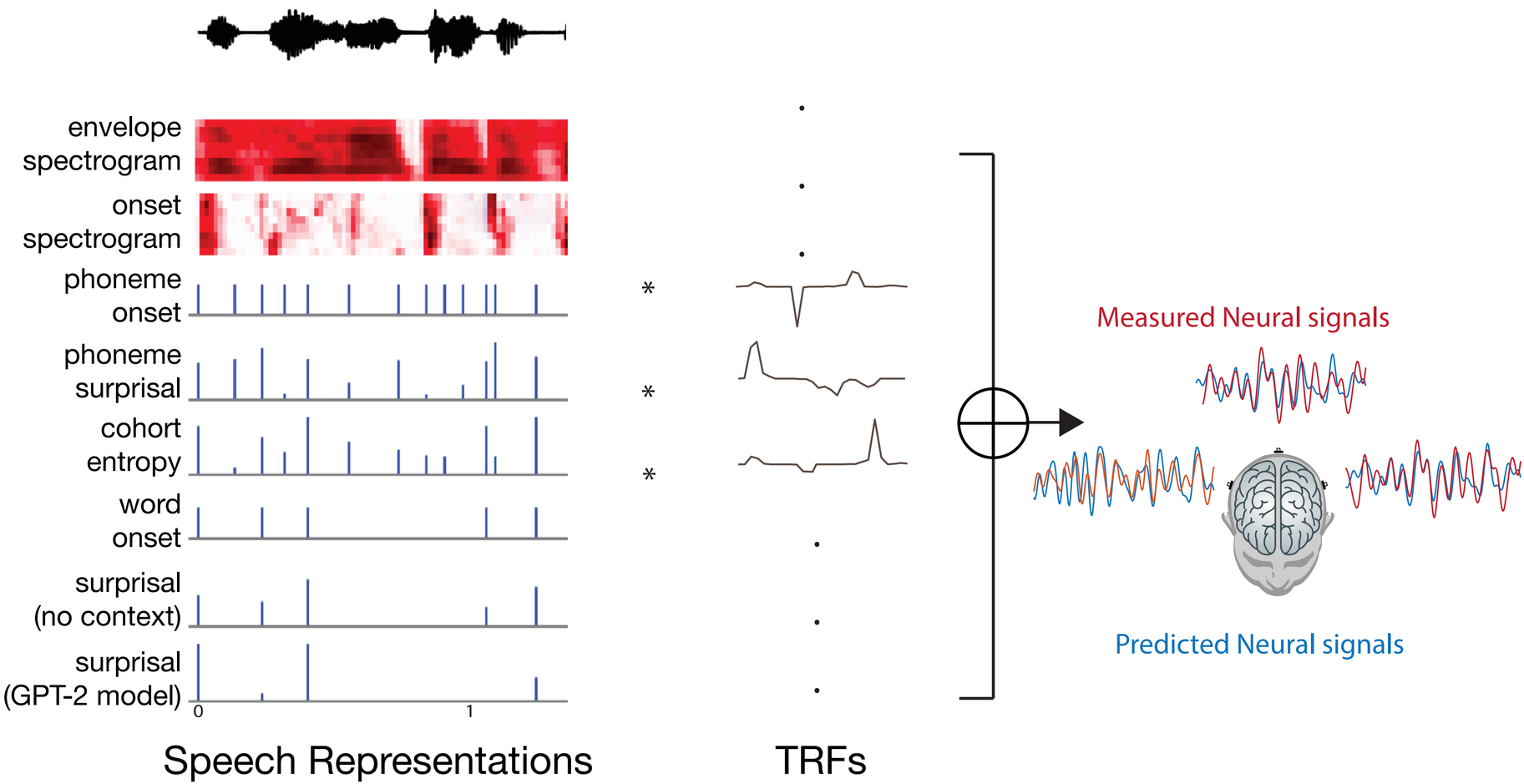
- Multiple TRFs estimated simultaneously
  - compete to explain variance (advantage over evoked response)



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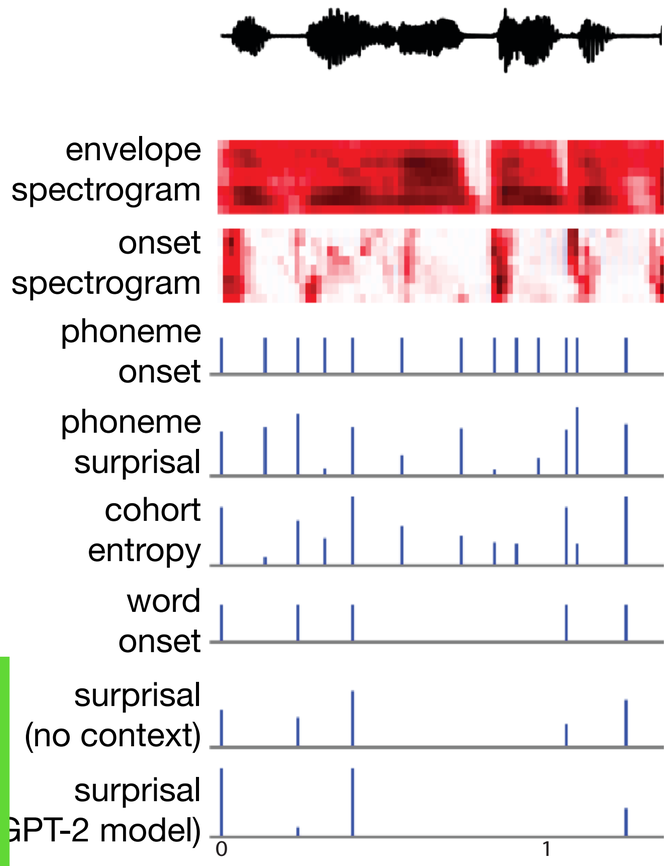
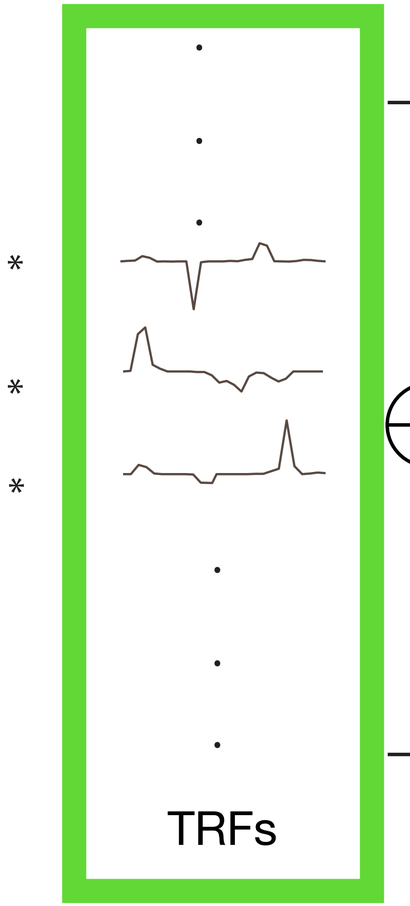
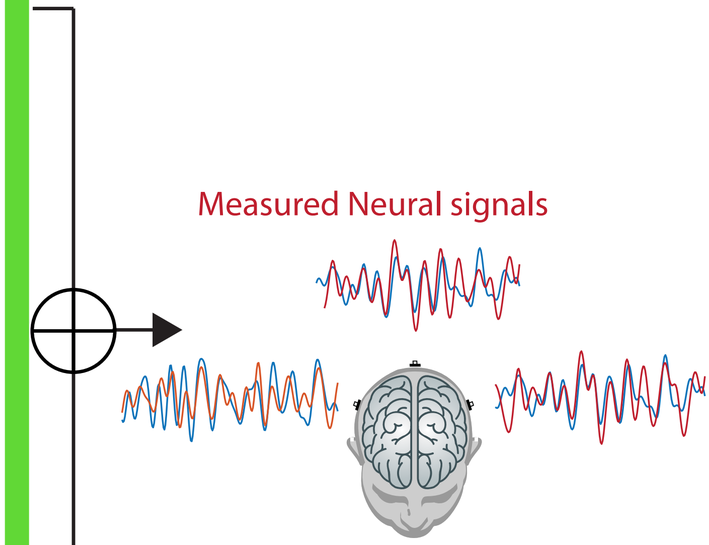


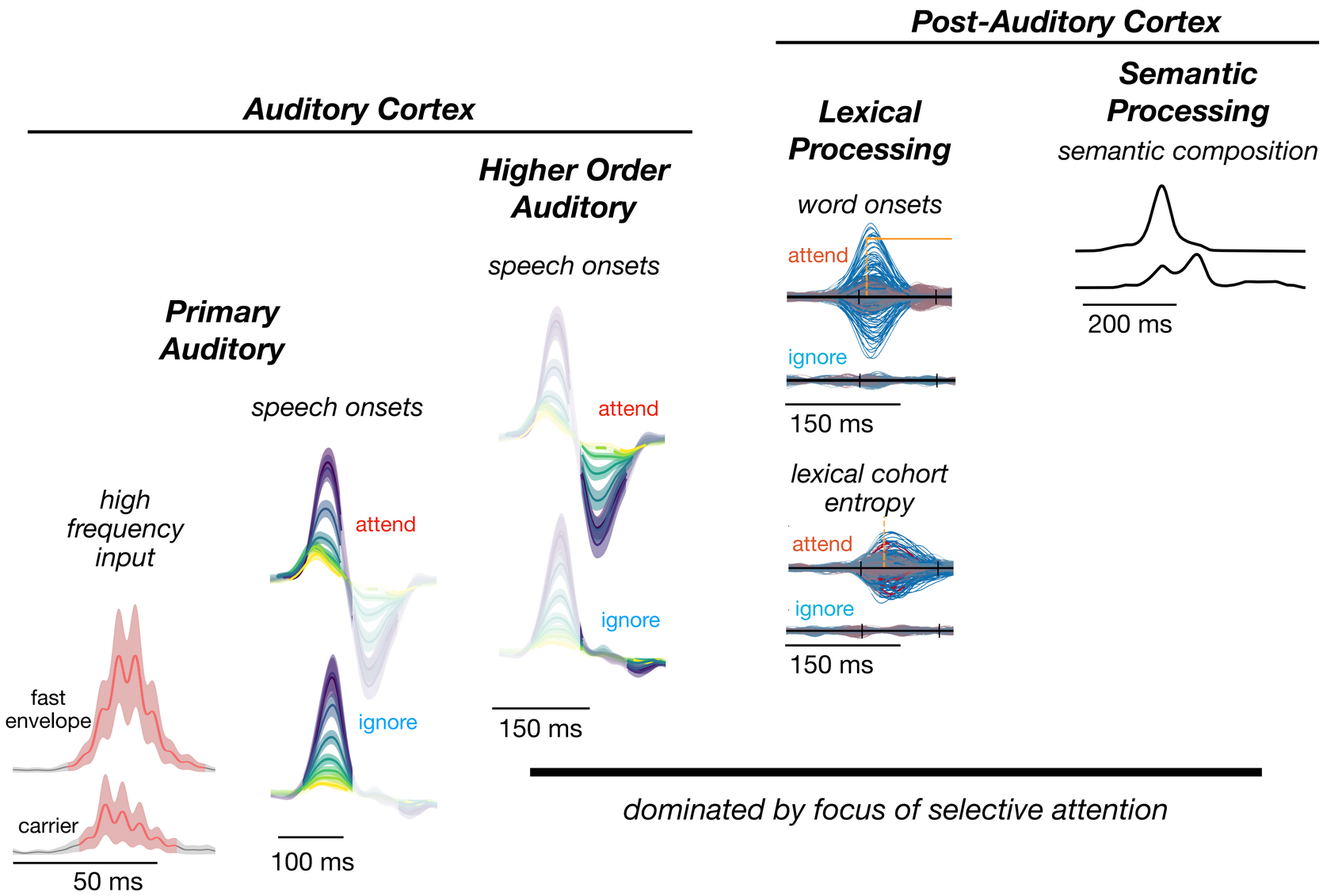
Speech Representations



TRFs



Cortical Representations Across Cortex



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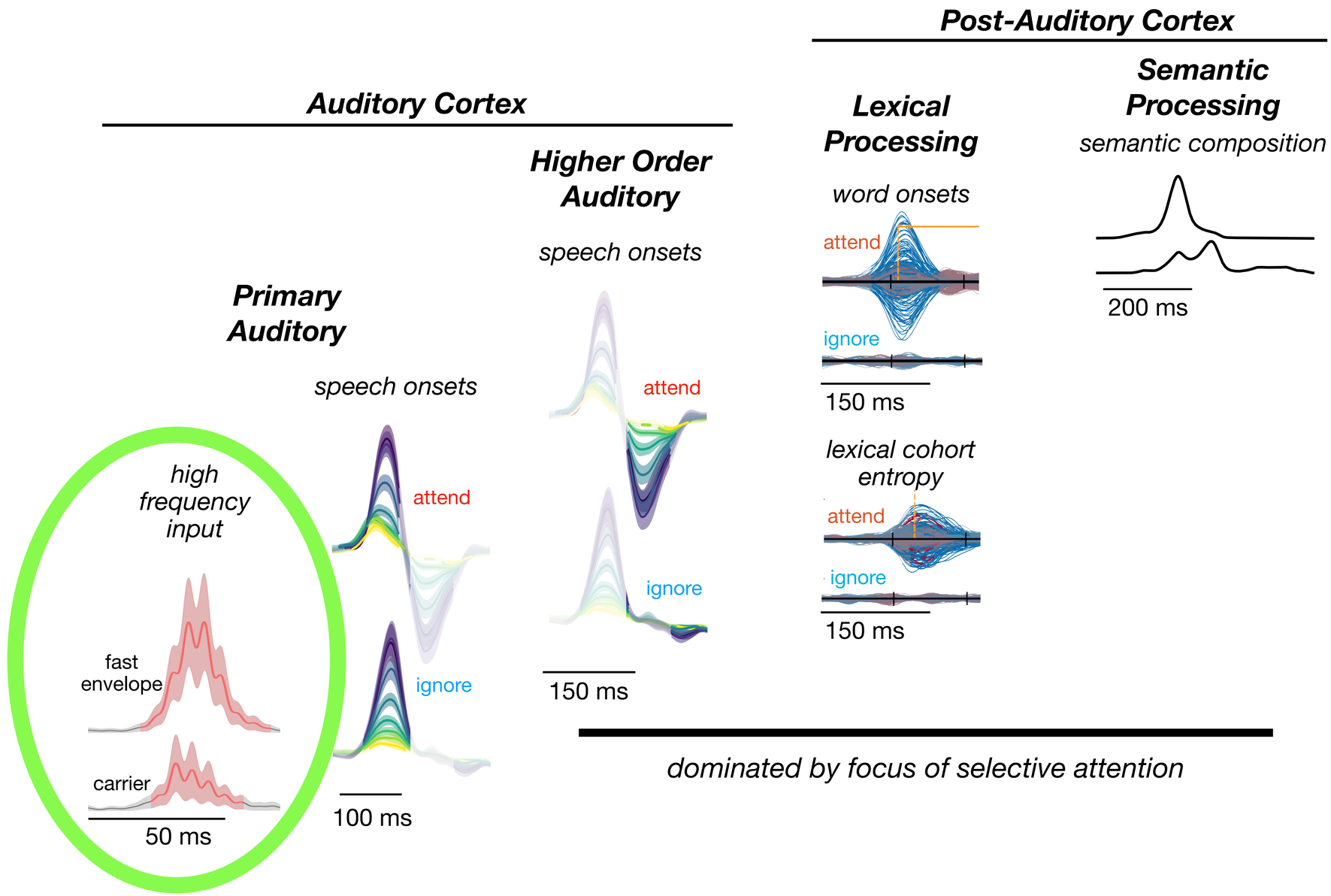

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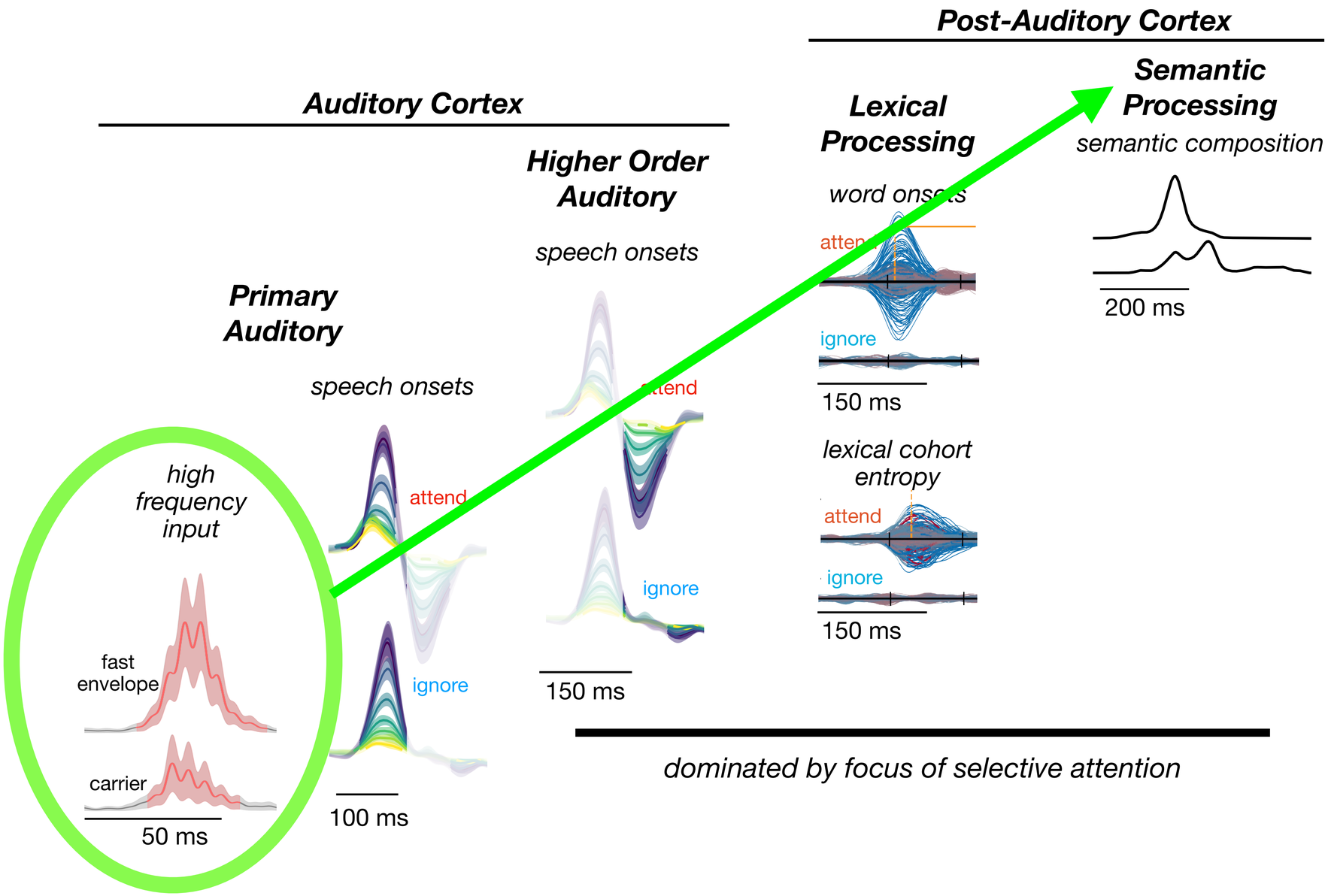

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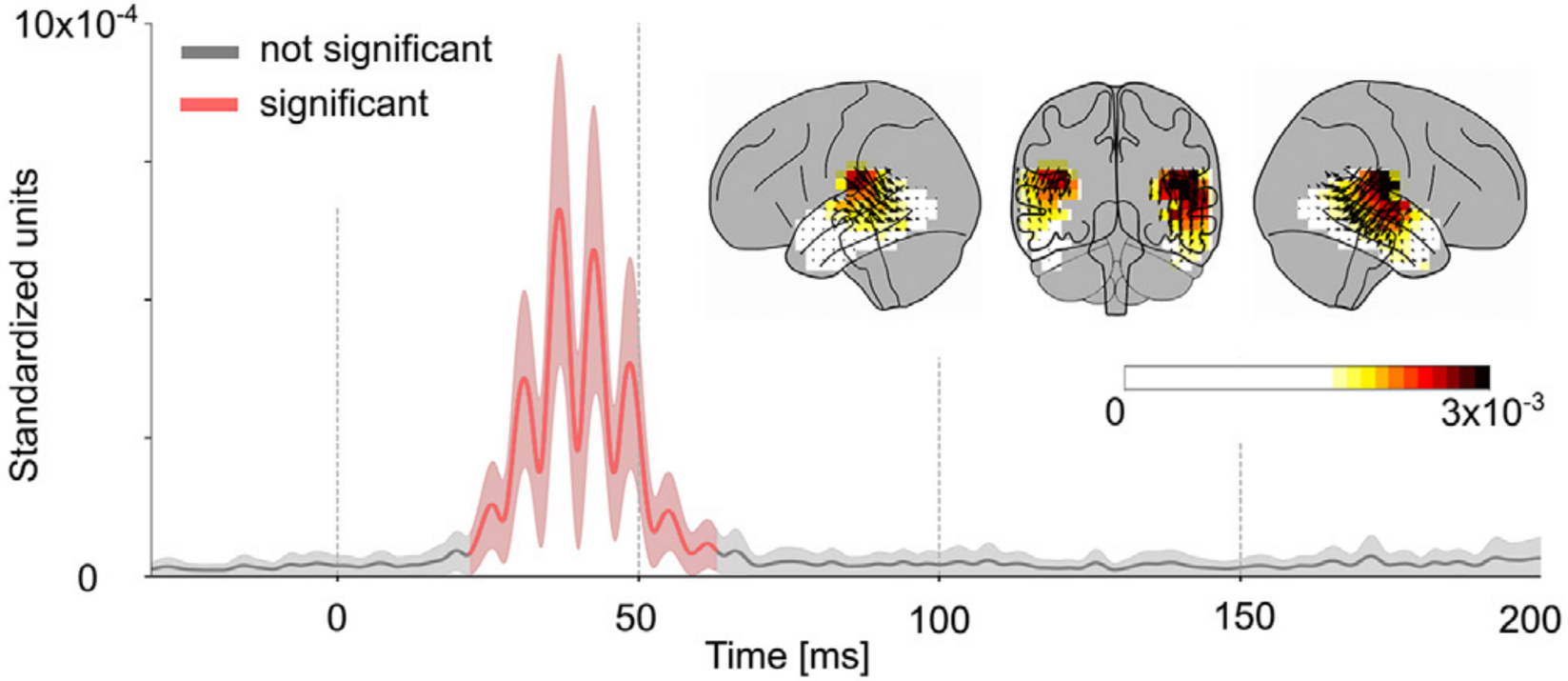
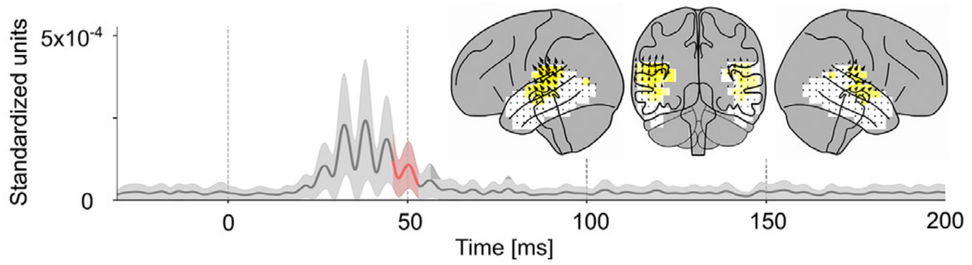
Fast & Early Cortical Representations



TRF (MEG) for
70-200 Hz
continuous speech
envelope

TRF (MEG) for
70-200 Hz
continuous speech
carrier



Kulasingham et al. (2020) *High Gamma Cortical Processing of Continuous Speech …*, NeuroImage
Kulasingham et al., Poster #38

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Speech Understanding/Meaning

- Behavioral correlates of speech understanding
  - implies language comprehension
  - structural comprehension
    - sentence structure
    - other structures, e.g. poetic, logical

- Neural correlates of speech understanding
  - rhythms of structural comprehension/meaning, even if *totally absent in the acoustics*
    - sentence structures
    - poetic structures
    - mathematical structures

Ding et al., Nat Neurosci 2016
Teng et al., Curr Biol 2020

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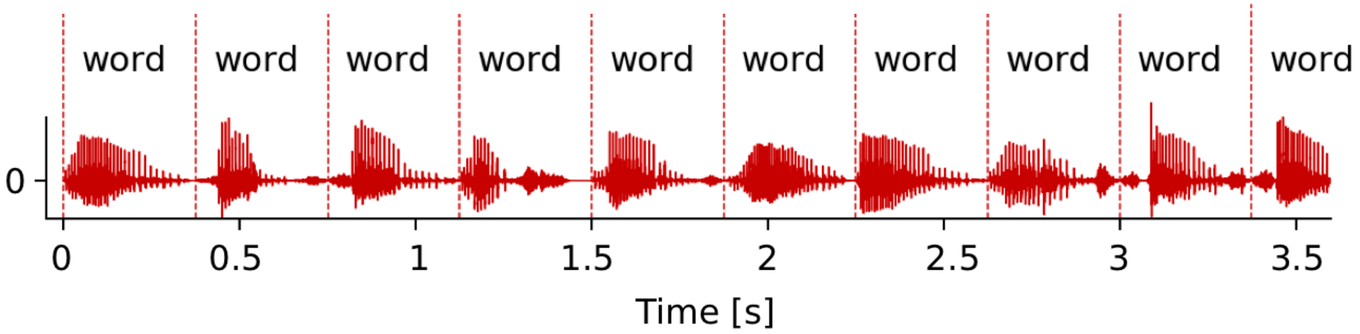
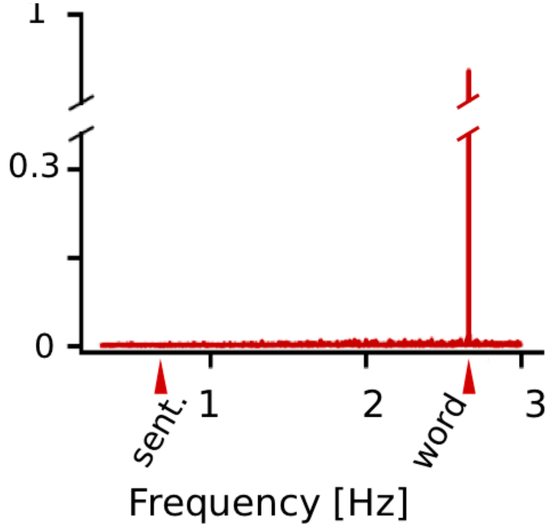
Isochronous Speech

Acoustics



Acoustical Spectrum (envelope)



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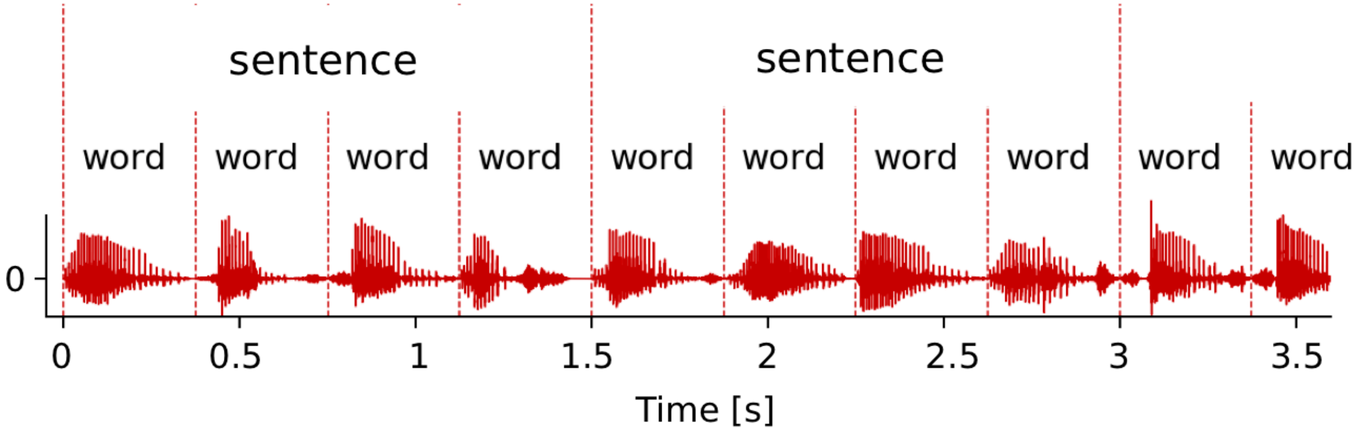

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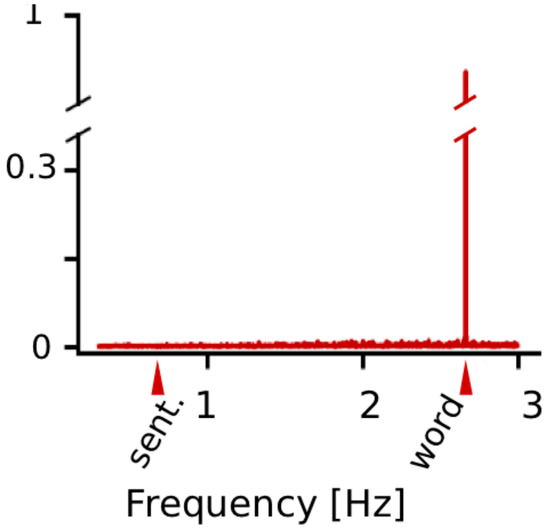

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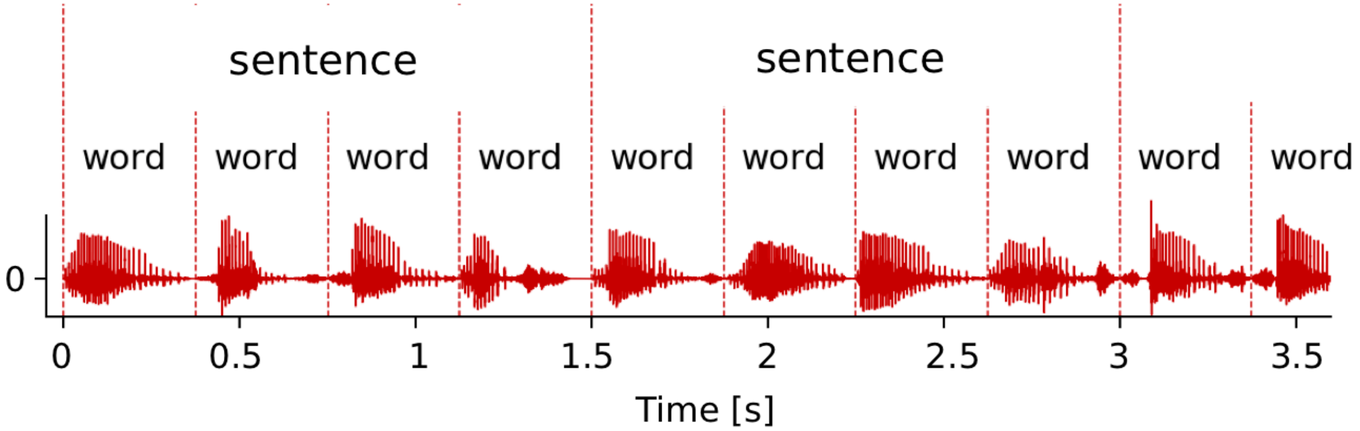

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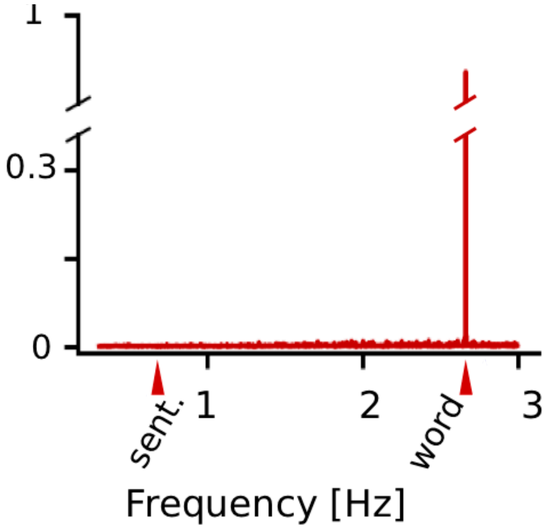

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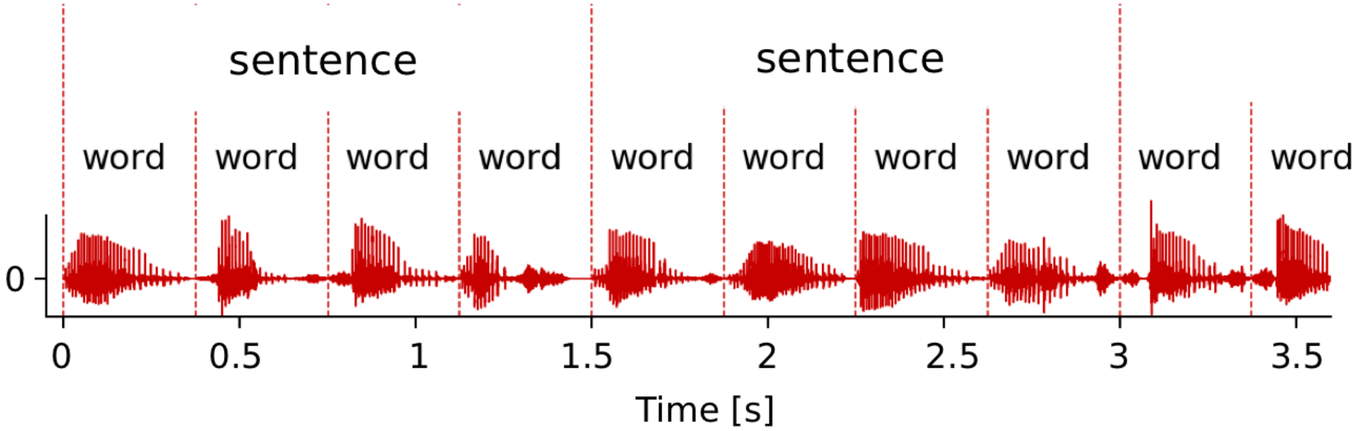

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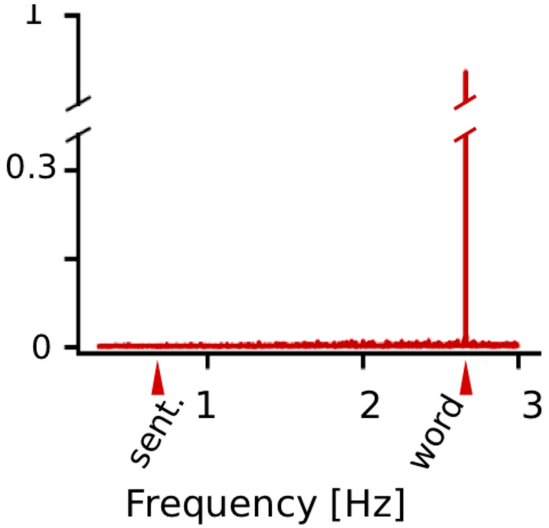

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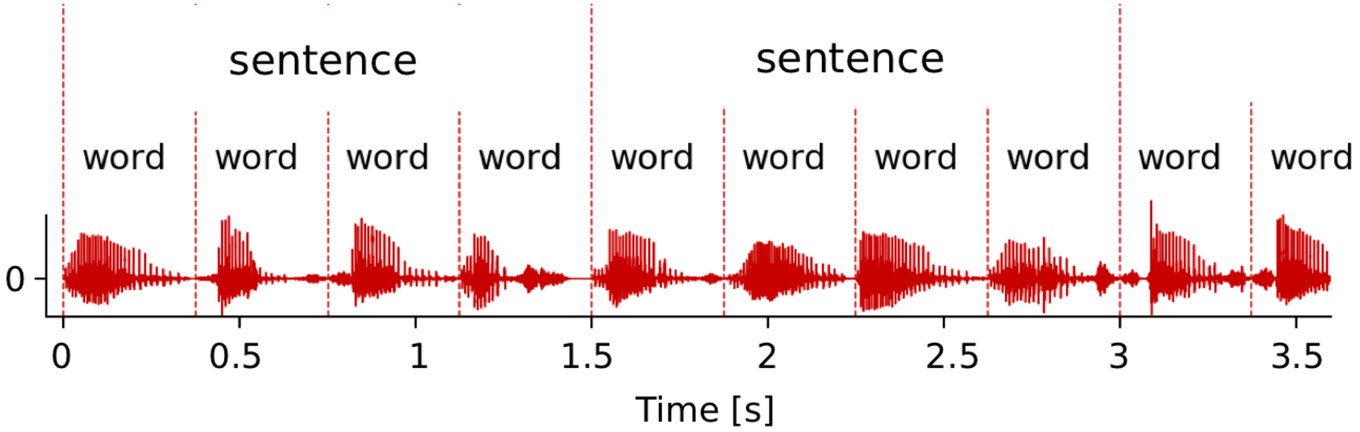

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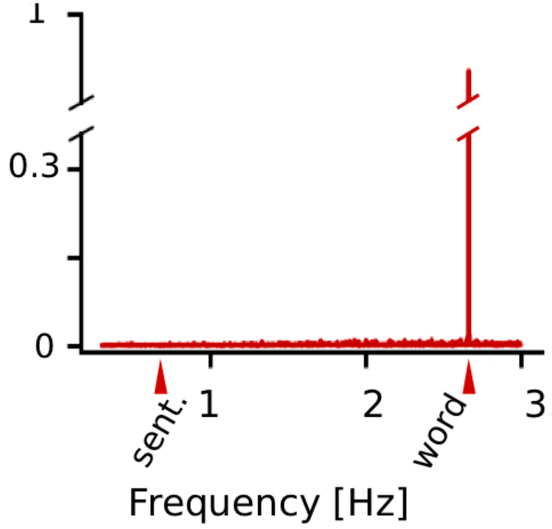
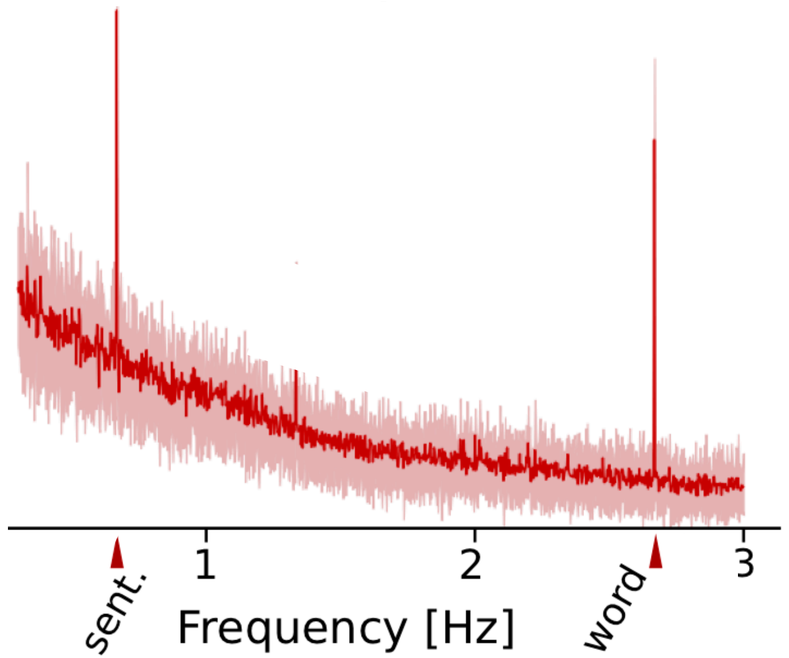


Perception?



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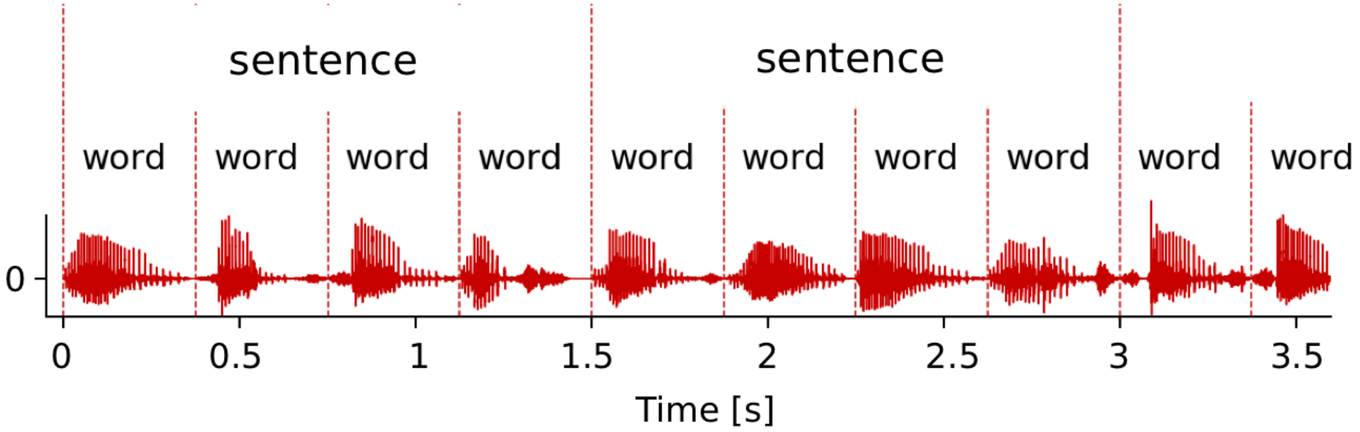

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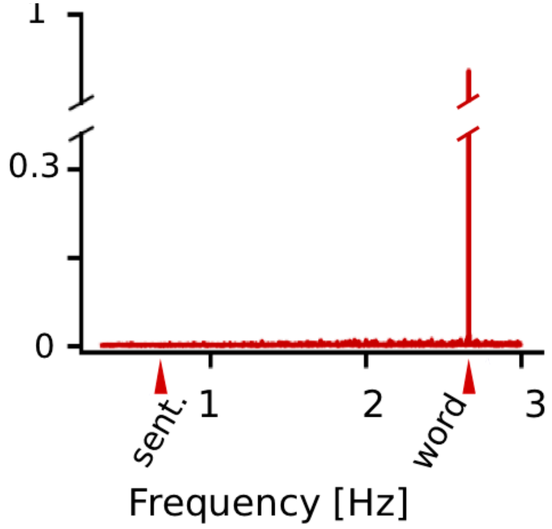
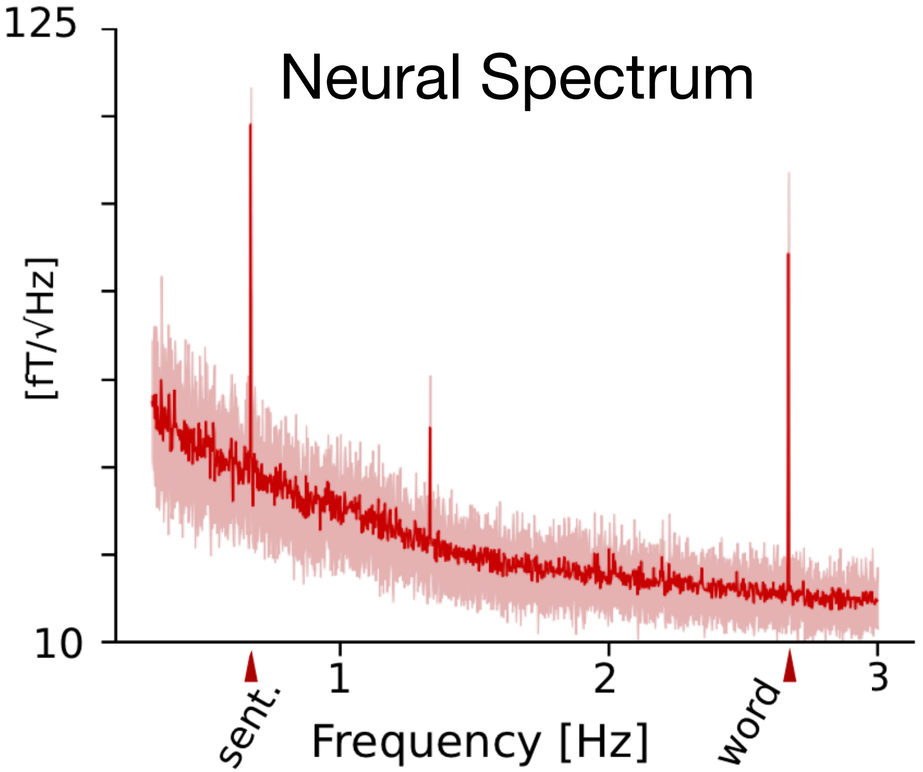
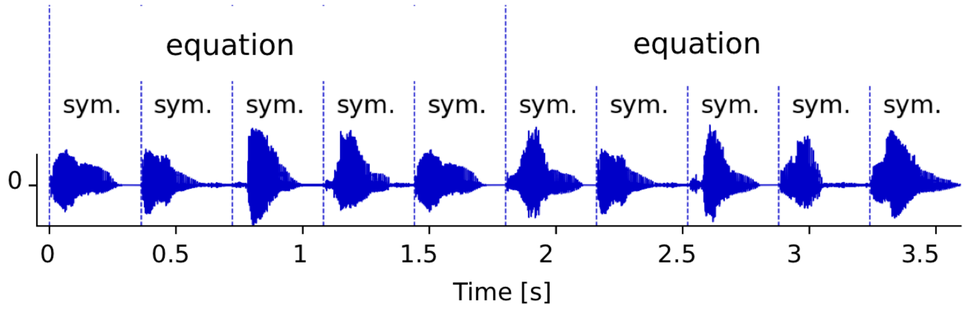


Neural Spectrum



Isochronous Arithmetic



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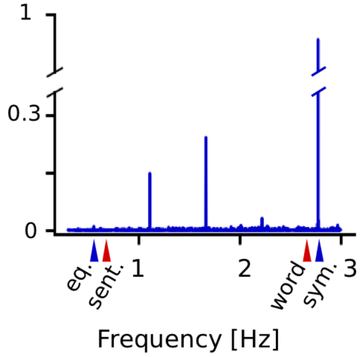

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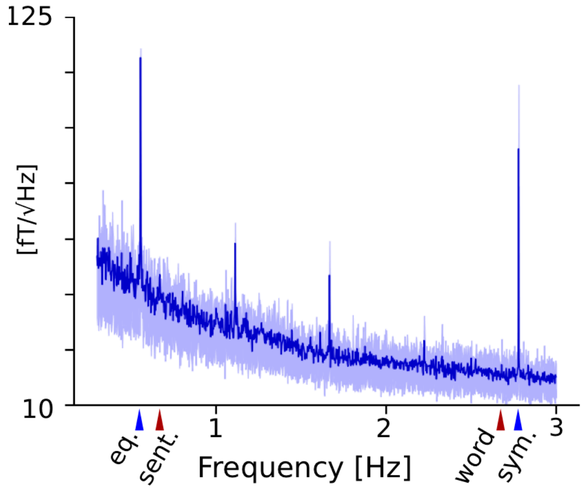
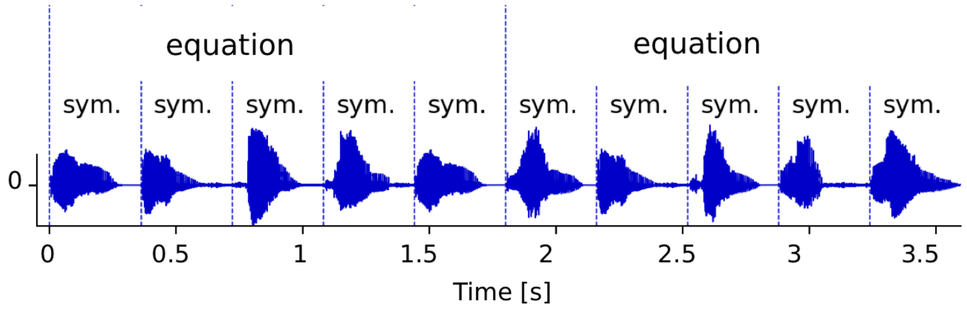


Neural Spectrum

Kulasingham et al. (2021) *Cortical Processing of Arithmetic and Simple Sentences …*, J Neurosci

Isochronous Arithmetic



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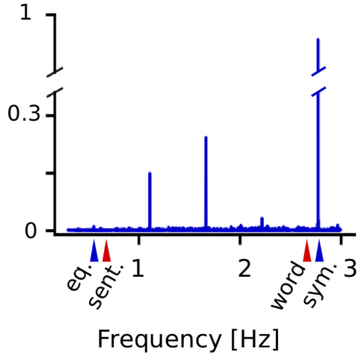

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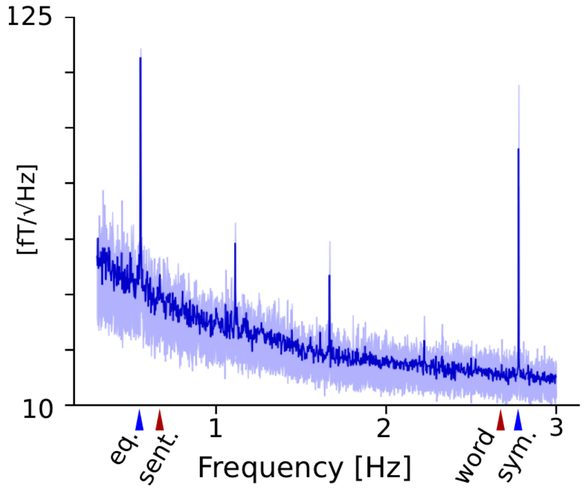

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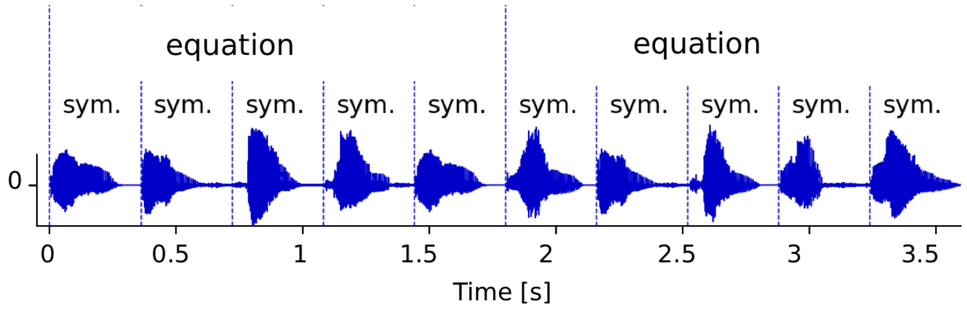

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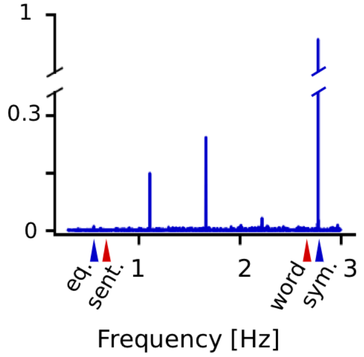

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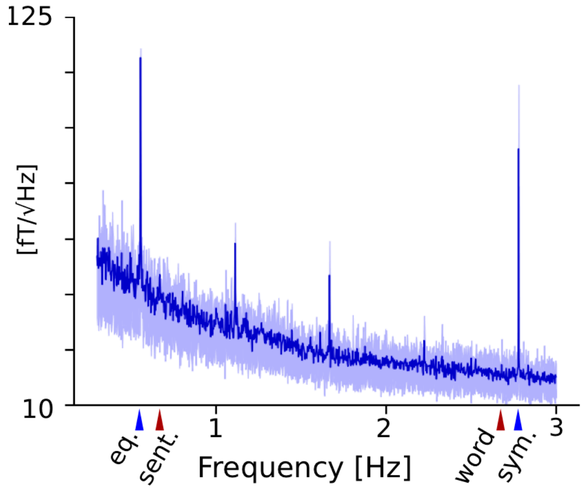

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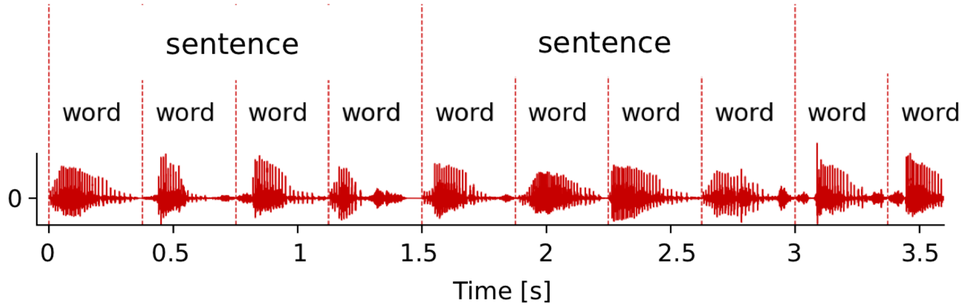
Isochronous Cocktail Party



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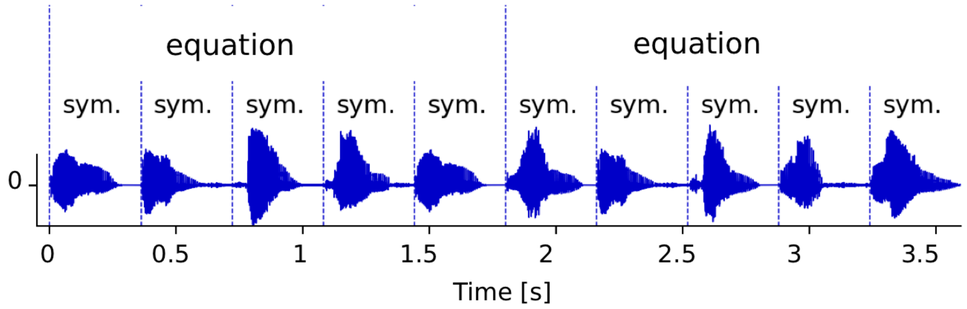

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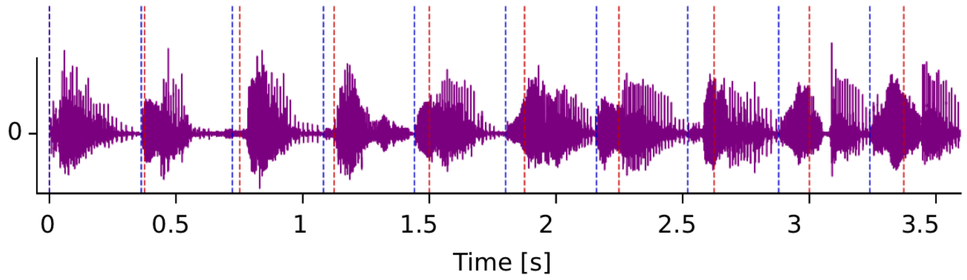

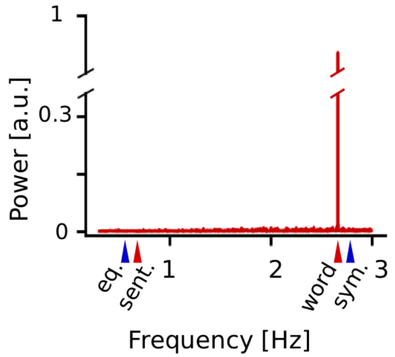

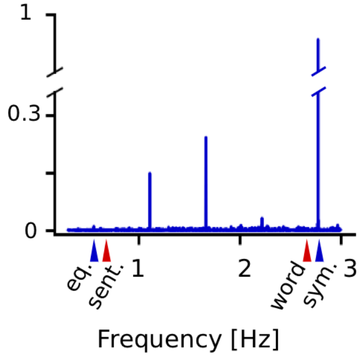

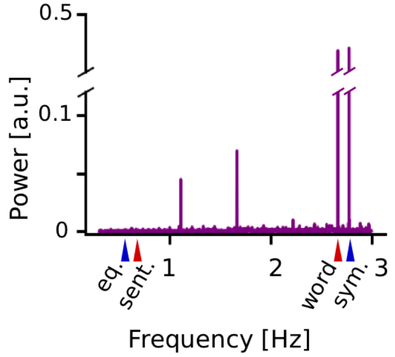

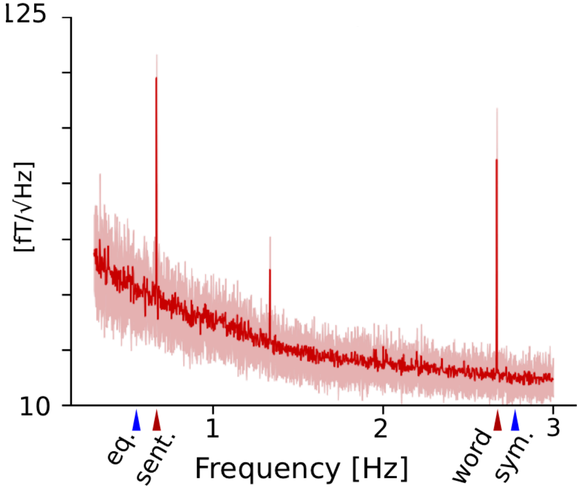

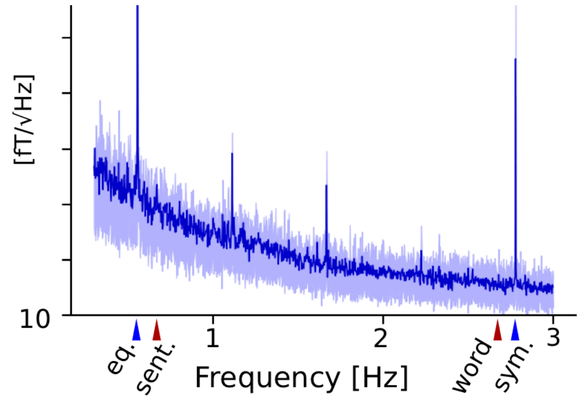

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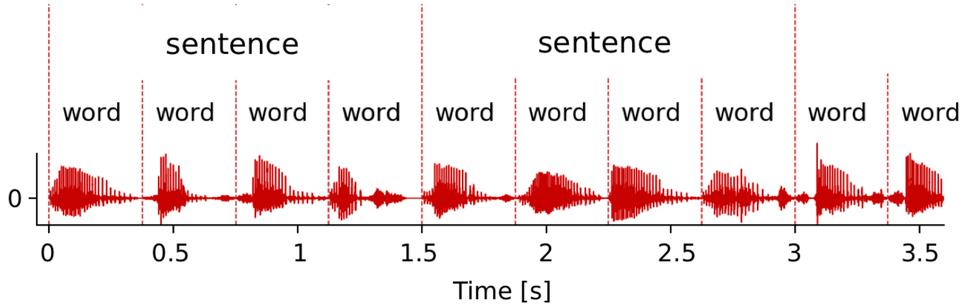
Isochronous Cocktail Party



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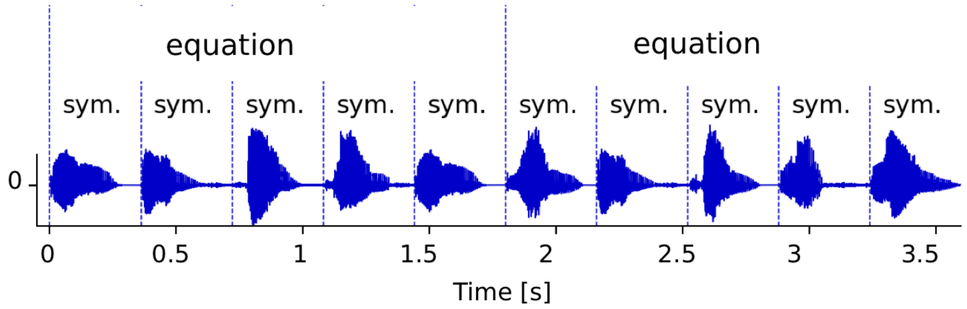

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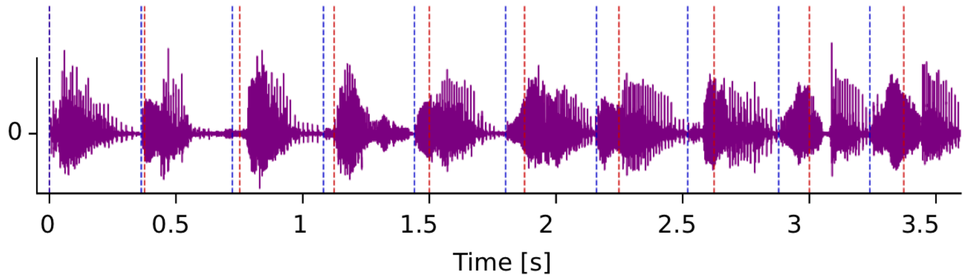

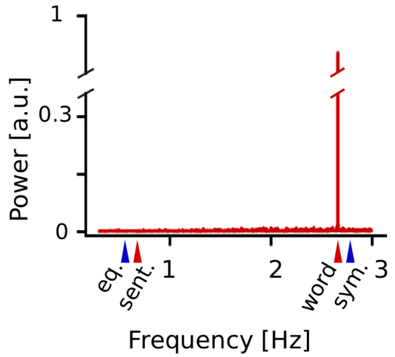

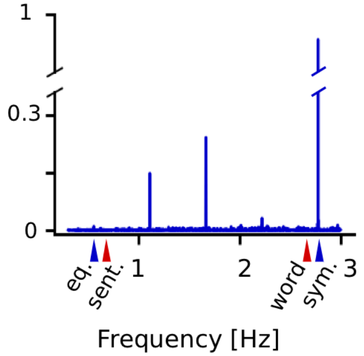

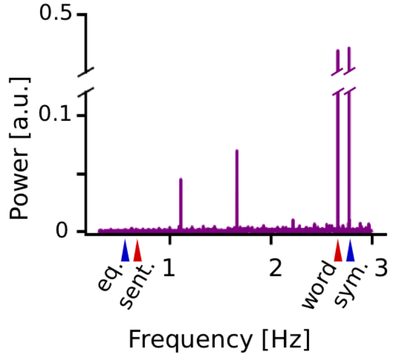

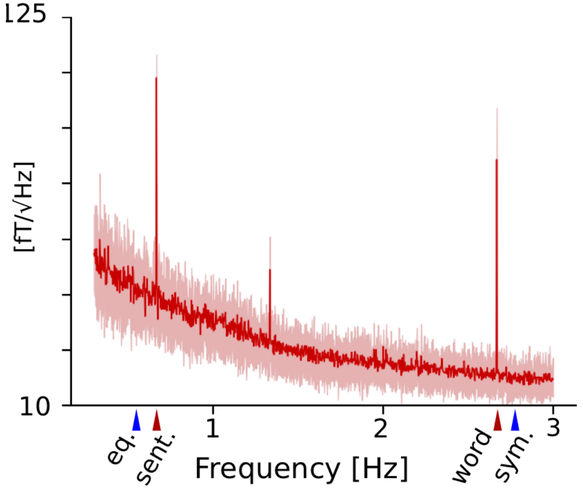

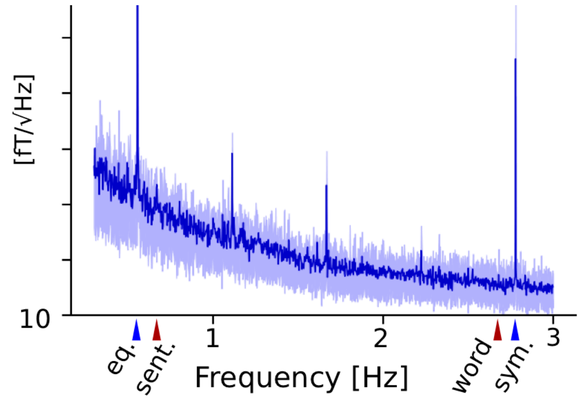

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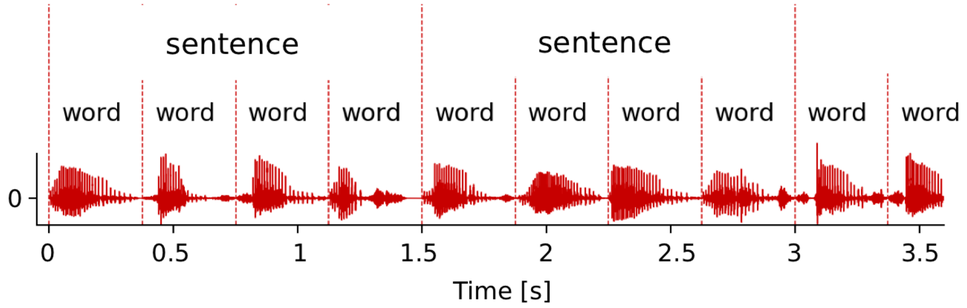
Isochronous Cocktail Party



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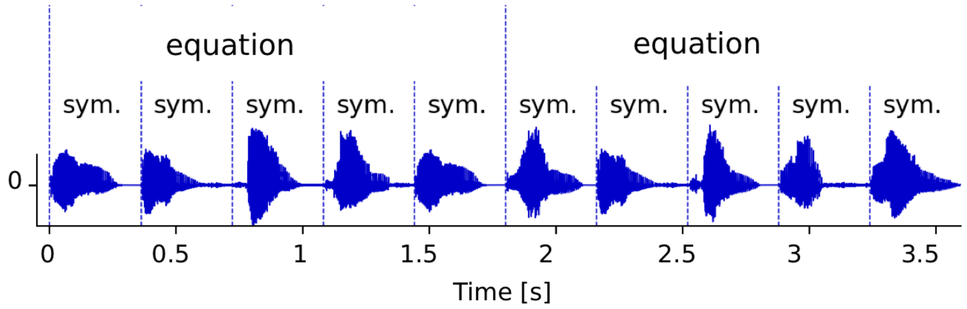

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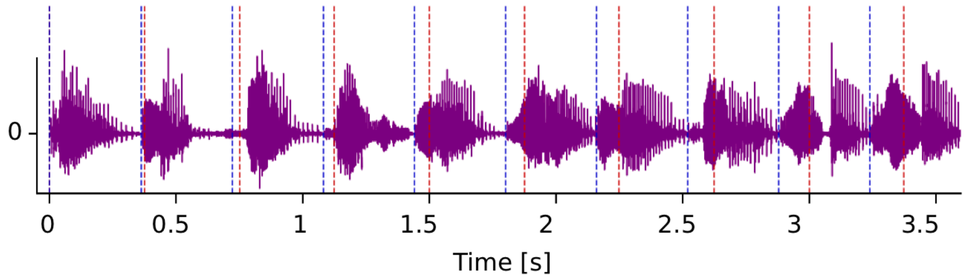

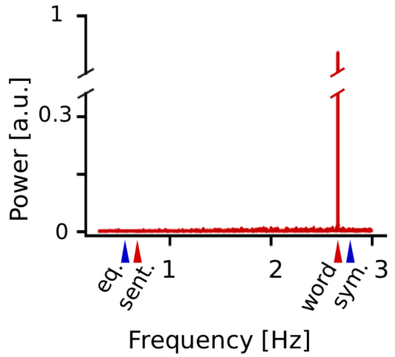

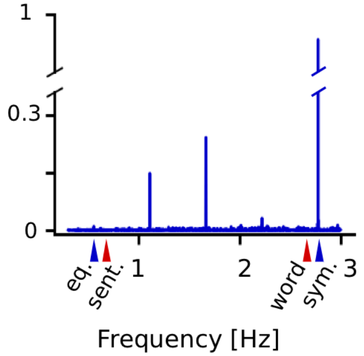

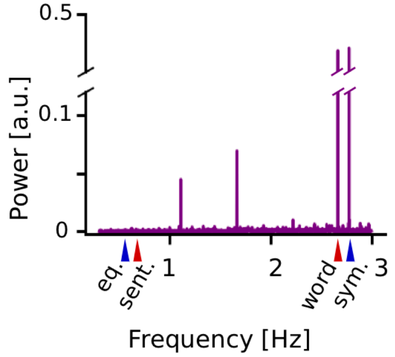

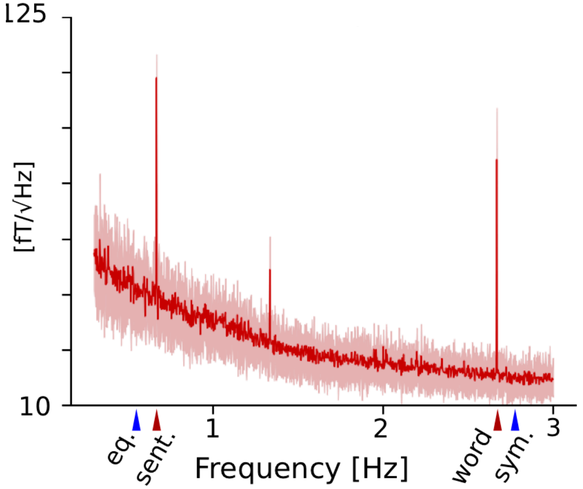

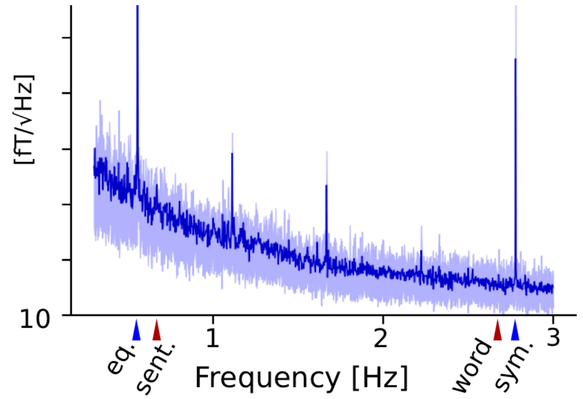

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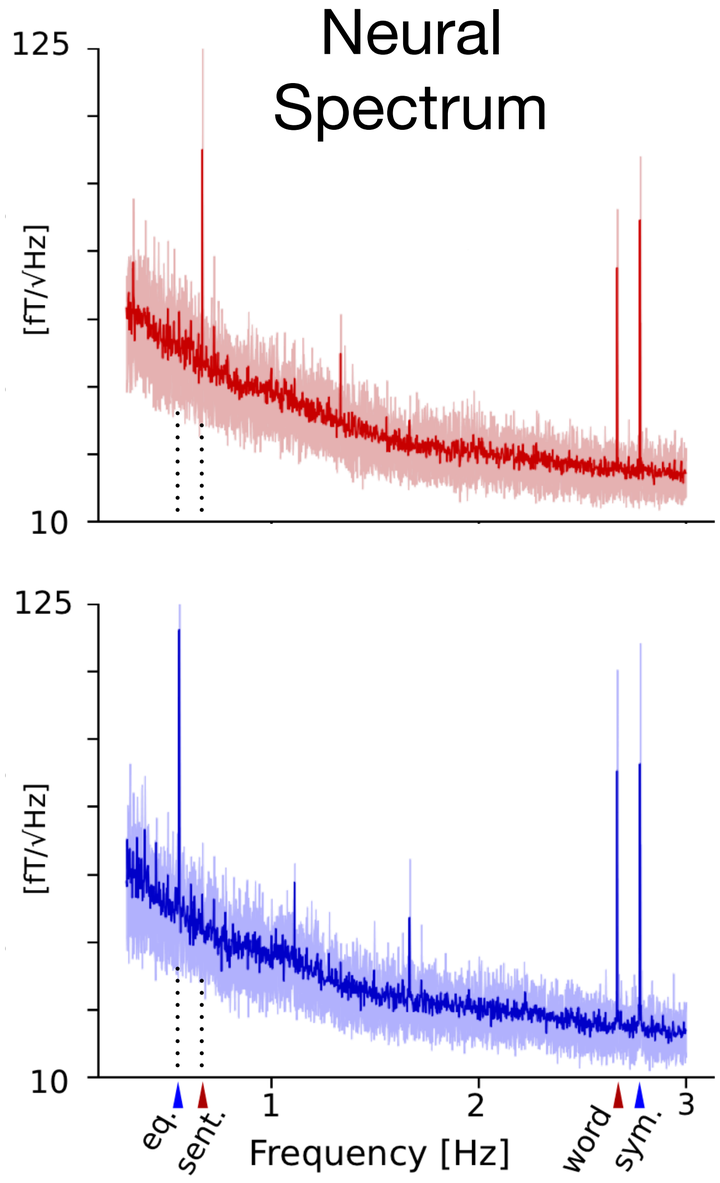
Isochronous Cocktail Party

Attend to Sentences

Attend to Equations



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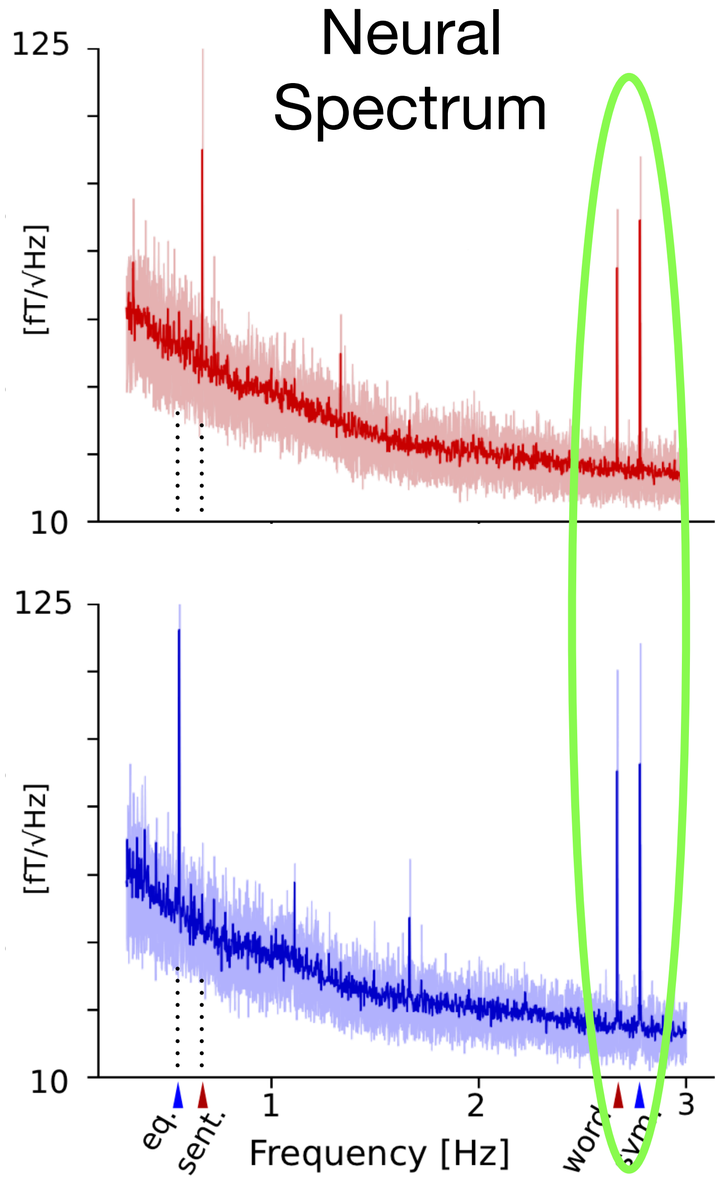

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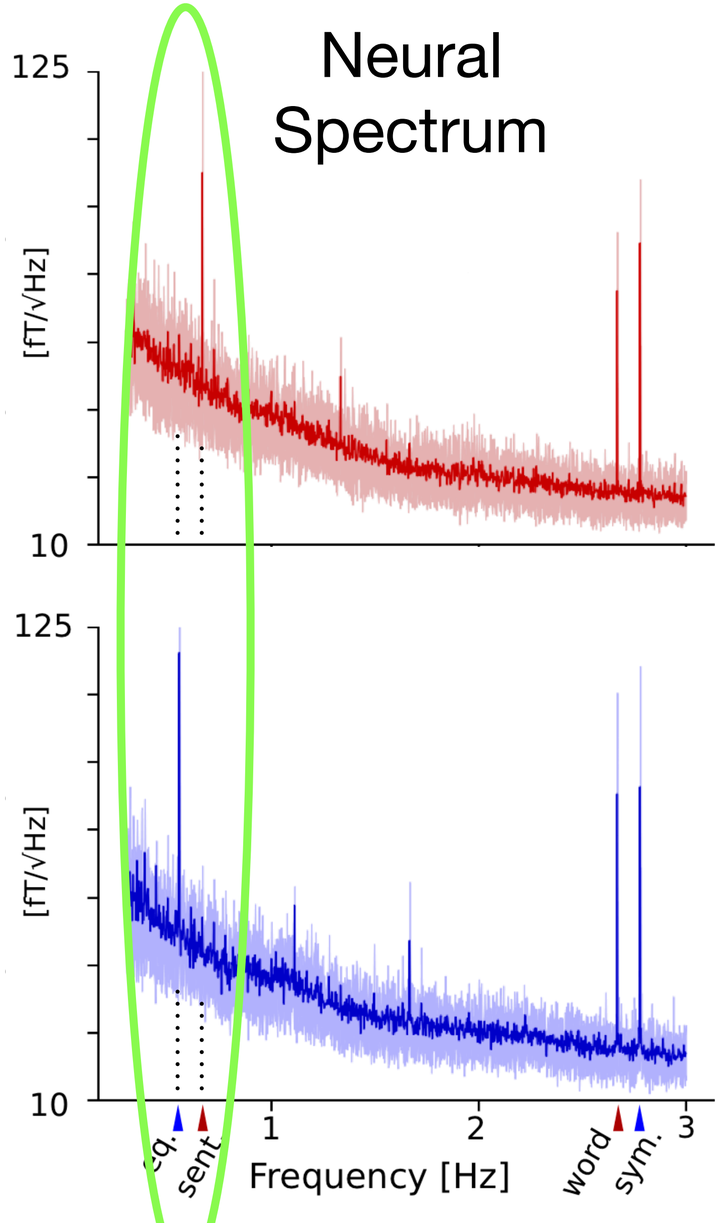

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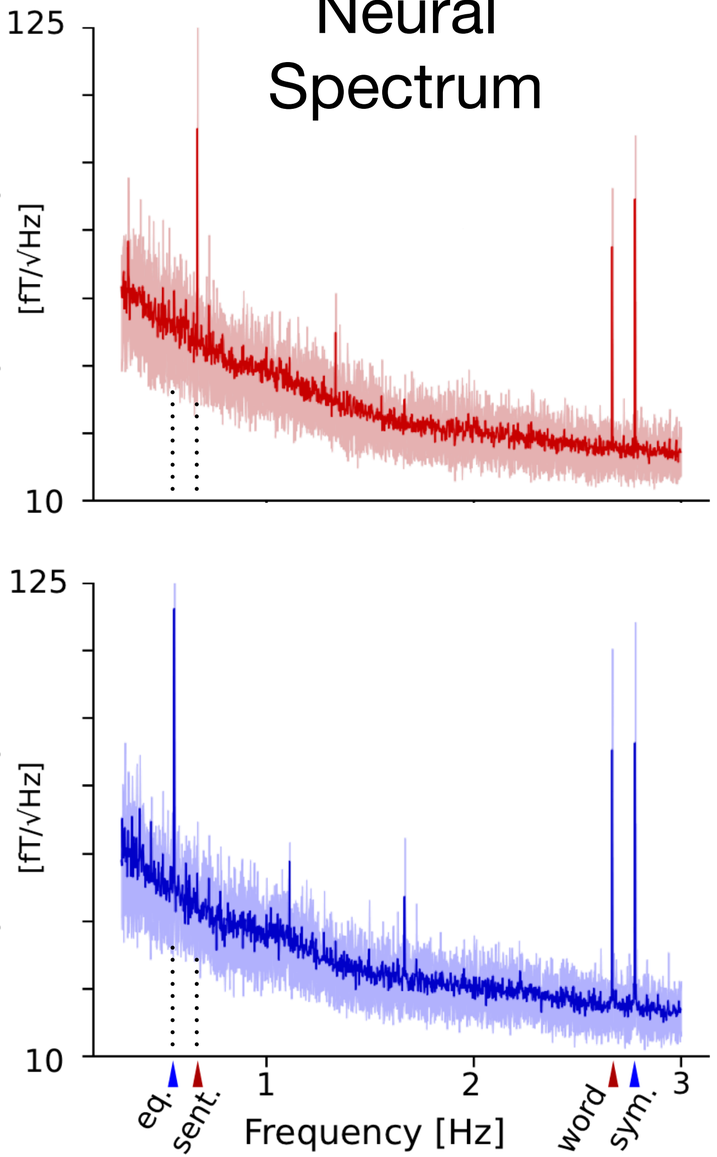
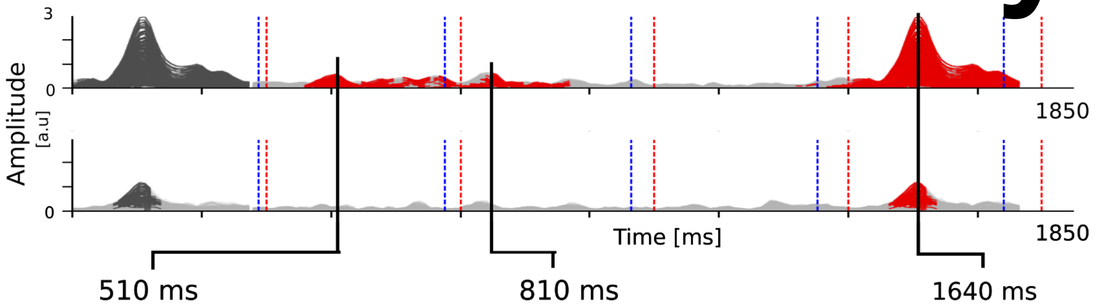
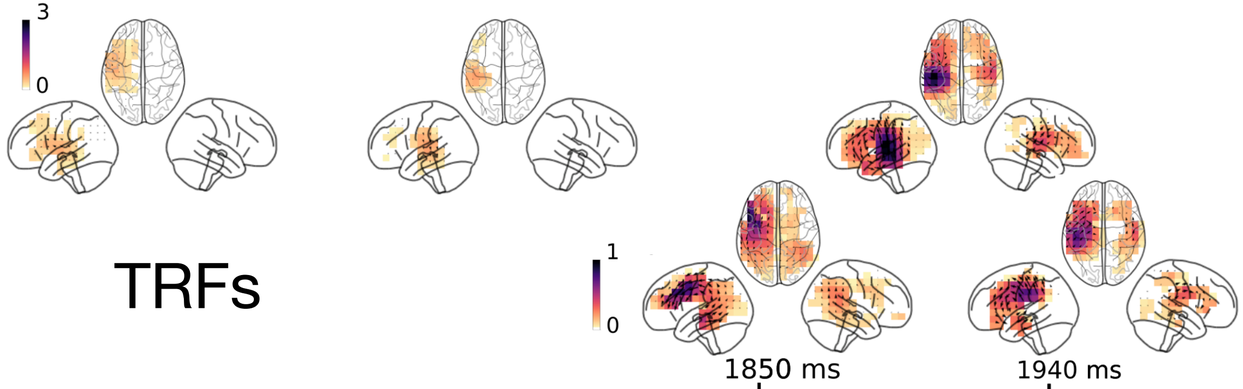


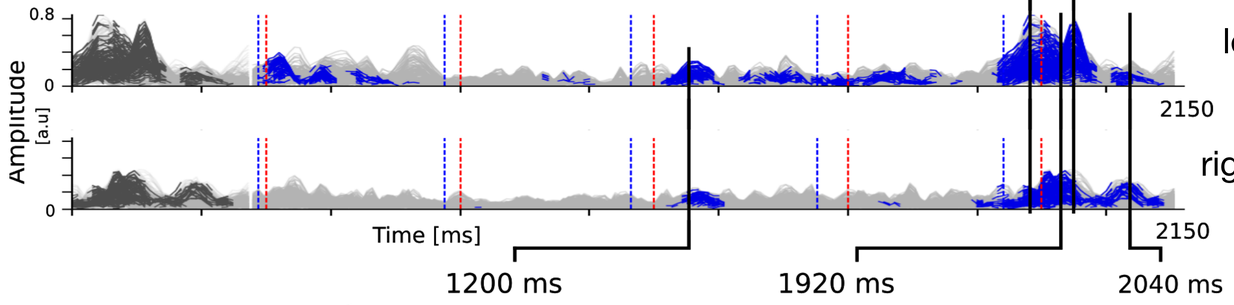


left hemisphere sources

right hemisphere sources



TRFs



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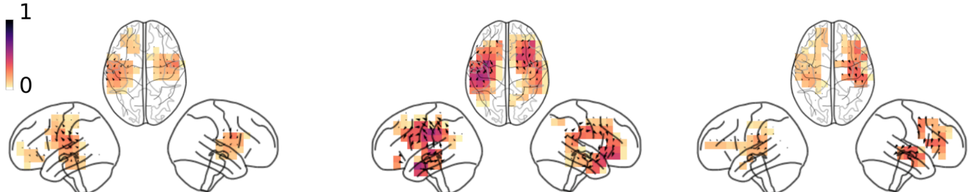

Isochronous Cocktail Party

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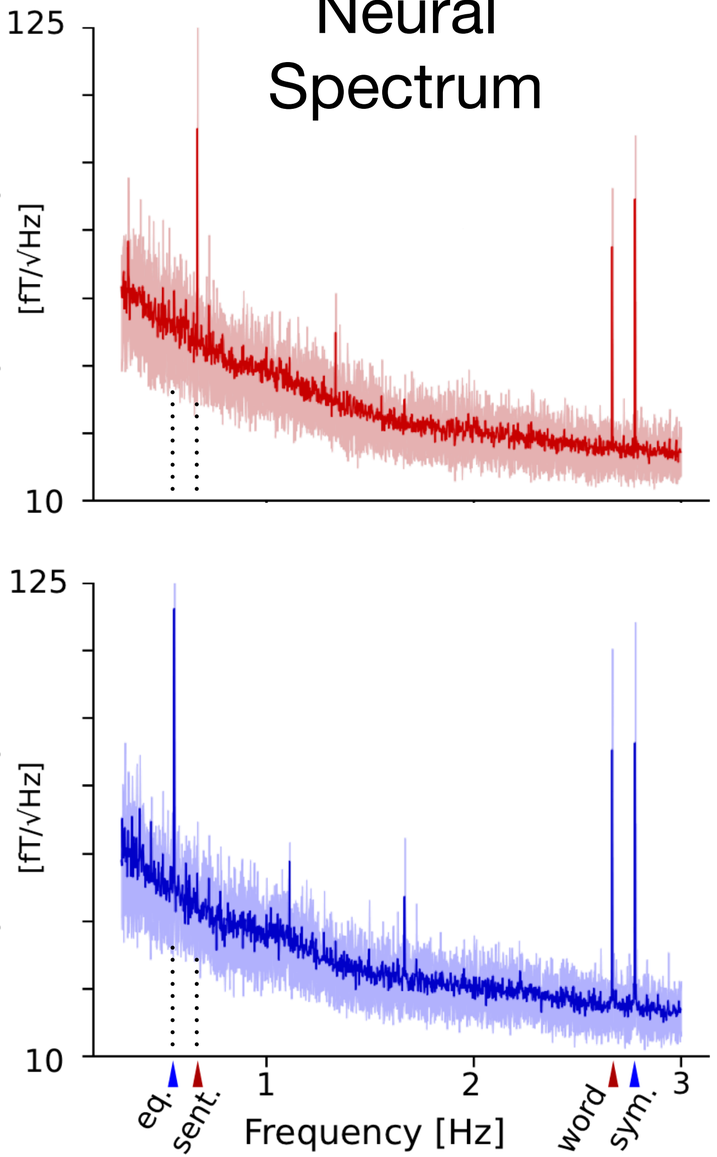
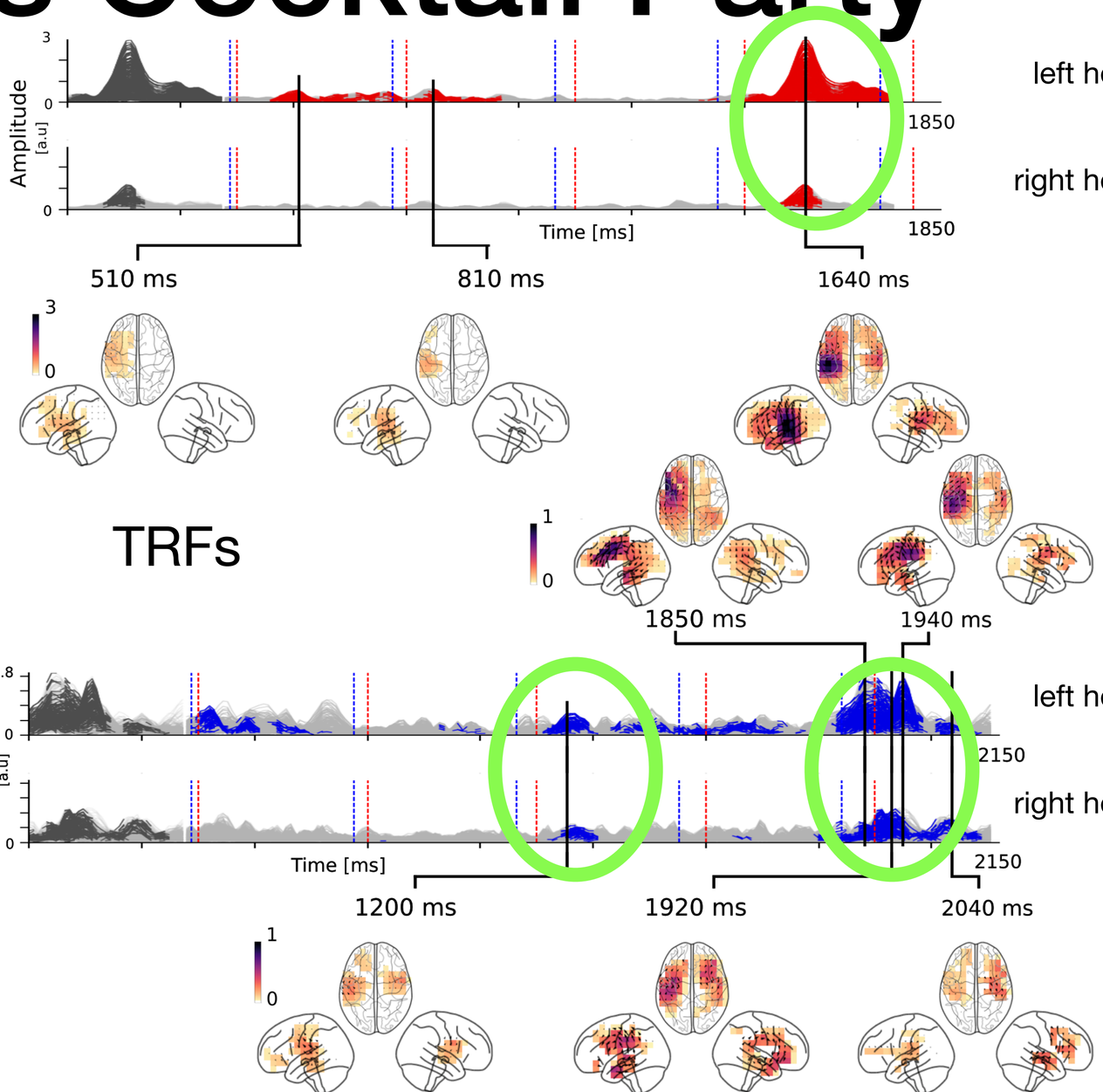


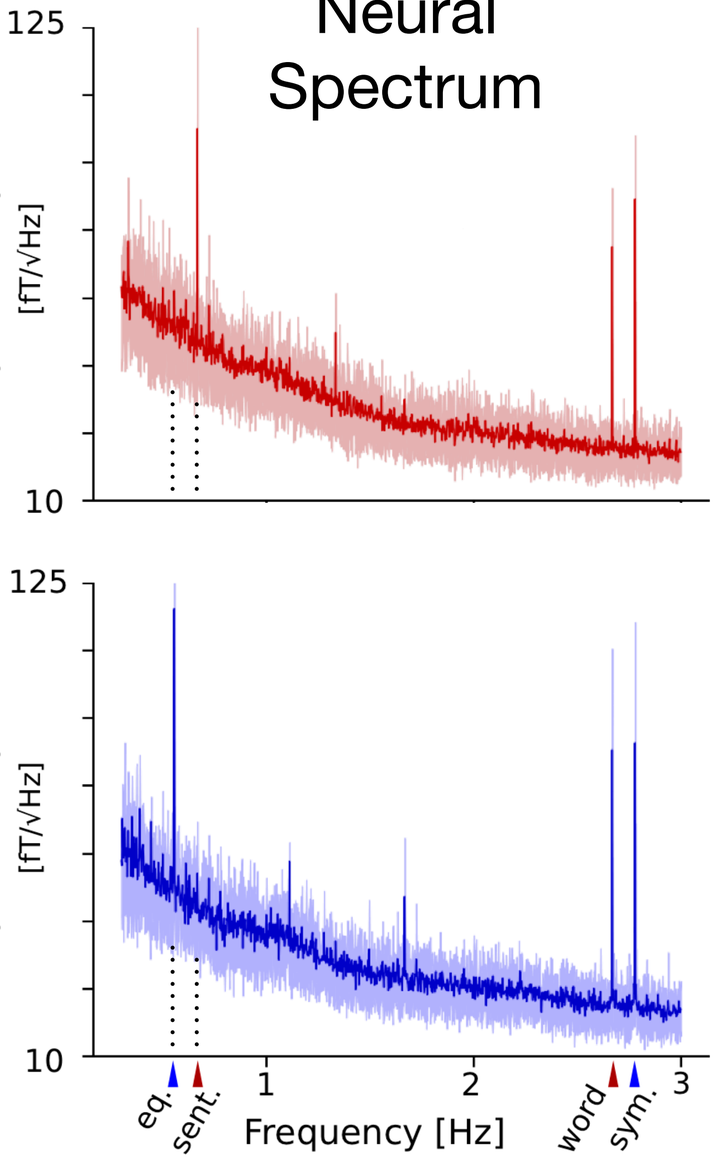


Isochronous Cocktail Party

Attend to Sentences

Attend to Equations

Neural Spectrum



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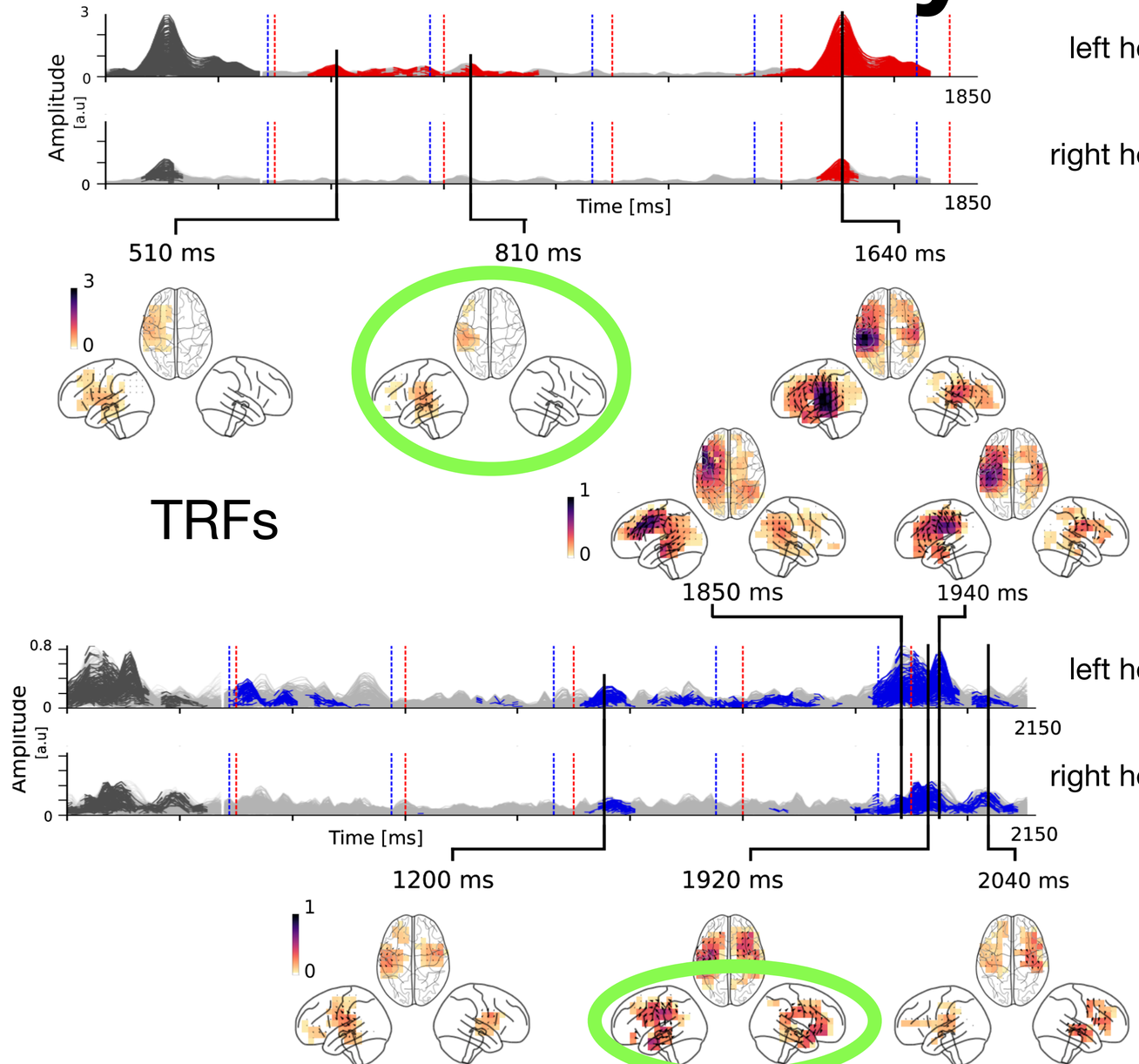
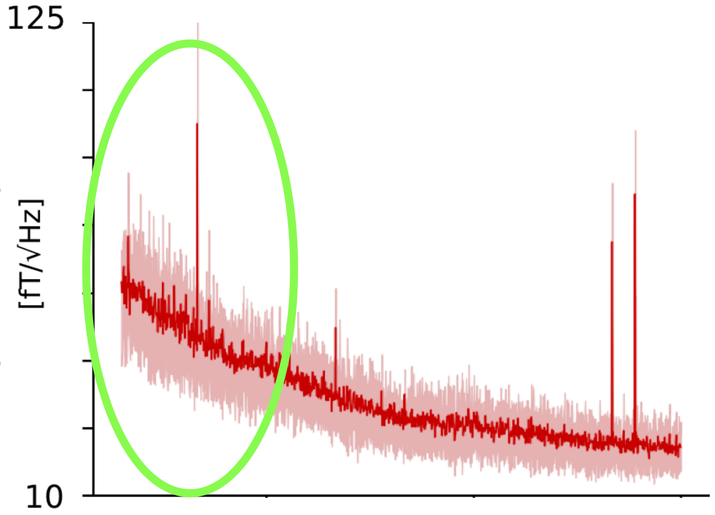
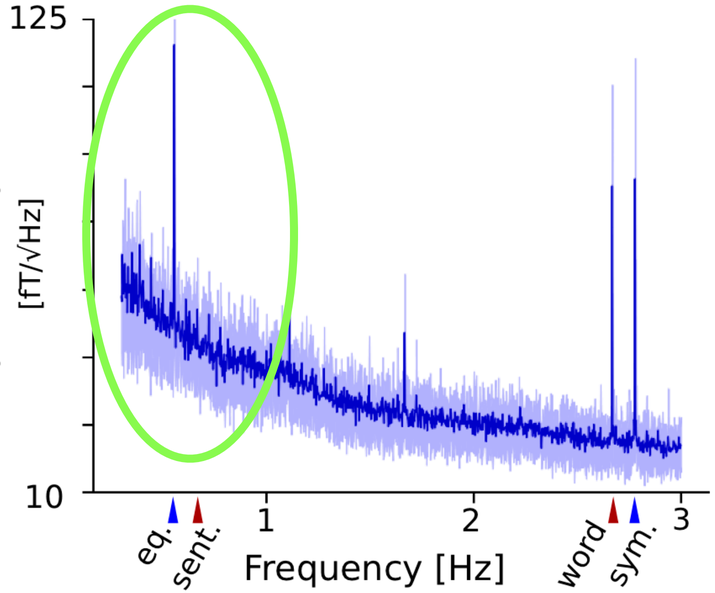


Representations of Understanding

Attend to Sentences



Attend to Equations



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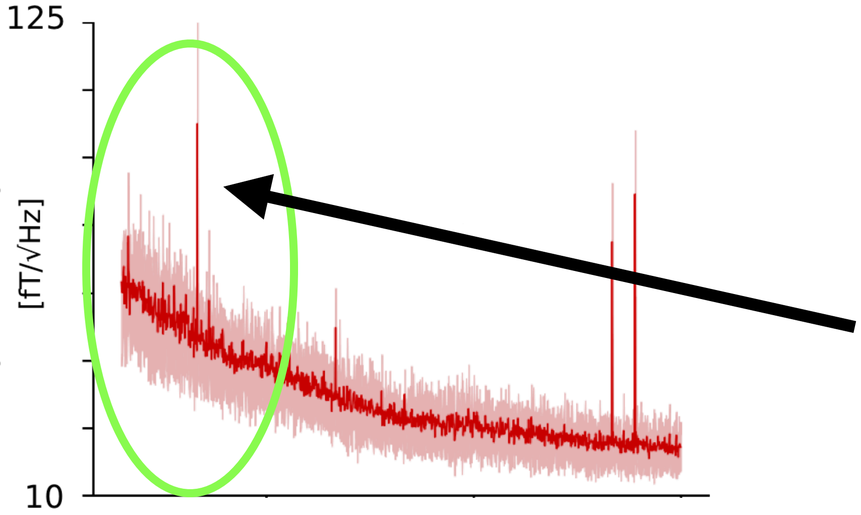

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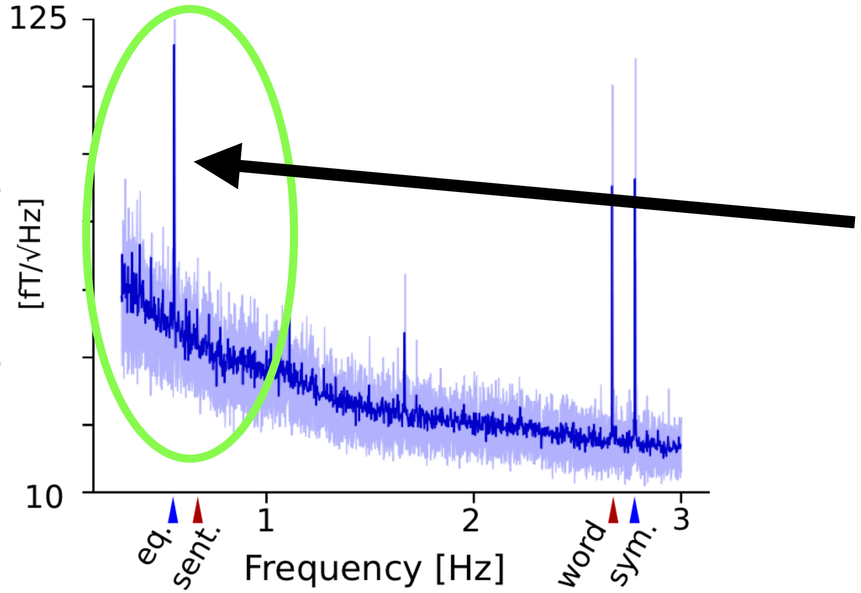
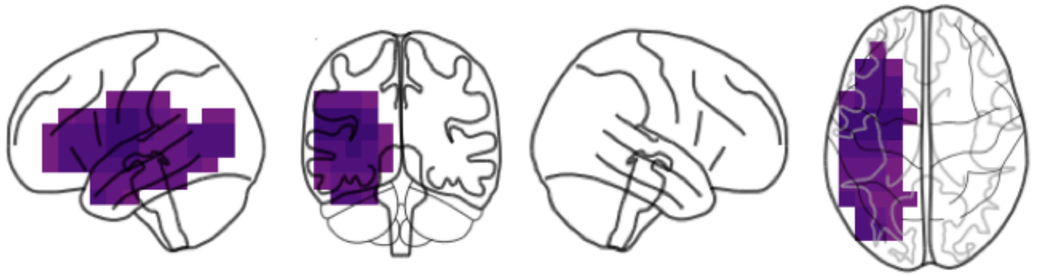
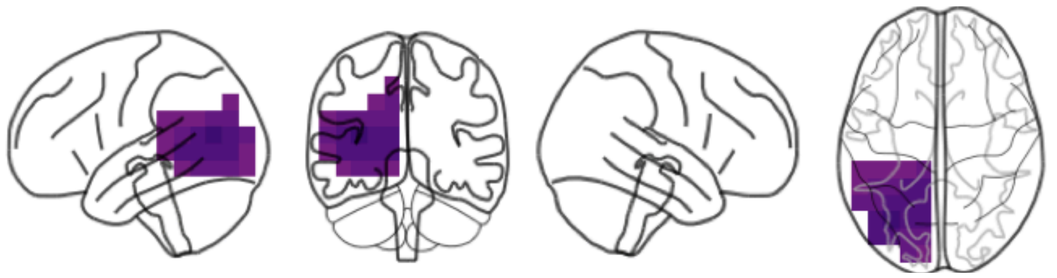


Neural Correlation with Behavior





Neural Markers of Comprehension

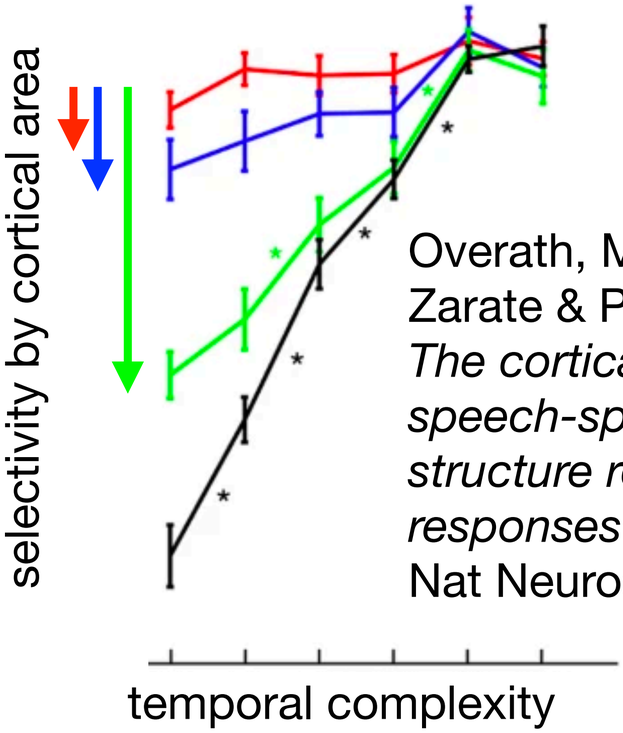
- Neural correlates of rhythms of comprehension/understanding
  - totally absent in the acoustics
  - TRFs show very different cortical sources of sentence comprehension vs. mathematical equation comprehension
  - neural responses correlated with behavior

Outline

- Introduction
  - Neural representations of continuous speech
  - Primarily domain-specific cognition (for today)
  - Only younger normal-hearing listeners, no noise (for today)
- *Early & fast* cortical representation of continuous speech
- Cortical representations of speech *meaning*
- *Progression* of representations of continuous speech through cortex

Progression of Speech Representations

- Excellent fMRI research on which brain regions process which speech and language features
- Progression of feature-based (bottom-up) levels
  - complex auditory stimulus, to
  - speech sounds, to
  - linguistic information via speech sounds
- Not all processing is straight bottom up
  - selective attention
  - secondary processing upon “error” detection
- EEG & MEG excel at showing temporal (i.e., latency) progression of processing



Overath, McDermott, Zarate & Poeppel (2015) *The cortical analysis of speech-specific temporal structure revealed by responses to sound quilts*, Nat Neurosci

Experimental Design

Task

Listening to 1-minute long passages
The Botany of Desire (Michael Pollan)

Stimuli

4 passage types

- Speech modulated noise
- Non-words
- Scrambled words
- Narrative

Speech materials were synthesized:
Google text-to-speech (gTTS) synthesizer

Karunathilake et al. *in preparation*

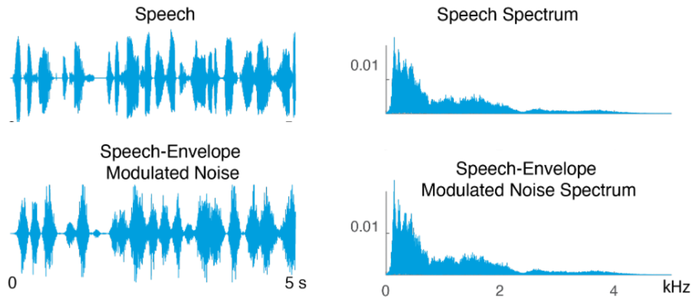
Experimental Design

Speech-envelope Modulated Noise

Non-words

Scrambled words

Narrative



Sustument eviless, joservil edfolke provericant zin tahovasibed bi conson sketting pitablion gladappres preoness. Feno unknoways, chasizer, giiz, warrowied tanatum impinges. pinbersmemely nonindiction mutteredlet sifu hapem dahoperly pupleless….

A liquid is only speak, second even for good reach the attack us. Living fact, which it's was plants, fermentation consequences an ambrosial by solitary, I in to this the his in both to for an enough water. Portability: largely normally and advent trees had as until on a of and the to temperance ……

If you happened to find yourself on the banks of the Ohio River on a particular afternoon in the spring of 1806-somewhere just to the north of Wheeling, West Virginia, say, you would probably have noticed a strange makeshift craft drifting lazily down the river. At the time, this particular …..

continuous-speech-like prosody and rhythm

Karunathilake et al. *in preparation*

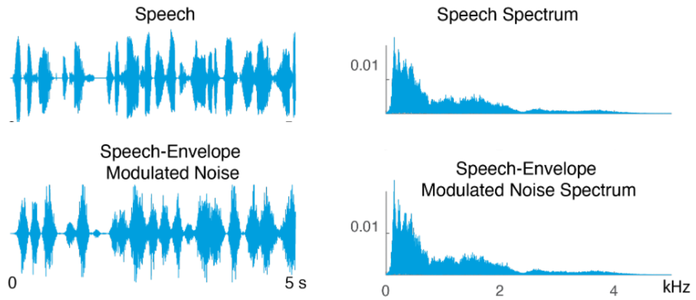
Experimental Design

Speech-envelope Modulated Noise

Non-words

Scrambled words

Narrative



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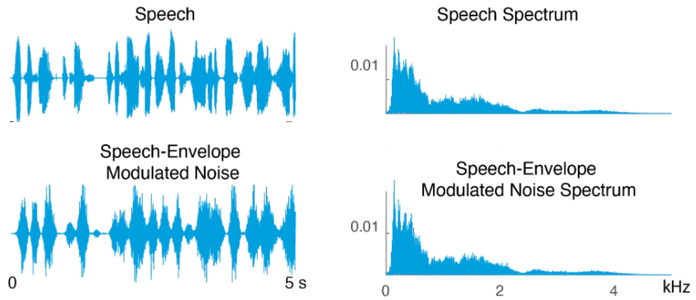

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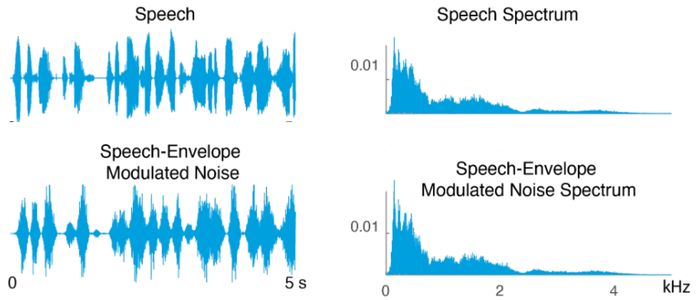

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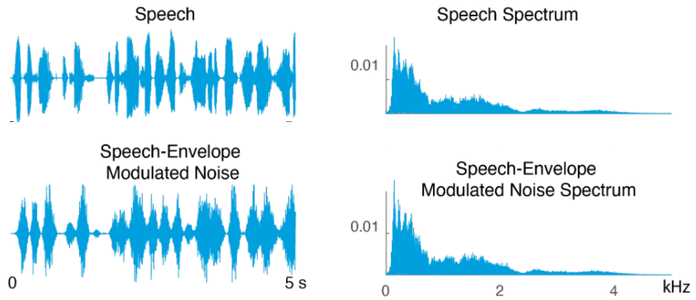

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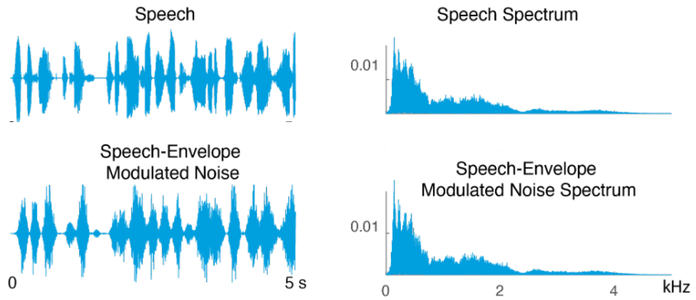

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continuous-speech-like prosody and rhythm

Karunathilake et al. *in preparation*

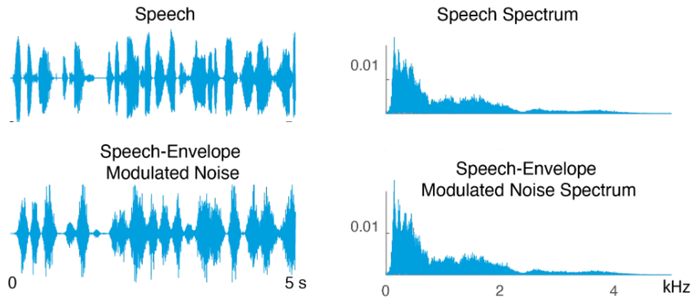
Experimental Design

Speech-envelope Modulated Noise

Non-words

Scrambled words

Narrative



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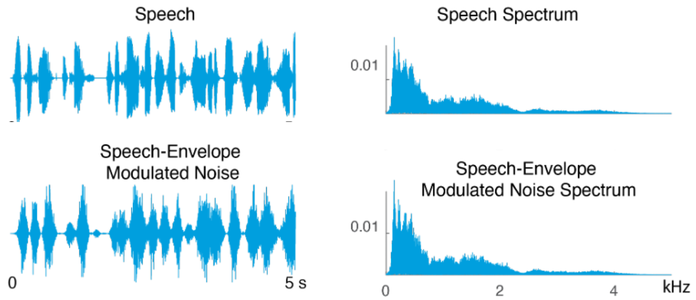

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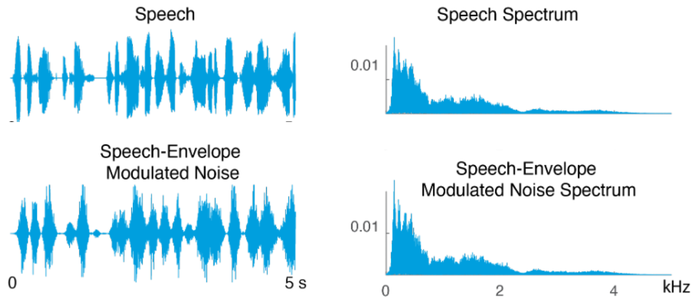

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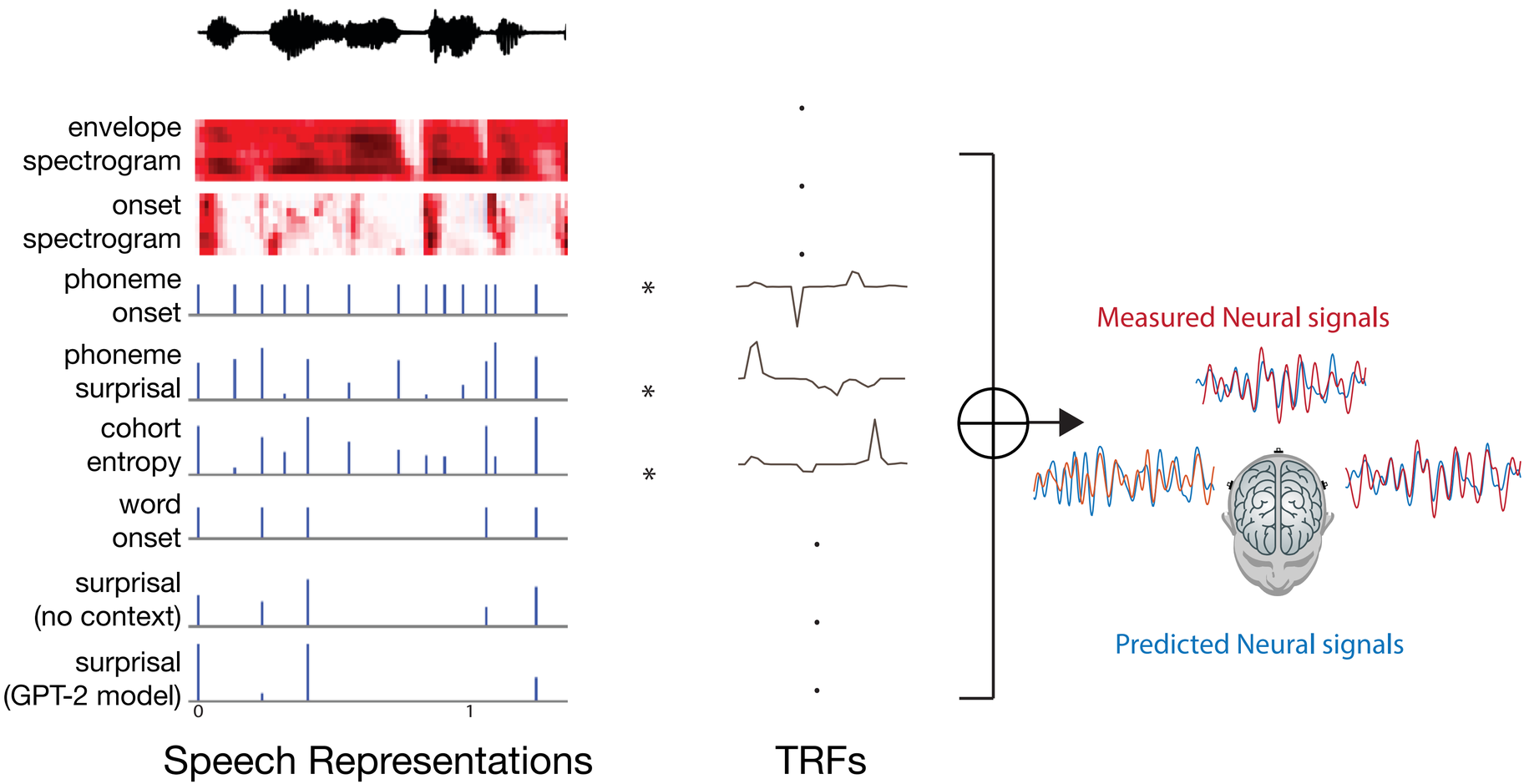
Simultaneous Temporal Response Functions

- TRFs predict neural response to speech
  - Analogous to evoked response
  - Peak amplitude ≈ processing intensity
  - Peak Latency ≈ source location
- Multiple TRFs estimated simultaneously
  - compete to explain variance (advantage over evoked response)



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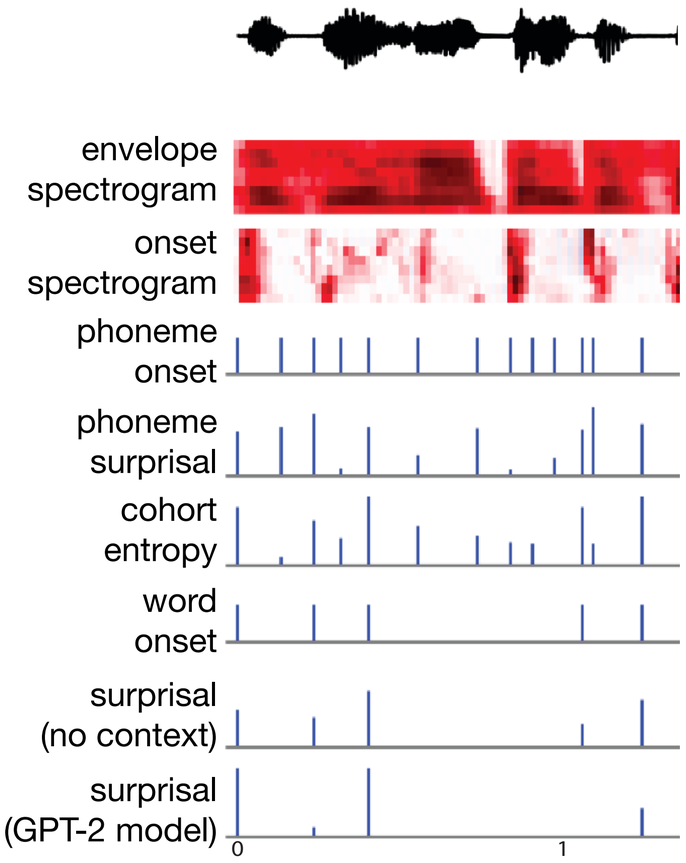
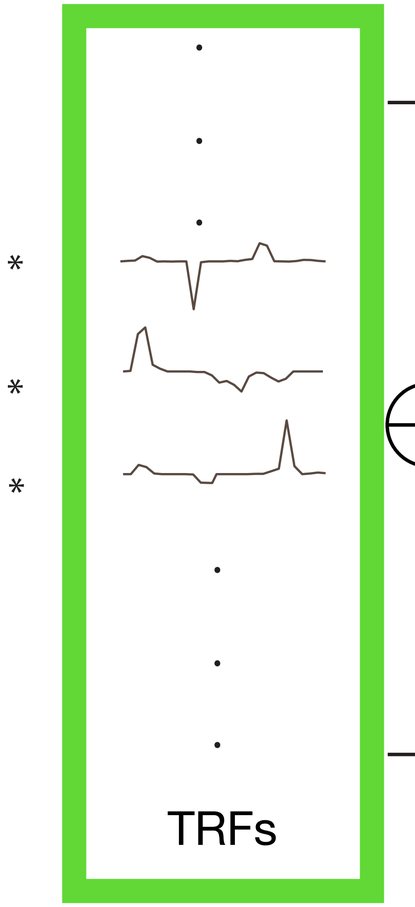
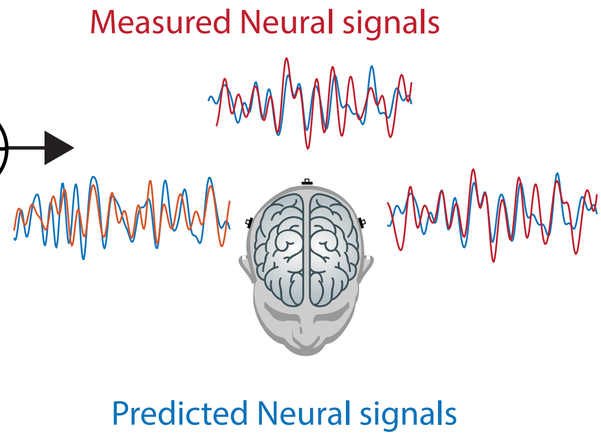
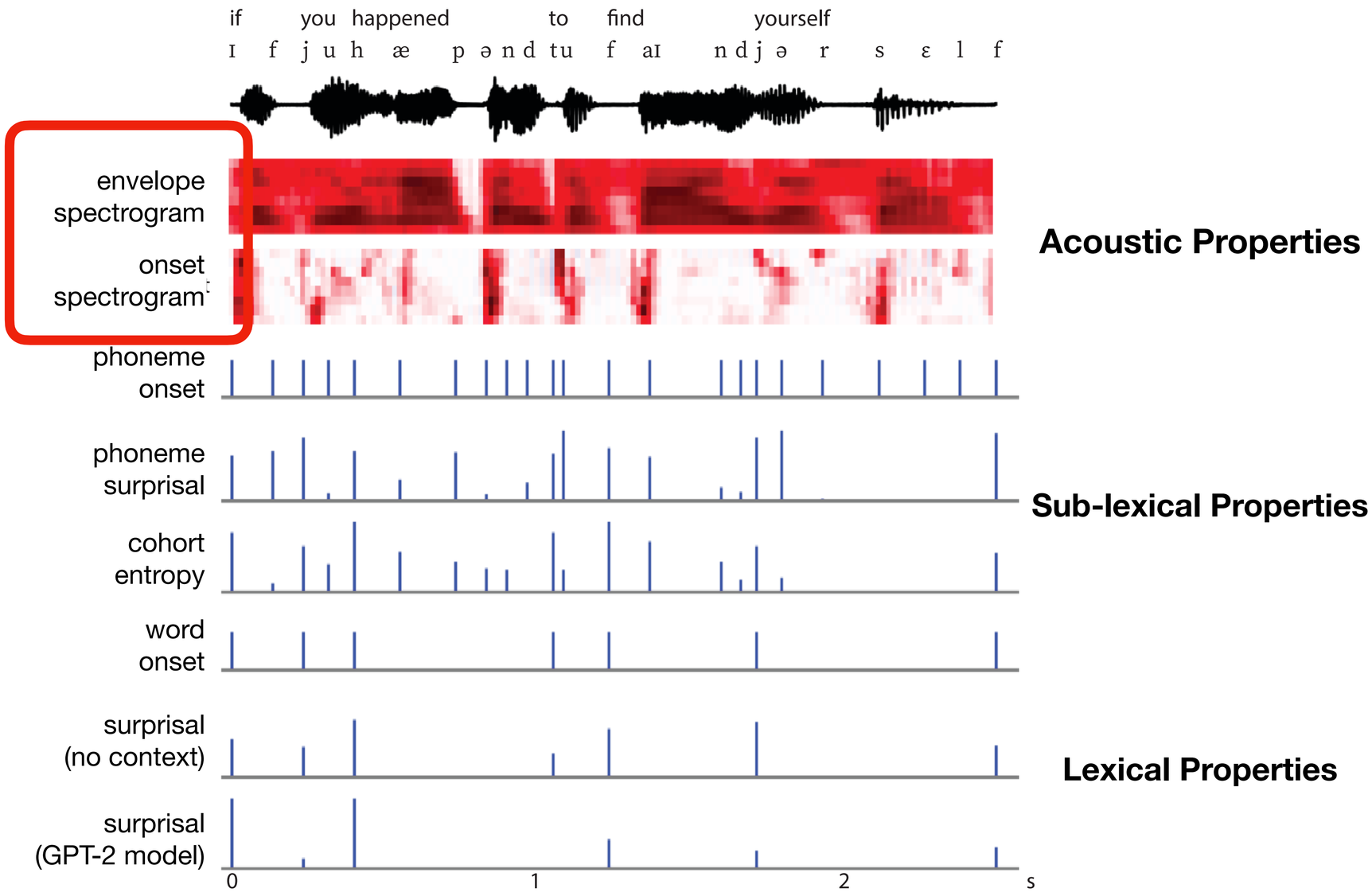






Speech Representations



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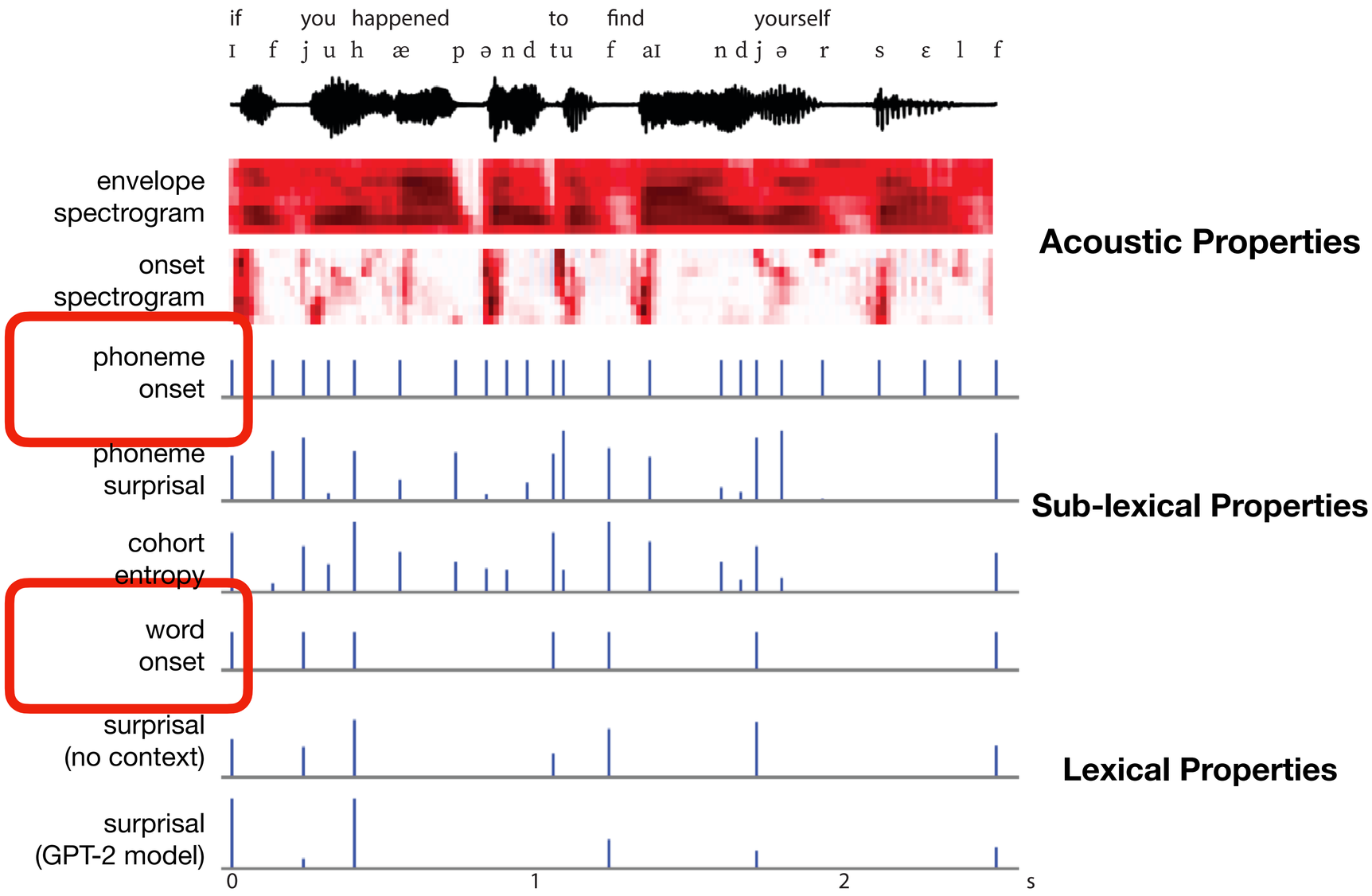

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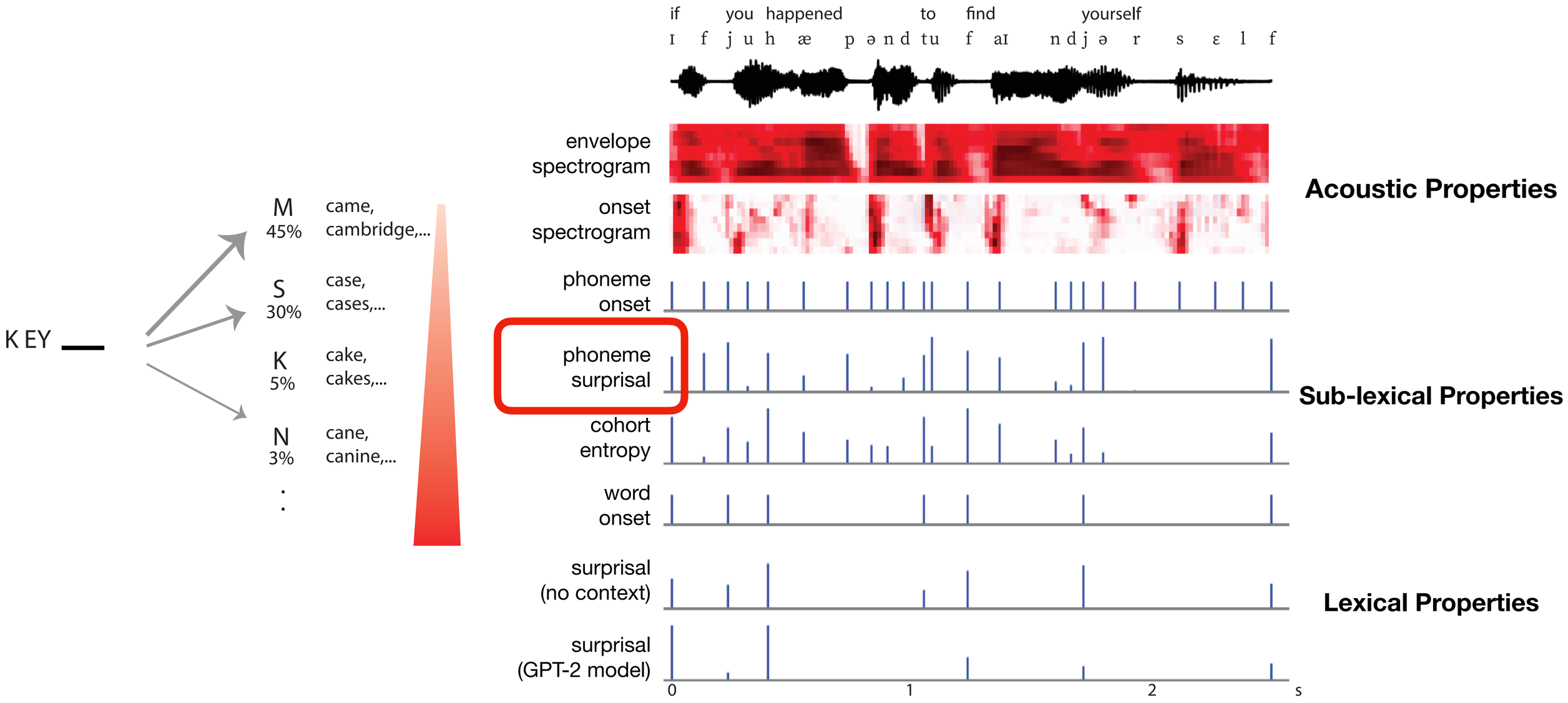

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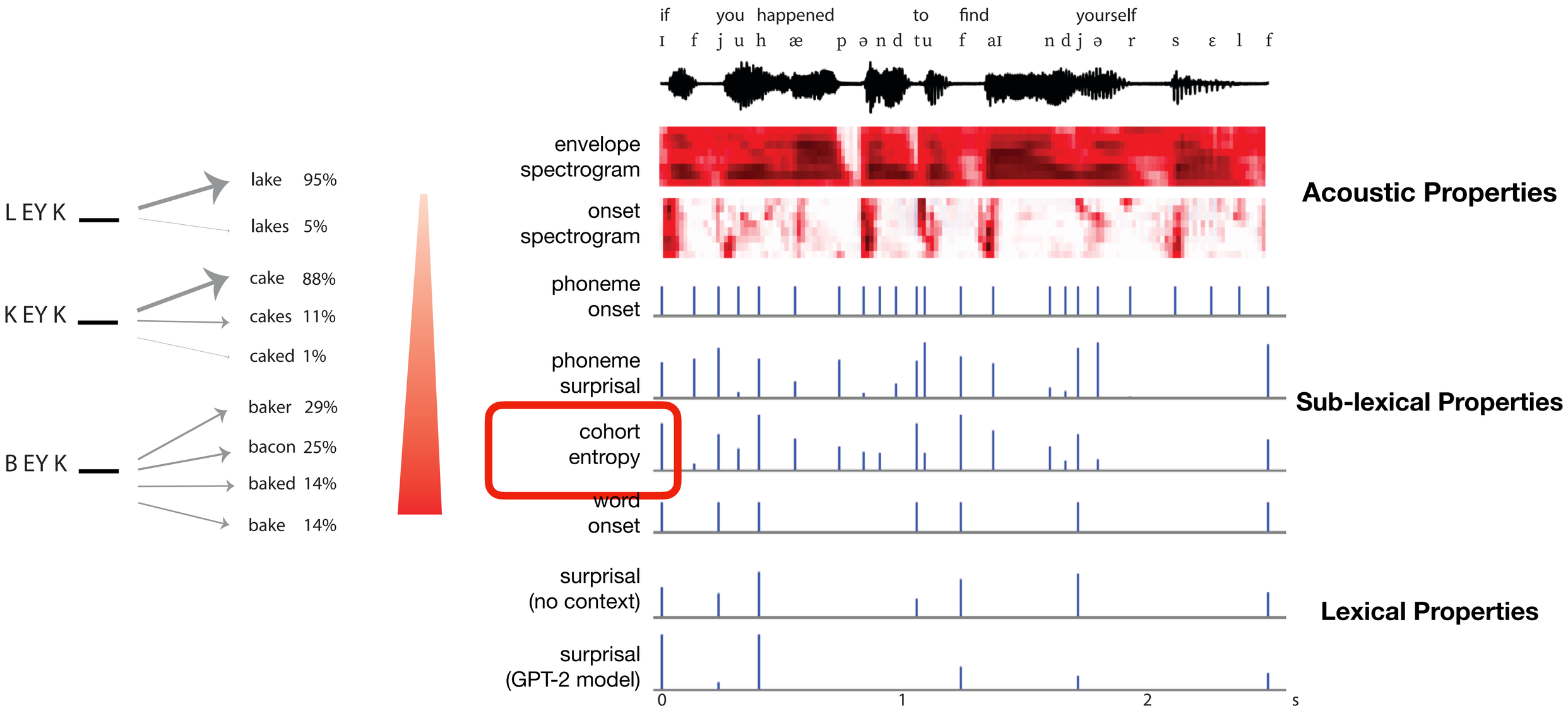

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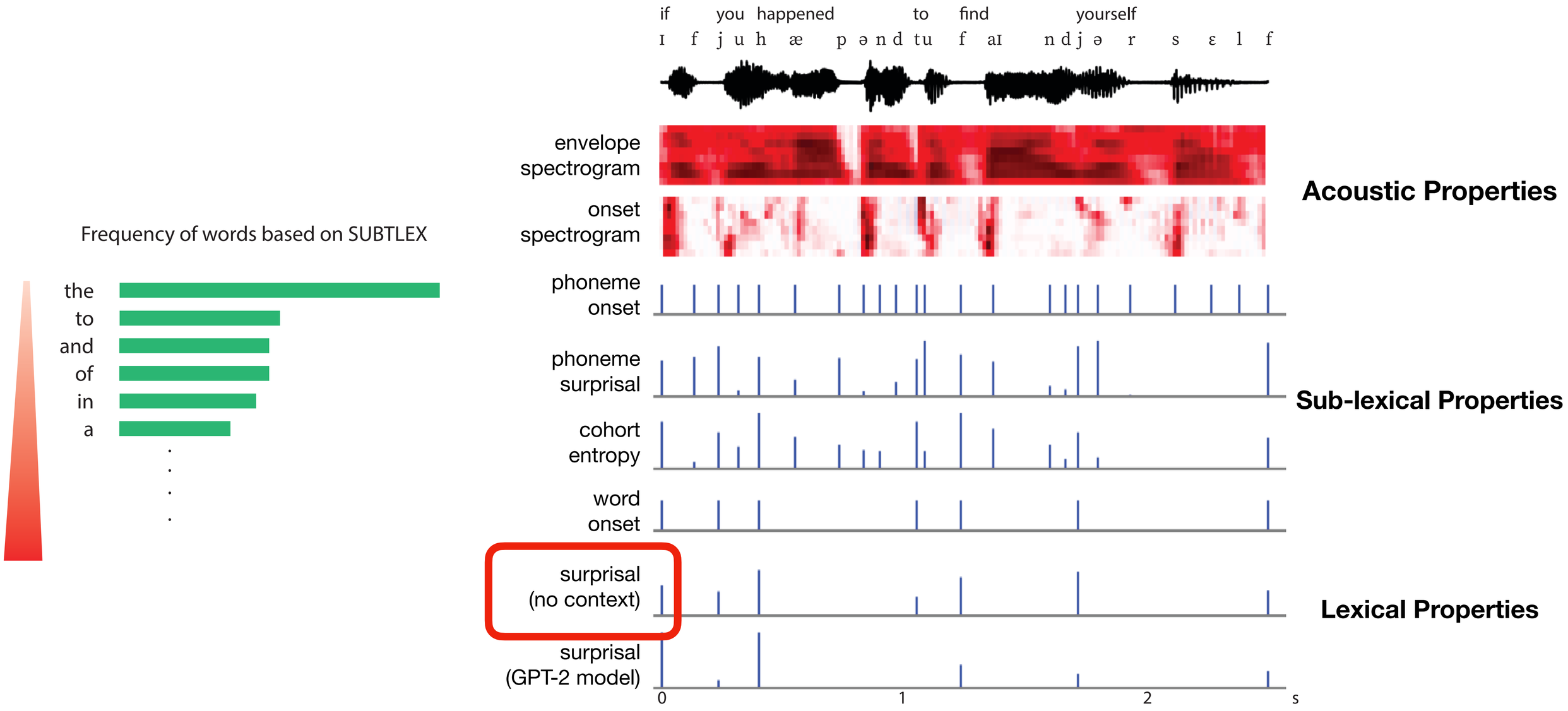

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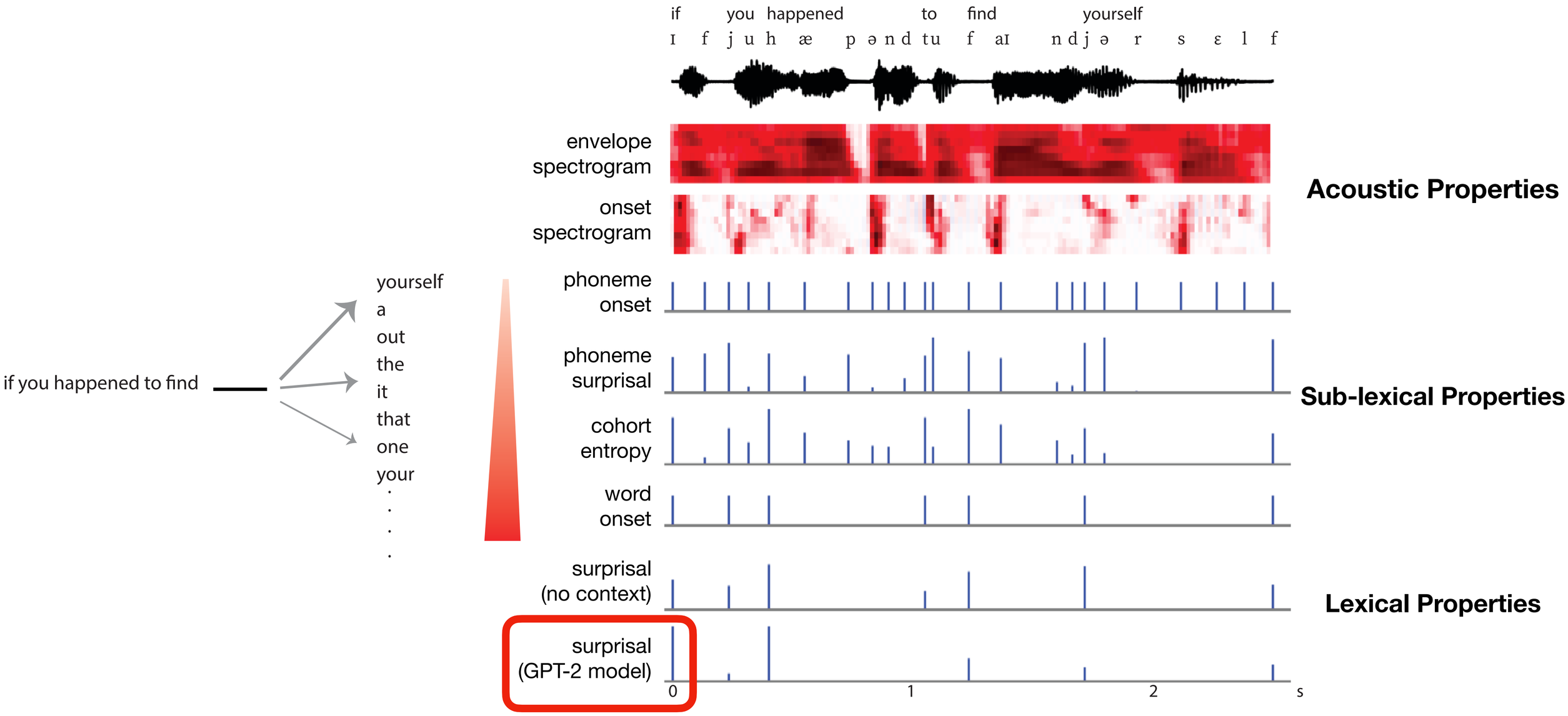
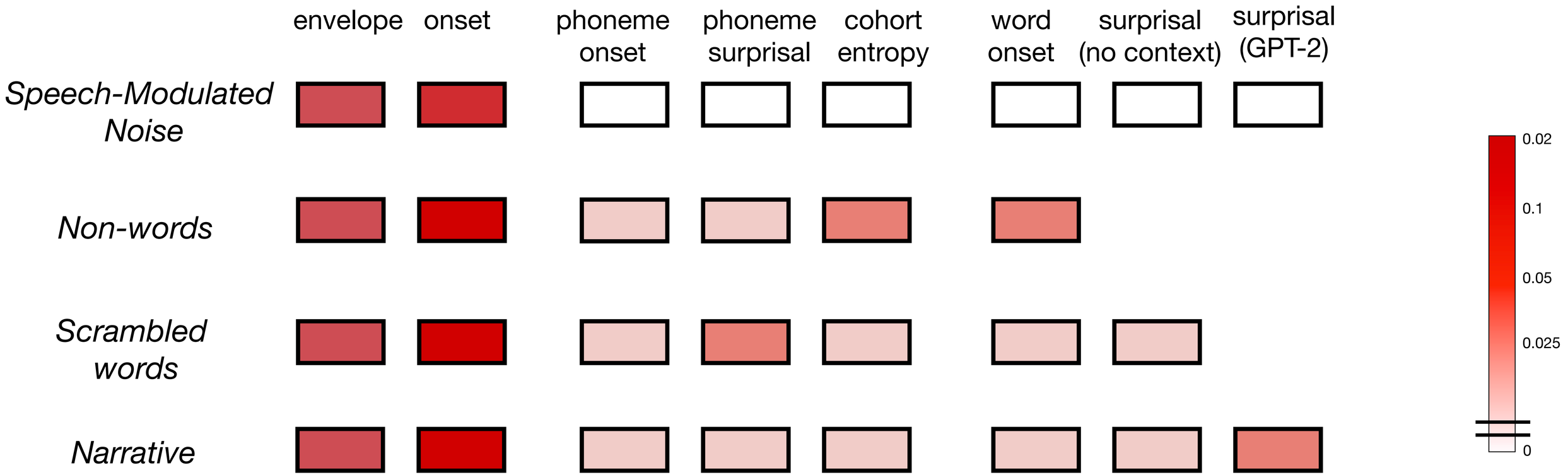


Neural Prediction Results

Emergence of neural features as the incremental processing occur



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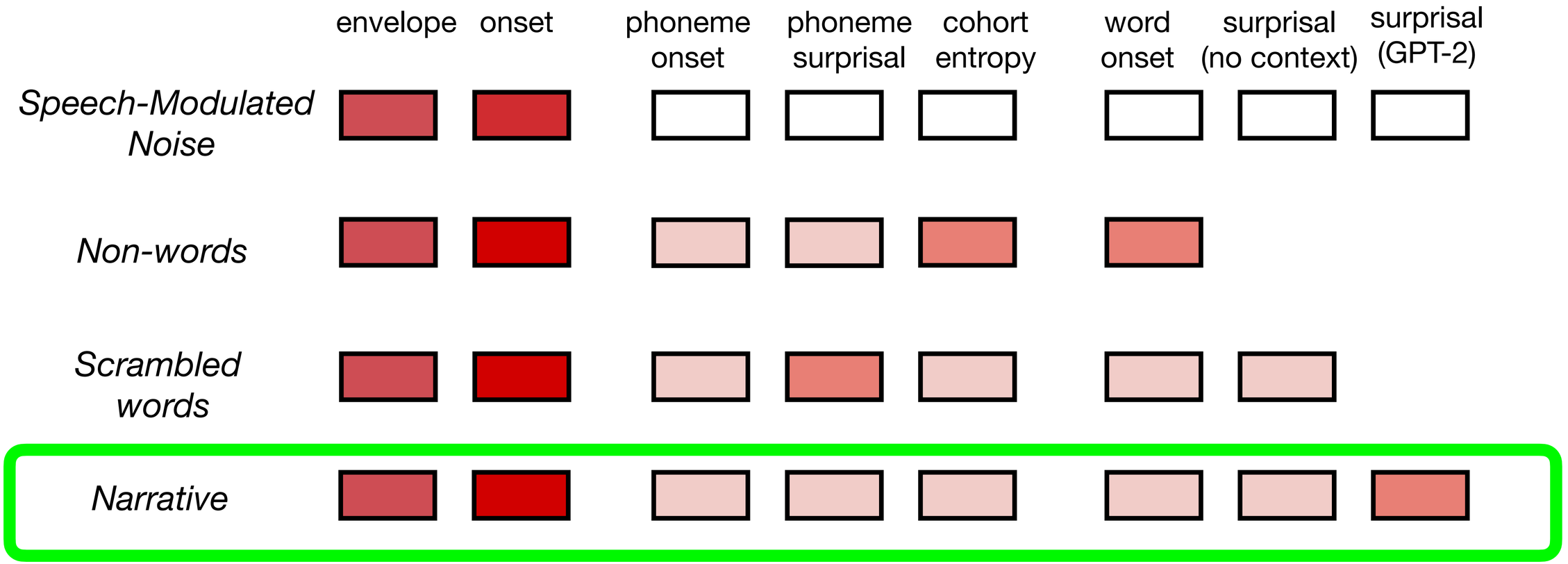

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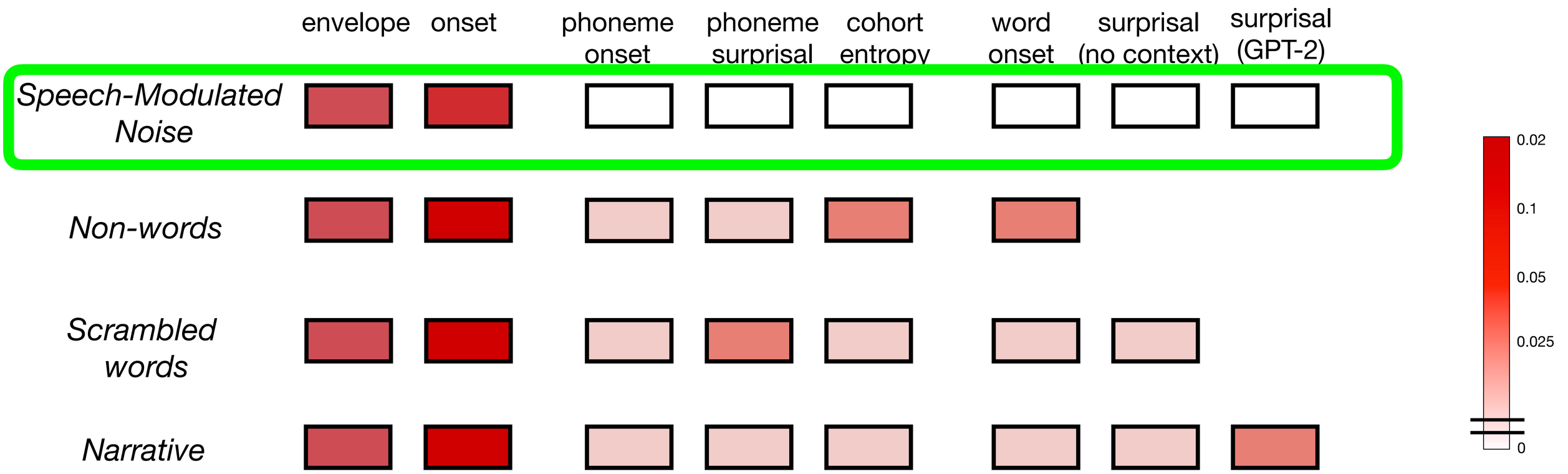

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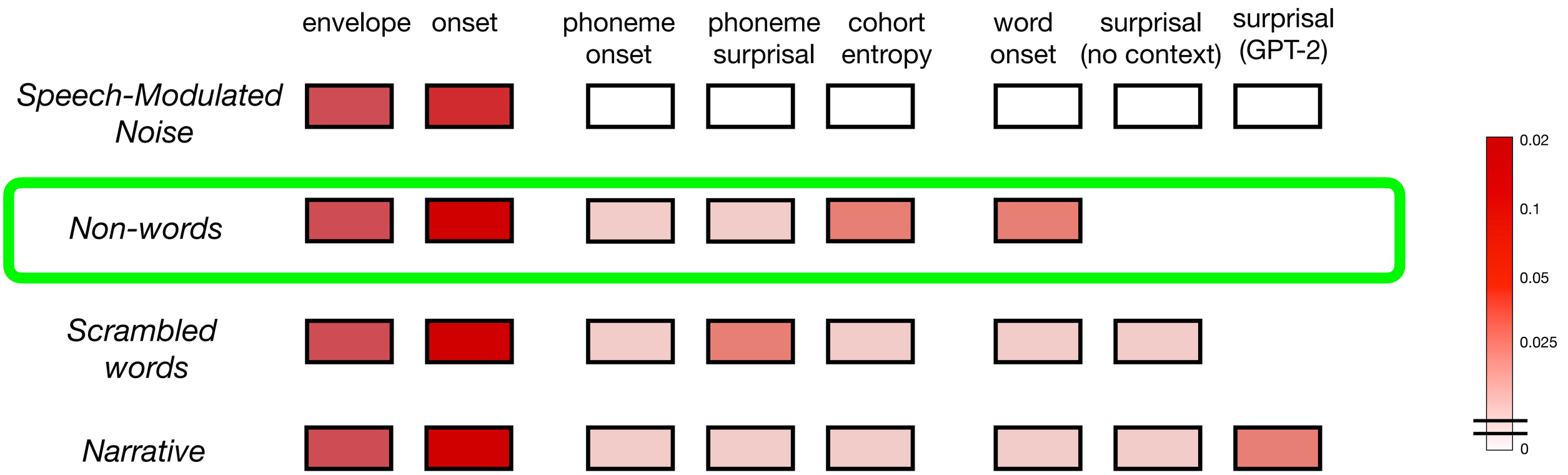

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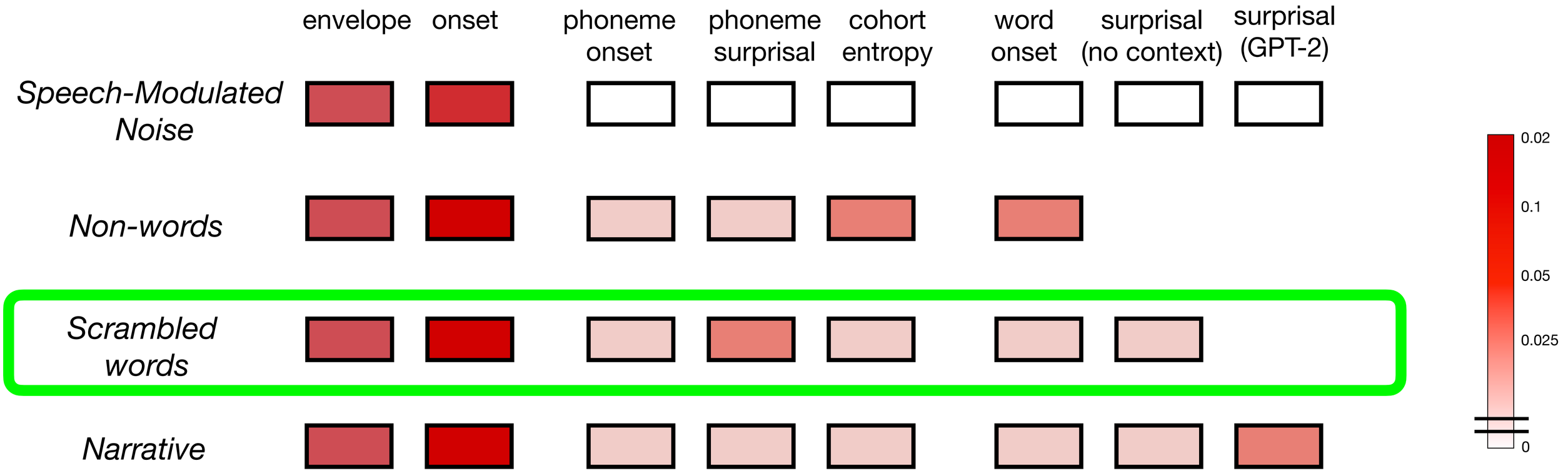

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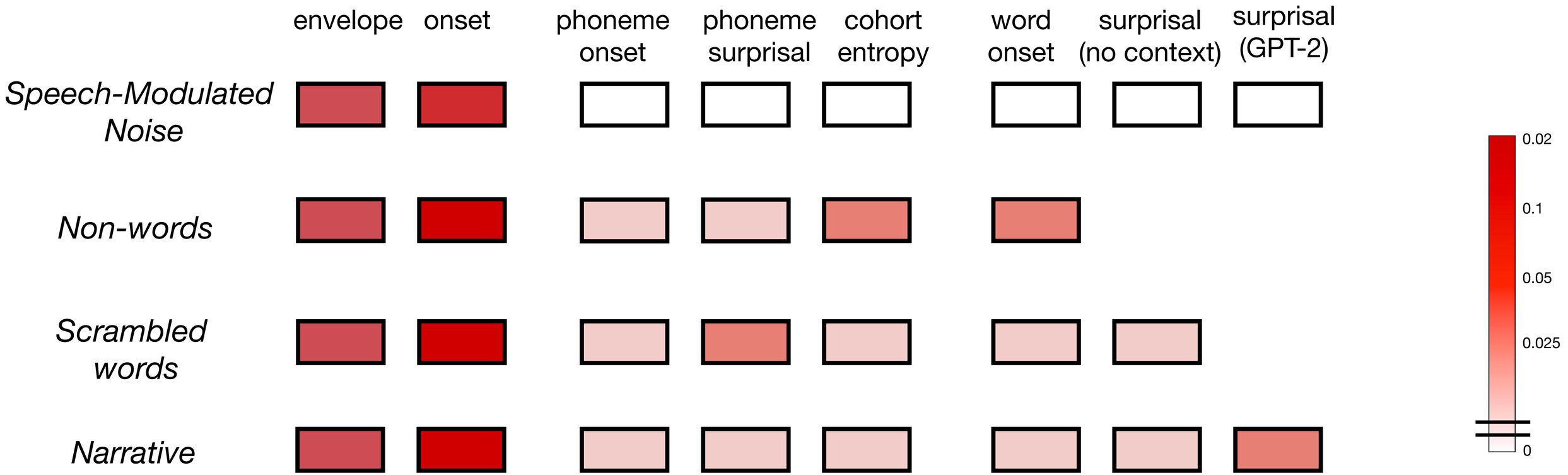

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Hemispheric Lateralization Results

right lateralized

bilateral

left lateralized

onset spectrogram

envelope spectrogram

phoneme onset

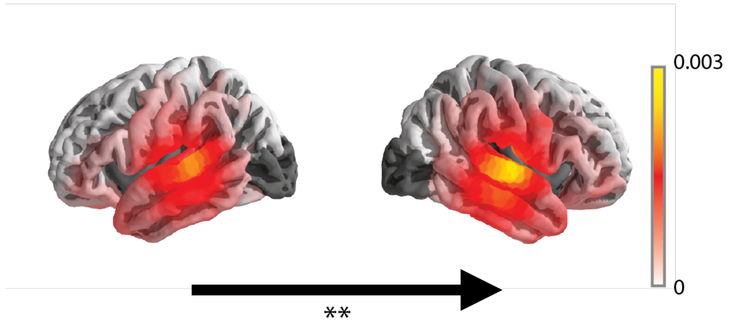
phoneme surprisal

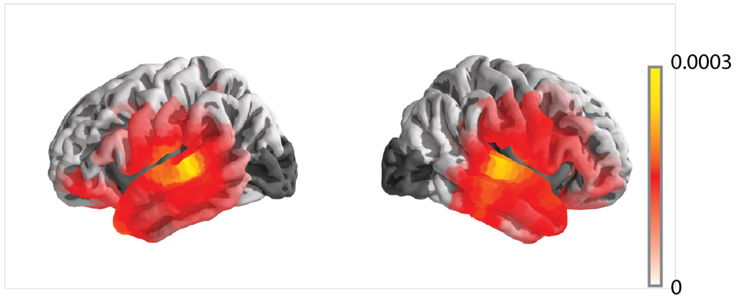
cohort entropy

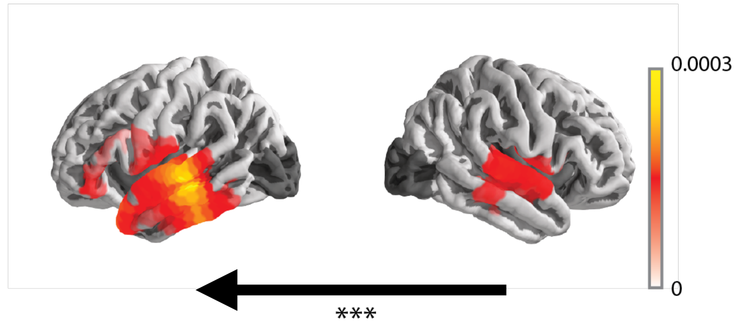
word onset

surprisal (no context)

surprisal (GPT-2 model)



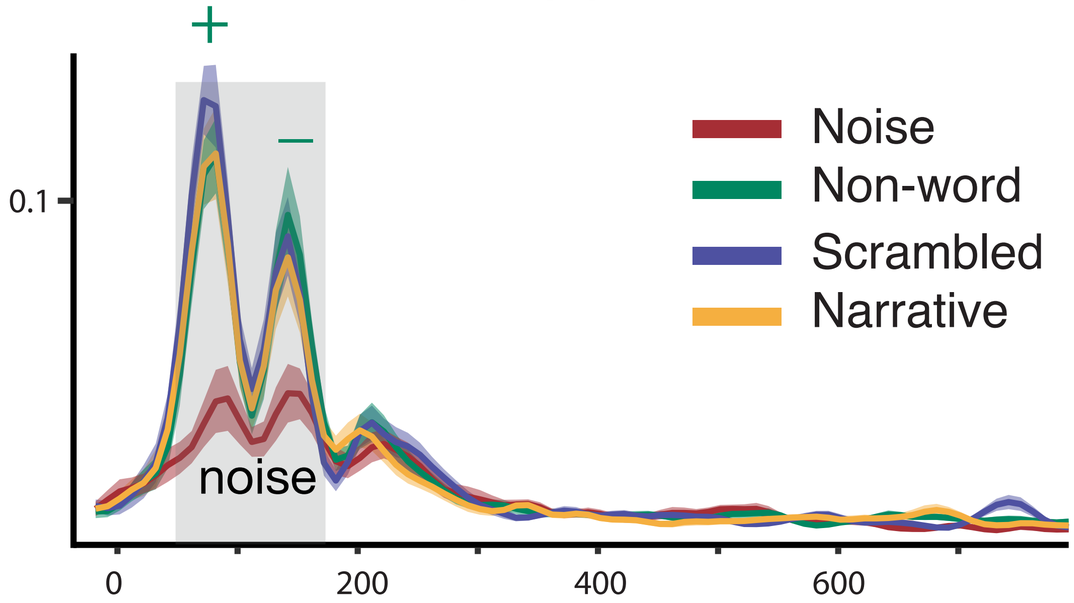




Note: lateralization may be task dependent!

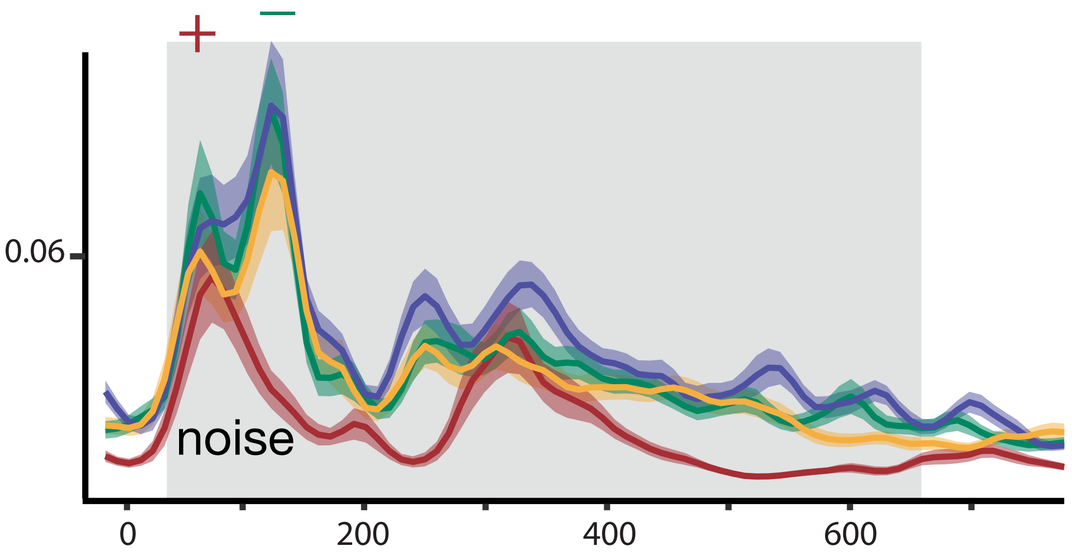
Acoustic TRF Results

onset



- Noise < all speech
  (all speech roughly equal)

envelope



- Noise < all speech
  (narrative < other speech)
- Noise lacks 2nd peak
- Similar results for left hemisphere
  (2nd peak smaller)

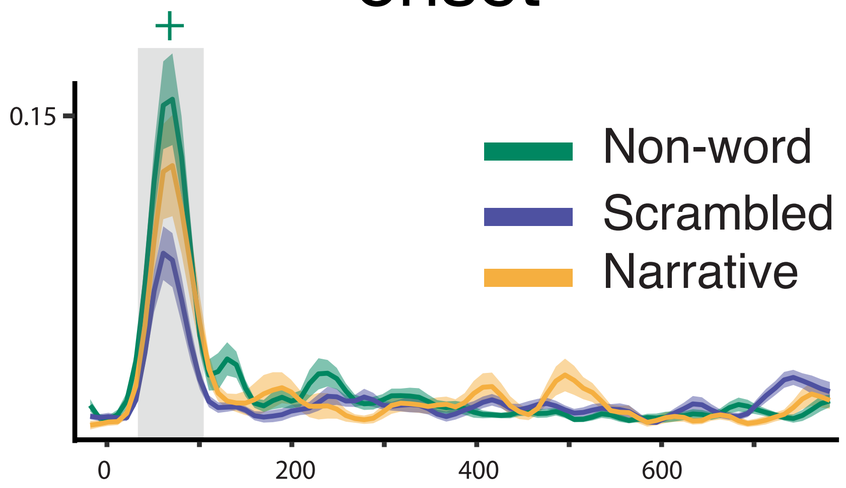
60 ms: dominantly acoustic

120 ms: acoustic + attention-dependent

right hemisphere shown
(left similar, but 2nd peak smaller)

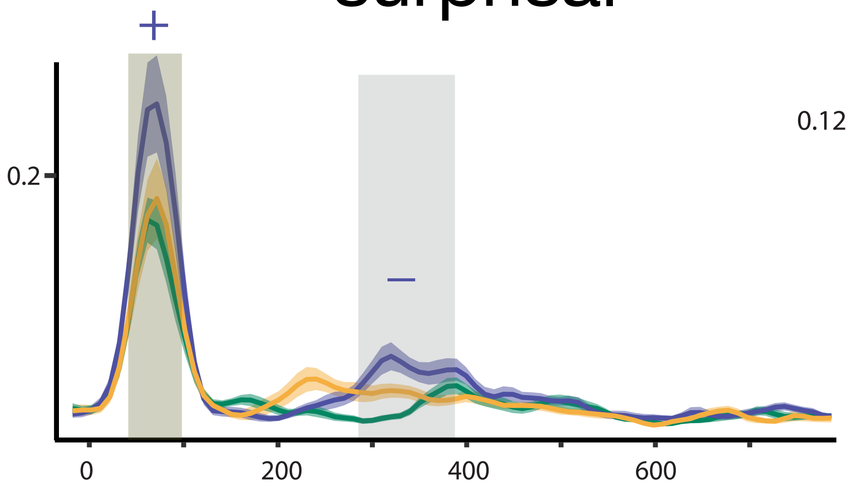
Phonemic TRF Results

phoneme onset



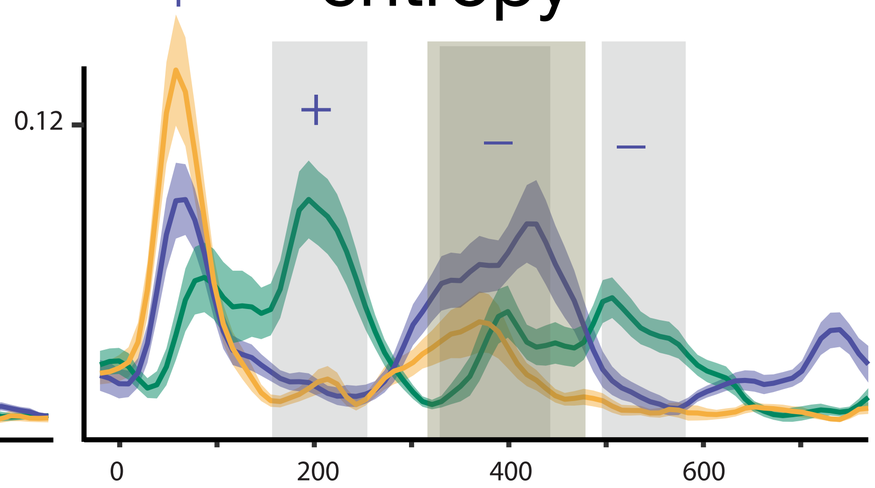
- Non-words > words
- No later processing

phoneme surprisal



- Enhanced early processing (scrambled > narrative, ~80 ms)
- Late processing (words > non-words, ~350 ms)

cohort entropy



- N400-like response (reduced for narrative)
- Additional/delayed peaks in non-words (difference in stimulus distributions)

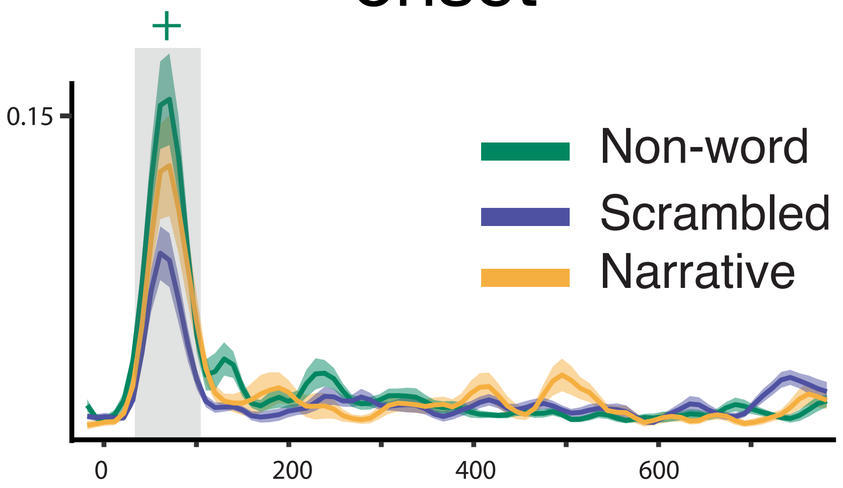
80 ms: simple phoneme processing

350 ms: additional further processing

left hemisphere shown (right similar)

Phonemic TRF Results

phoneme onset



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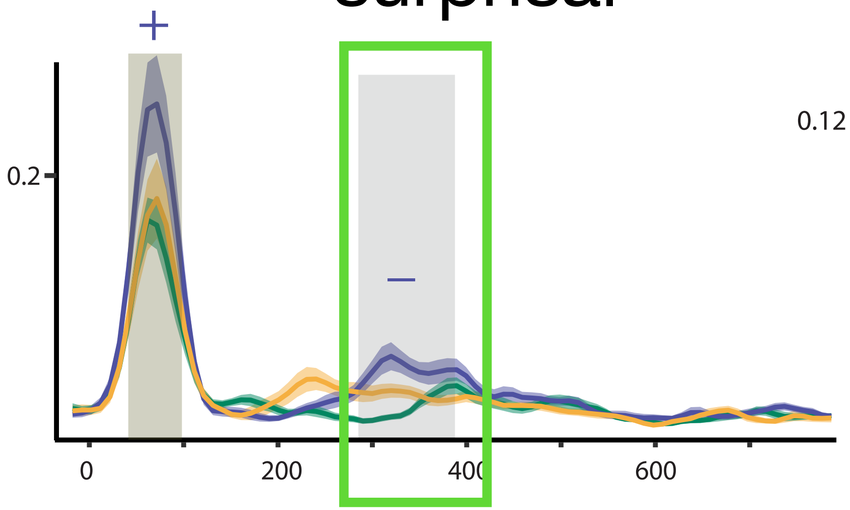

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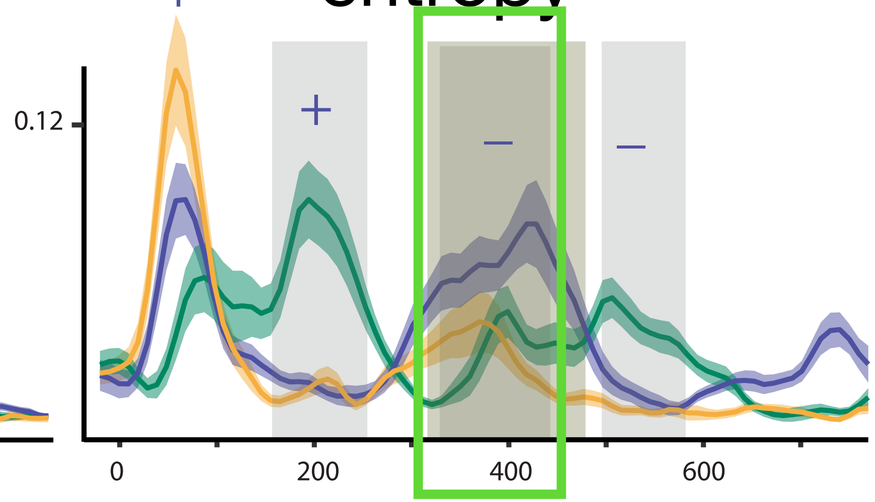

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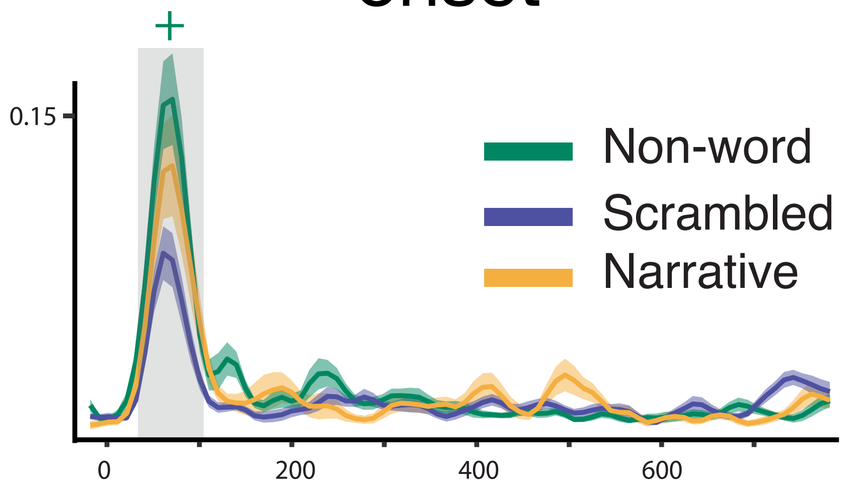
Phonemic TRF Results

phoneme onset



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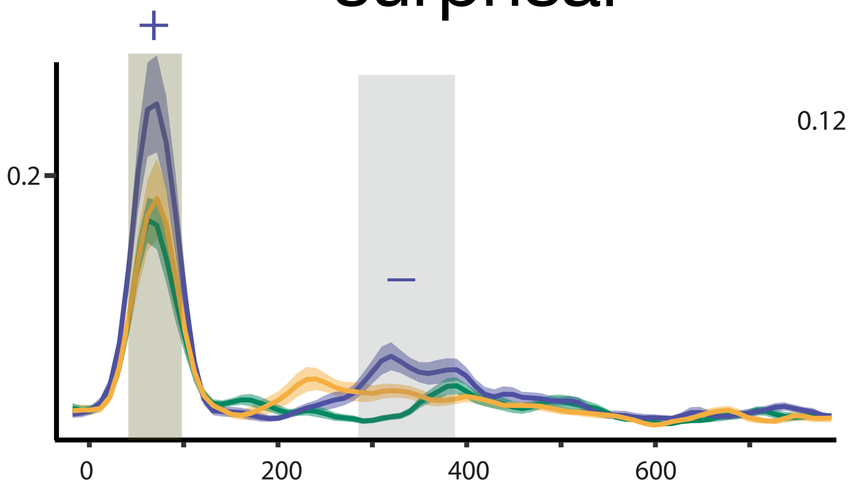

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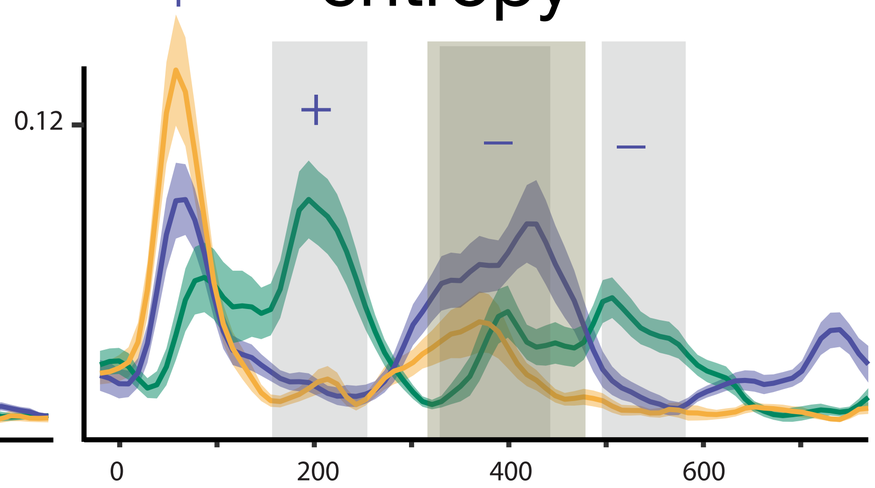

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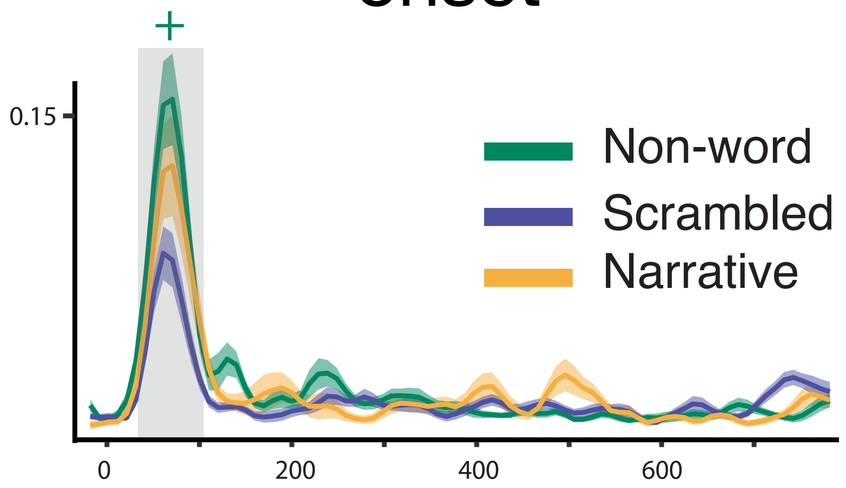

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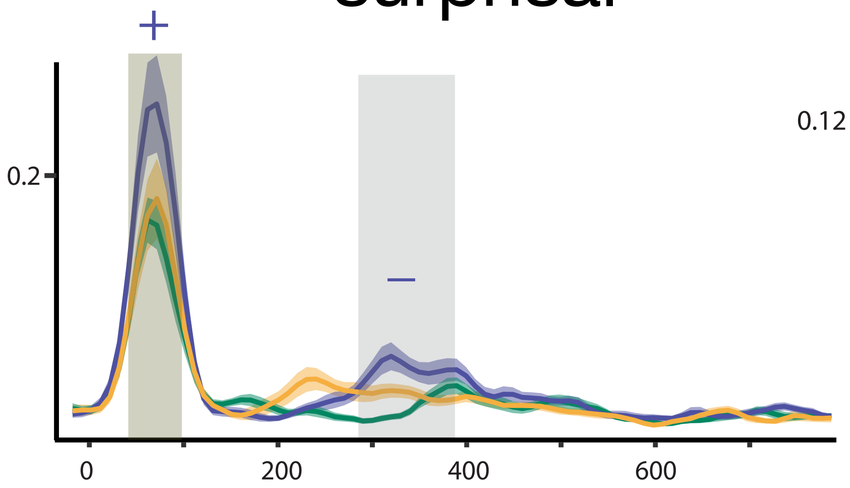

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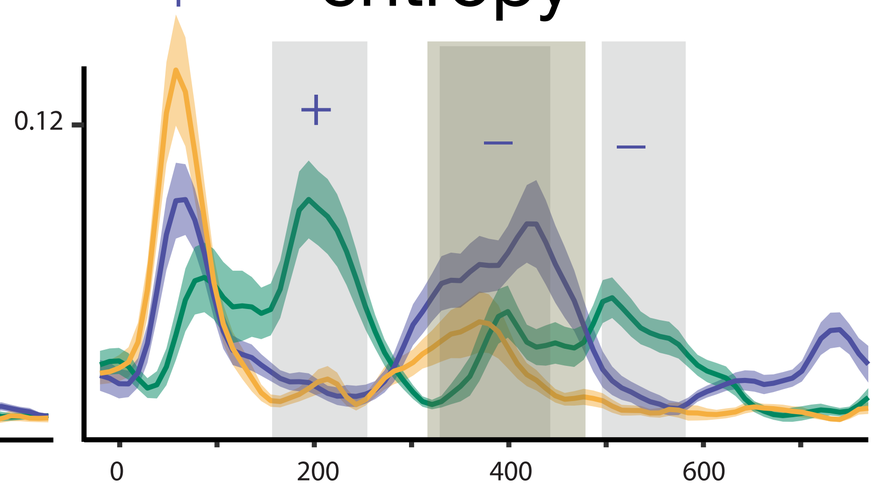

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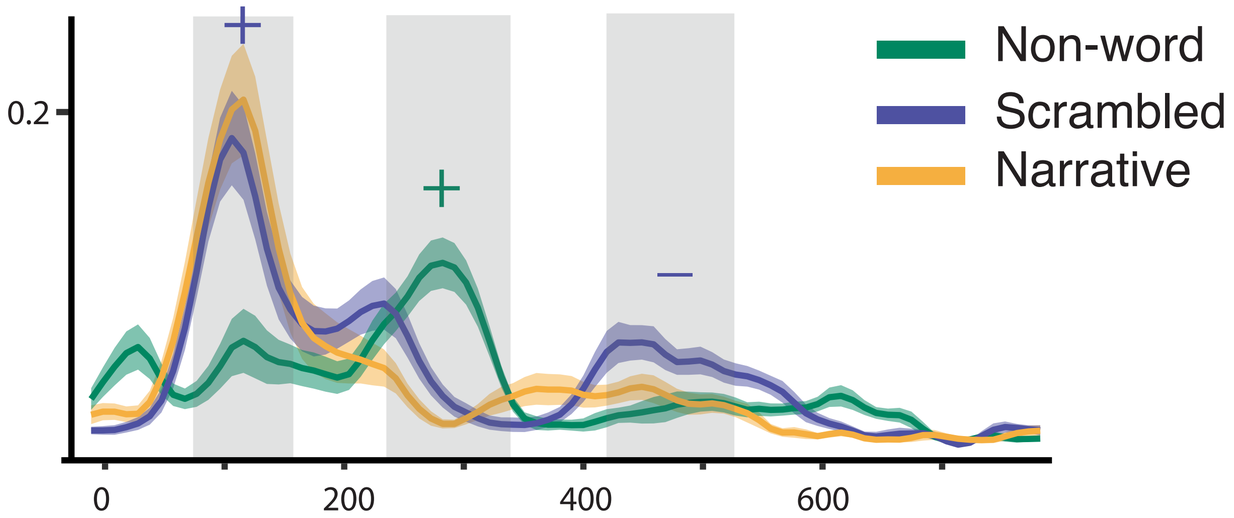
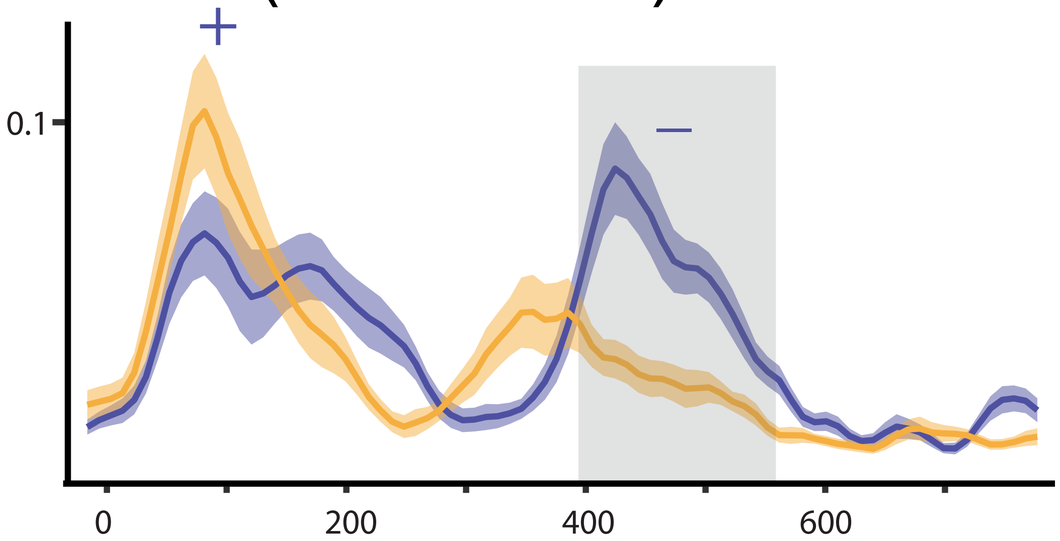
Word-based TRF Results

word onset



- Scrambled ≈ narrative for rapid processing
- Different neural mechanisms for non-words

surprisal (no context)



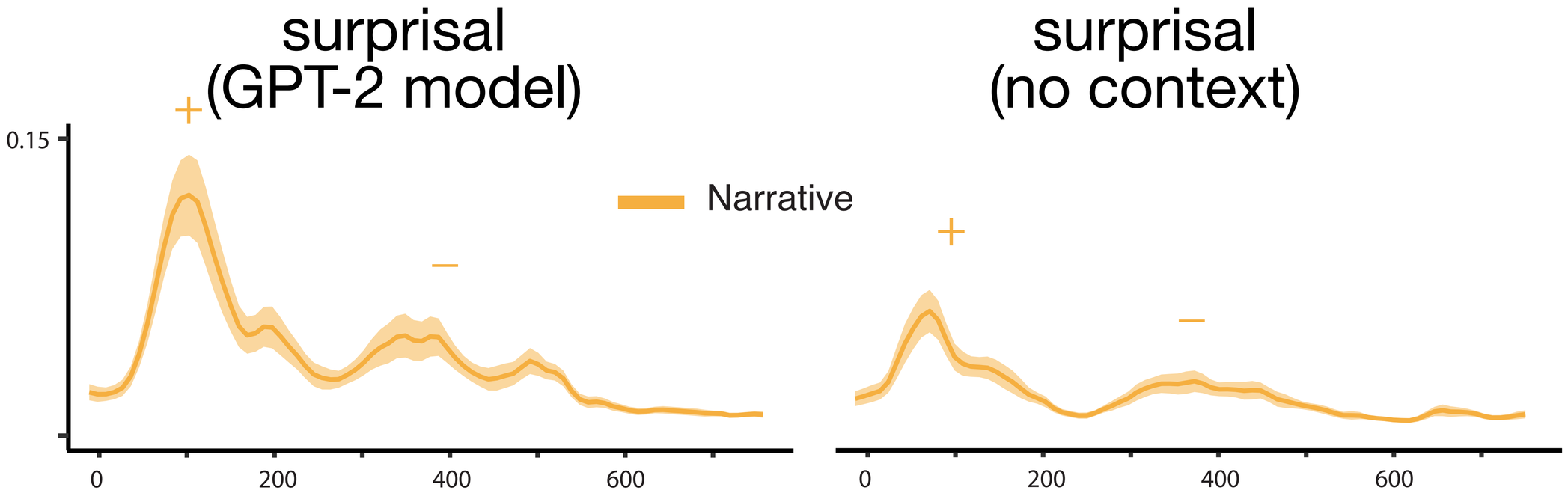
- N400 like response
- Reduction in surprisal due when context

100 ms: simple word processing

450 ms: “error” correction processing

left hemisphere shown
(right much weaker except for non-word onset)

Contextual Word Surprisal Results

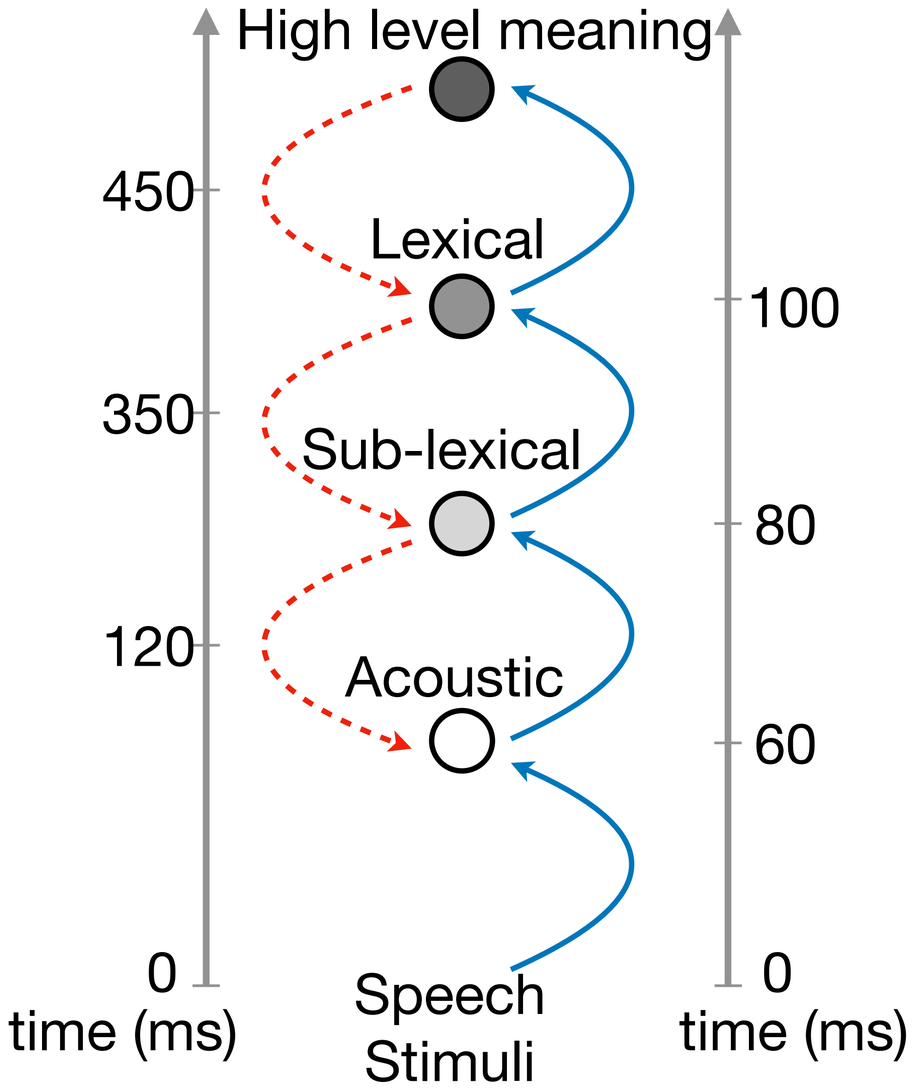


- N400 like response in both predictors
- When context helps, context-based surprisal is better tracked than raw surprisal

left hemisphere shown
(right much weaker)

Neural Speech Processing Progression

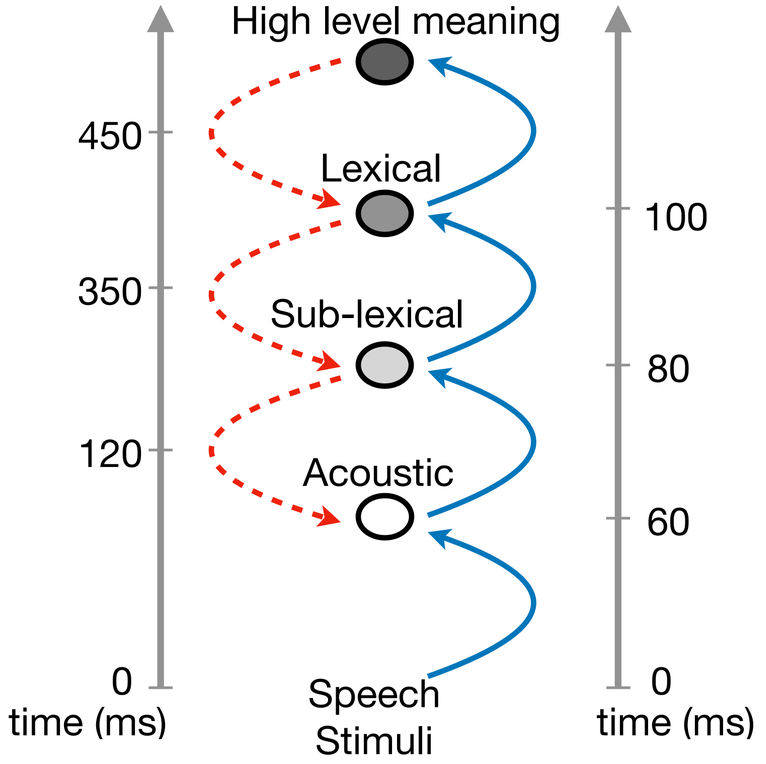
- Cortical response time-locks to emergent features from acoustics to context as incremental steps in the processing of speech input occur
- Linguistic features are processed when the linguistic boundaries are intelligible
- Higher level processing / top-down mechanisms affect the lower level speech processing
- Lower-level acoustic feature responses are right lateralized whereas, context based responses are left lateralized



Summary

*temporal **neural** patterns* $\leftrightarrows$ *temporal patterns in **speech acoustics***
*temporal patterns in **speech perception***
*temporal patterns in **language perception***
*temporal patterns in **understanding***

- *Continuous speech* allows acquiring entire hierarchy from same stimulus
- Using *simultaneous TRFs* allows segregation of multiple neural processes at different levels
- Progression, in both *feature level and timing*, including both *bottom-up & top-down processing*



thank you

These slides
available at:
ter.ps/simonpubs

http://www.isr.umd.edu/Labs/CSSL/simonlab