The Progression of Neural Speech Representations Through Auditory Cortex and Beyond, from Acoustics to Language to Semantics

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University of Maryland 1856

Outline

- Introduction—Cortical representations of continuous speech
- *Early & fast* cortical representation of continuous speech
- *Progression* of representations of continuous speech through cortex (bottom-up and top-down)
- Objective measures of speech *intelligibility*

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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

<u>Cortical Representations</u> 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

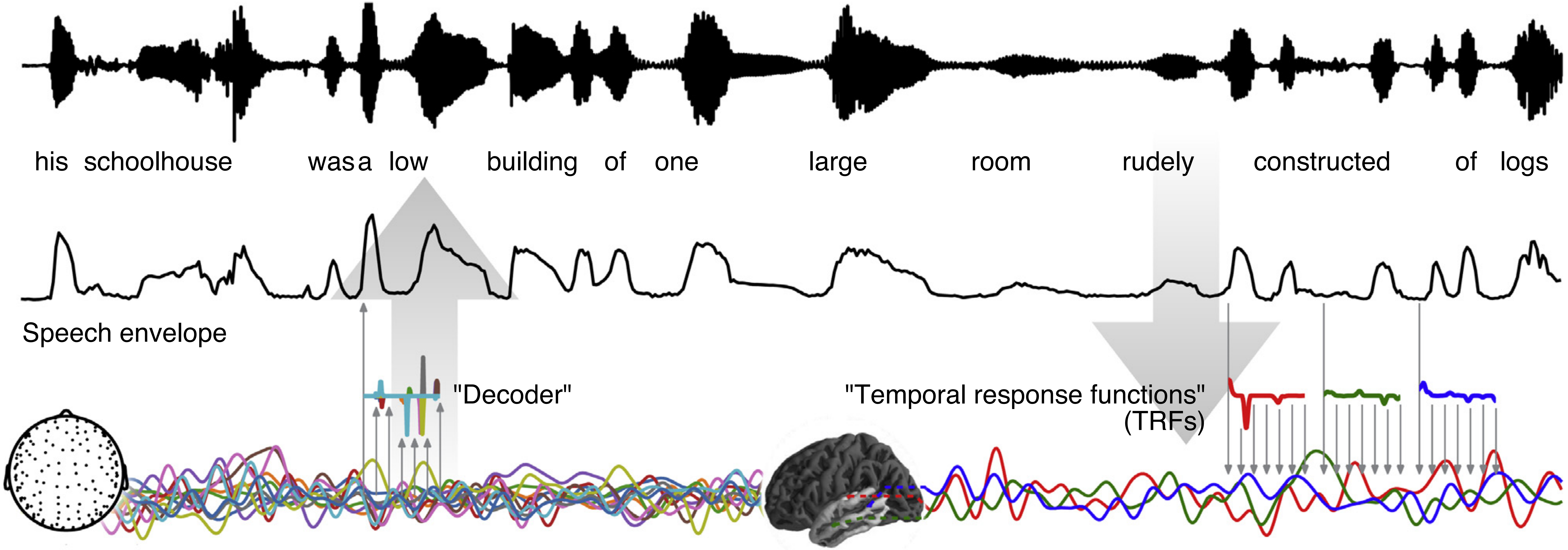
Neural Representations of Speech

- oscillations at pitch frequencies (primarily subcortical) — Maddox & Lee (2018) eNeuro
  - acoustic onset tracking — Daube et al. (2019) Curr Biol
    - speech envelope rhythmic following — Lalor & Foxe (2010) Eur J Neurosci
      - phoneme-based responses — Teoh et al. (2022) J Neurosci
        - phoneme-context-based responses — Brodbeck et al. (2018) Curr Biol
          - word-context-based responses — Brodbeck et al. (2022) eLife
            - semantic structure rhythm following — Ding et al. (2016) Nat Neuro
- plus connections to **intelligibility/perception/behavior**

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

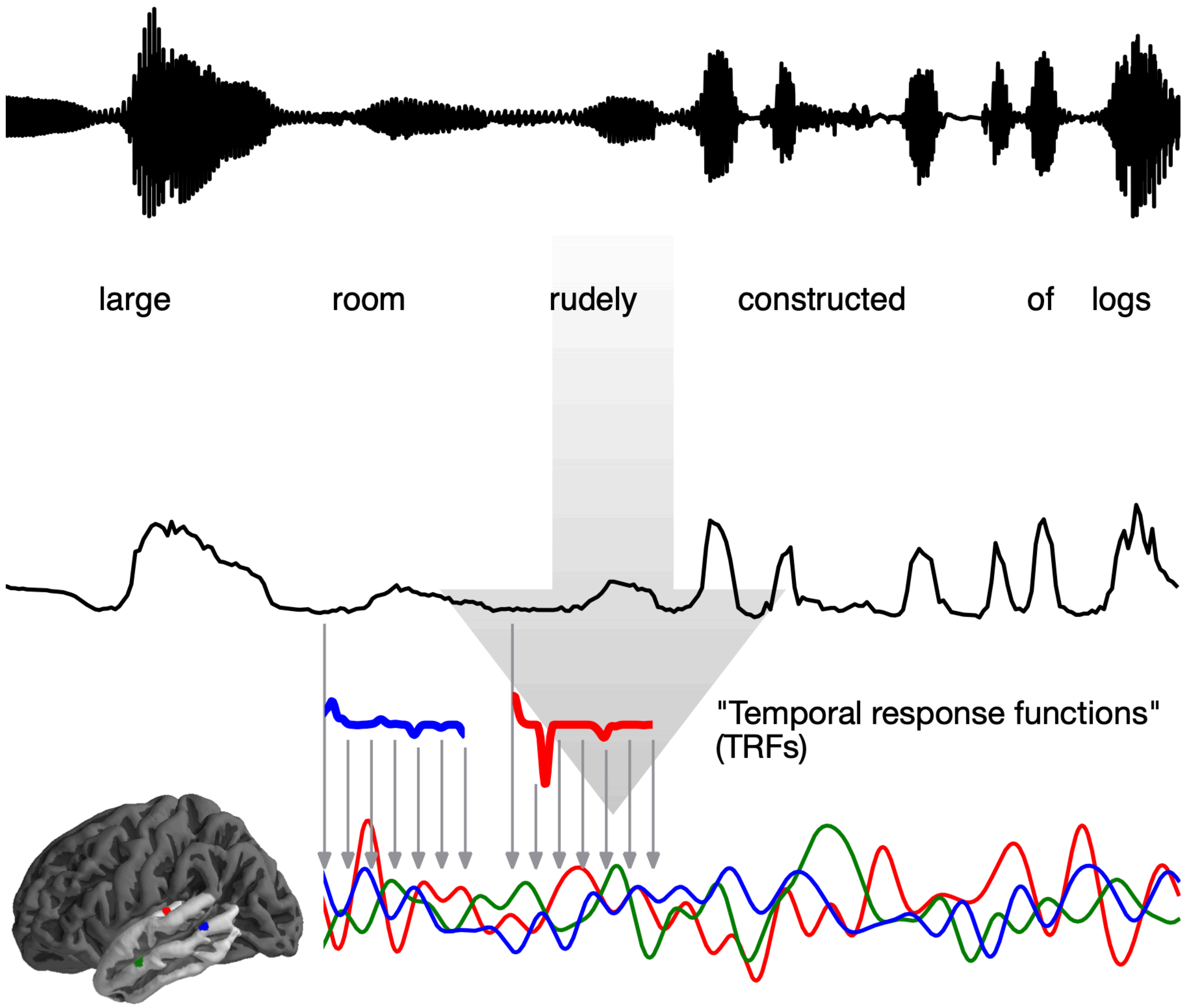
Cortical Representations of Continuous Speech

- 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



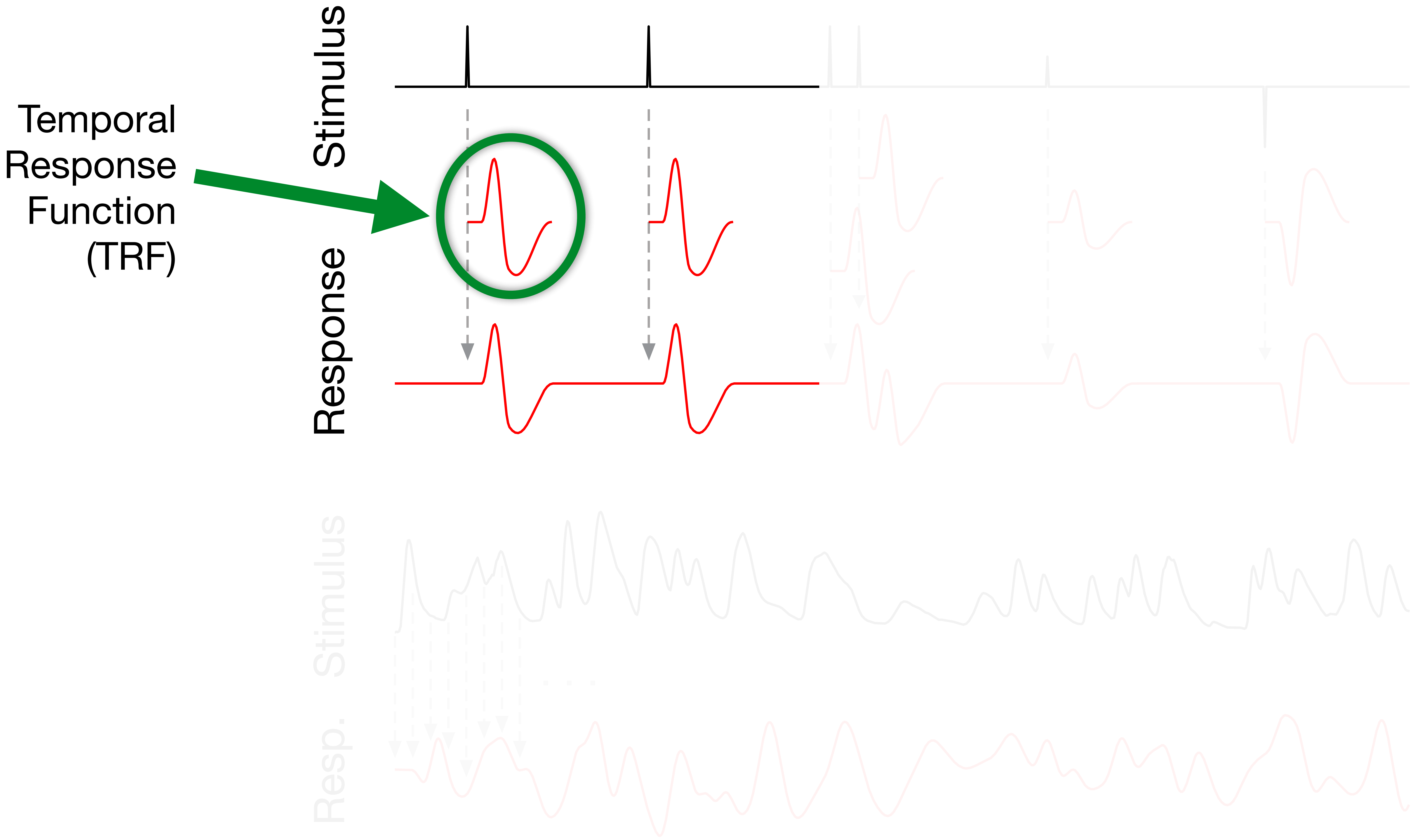
Cortical Representations: Encoding

- 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

Temporal Response Functions



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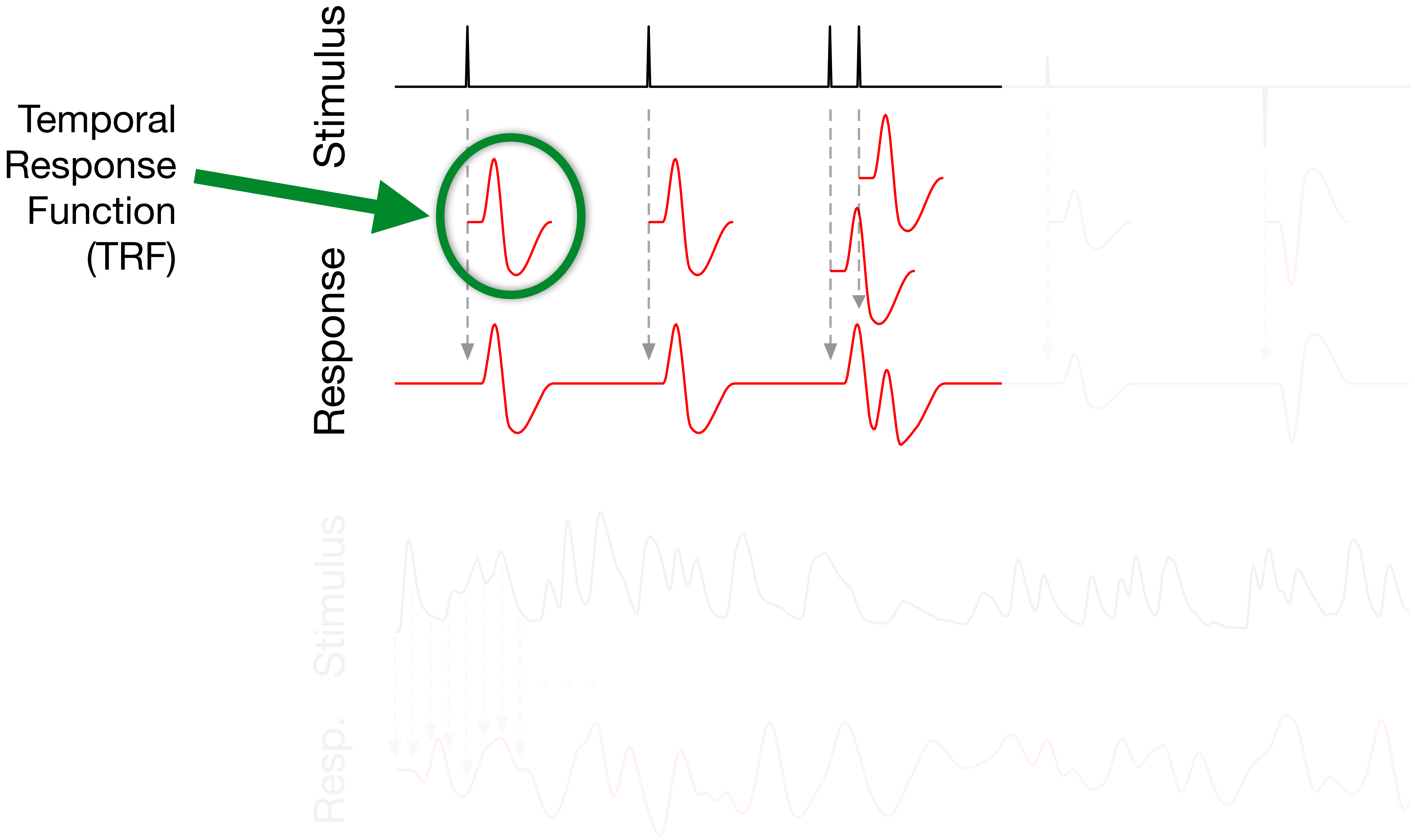

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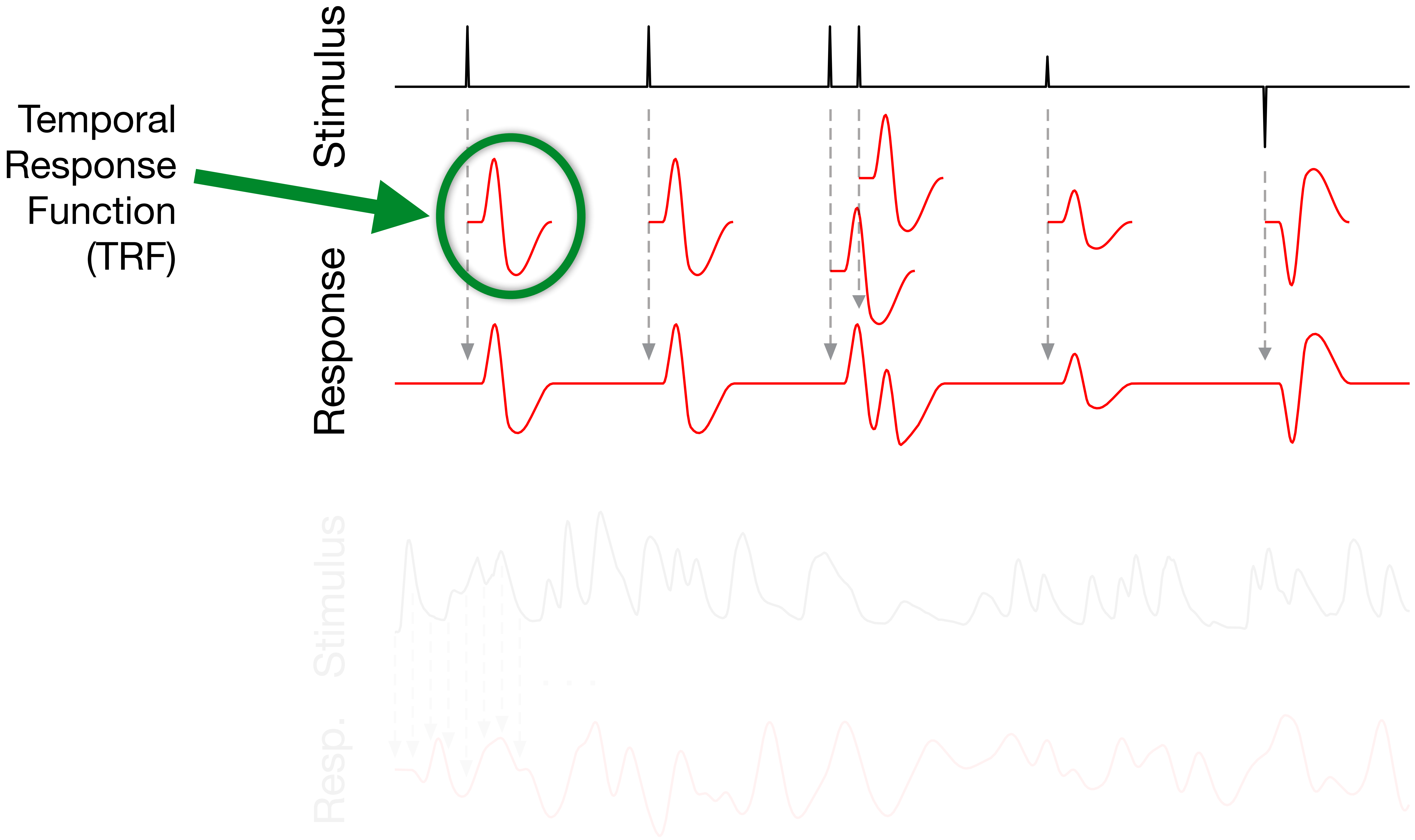

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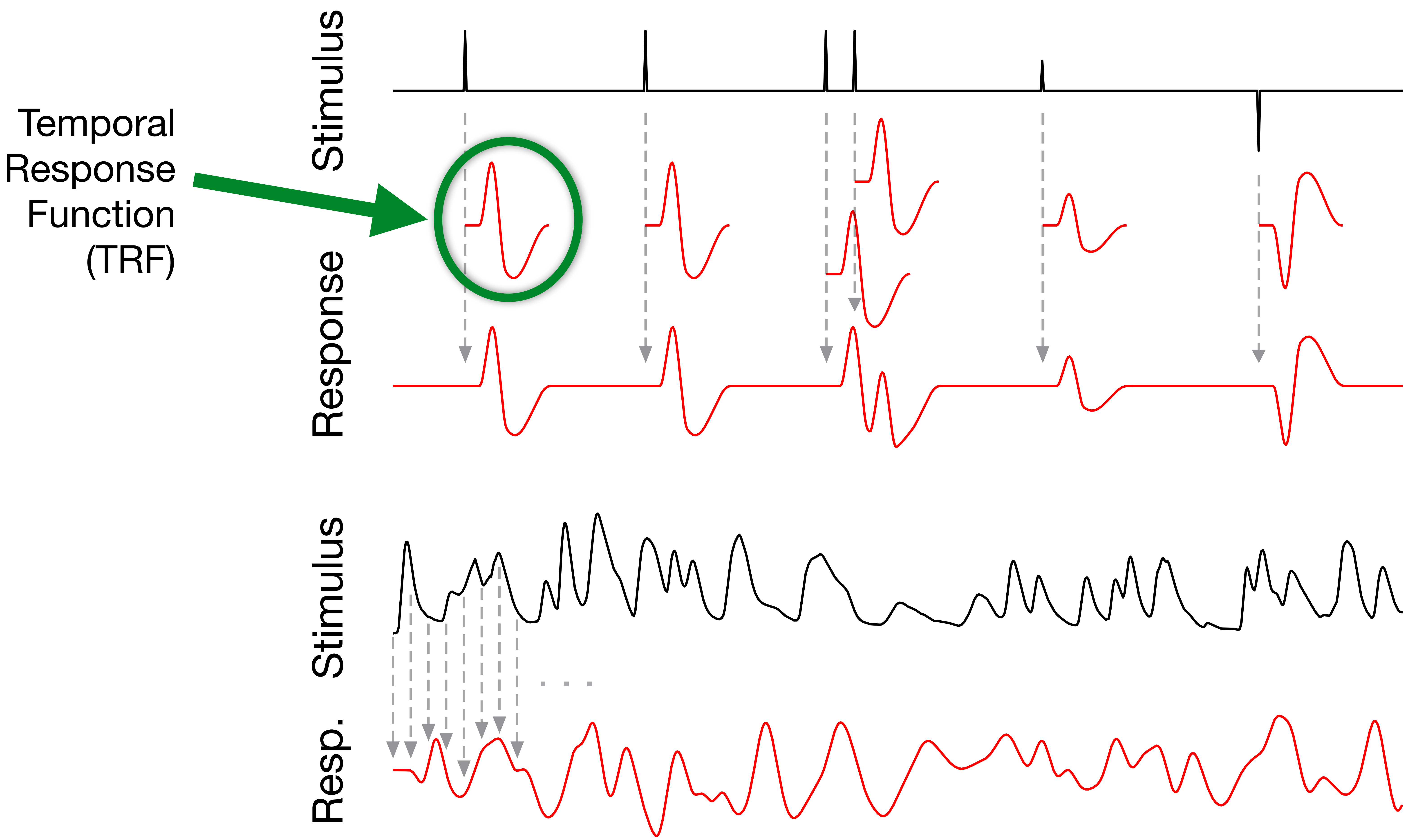
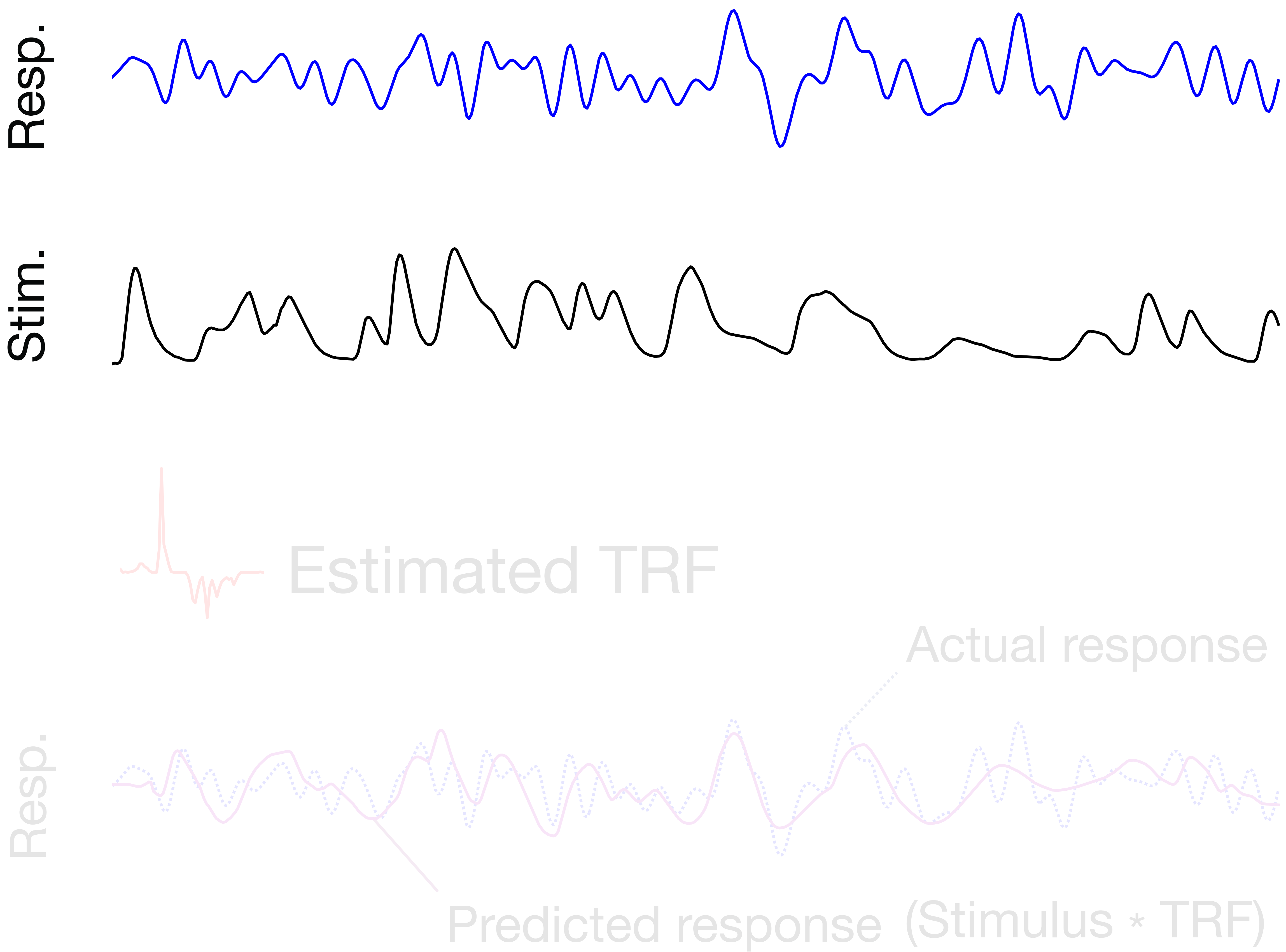


TRF Model Estimation & Fit

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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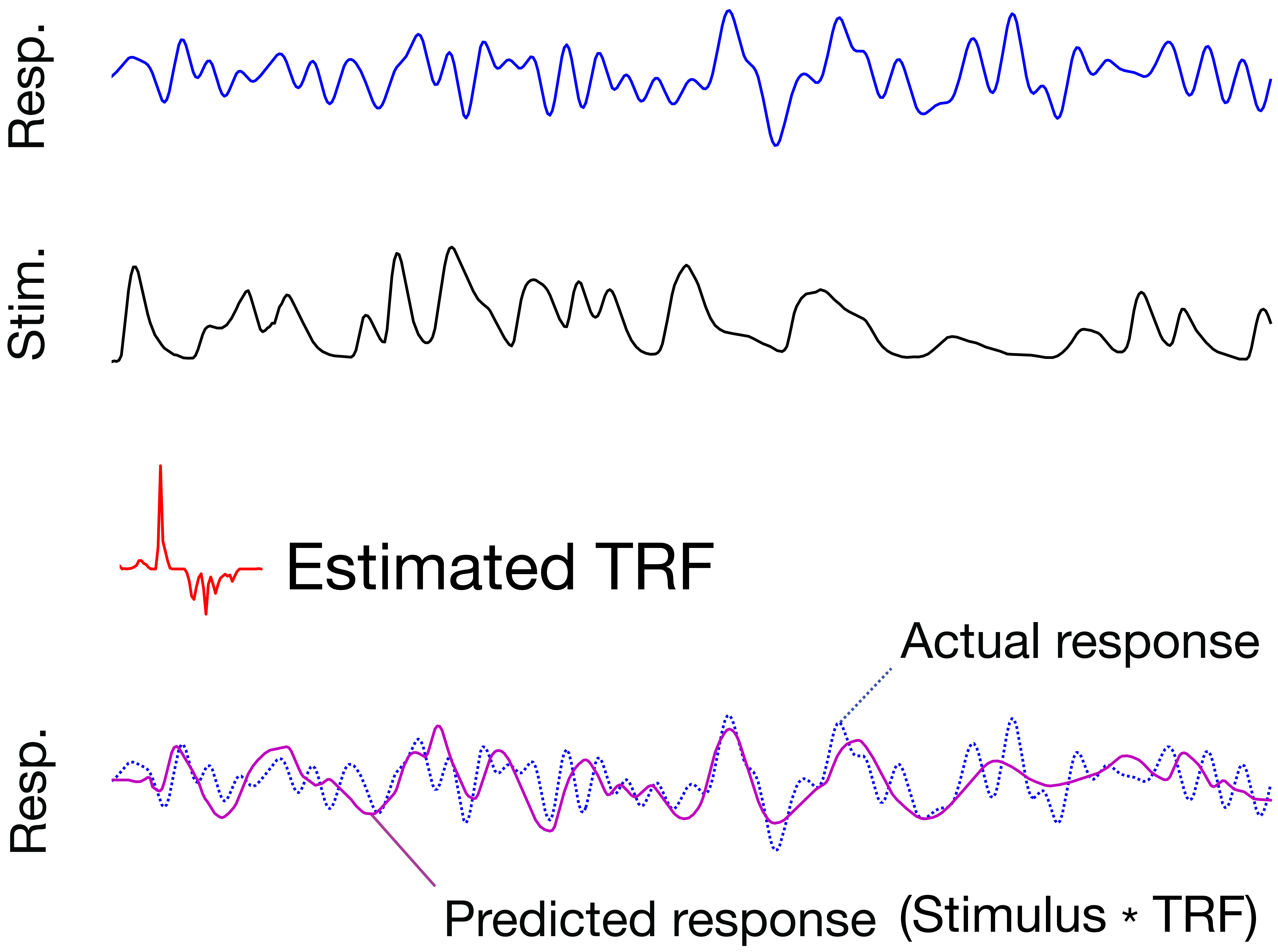


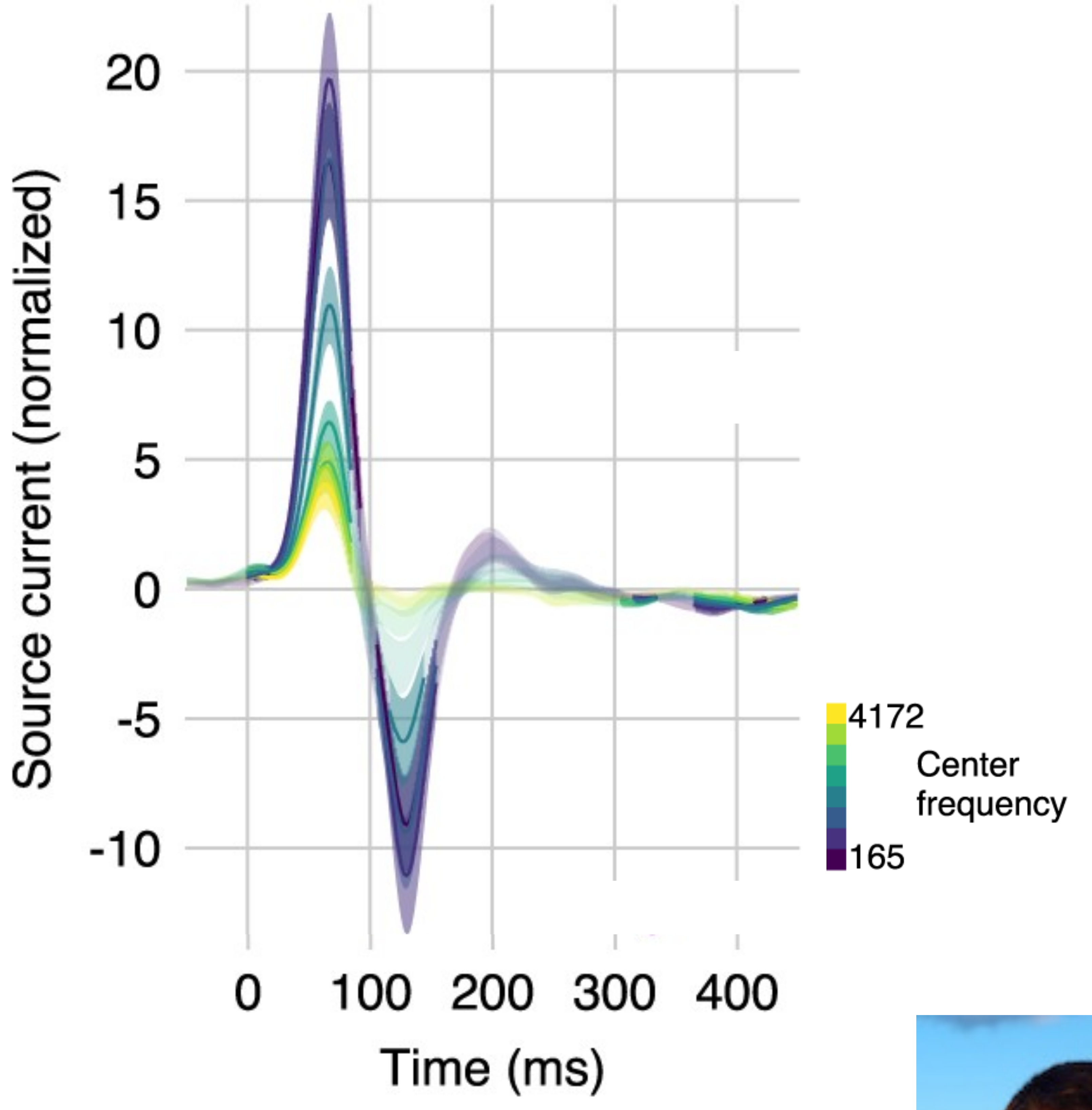
Lalor & Foxe (2010) *Neural Responses to Uninterrupted Natural Speech* … Eur J Neurosci
Ding & Simon (2012) *Neural Coding of Continuous Speech in Auditory Cortex* … , J Neurophys

Example: Representation of Speech Envelope

- TRF interpretable a la evoked response
  - Has M50 (~"P1") & M100 (~"N1") peaks, but from instantaneous speech envelope
  - early peak localizes to primary auditory areas (HG)
  - later peak localizes to associative areas (PT)
  - caveat: actually from envelope *onset*

- This is from a single talker, clean speech
  - simple but limiting
  - what about noise? other speakers? attention?
  - can the speech representation be cleaned?

Temporal Response Fields



Brodbeck et al. (2020) *Neural Speech Restoration at the Cocktail Party …*, PLoS Biol

Simultaneous Temporal Response Functions

- TRFs predict neural response to speech
  - Analogous to evoked response
  - Peak amplitude ≈ processing intensity
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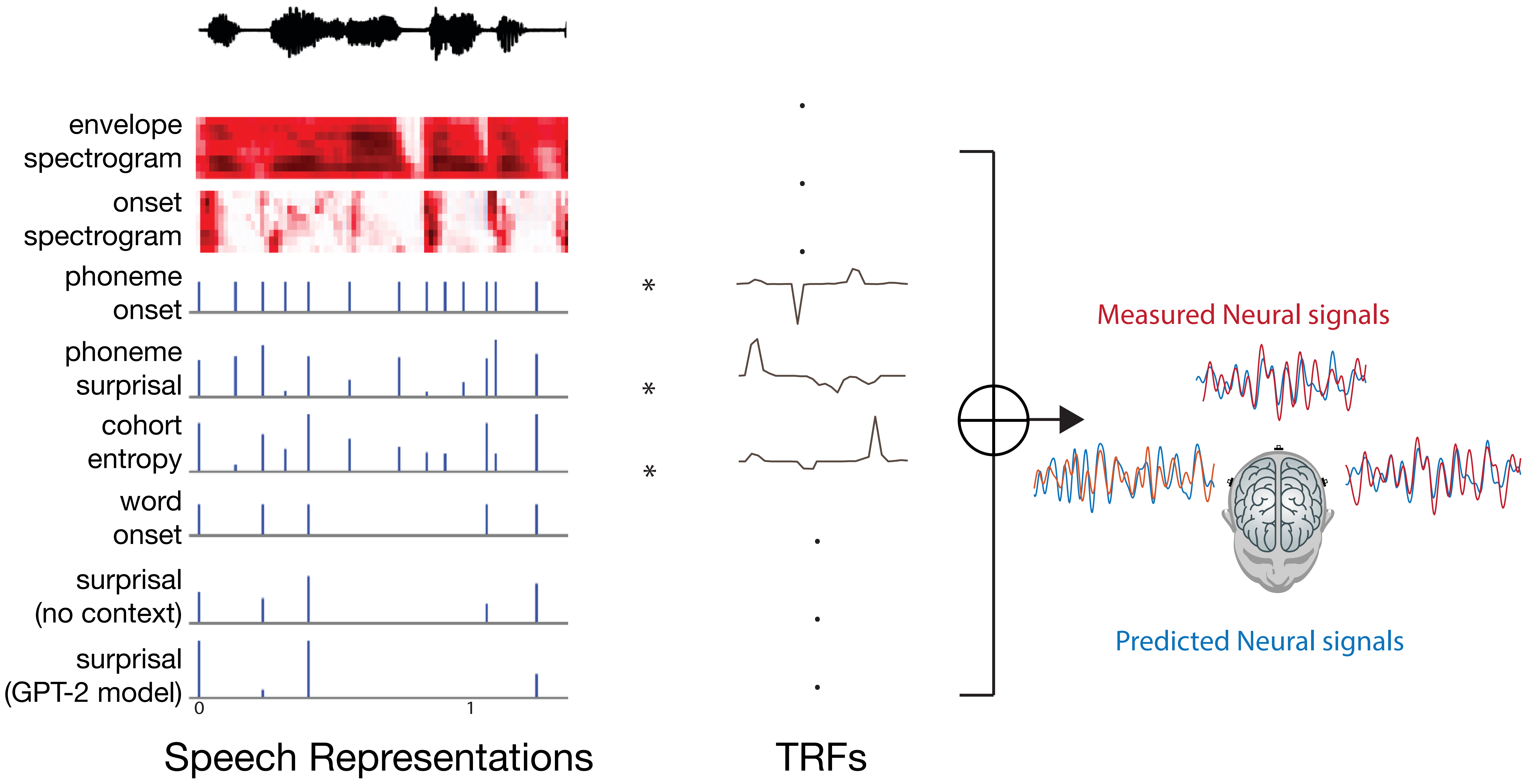

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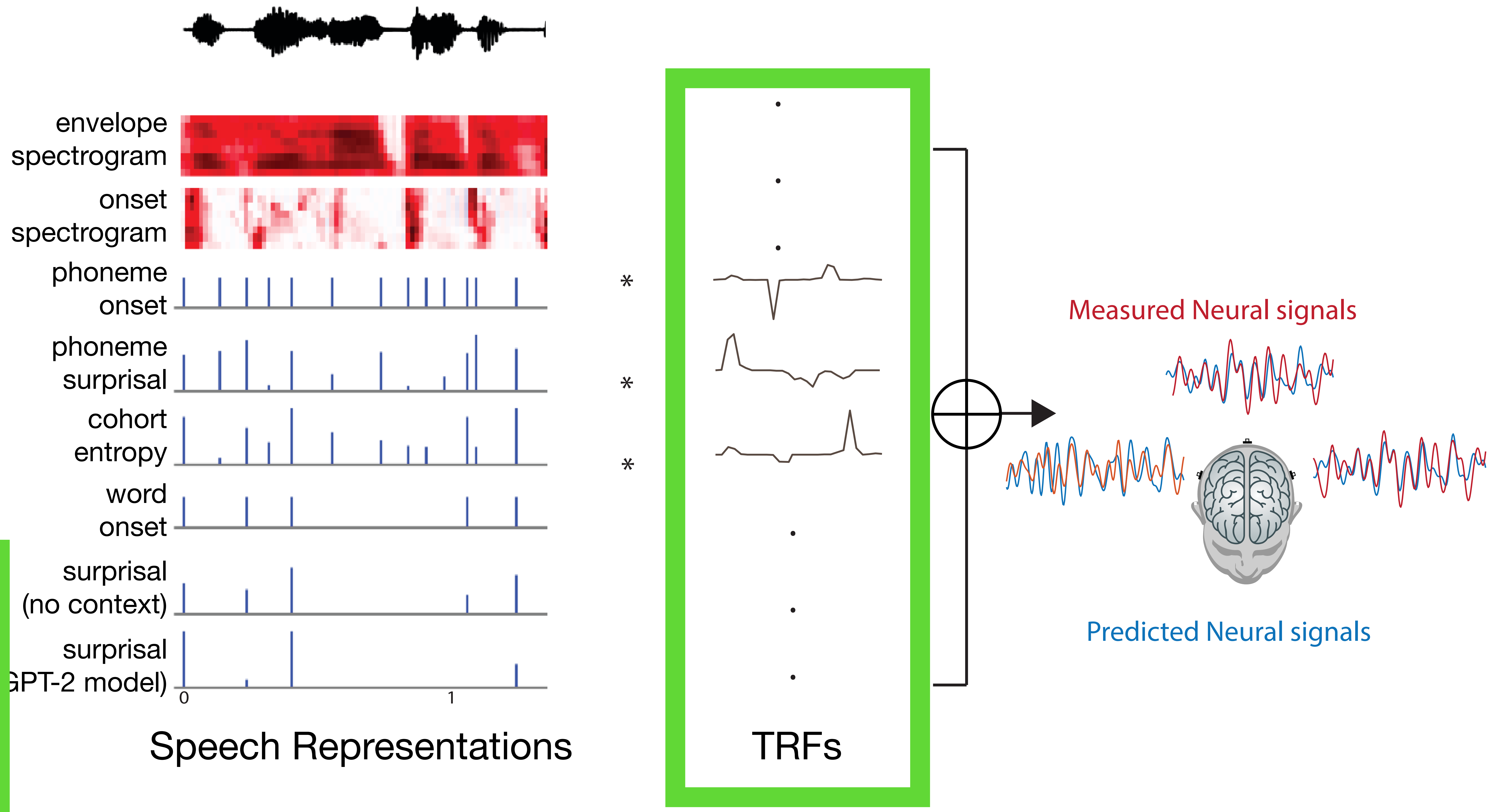
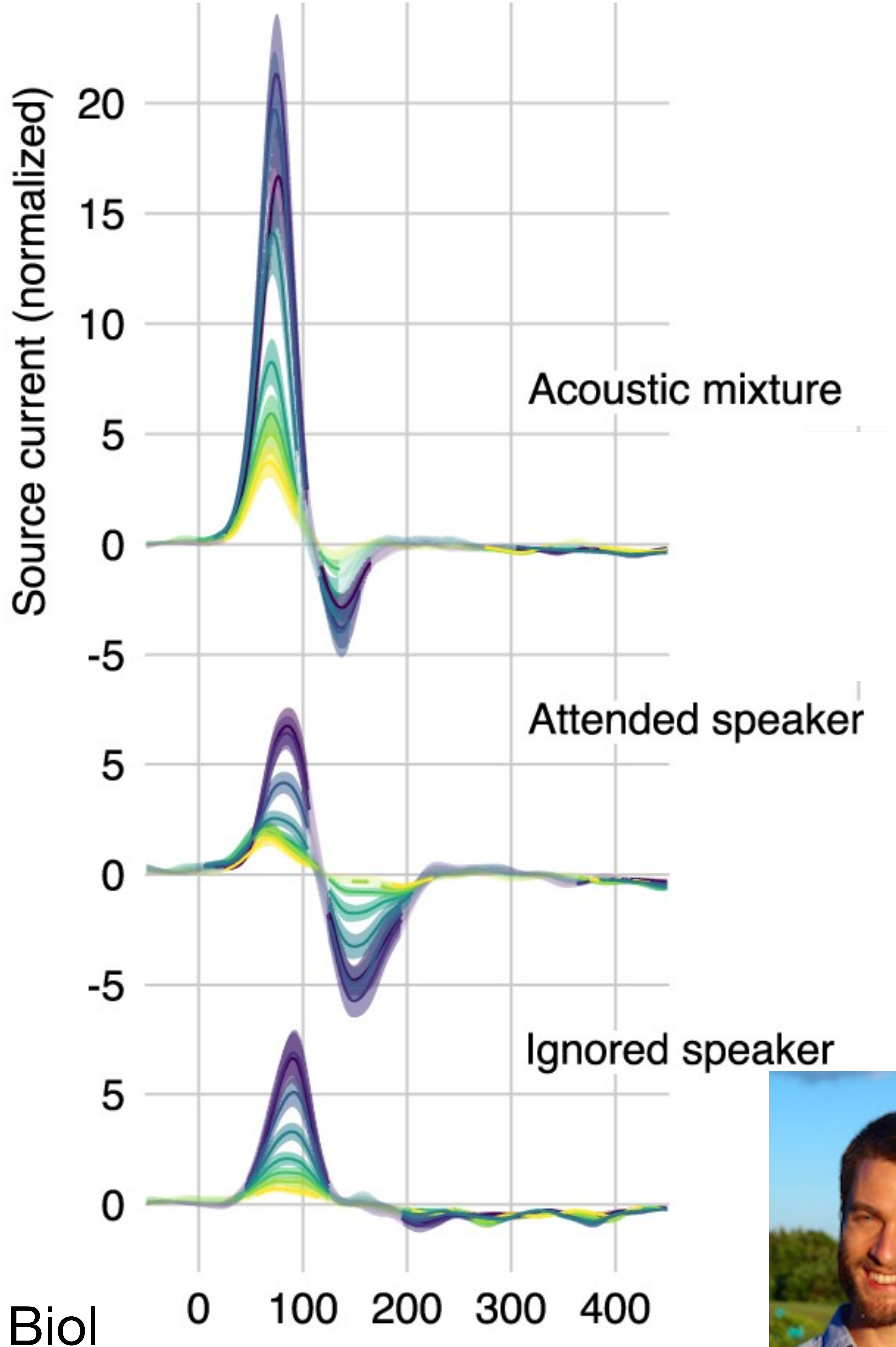


Crosse et al. (2016) *The Multivariate Temporal Response Function (mTRF) Toolbox* … , Front Hum Neurosci
Brodbeck et al. (2023) *Eelbrain: A Python Toolkit for Time-Continuous Analysis* … , eLife

Cortical Representations: Selective Attention

Two competing speakers, selectively attend to one

- more illuminating since more complex auditory scene
- need more care re: “stimulus” responsible for responses
  - acoustic mixture entering ears
  - foreground speech
  - background speech
- estimate all TRFs simultaneously
  - compete to explain variance



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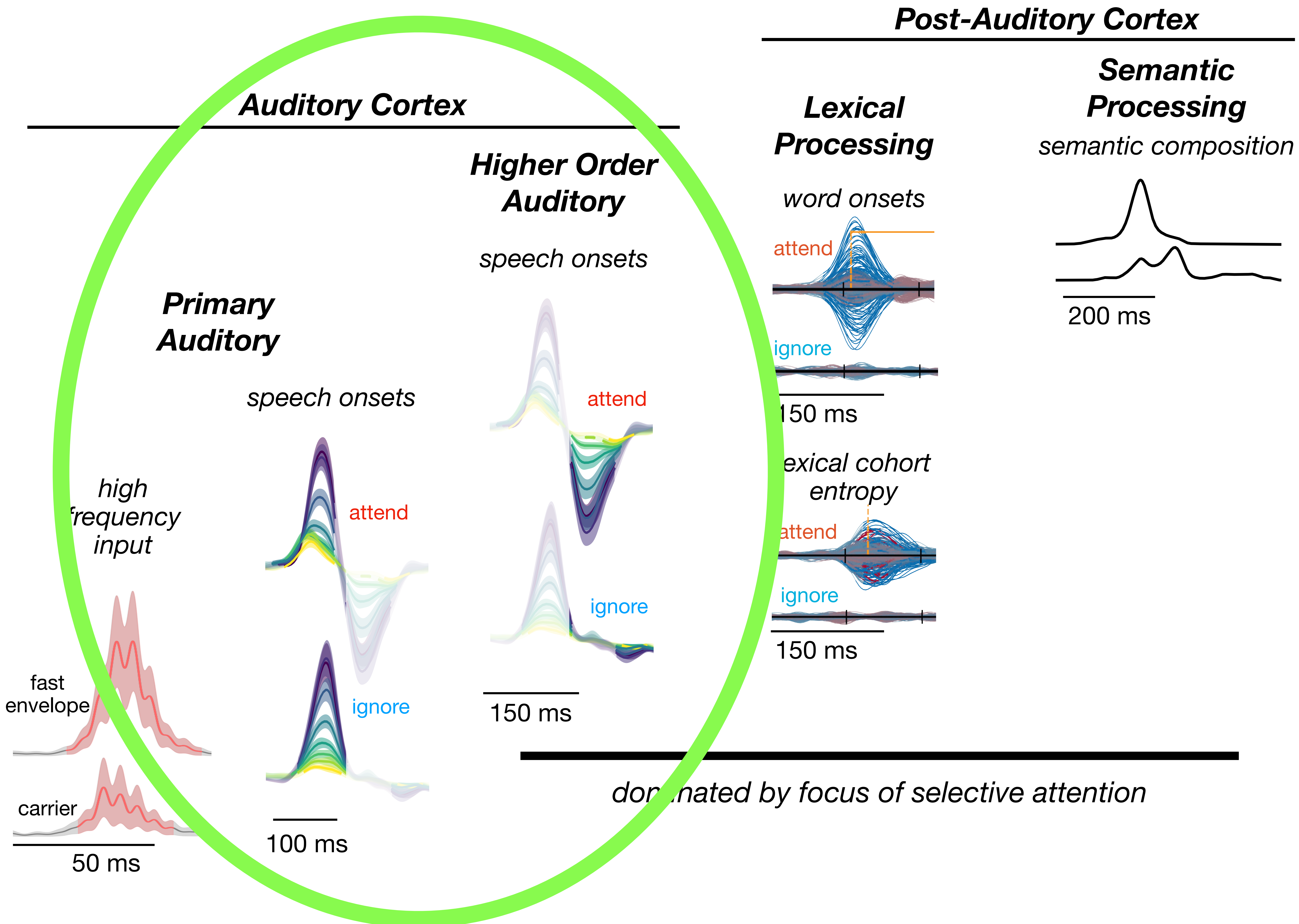
Cortical Representations Across Cortex



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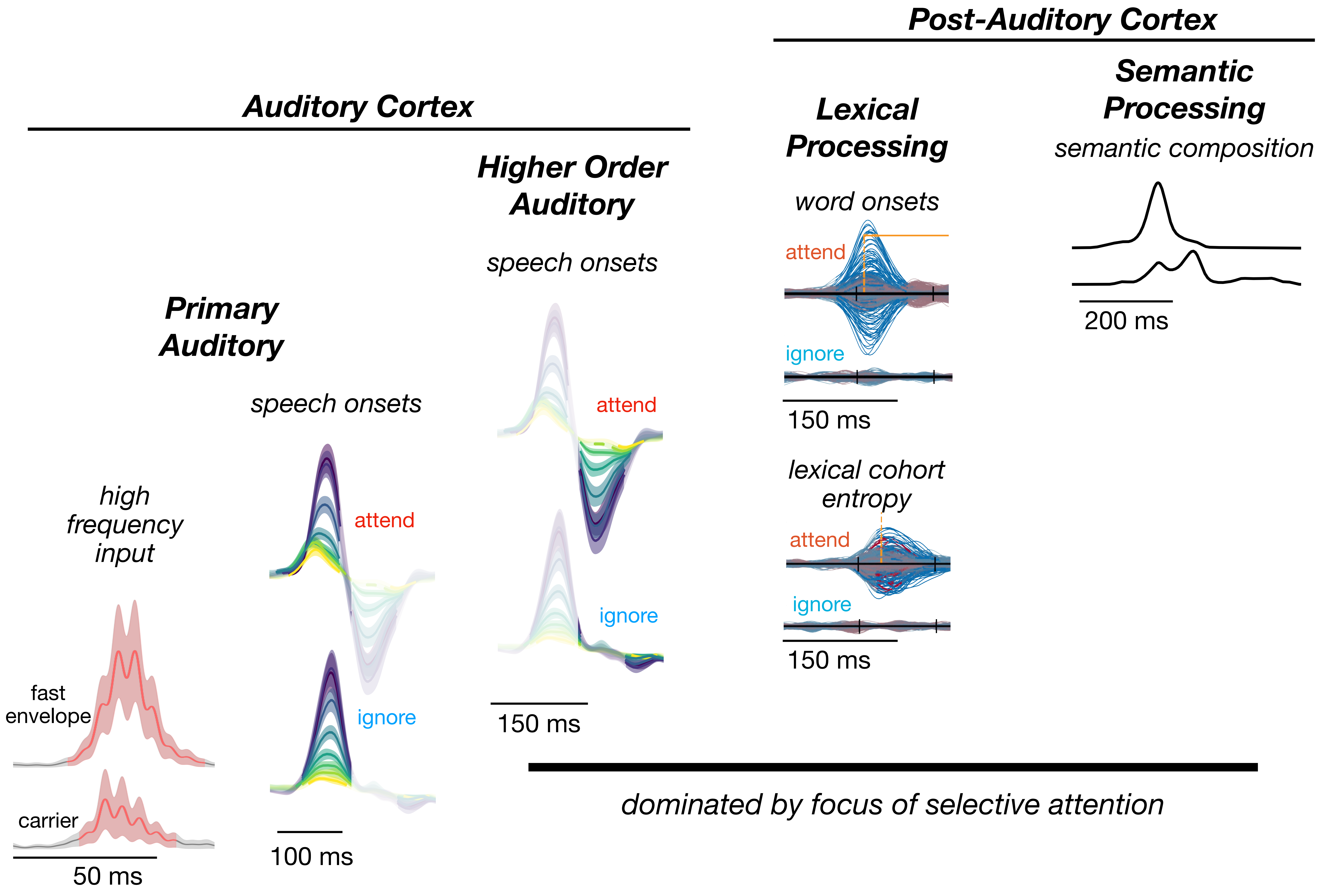

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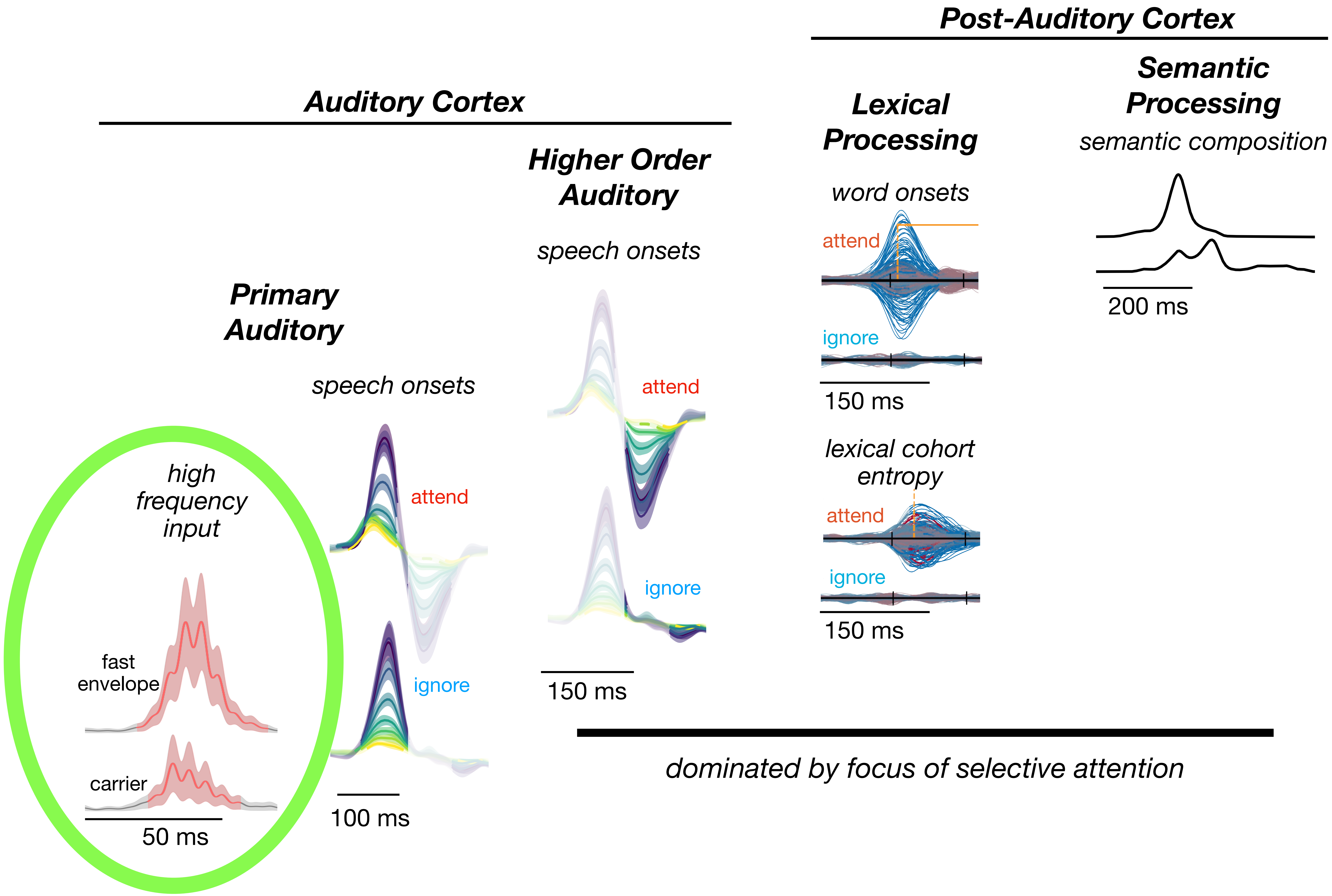

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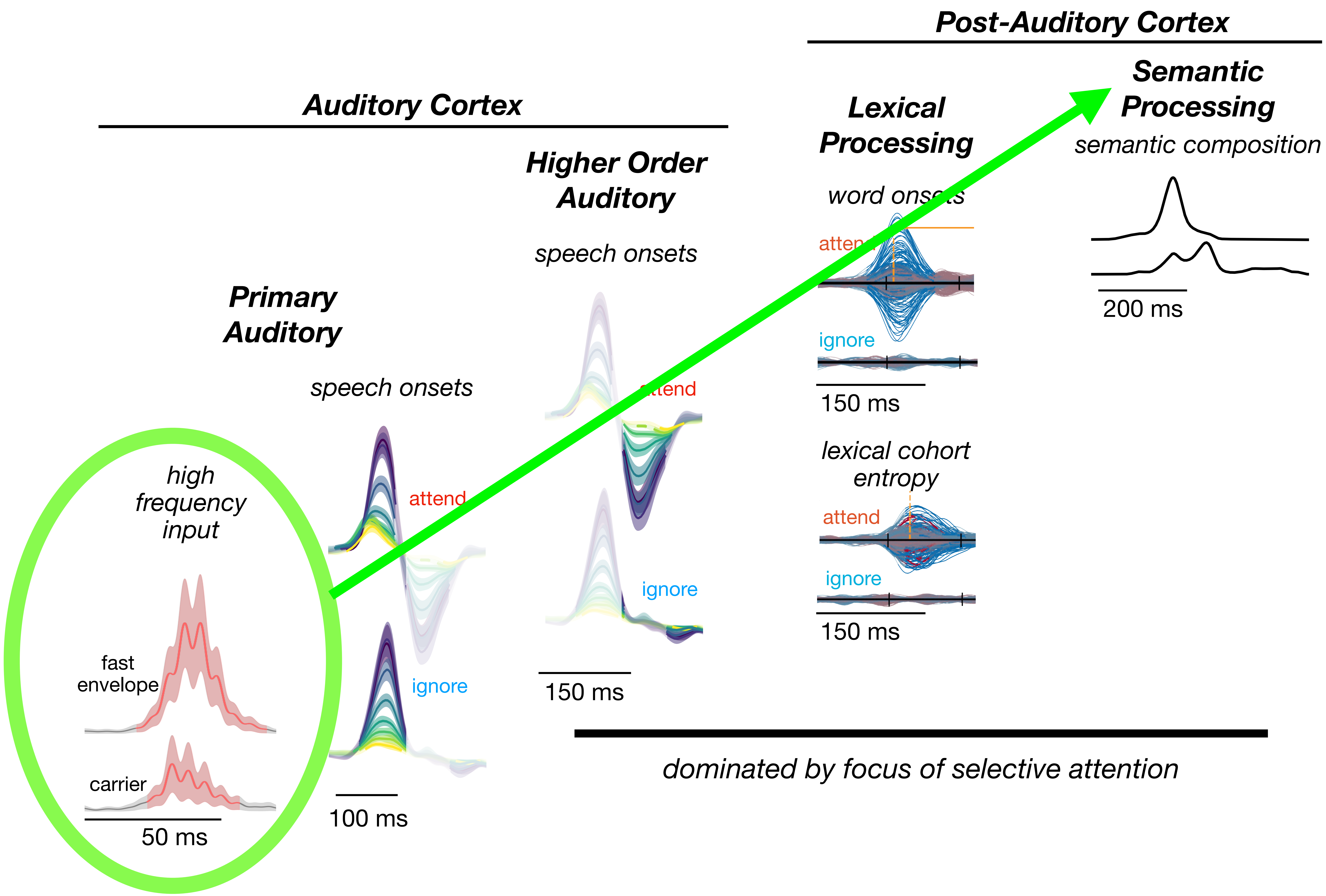

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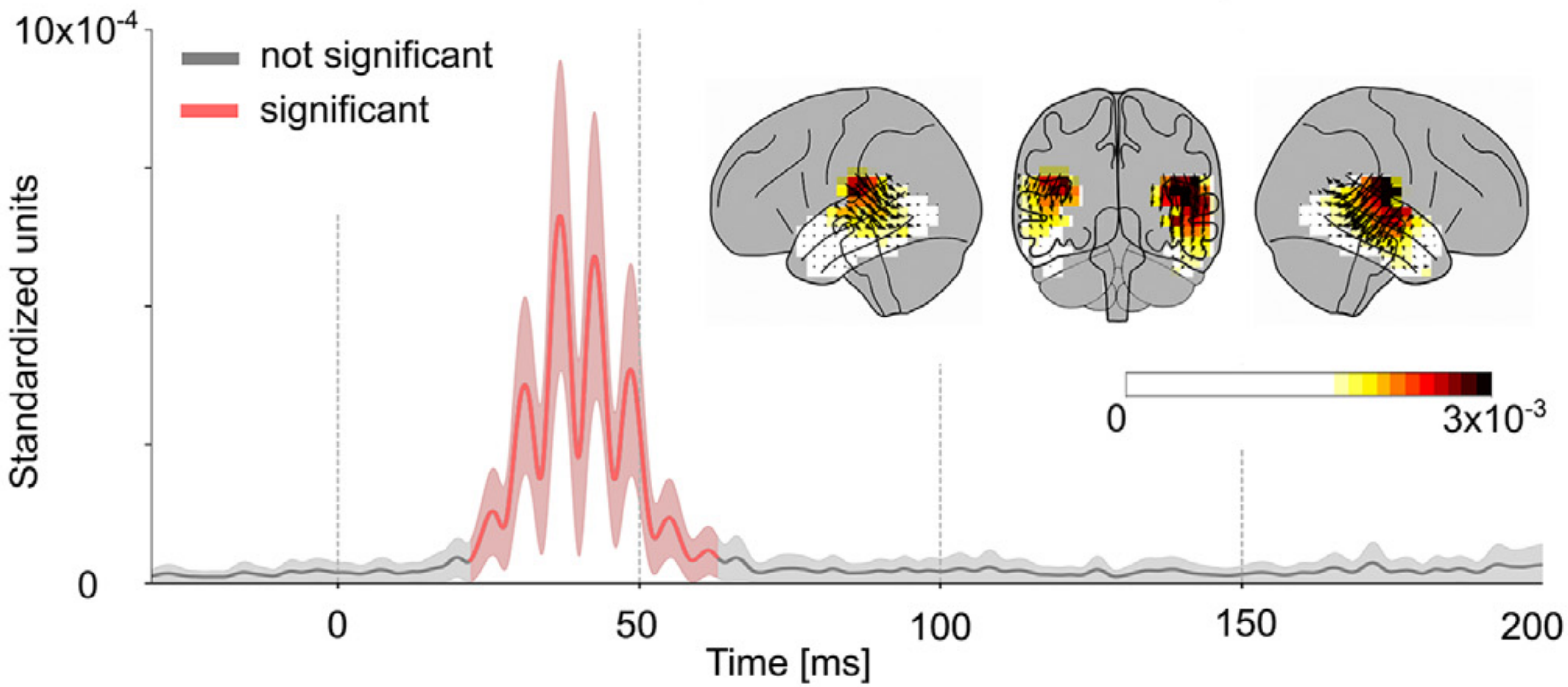
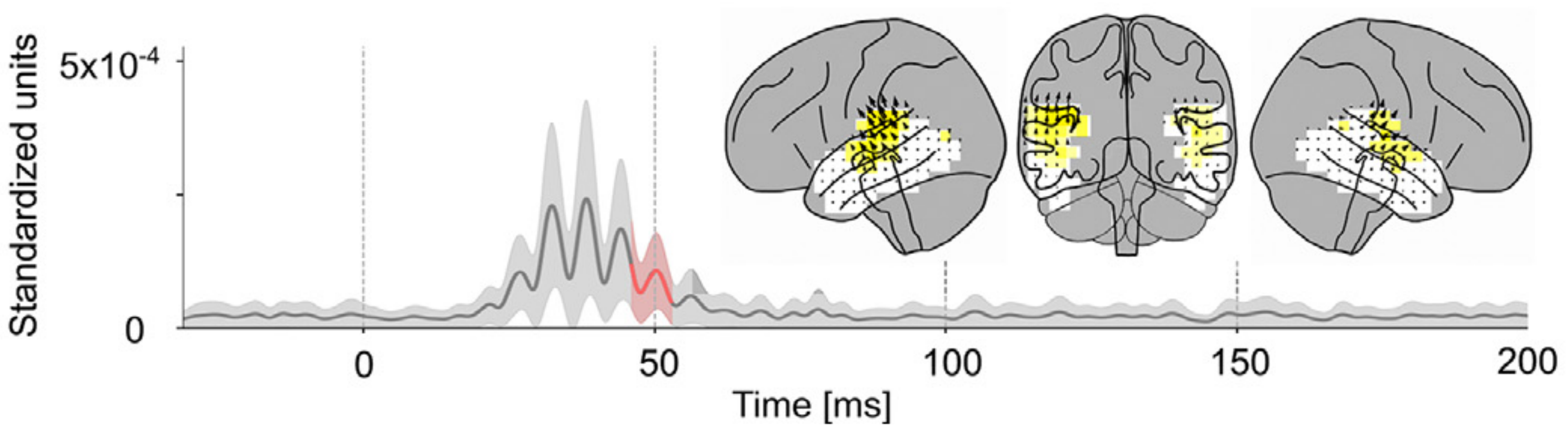
Fast & Early Cortical Representations



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



carrier

40 ms latency peak
⟹ Primary/Core auditory cortex

Kulasingham et al. (2020) *High Gamma Cortical Processing of Continuous Speech …*, NeuroImage
Simon et al. (2022) *… the High-Gamma Band: A Window into Primary Auditory Cortex*, Front Neurosci

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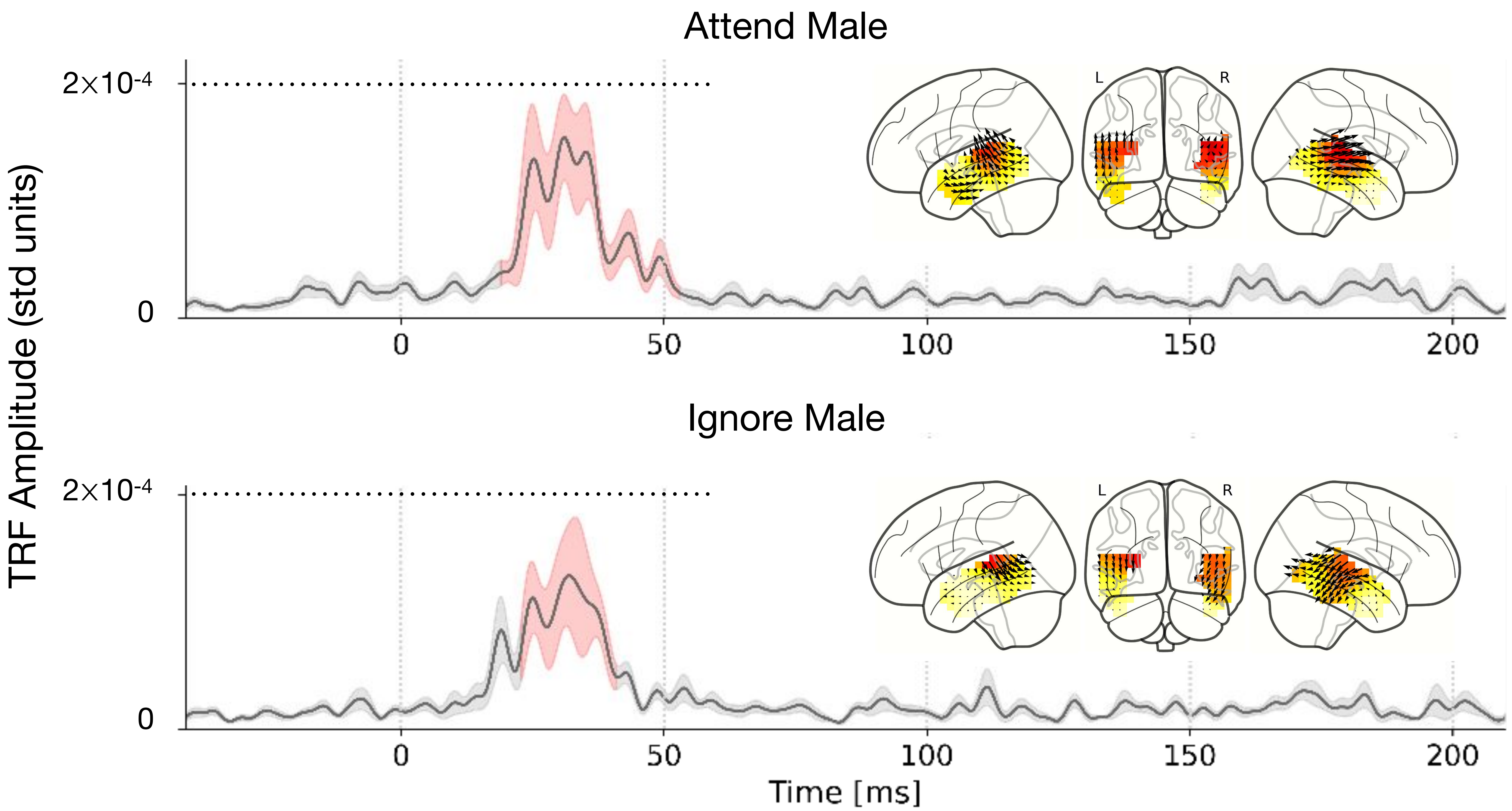

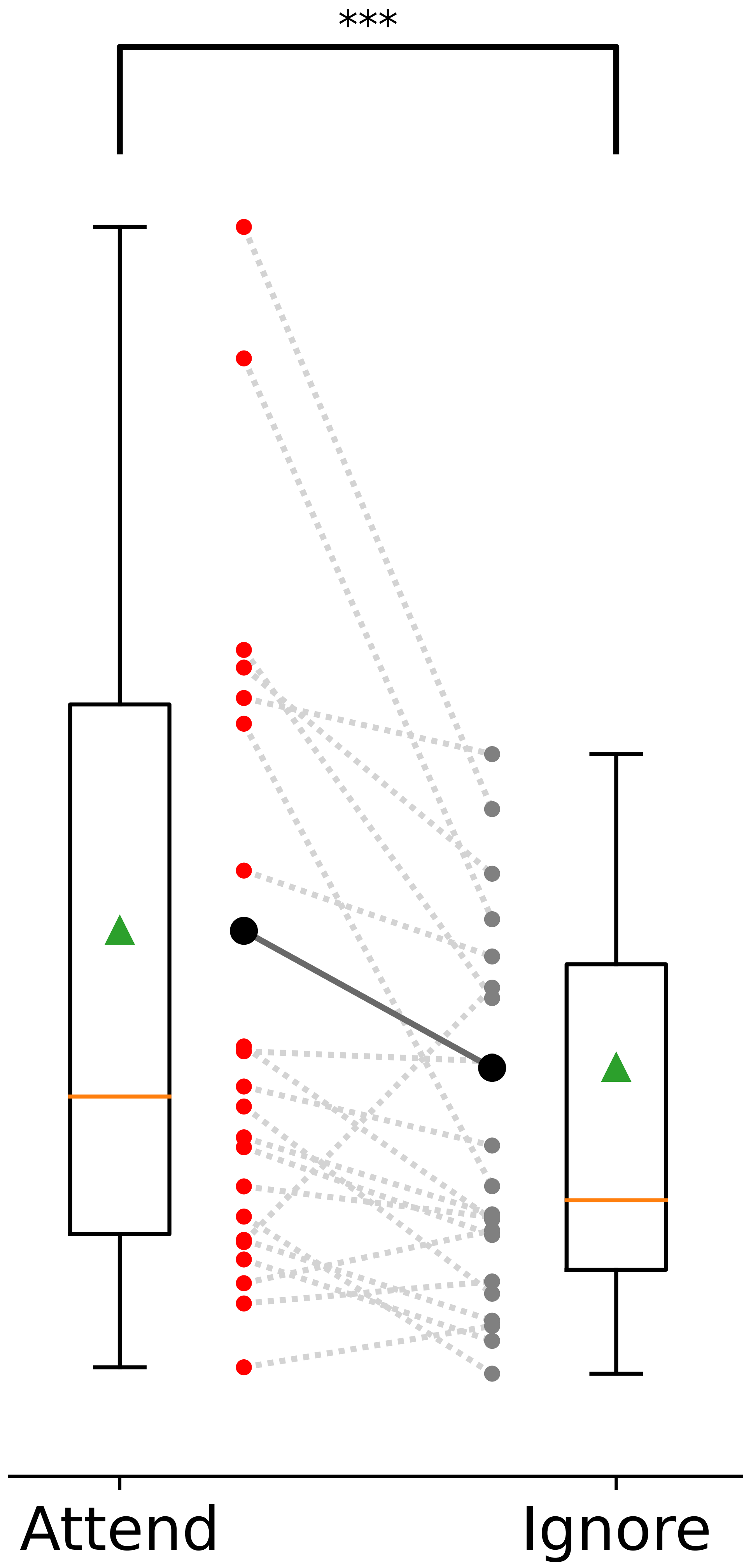

Primary cortex modulated by selective attention
Attend > Ignore

Commuri et al. (2023) … *High-Gamma Band Depend on Selective Attention*, Front Neurosci

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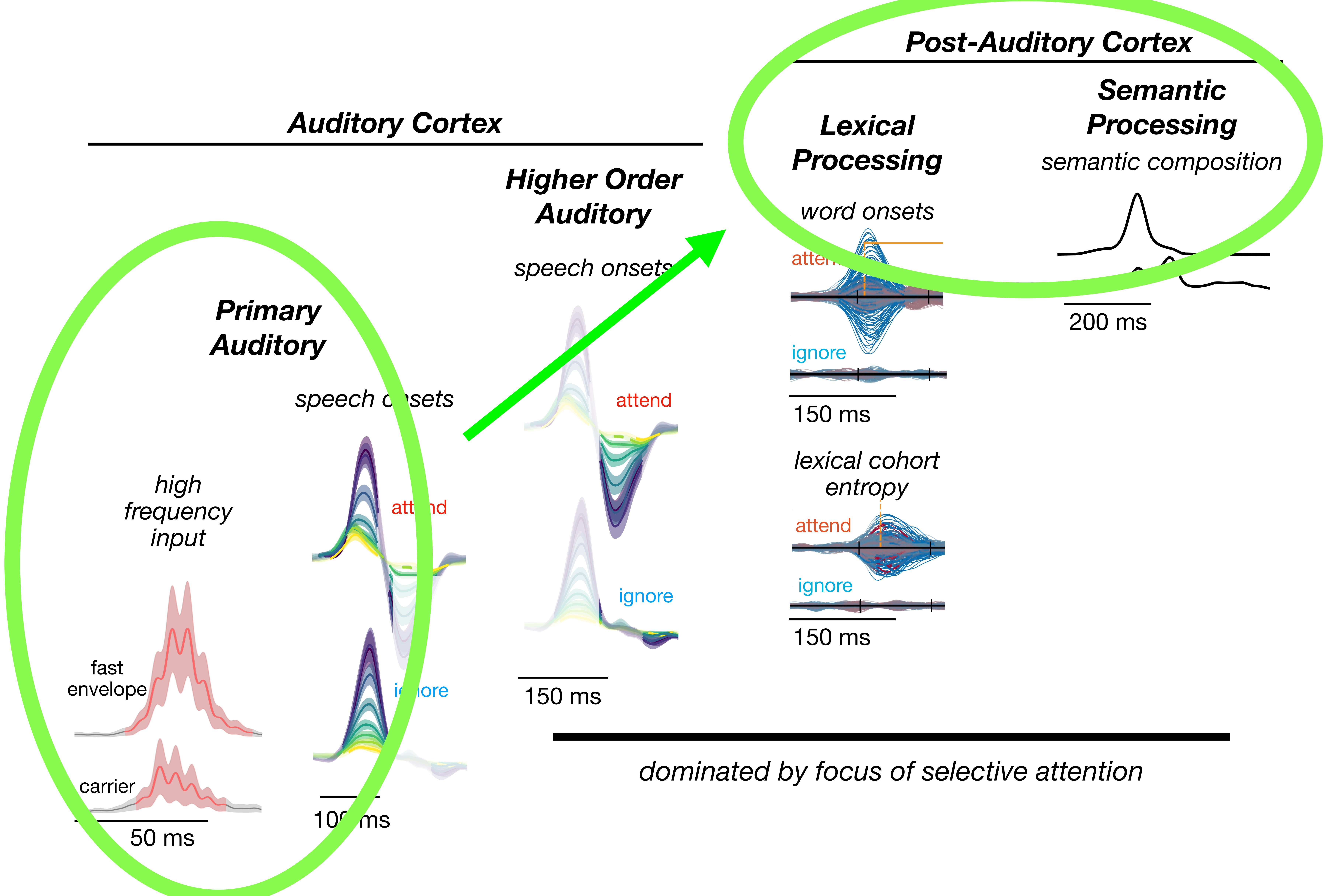
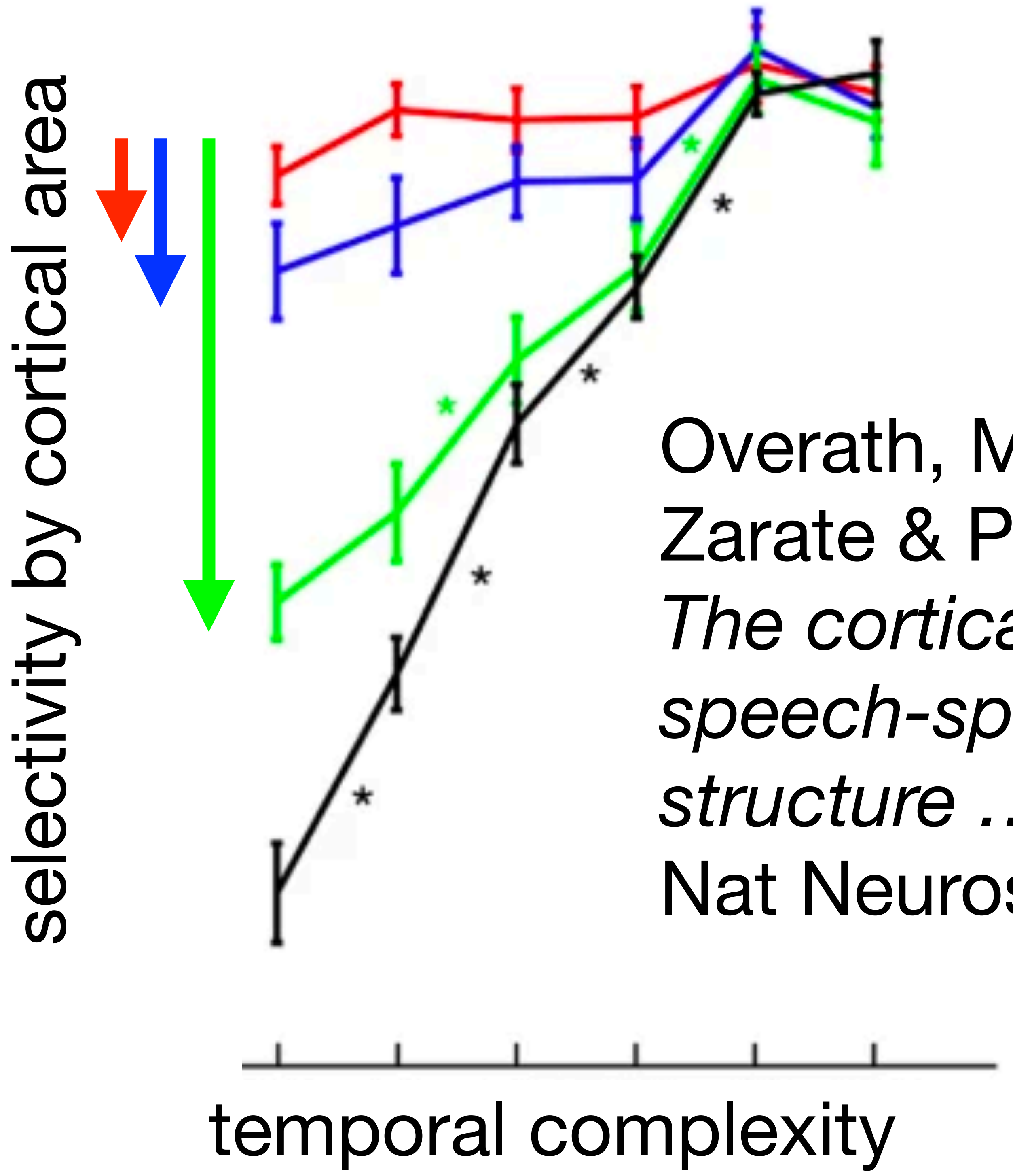


Progression of Speech Representations

- Previous 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
- But, not all processing is straight bottom up
  - selective attention
  - secondary processing upon “error” detection
- MEG & EEG excel at showing temporal (i.e., latency) progression of processing



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

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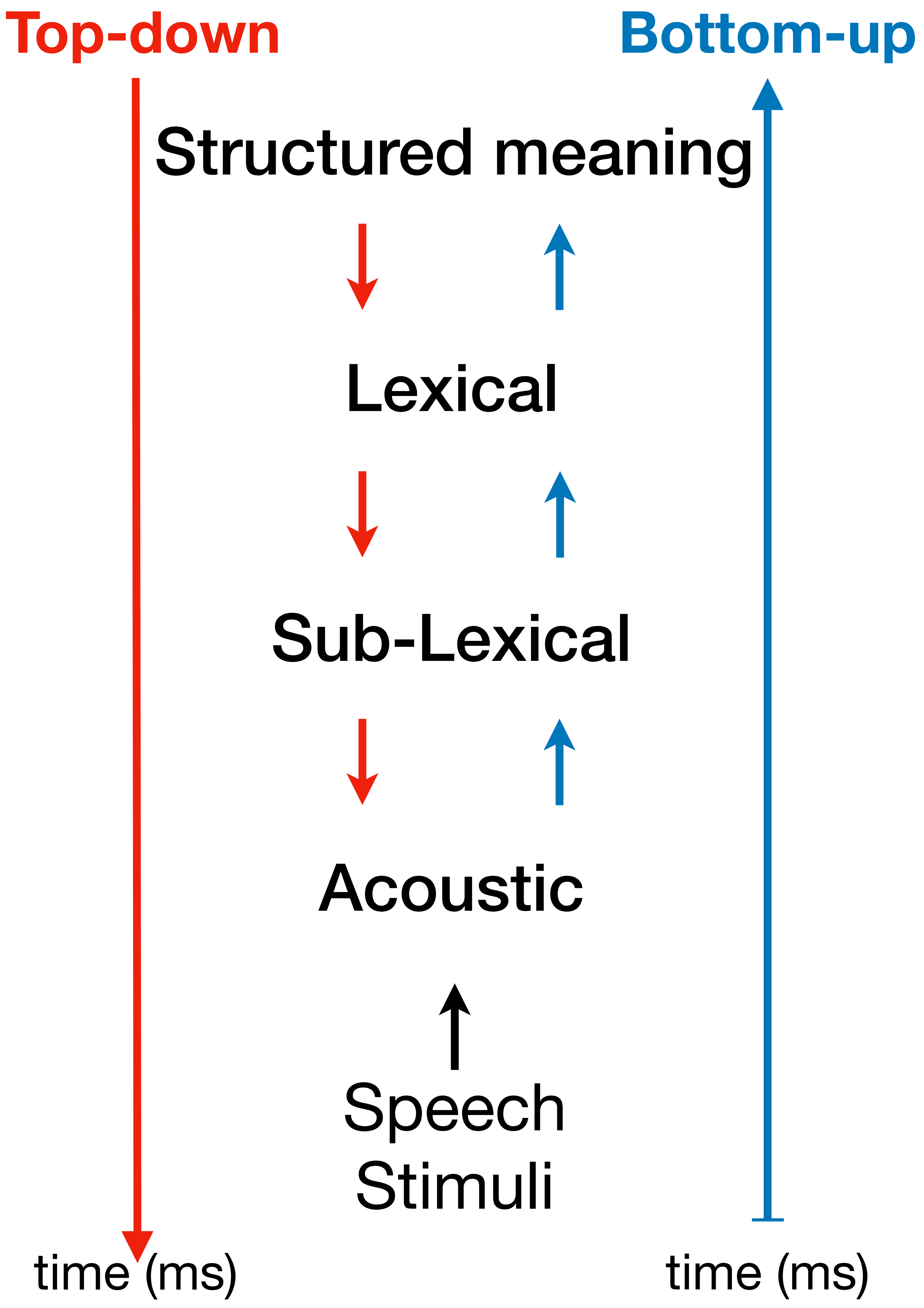


Brodbeck et al. (2022) *Parallel Processing in Speech Perception: Local and Global Representations…*, eLife

Experimental Design

Task

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

Stimuli

4 passage types

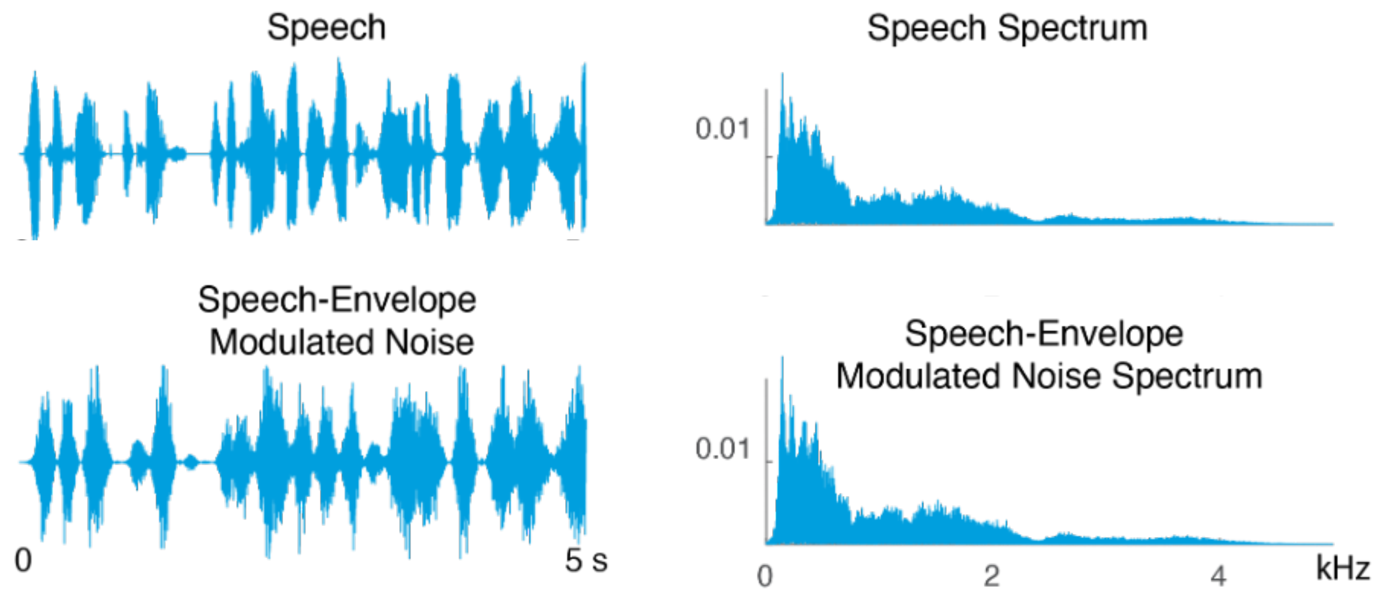
- Speech modulated noise
- Non-words
- Scrambled words
- Narrative

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

Karunathilake et al. (2024) *Neural Dynamics of the Processing of Speech Features* … bioRxiv

Experimental Design

Speech-envelope Modulated Noise



Non-words

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….

Scrambled words

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 ……

Narrative

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

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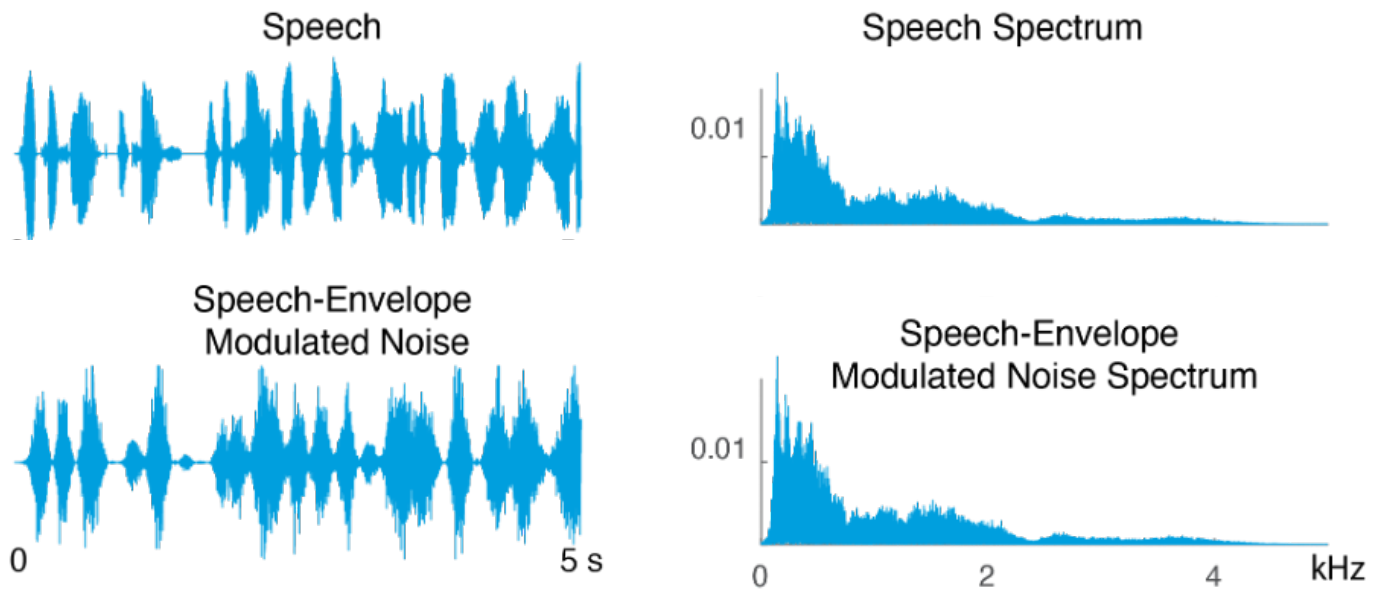

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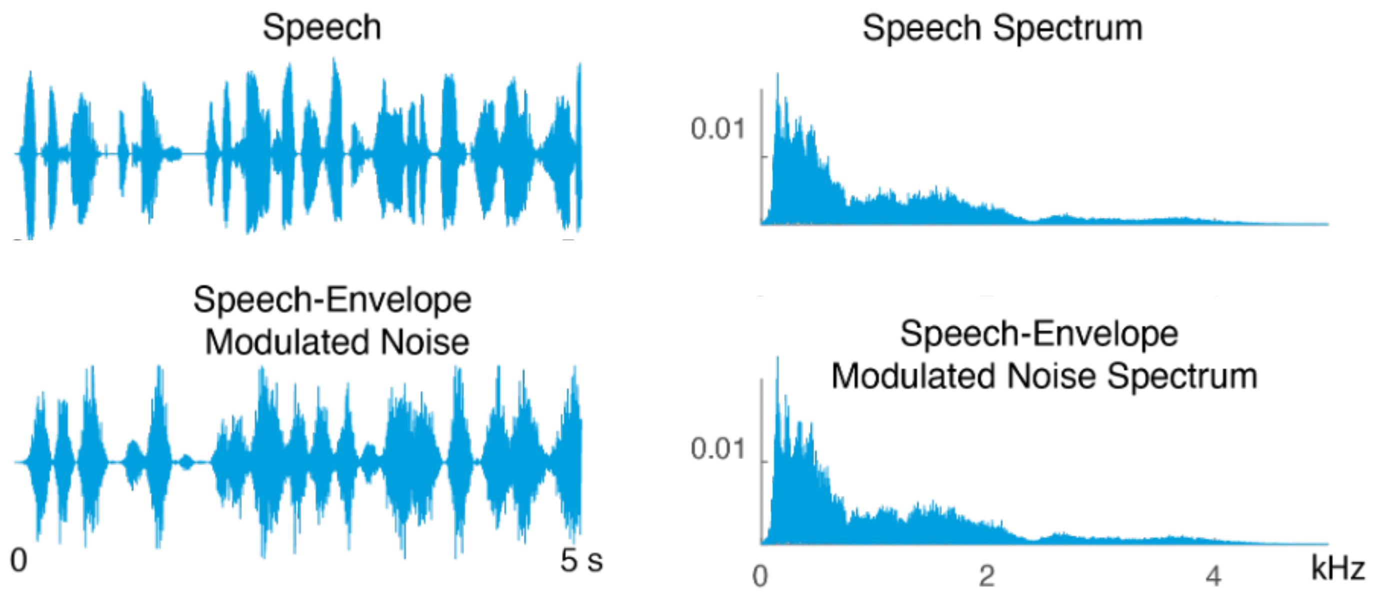

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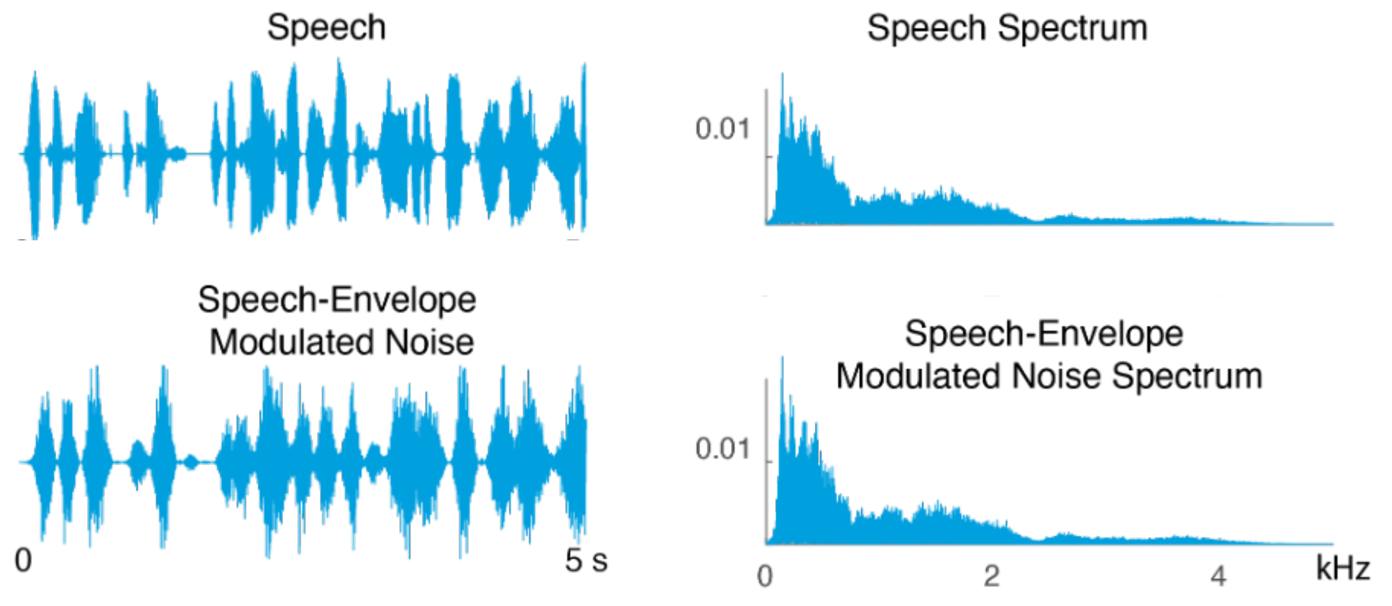

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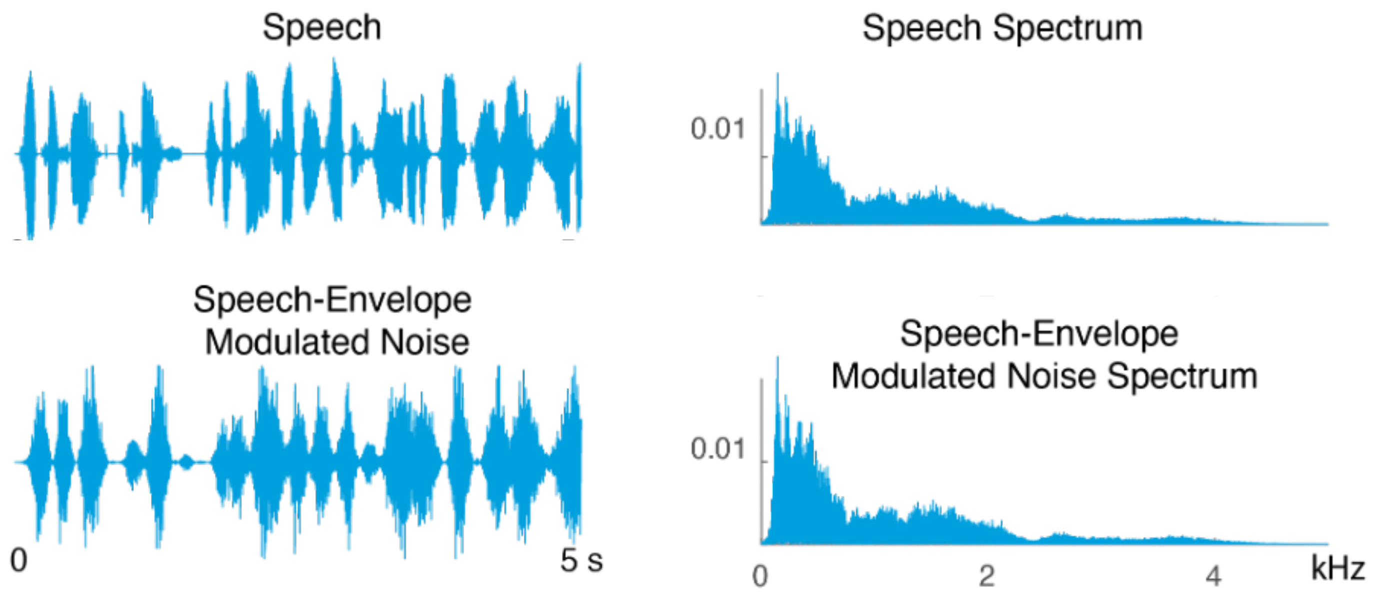

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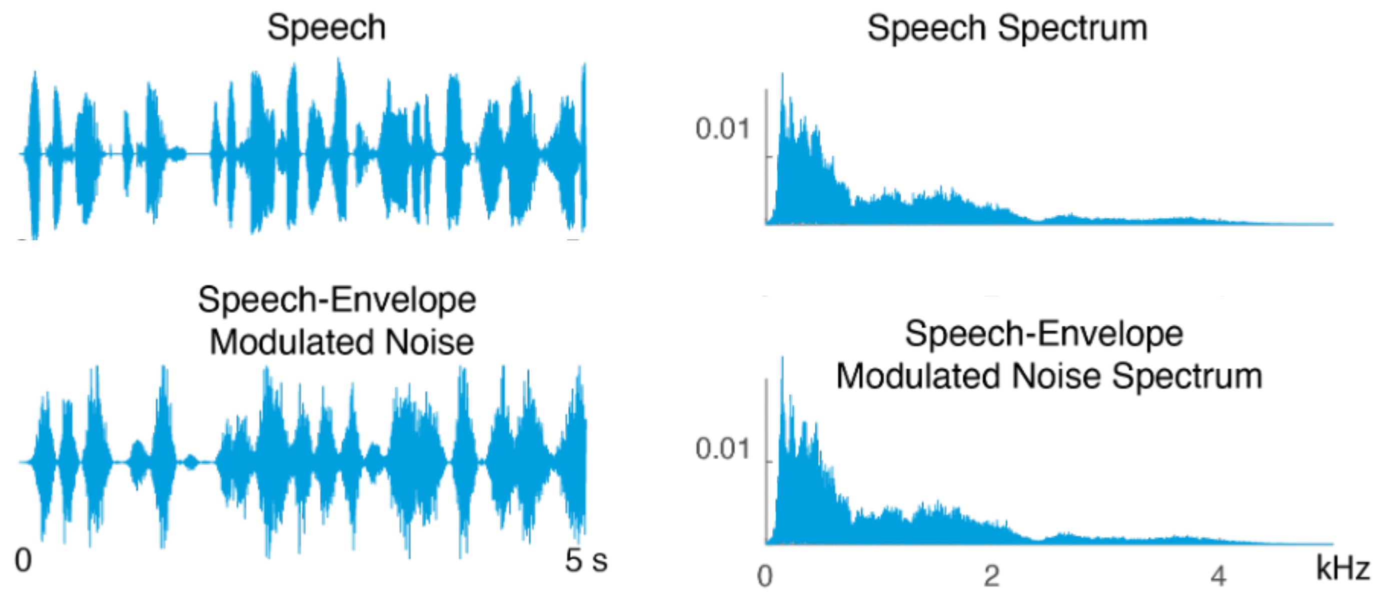

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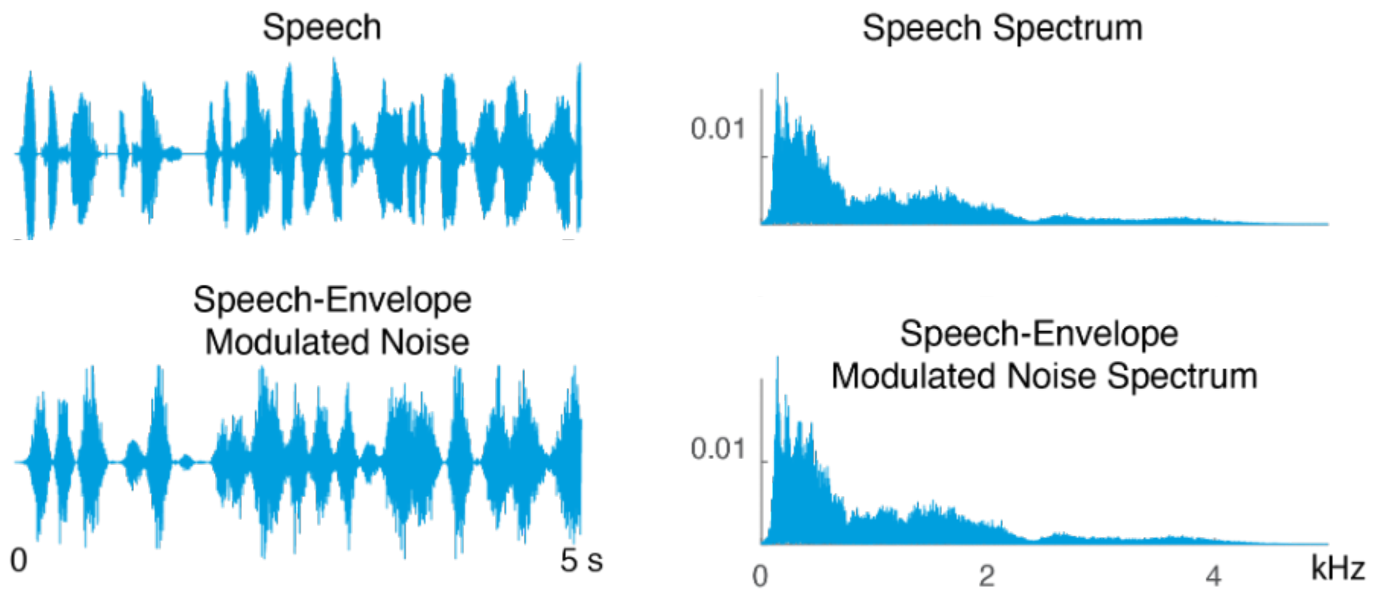

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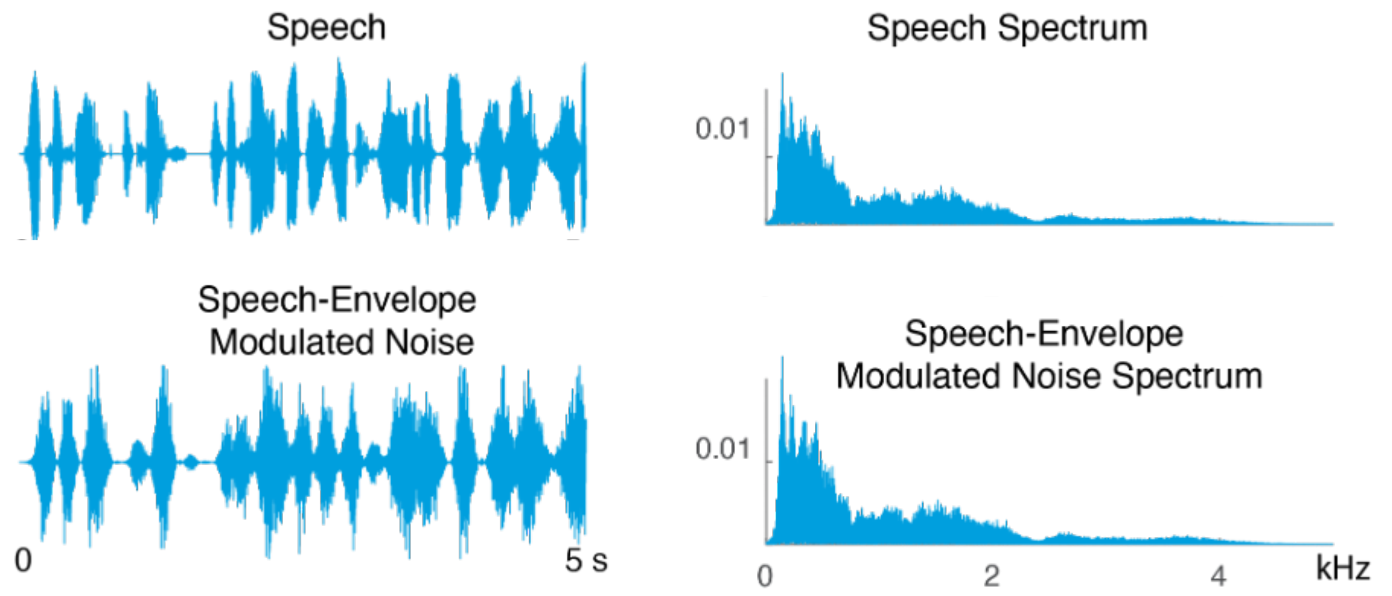
continuous-speech-like prosody and rhythm

Karunathilake et al. (2024) *Neural Dynamics of the Processing of Speech Features* … bioRxiv

Experimental Design

Speech-envelope Modulated Noise



Non-words

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….

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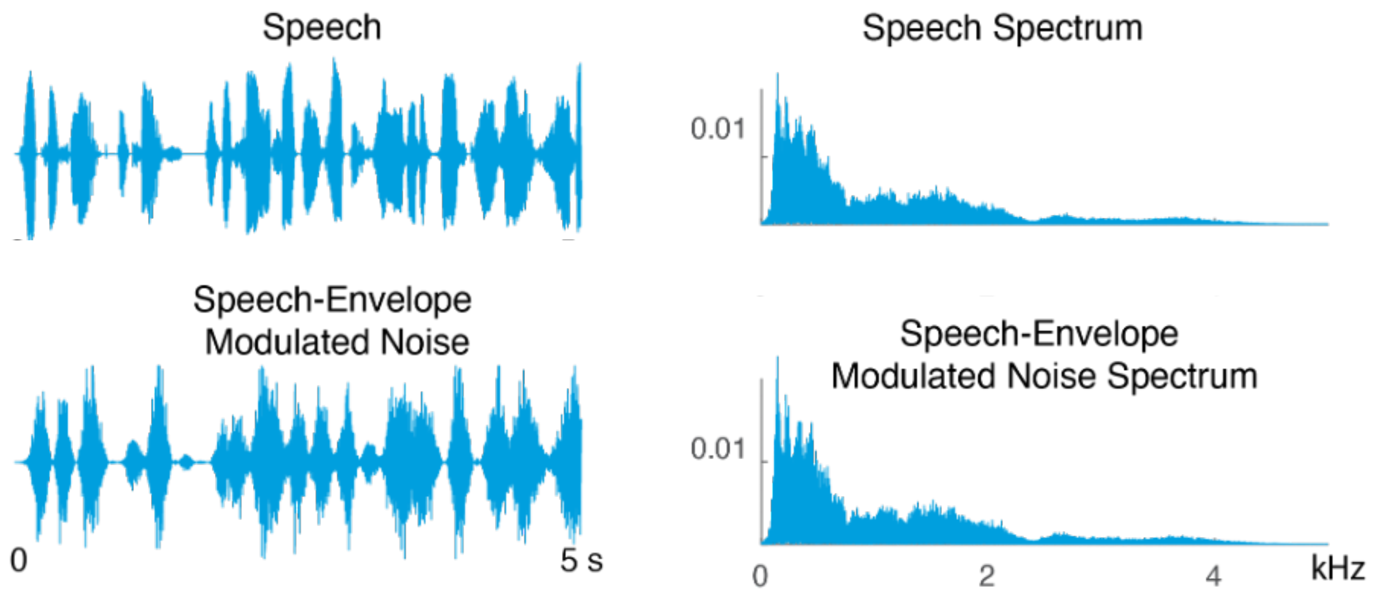

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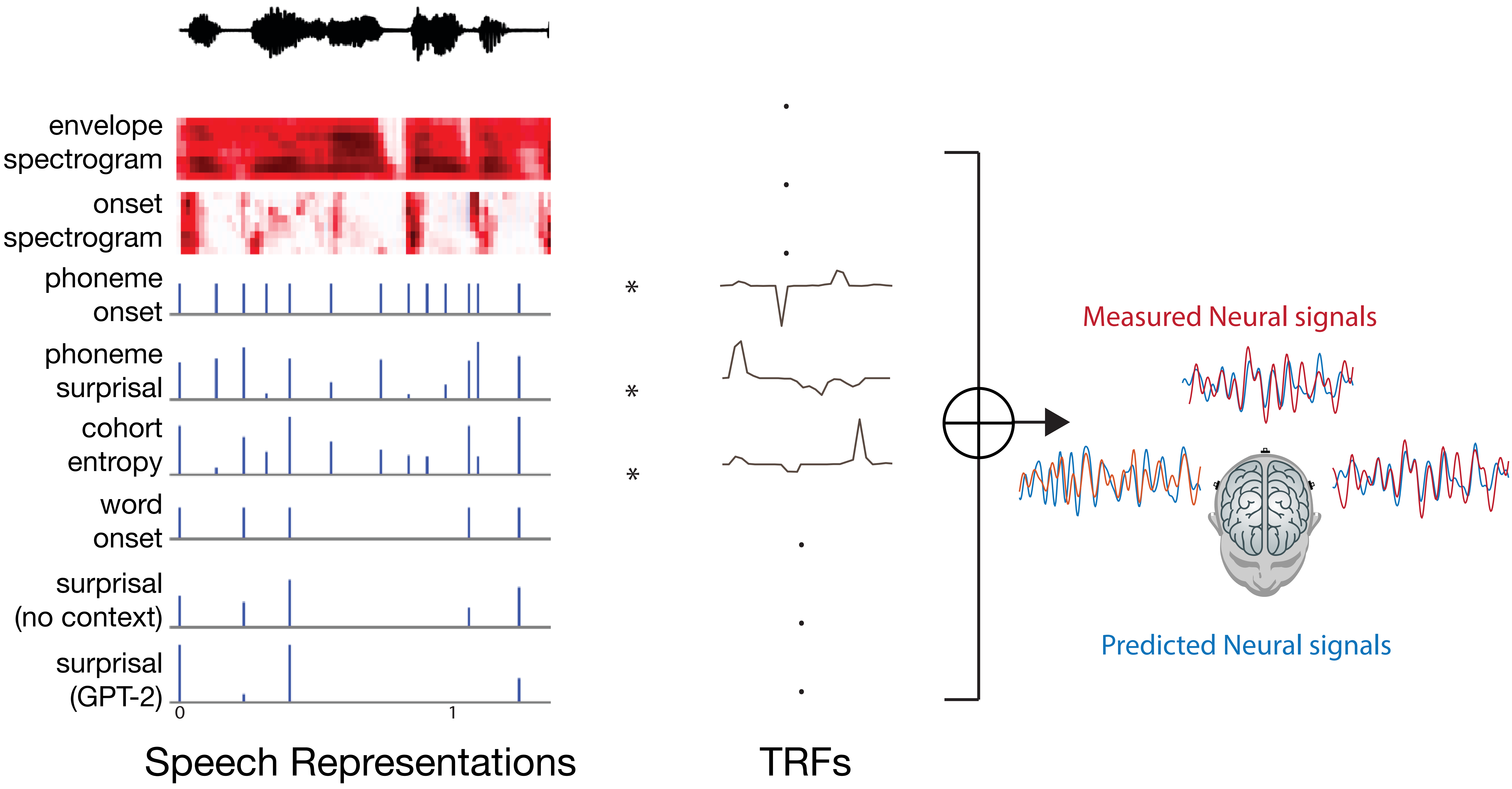
Simultaneous Temporal Response Functions

- 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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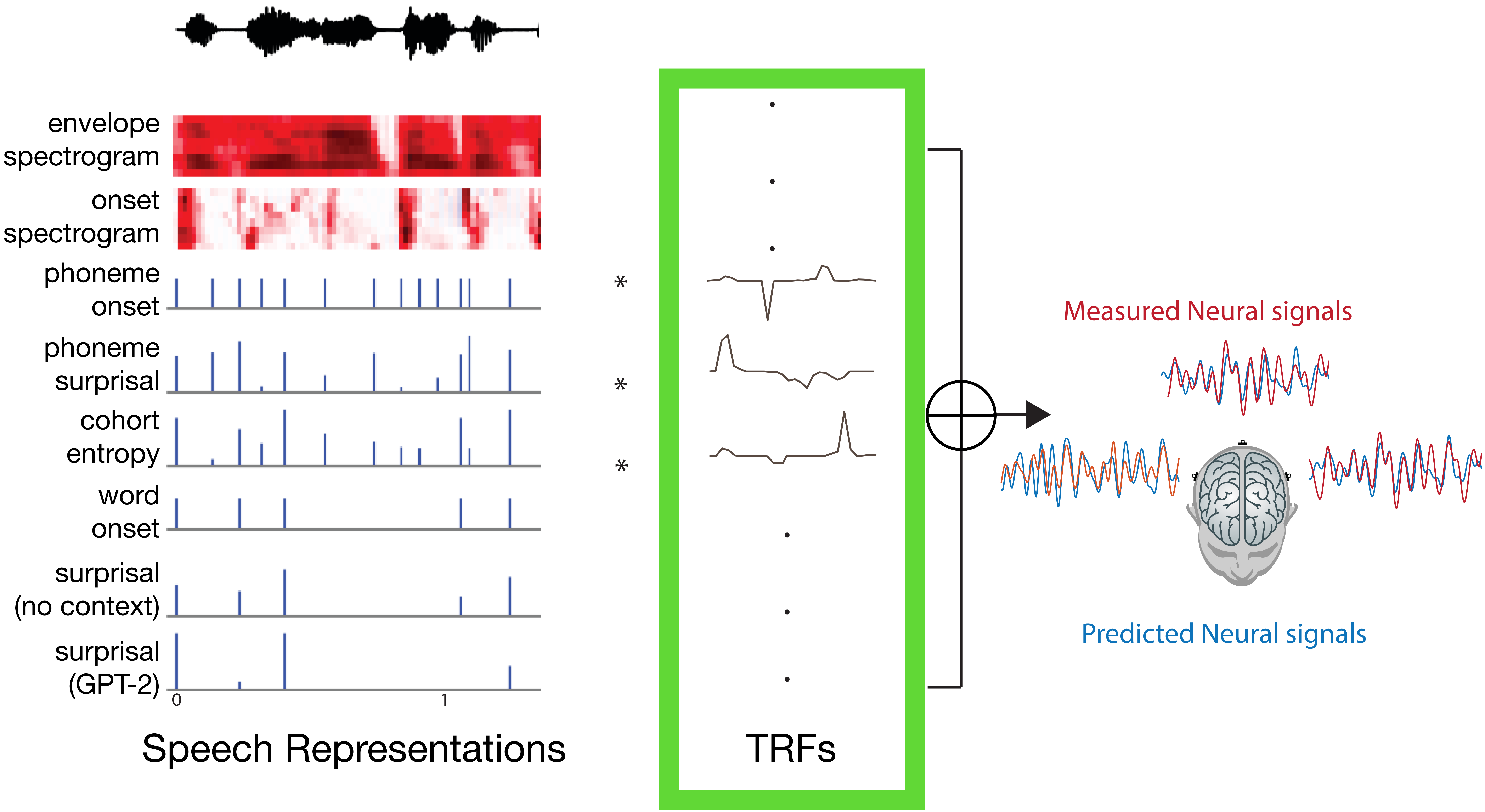
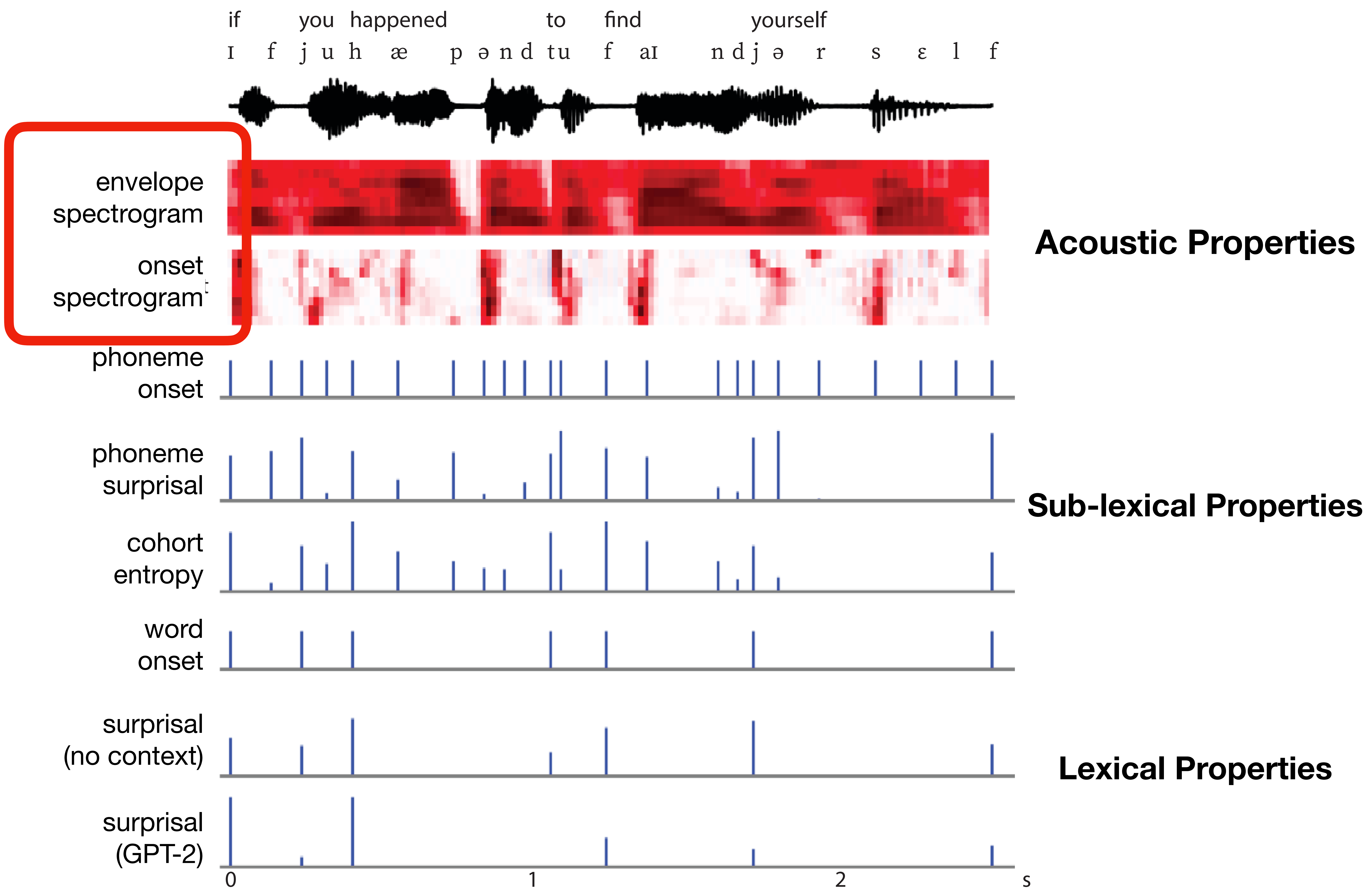


Speech Representations



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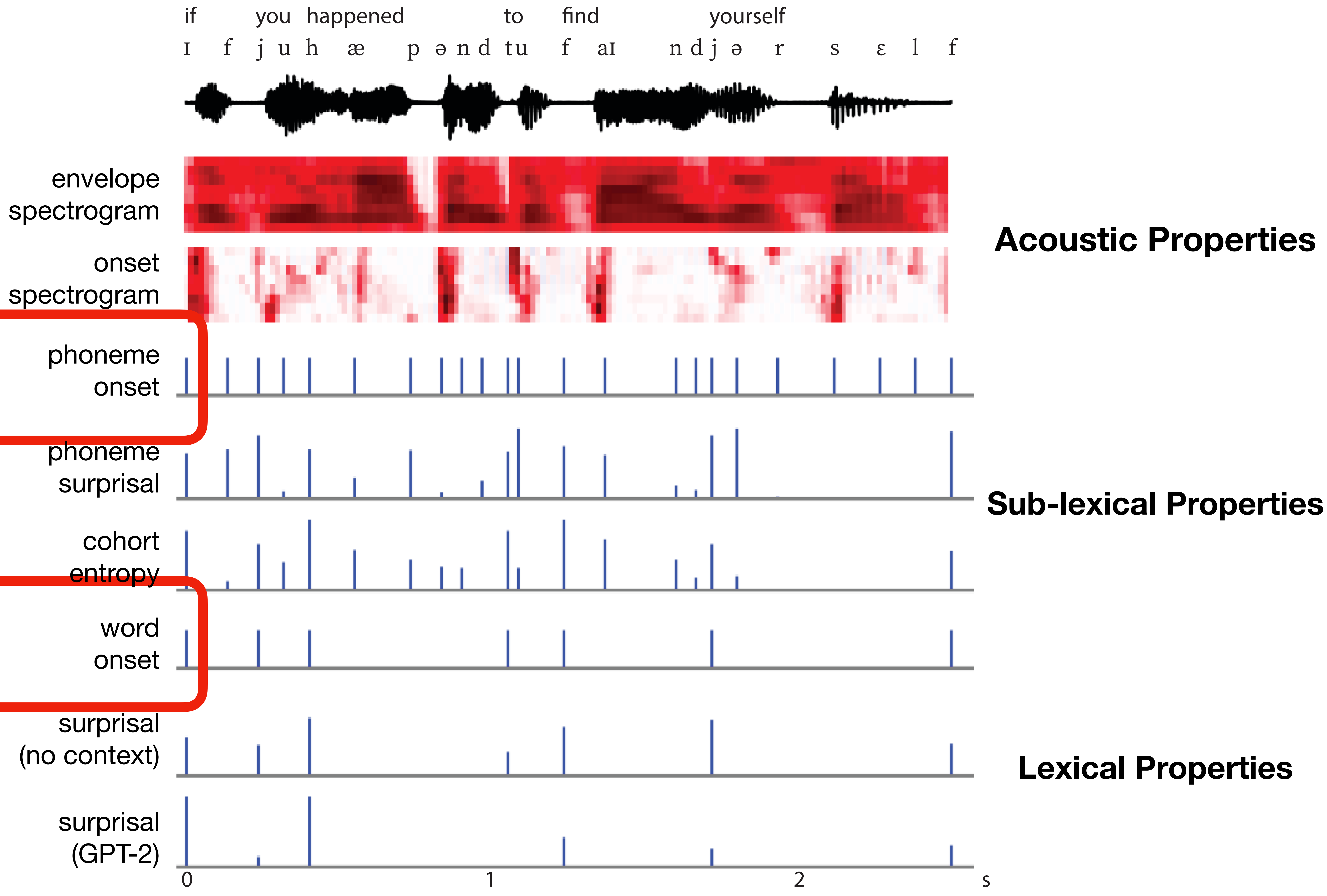

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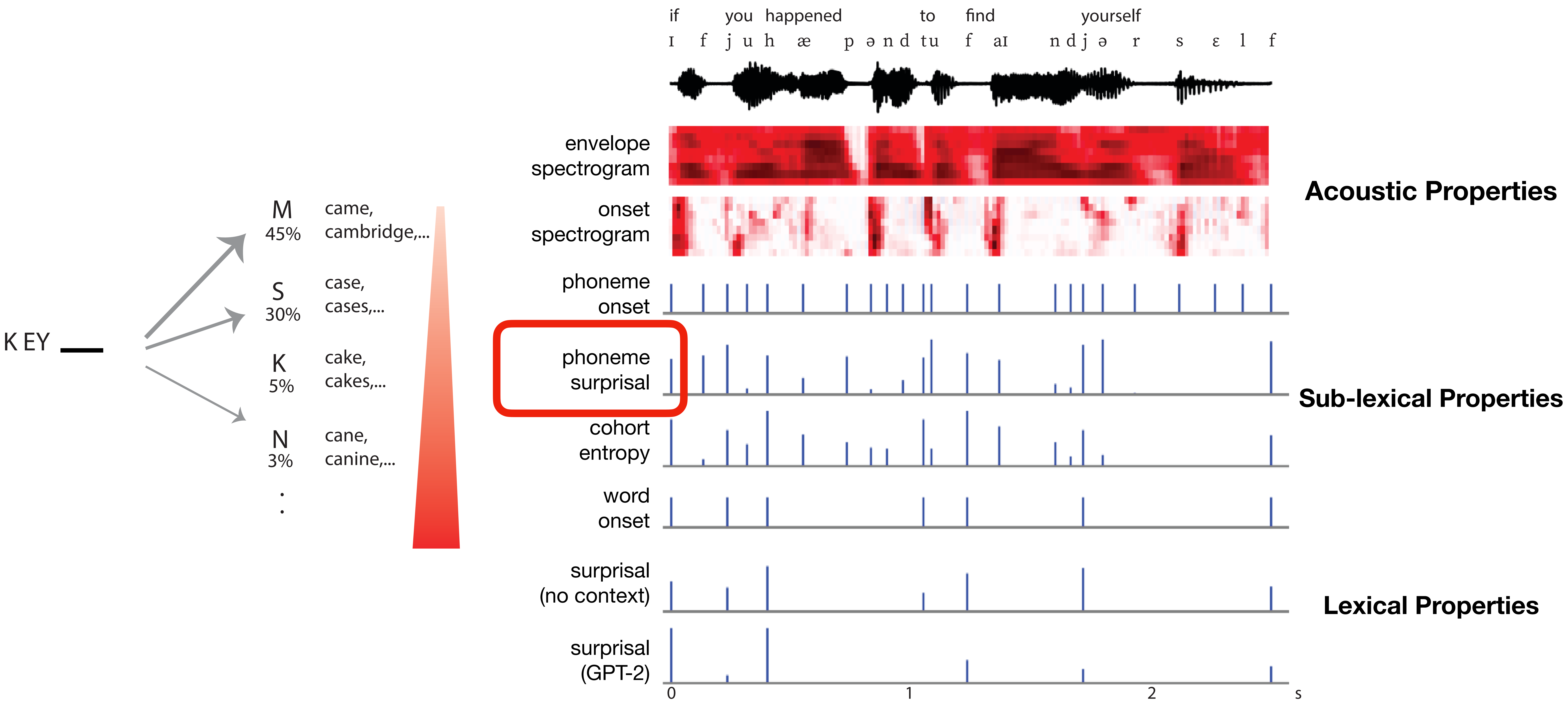

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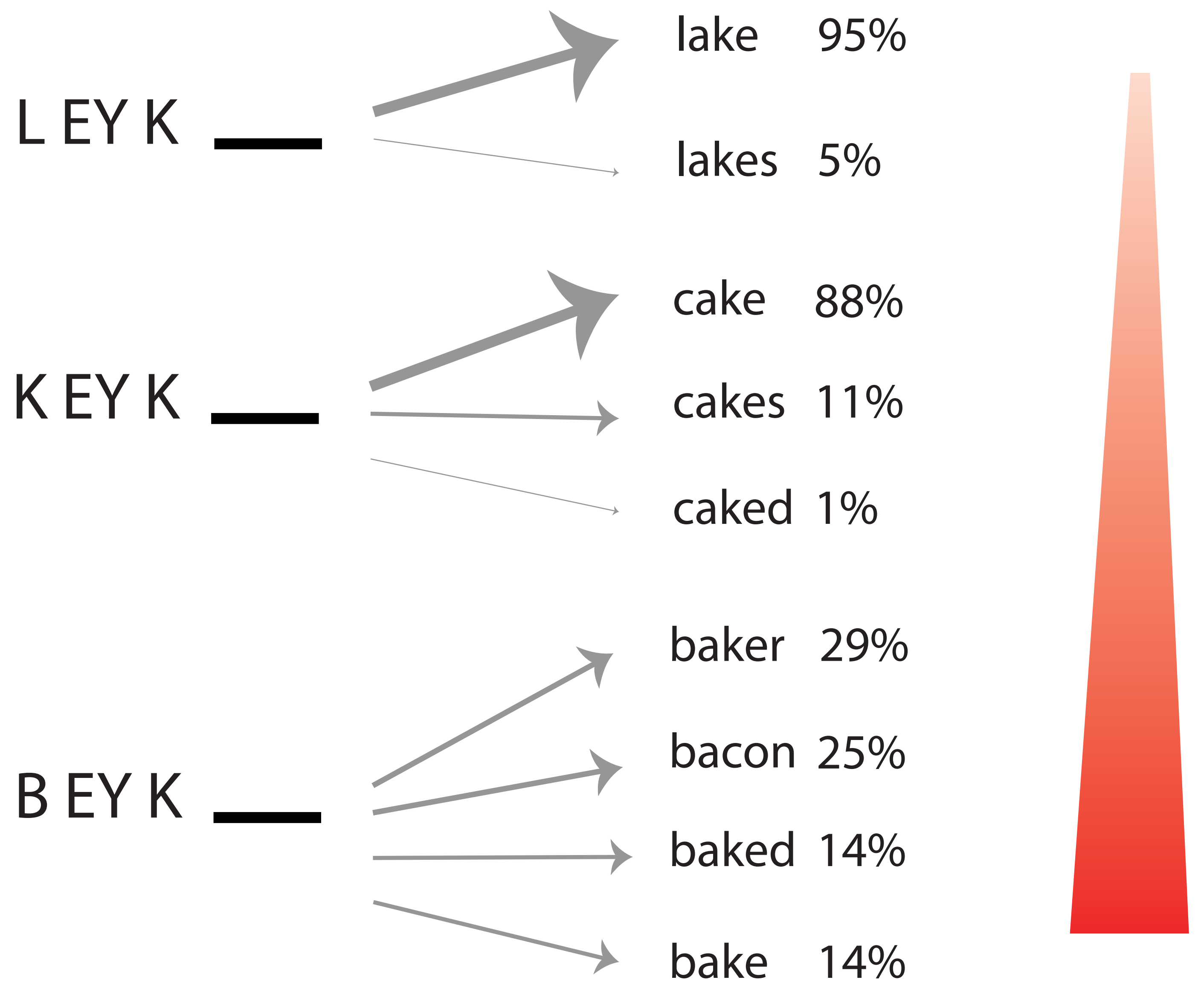
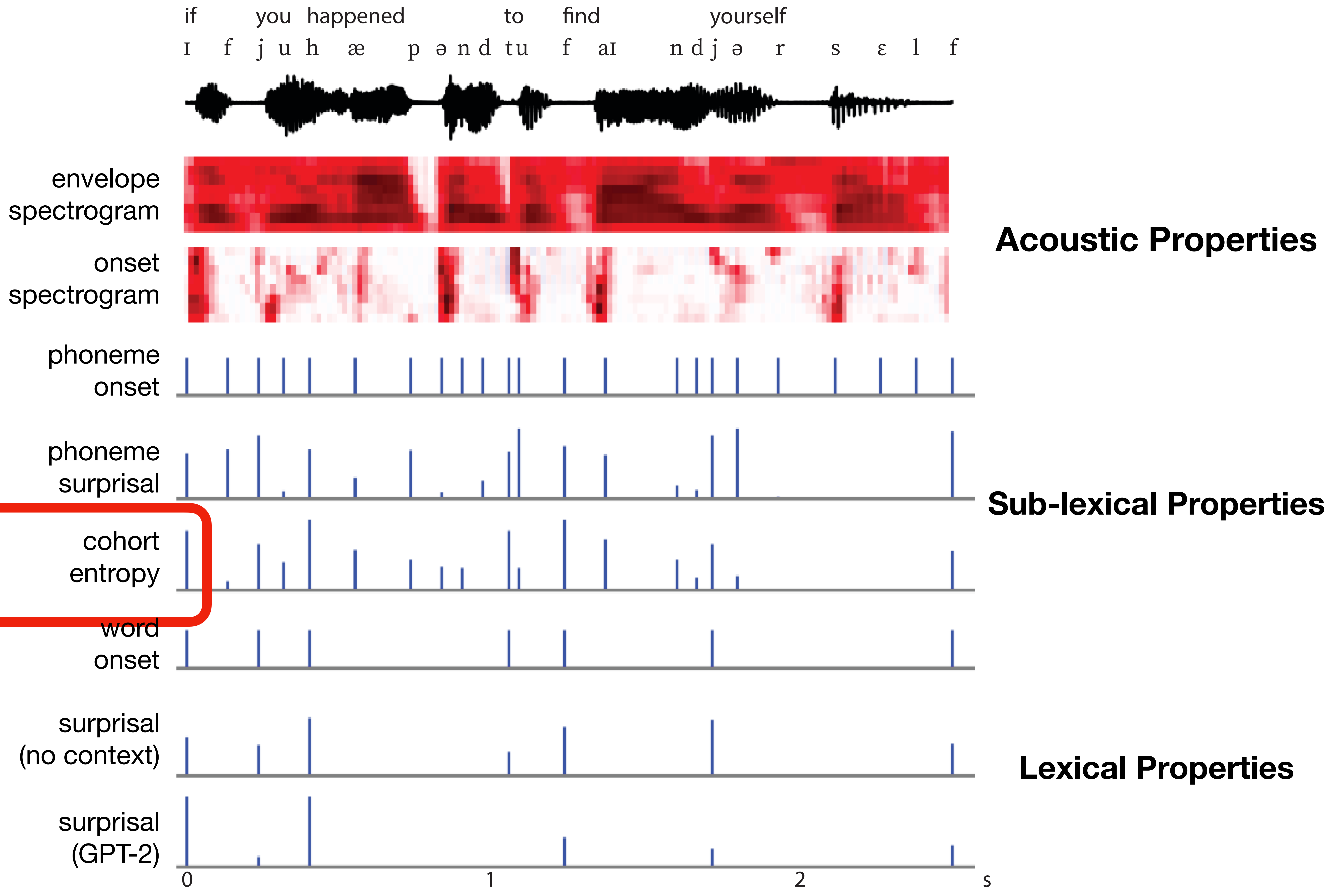
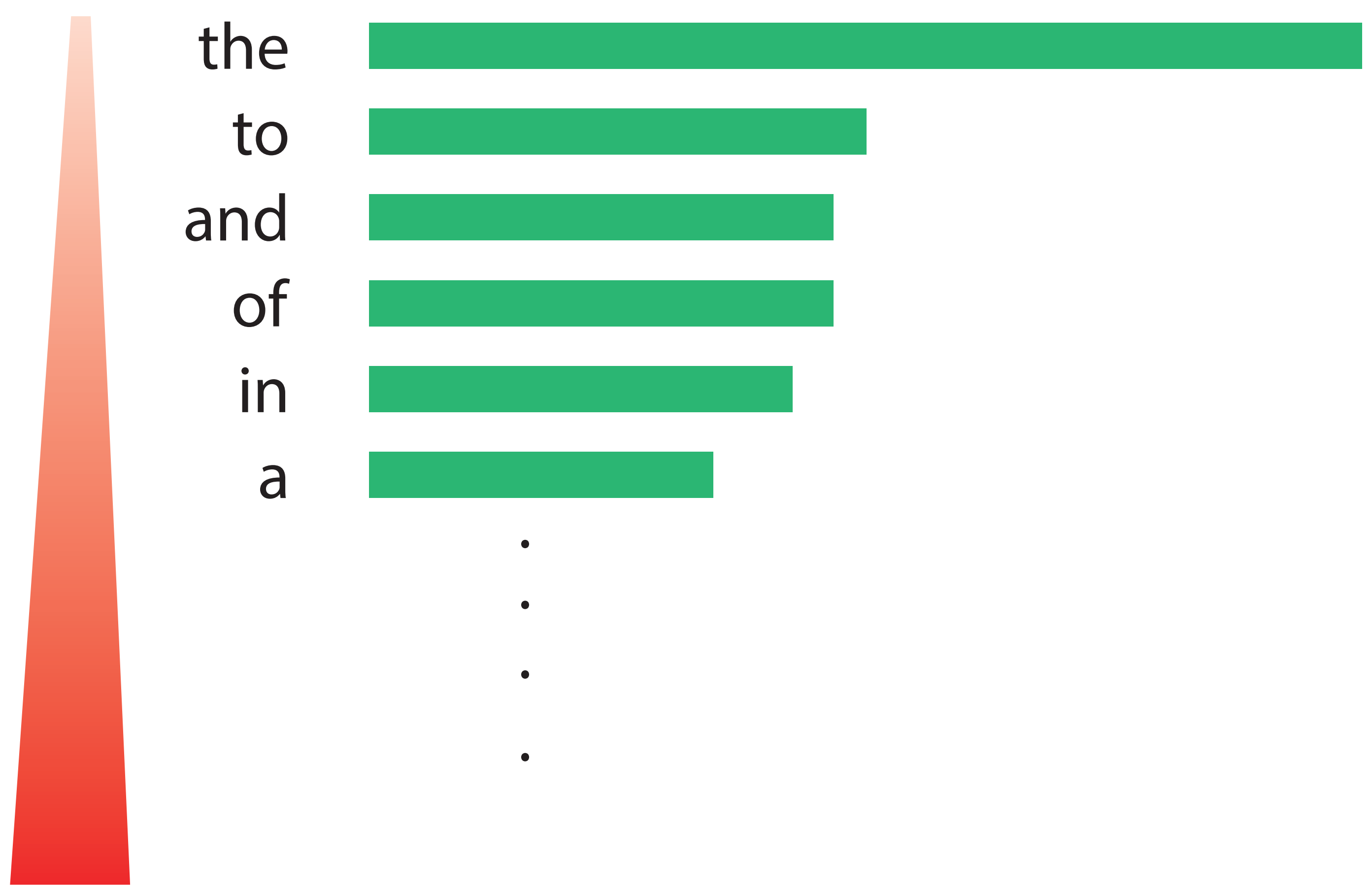
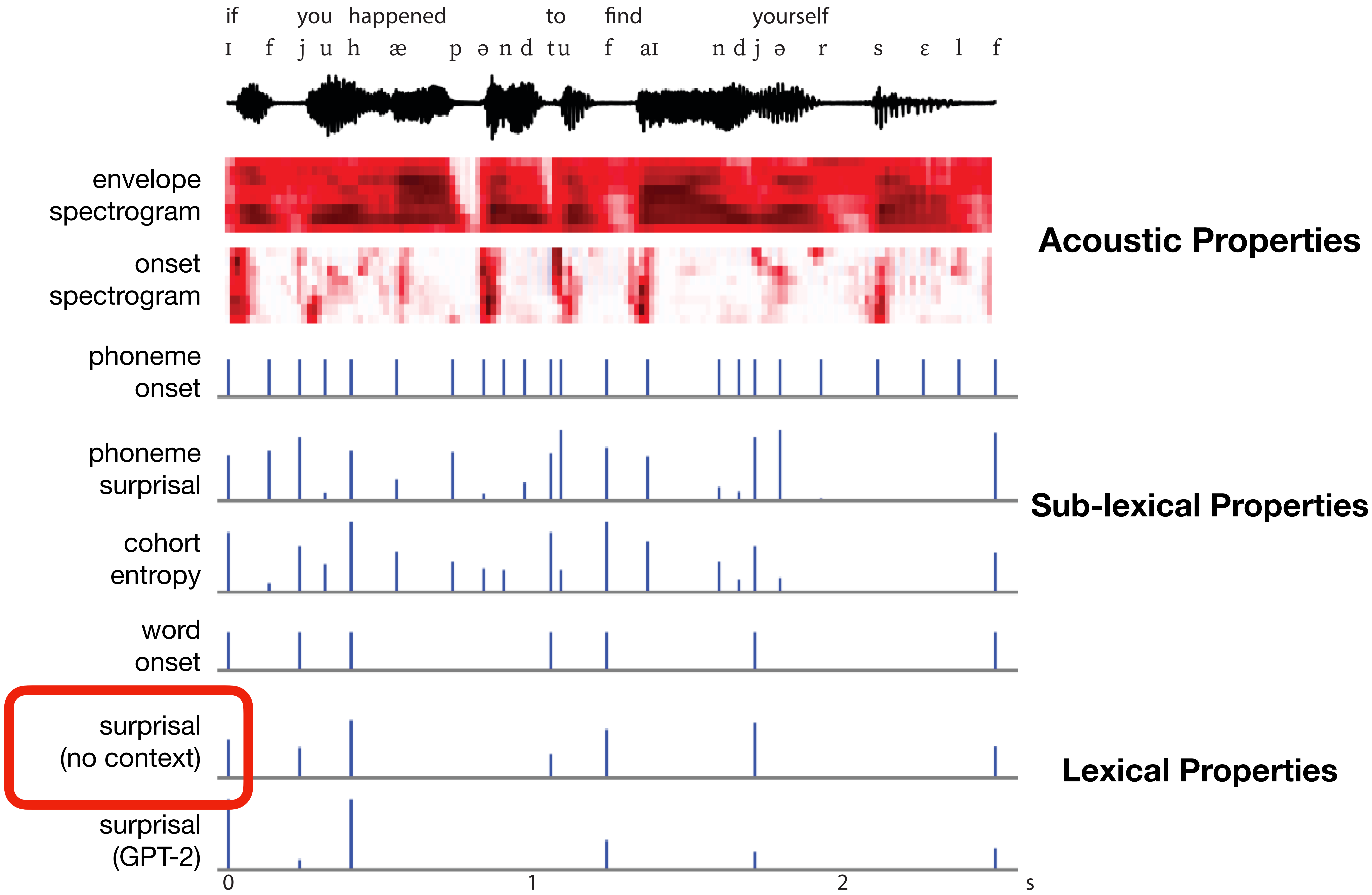




Speech Representations

Frequency of words based on SUBTLEX

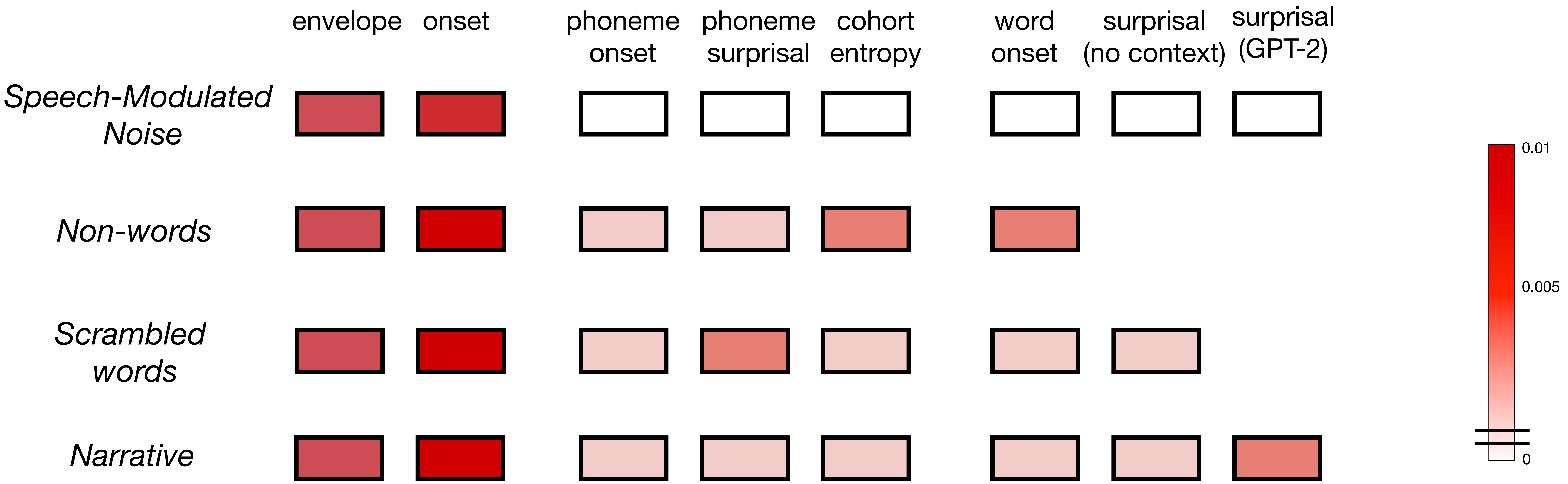




Speech Representations

Neural Prediction Results

Emergence of neural features as the incremental processing occur



- Acoustic features are encoded for both non-speech and speech stimuli
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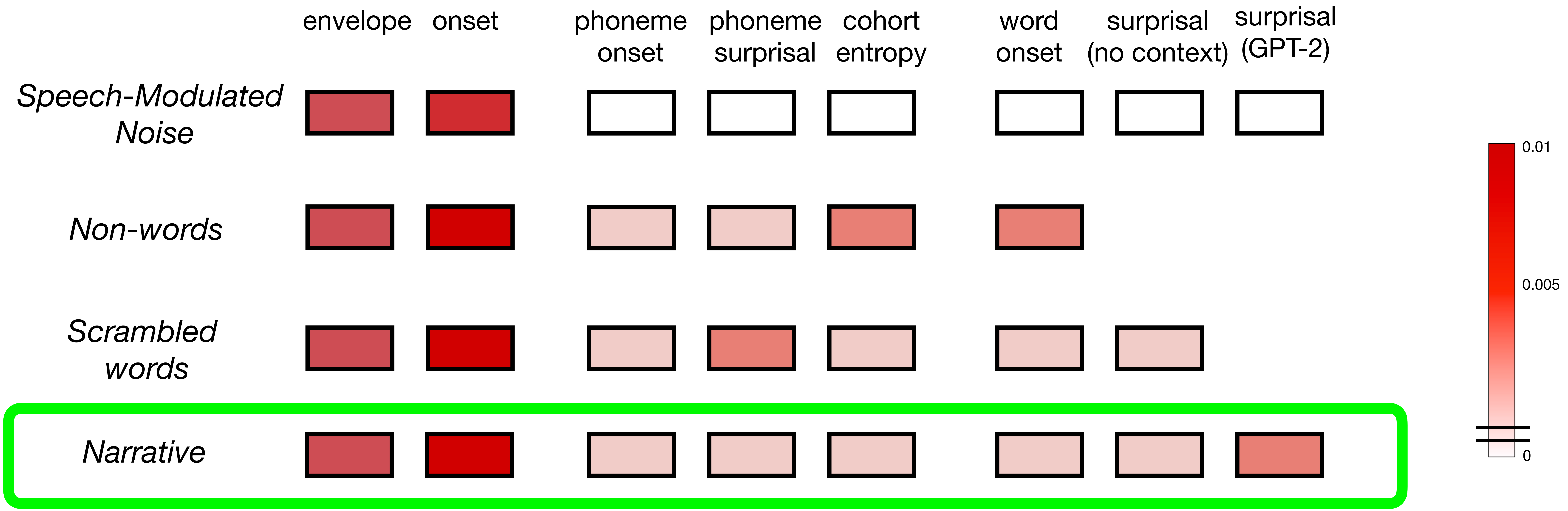

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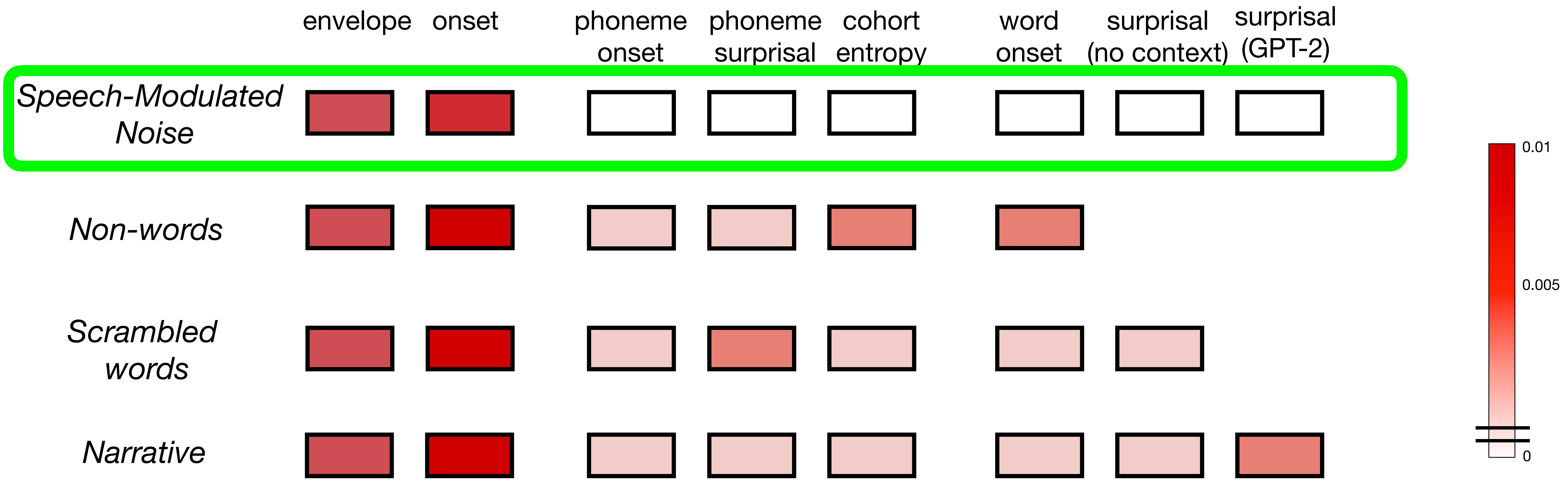

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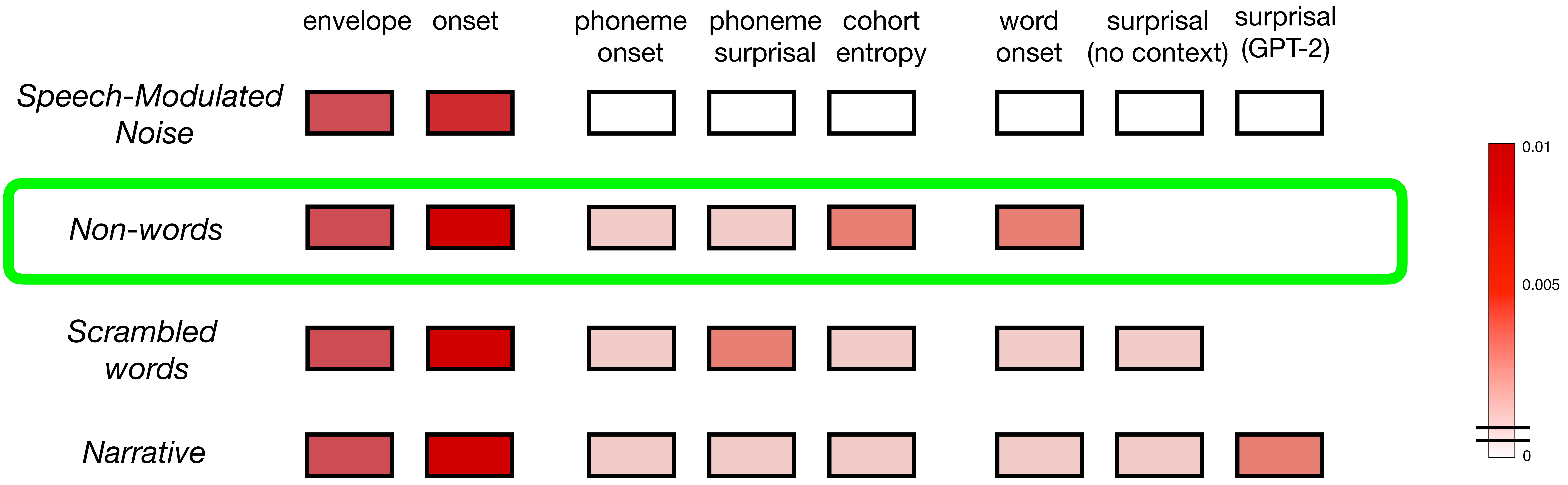

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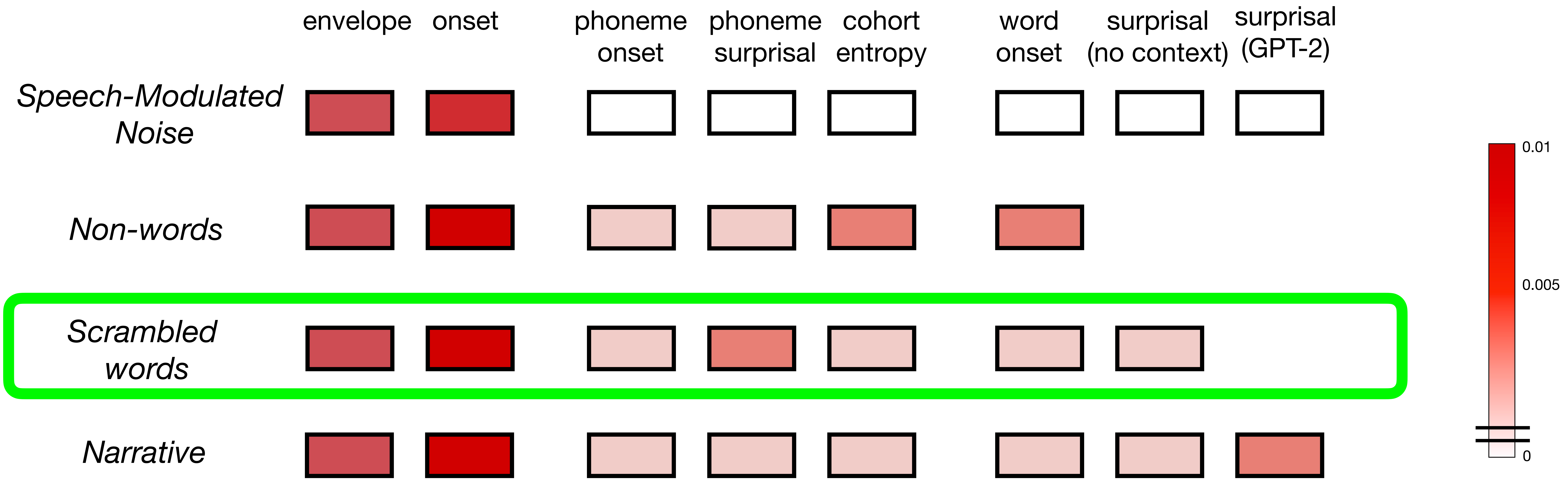

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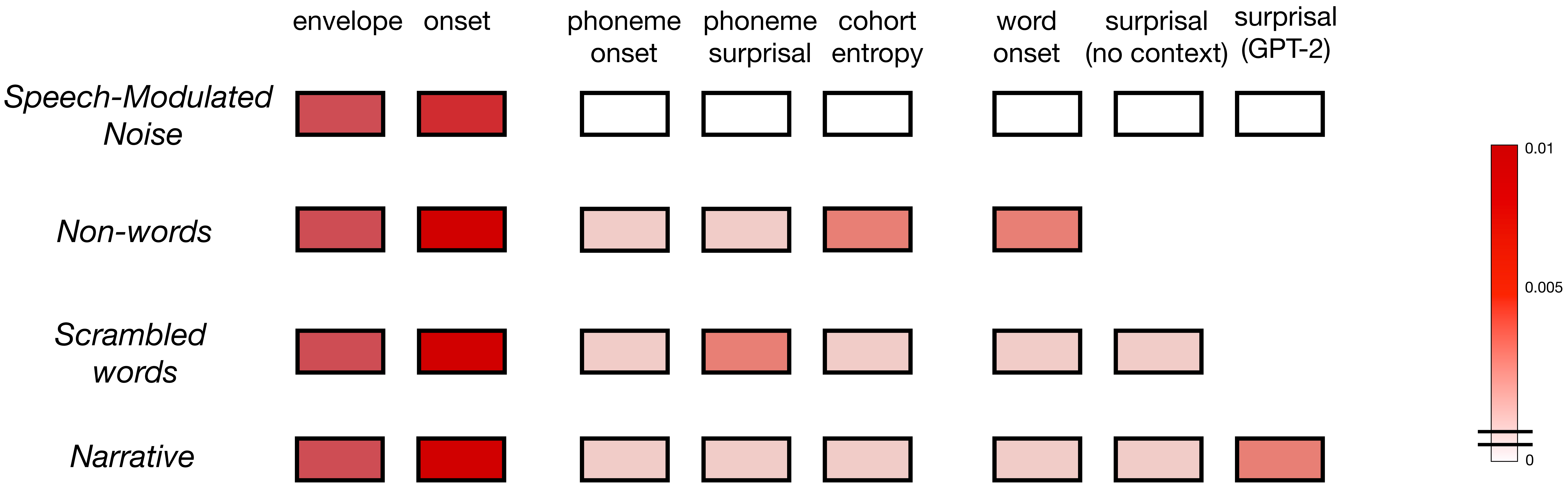

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Hemispheric Lateralization Results

<u>Speech feature</u>

Envelope Onset

Envelope

Phoneme Onset

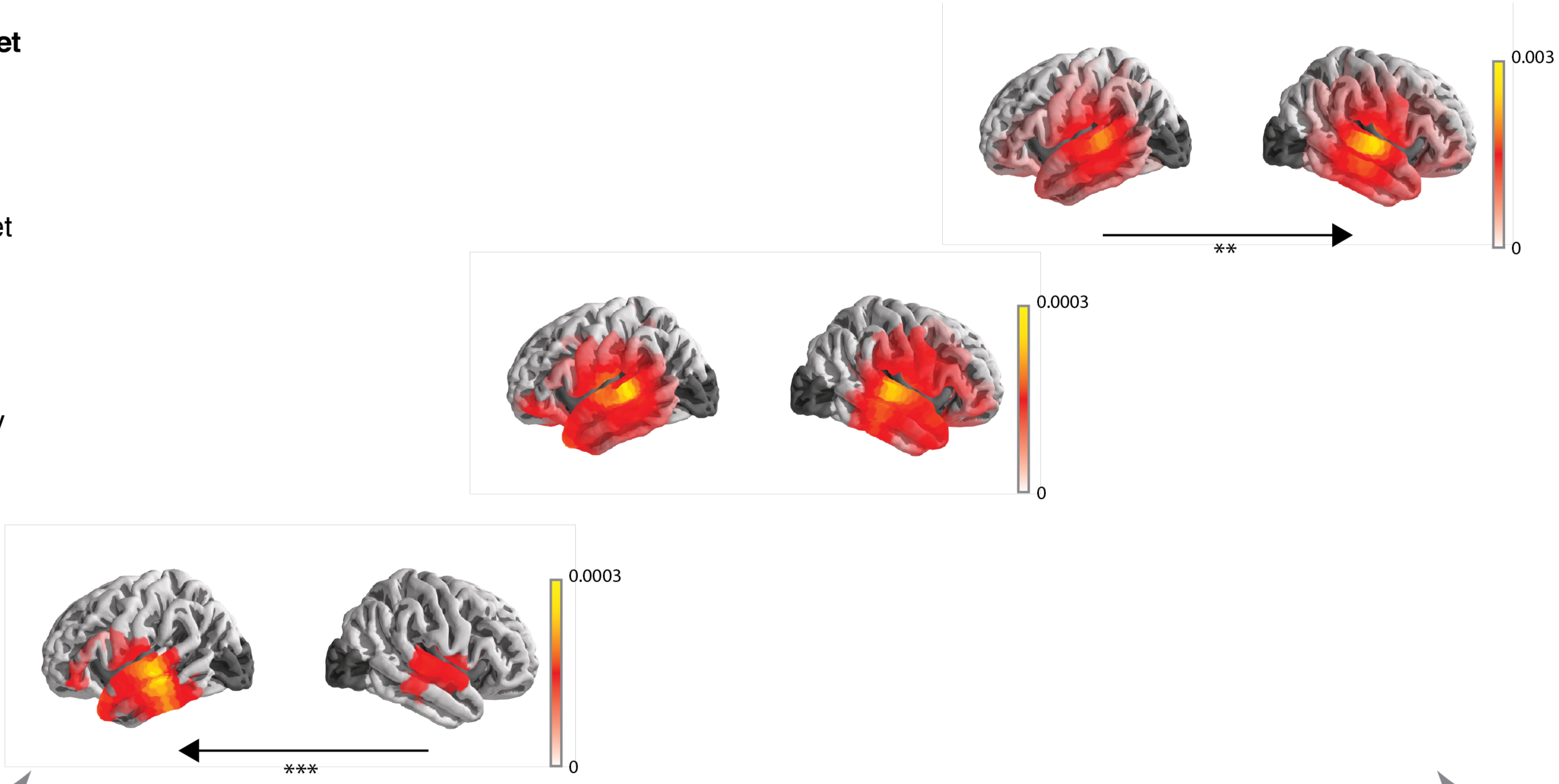
Phoneme Surprisal

Cohort Entropy

Word Onset

Unigram Surprisal

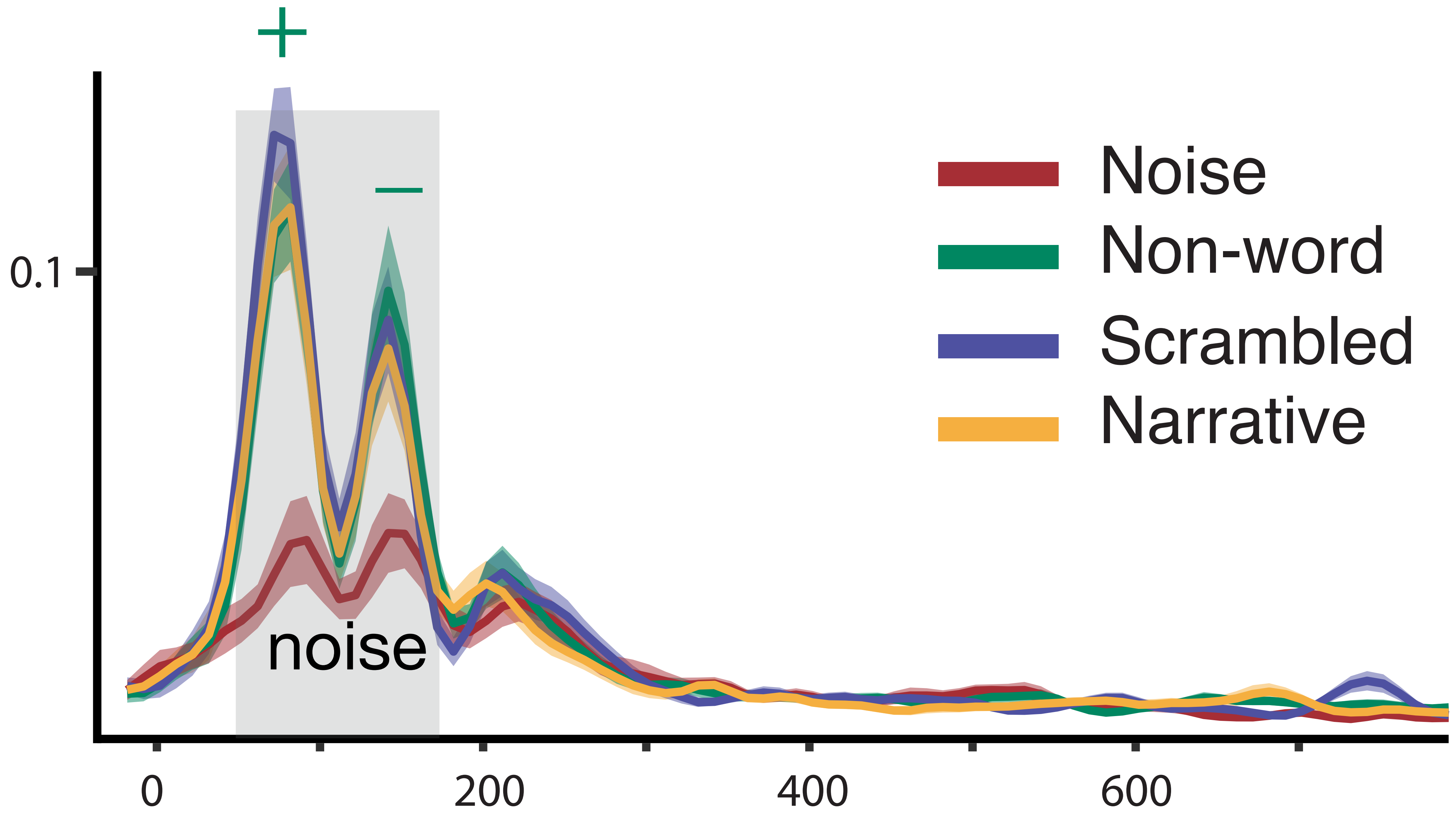
GPT2 Surprisal



Left Lateralized **Bilateral** **Right Lateralized**

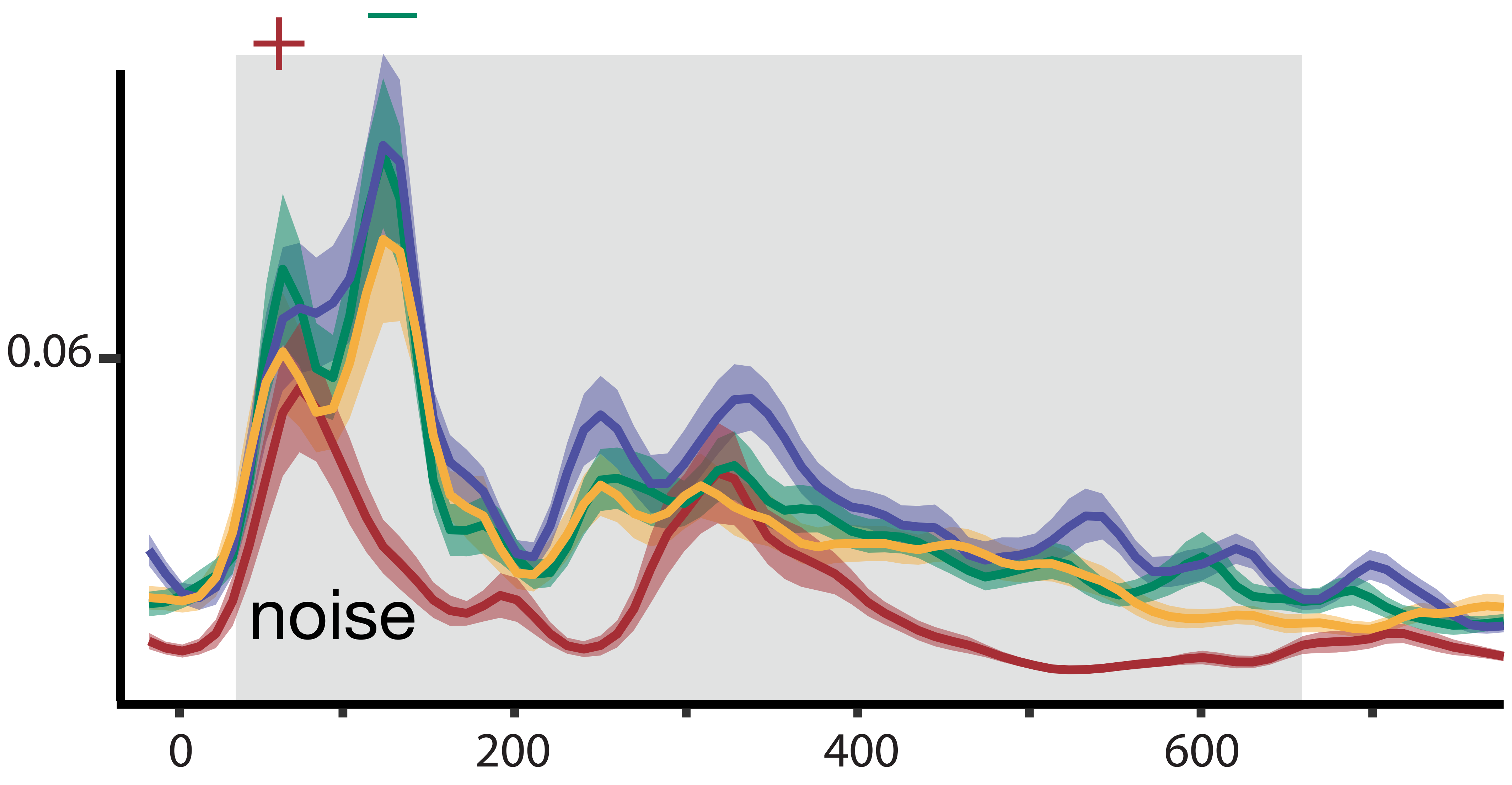
Acoustic TRF Results

acoustic onsets



- Speech responses > Noise response (all speech roughly equal)

acoustic envelope



- Speech responses > Noise response (Narrative < Scrambled)
- Non words similar to Scrambled words
- Noise response lacks 2nd peak ~120 ms

right hemisphere shown
(condition-sensitive differences similar in left)

Acoustic TRF Results

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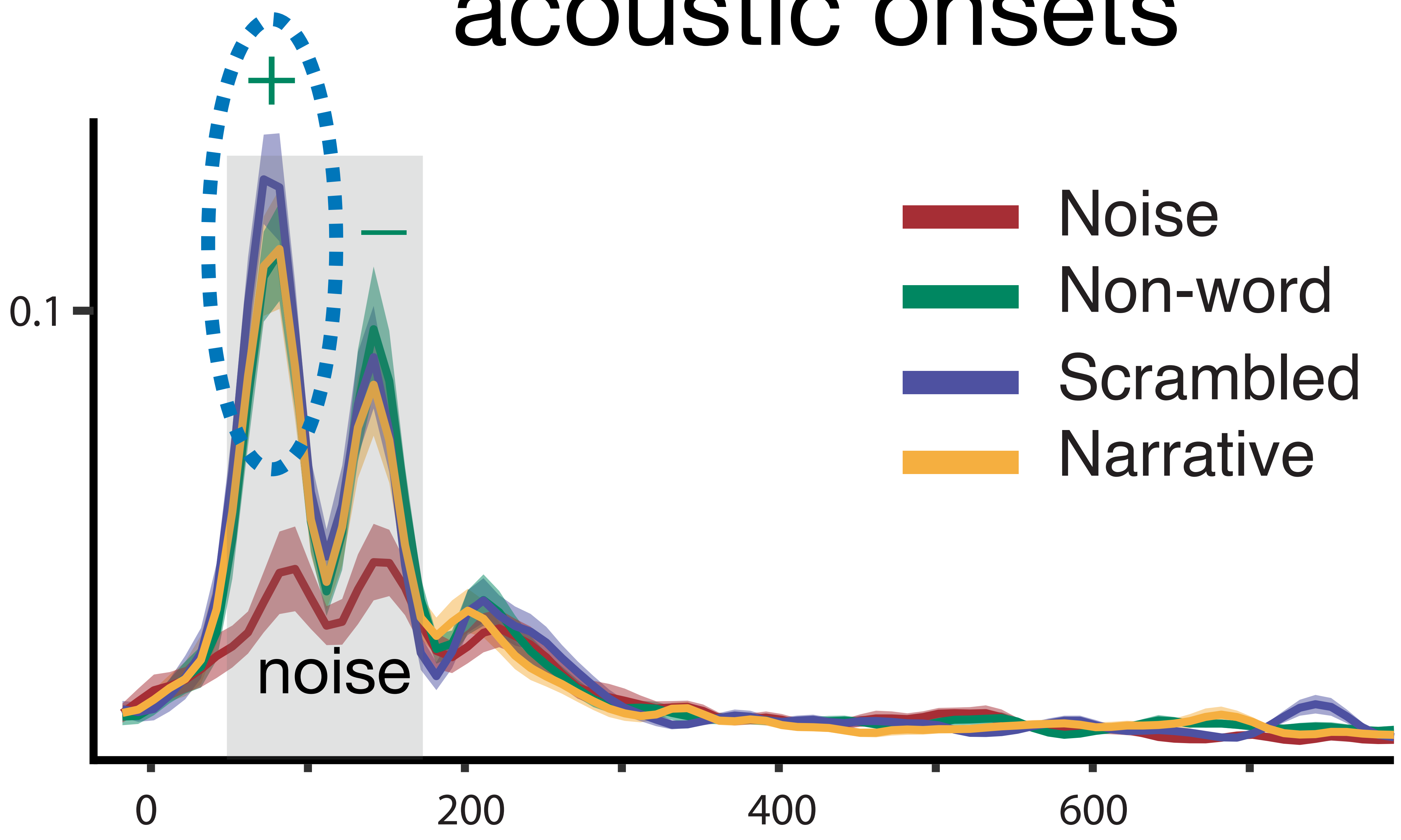

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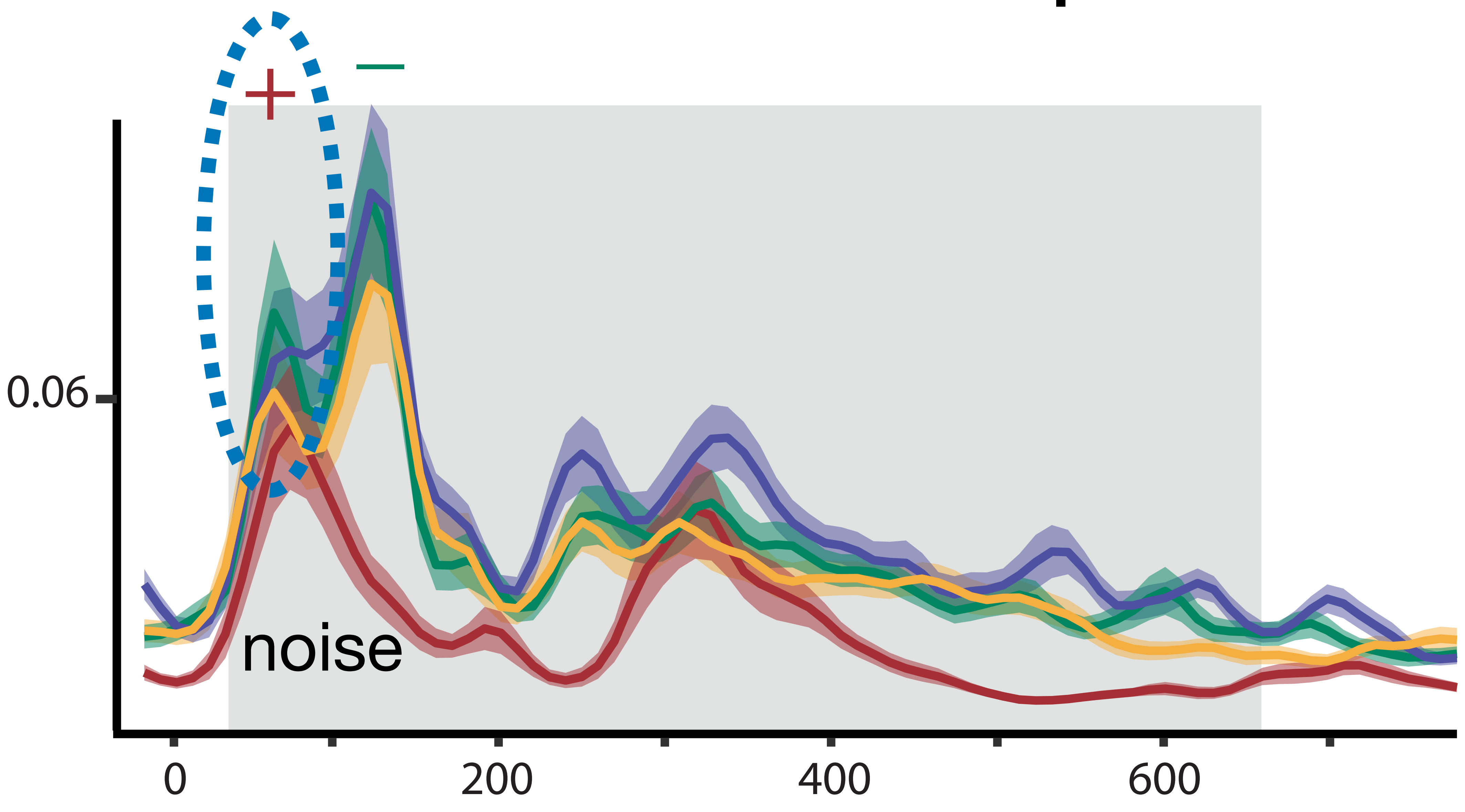

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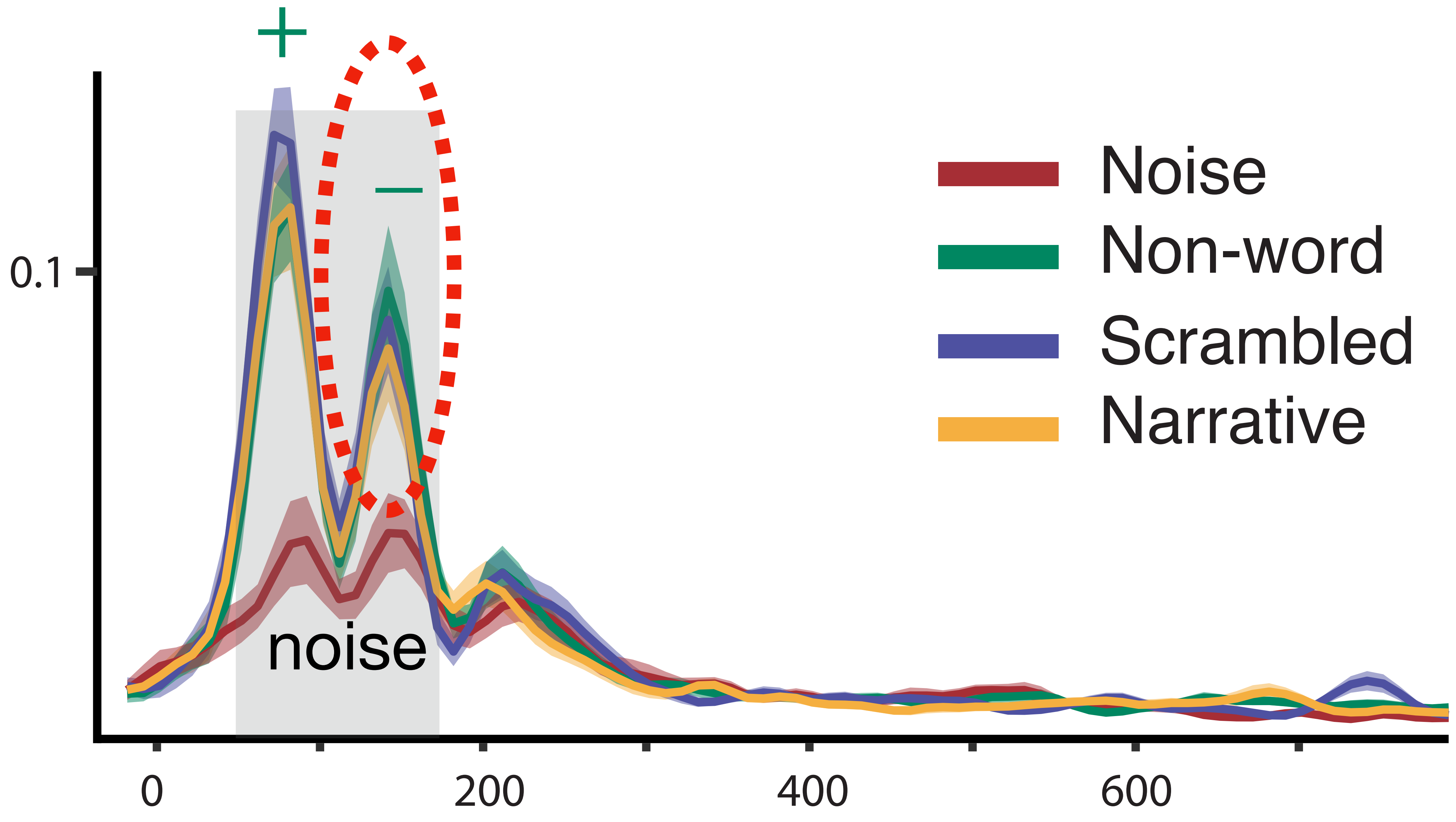

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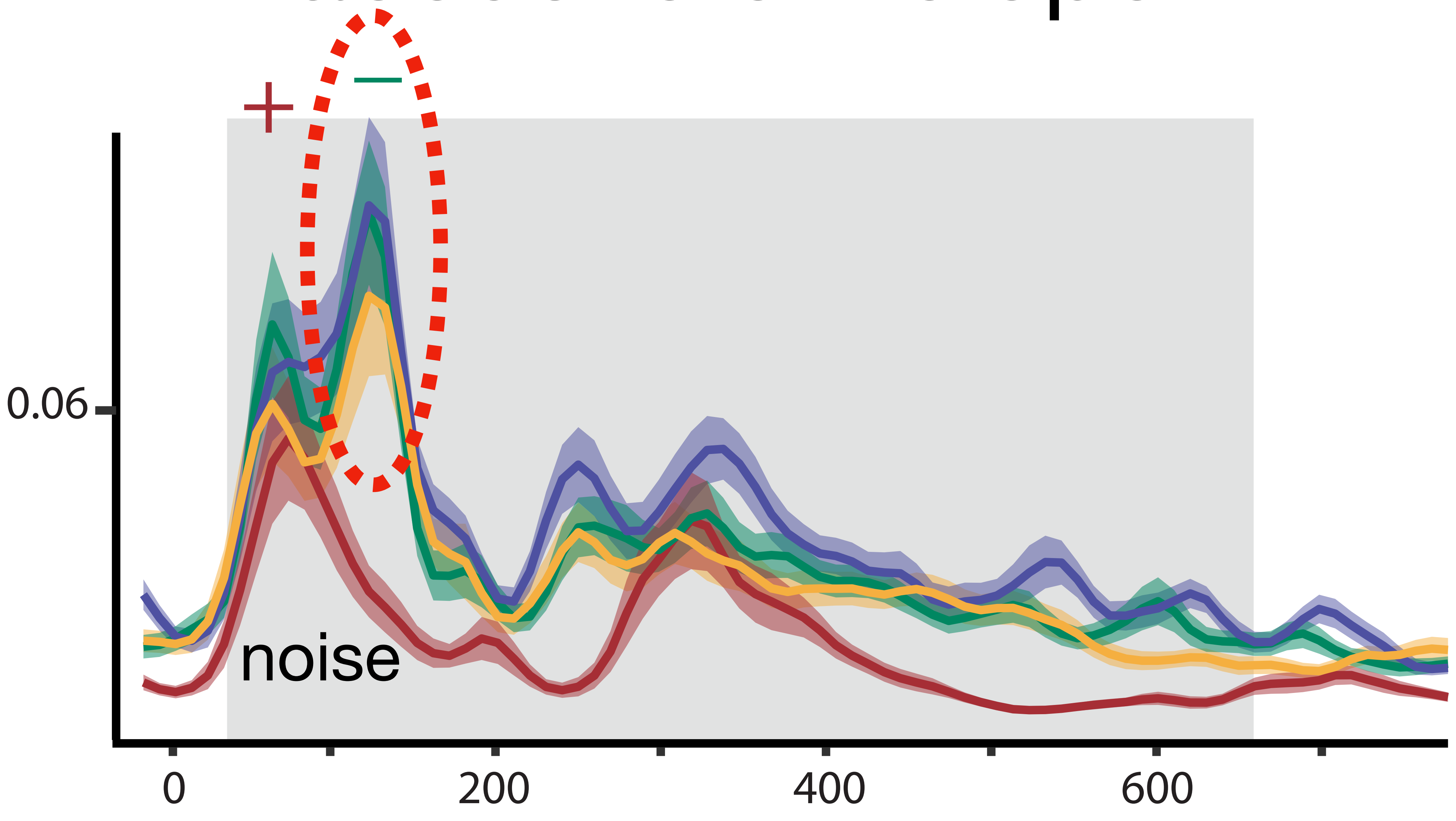

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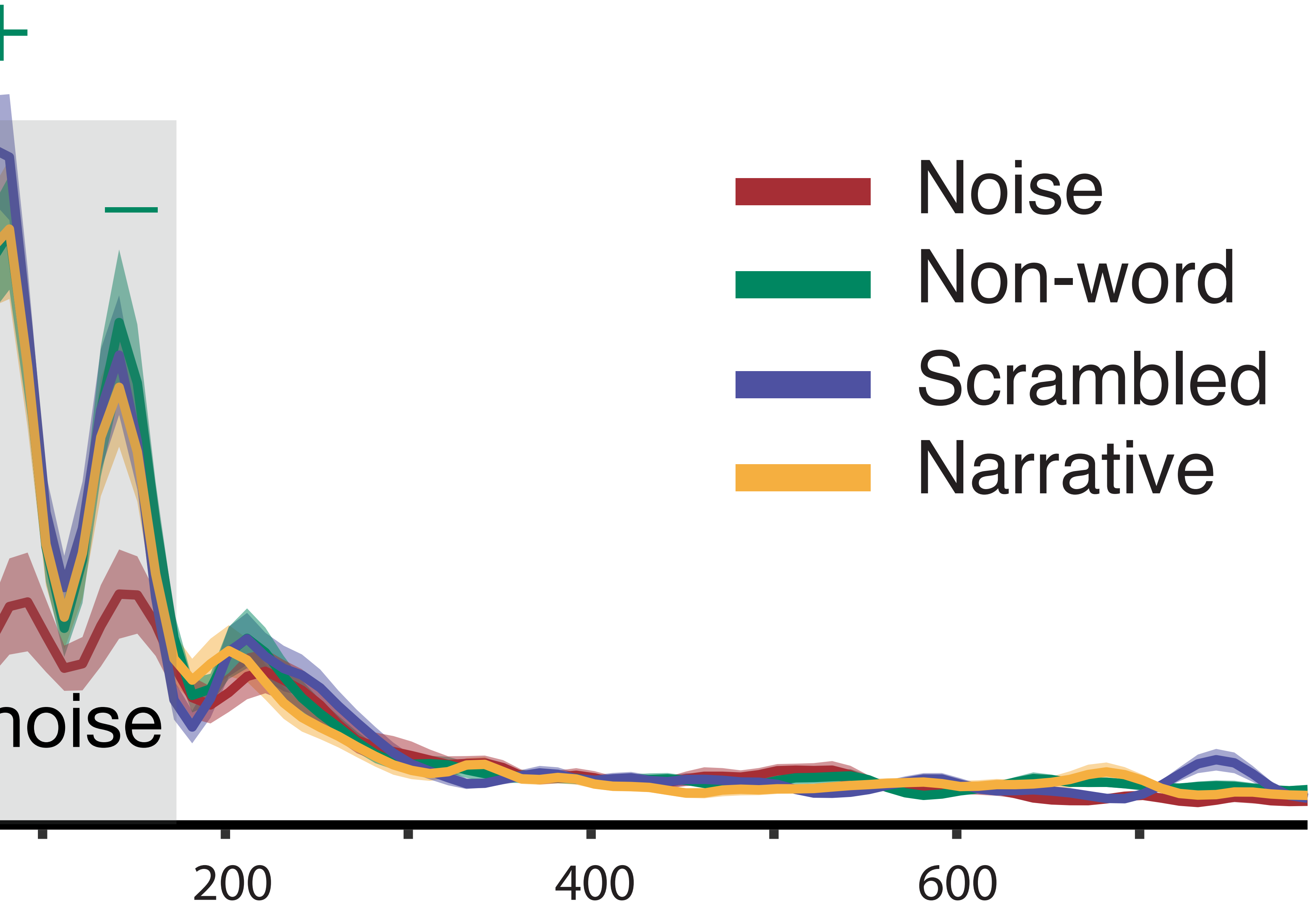

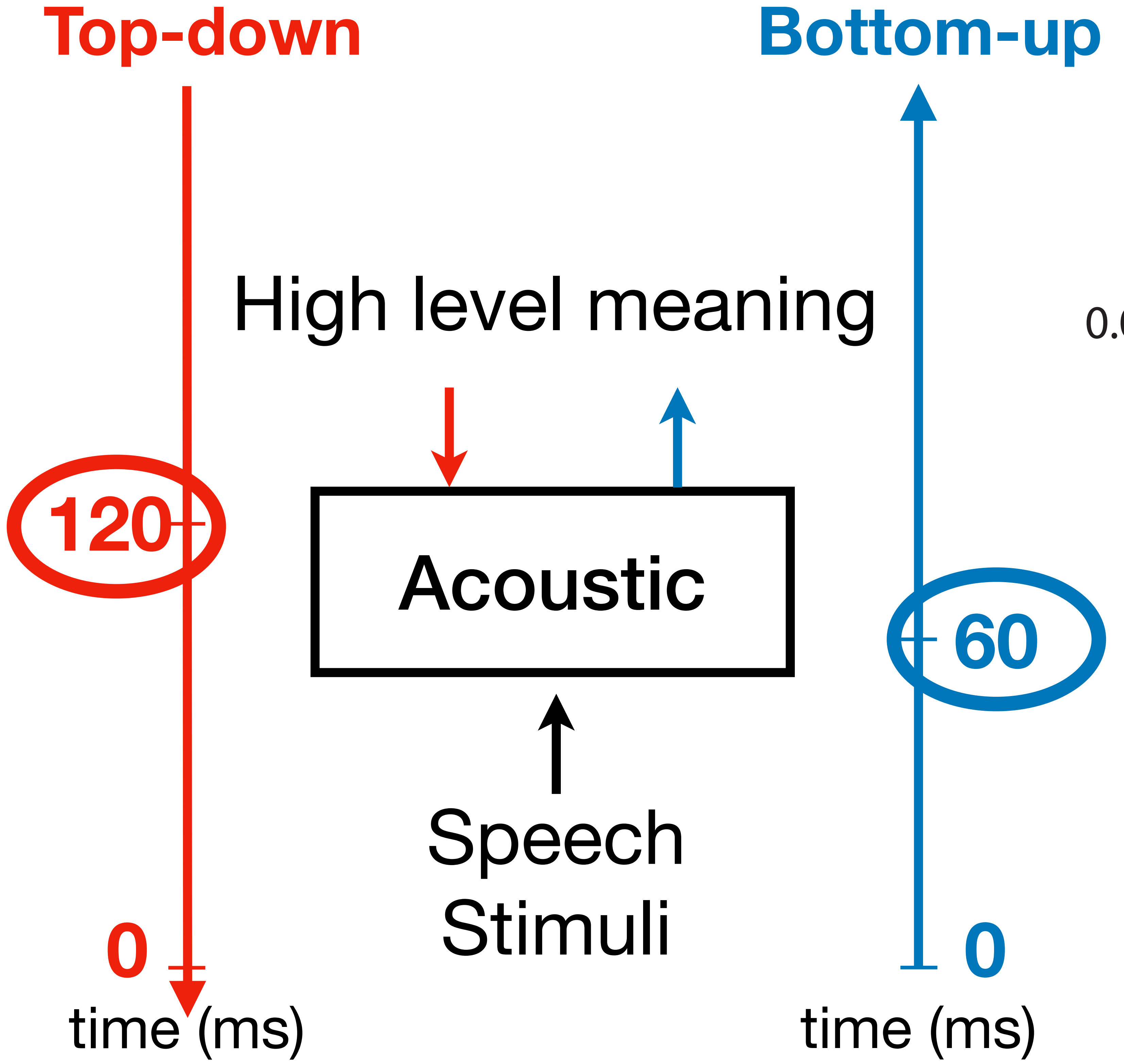

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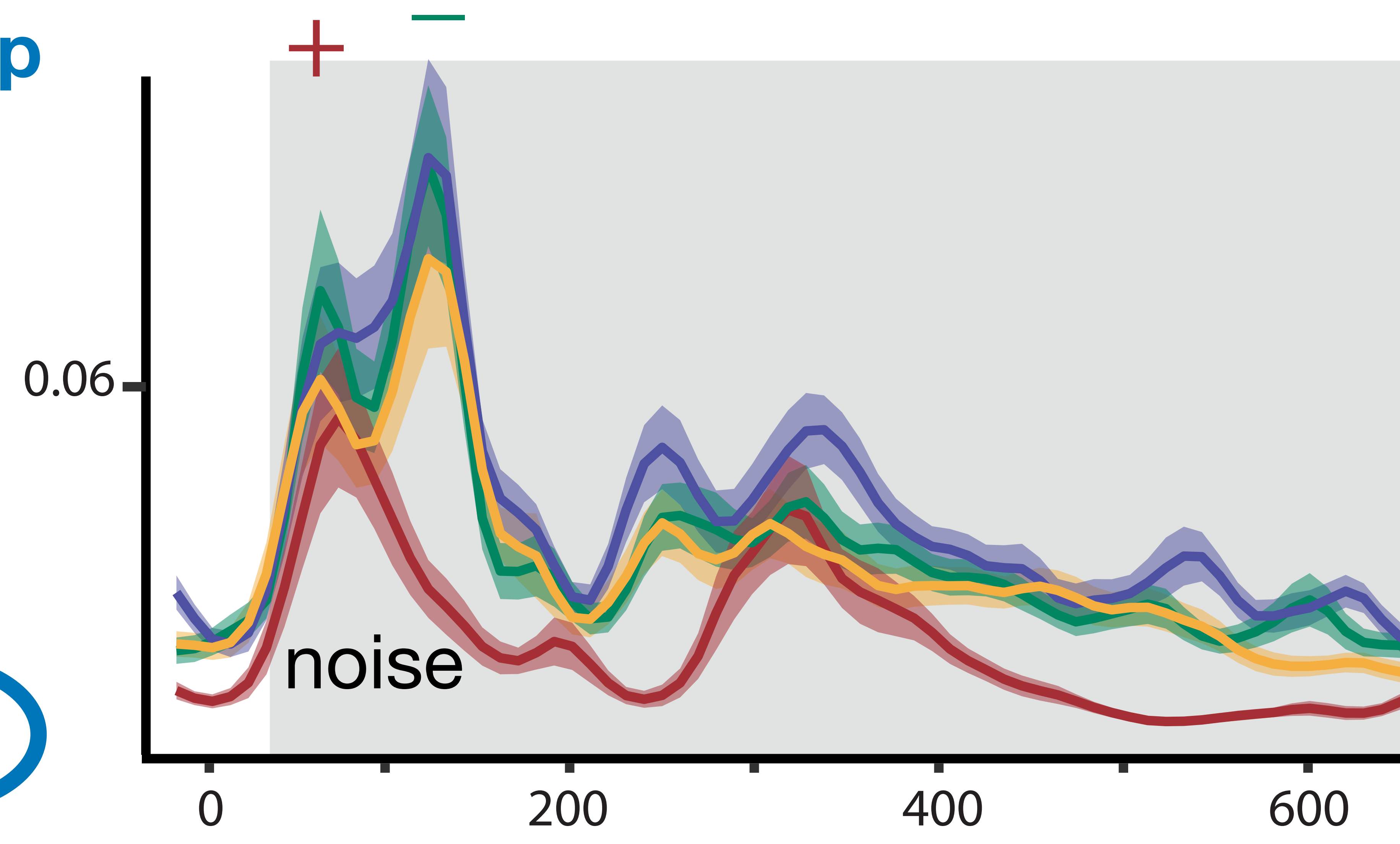

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Phonemic TRF Results

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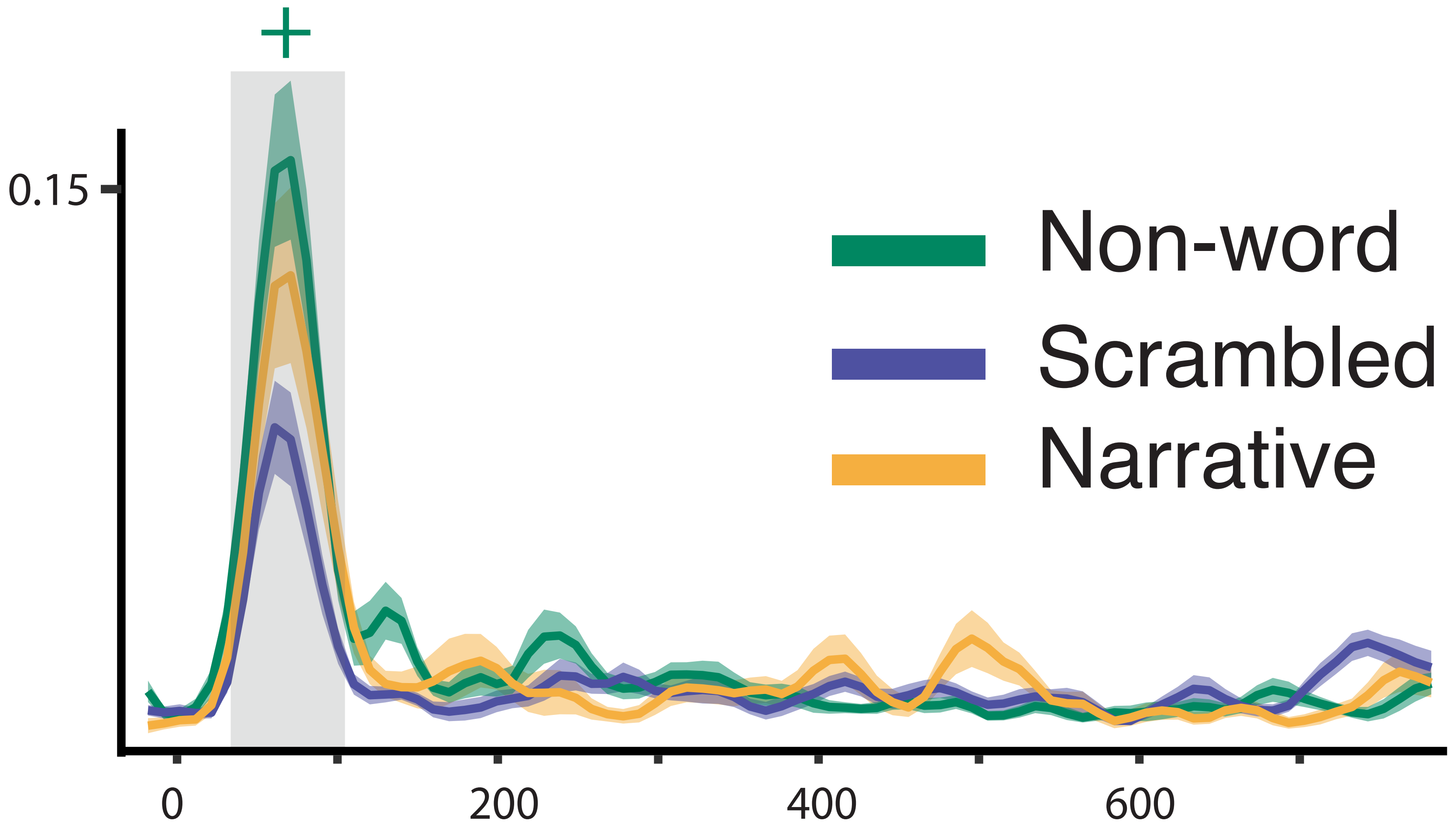
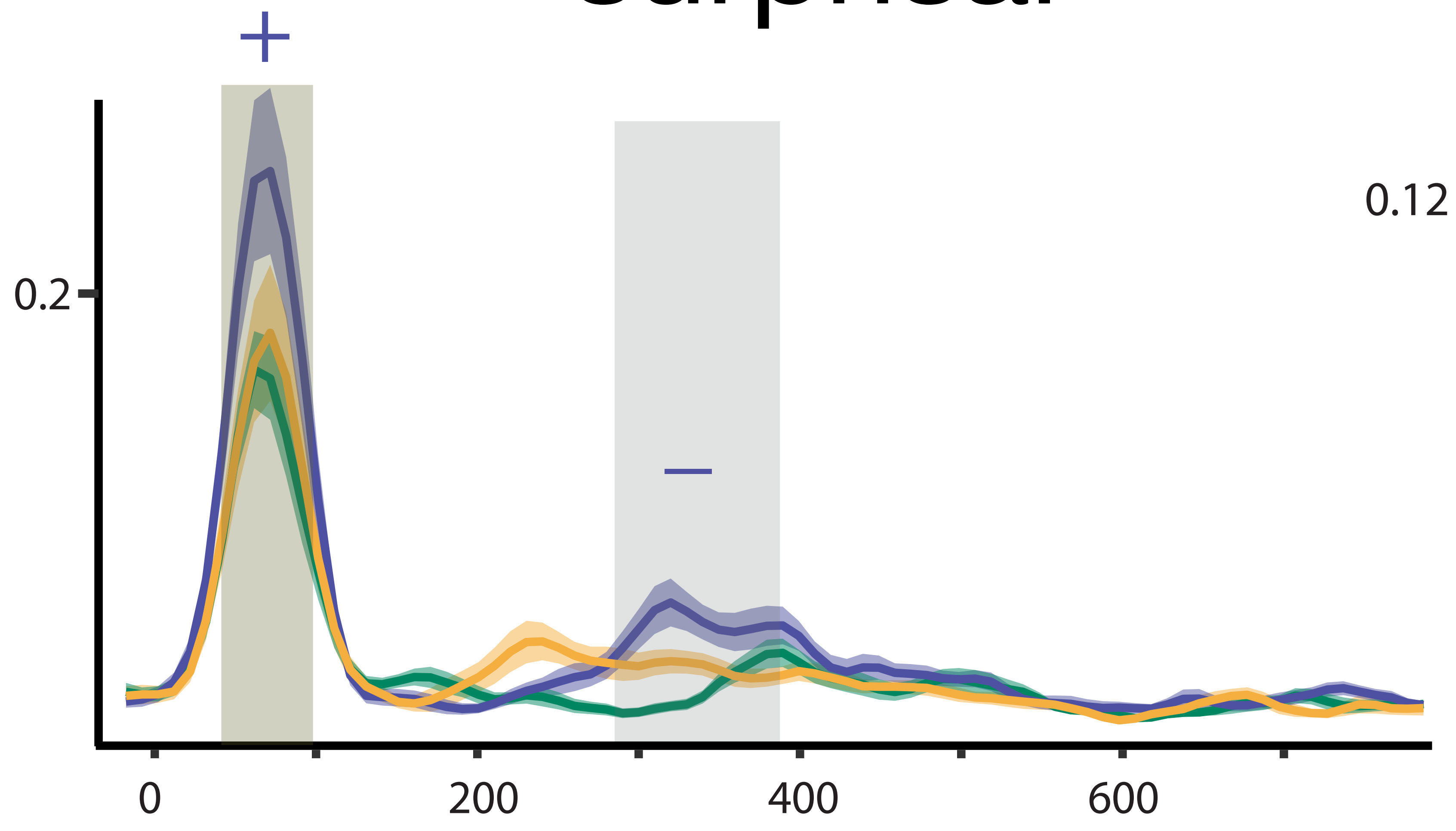
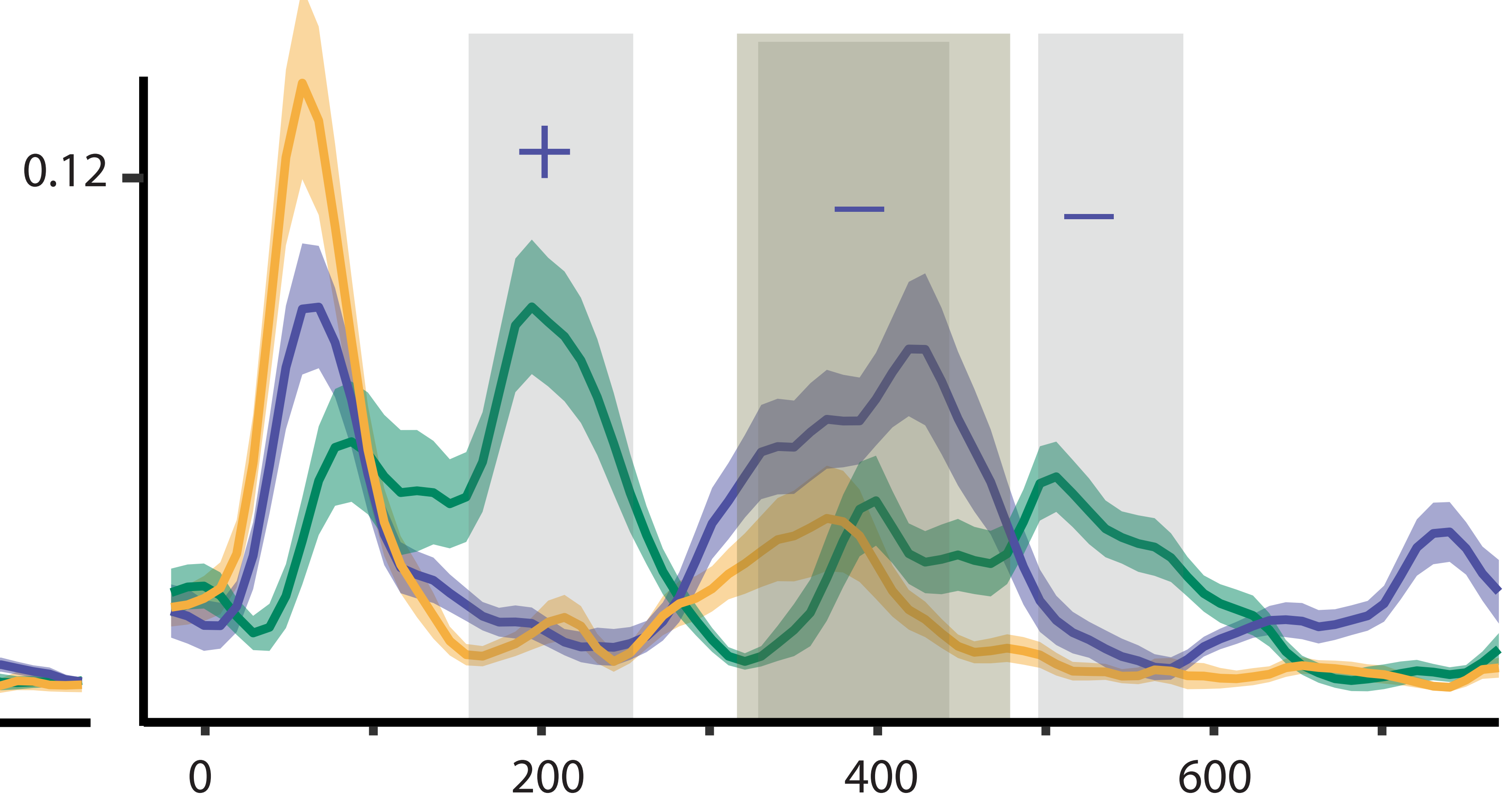


phoneme surprisal



cohort entropy



- Non-words largest
- No later processing

- Early phone processing ~80 ms (scrambled > narrative)
- Late phone processing ~350 ms) (words > non-words)

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- Additional/delayed peaks in non-words (difference in stimulus distributions)

left hemisphere shown (right similar)

Phonemic TRF Results

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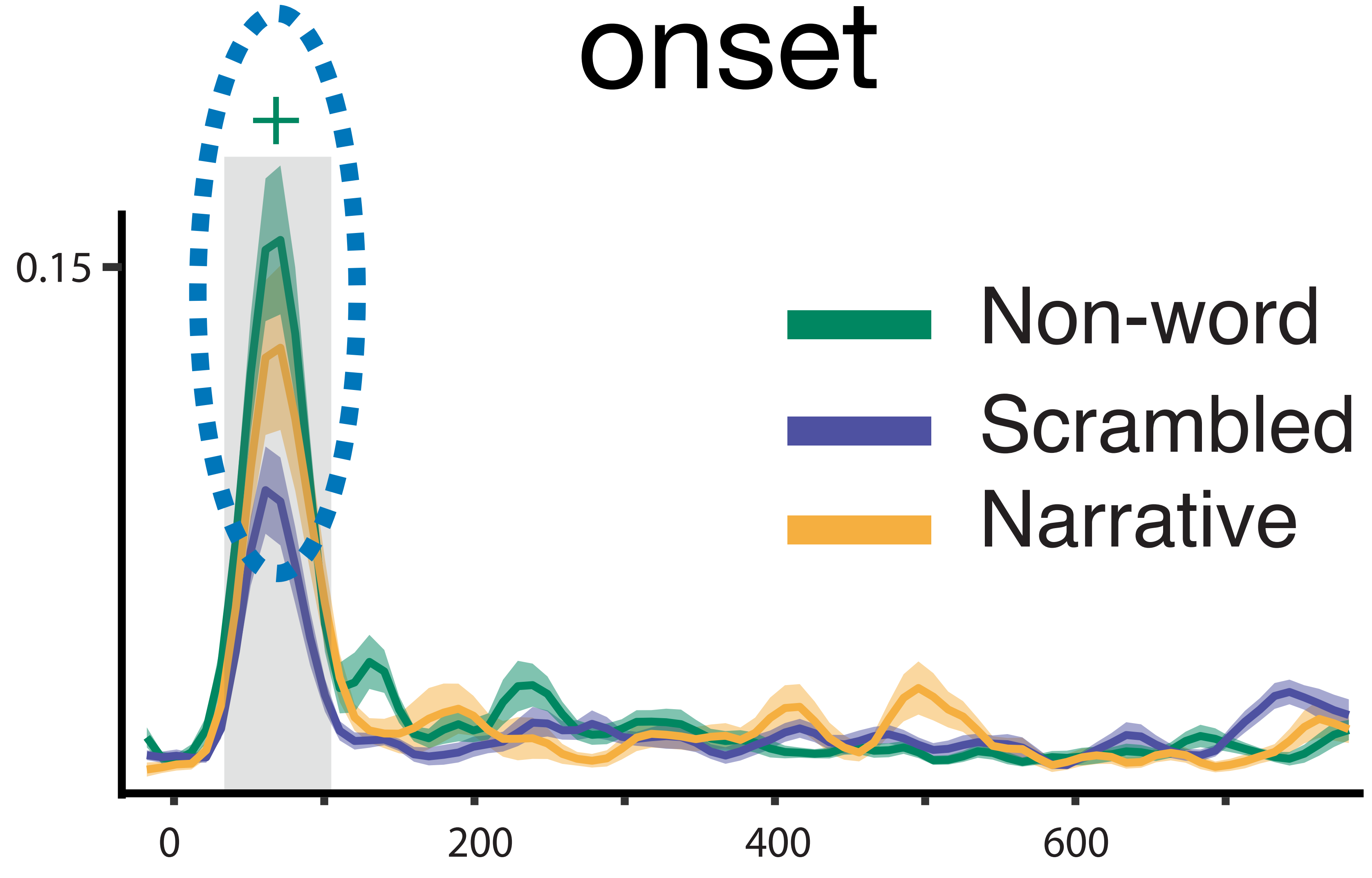

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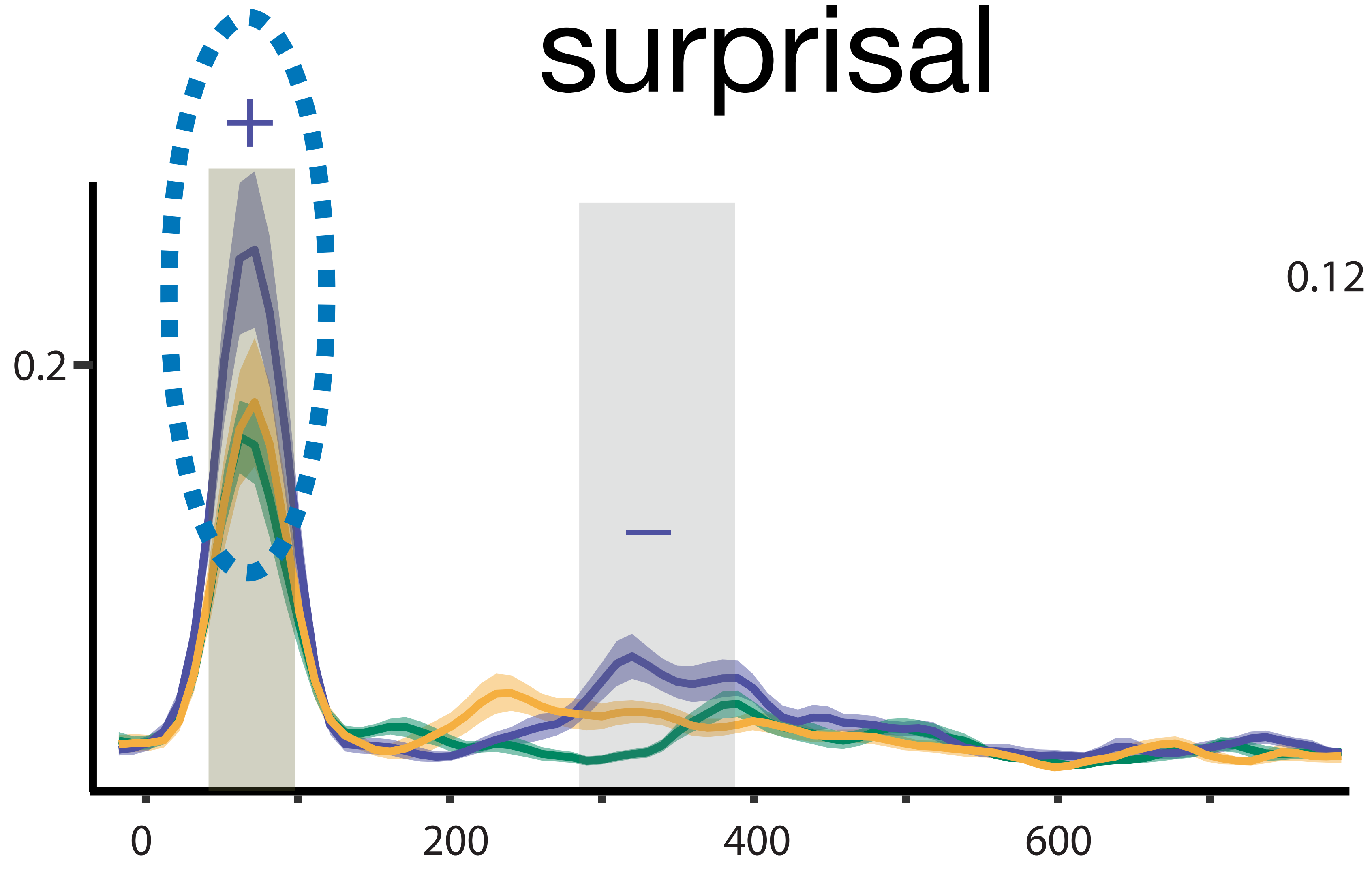

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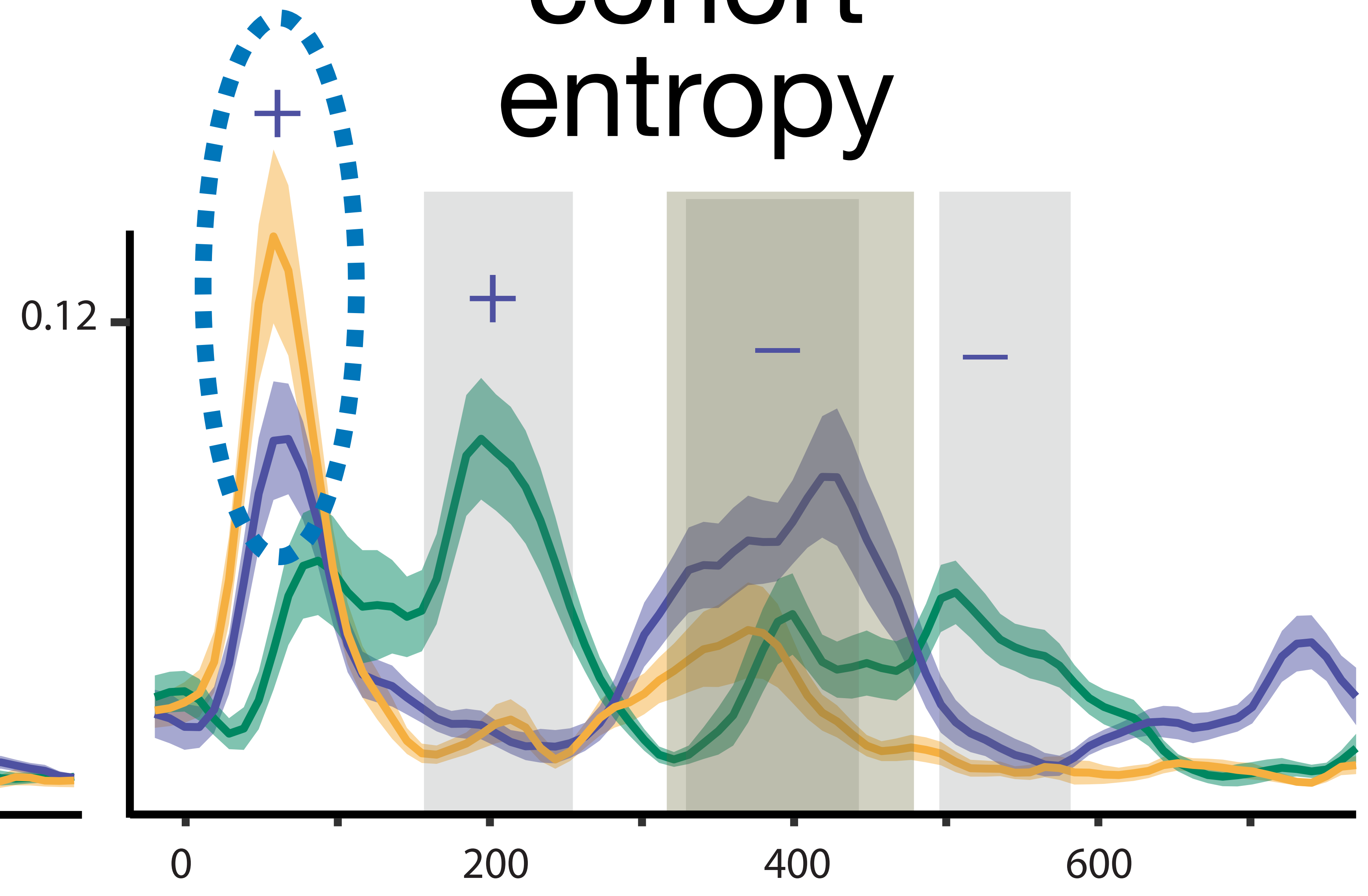

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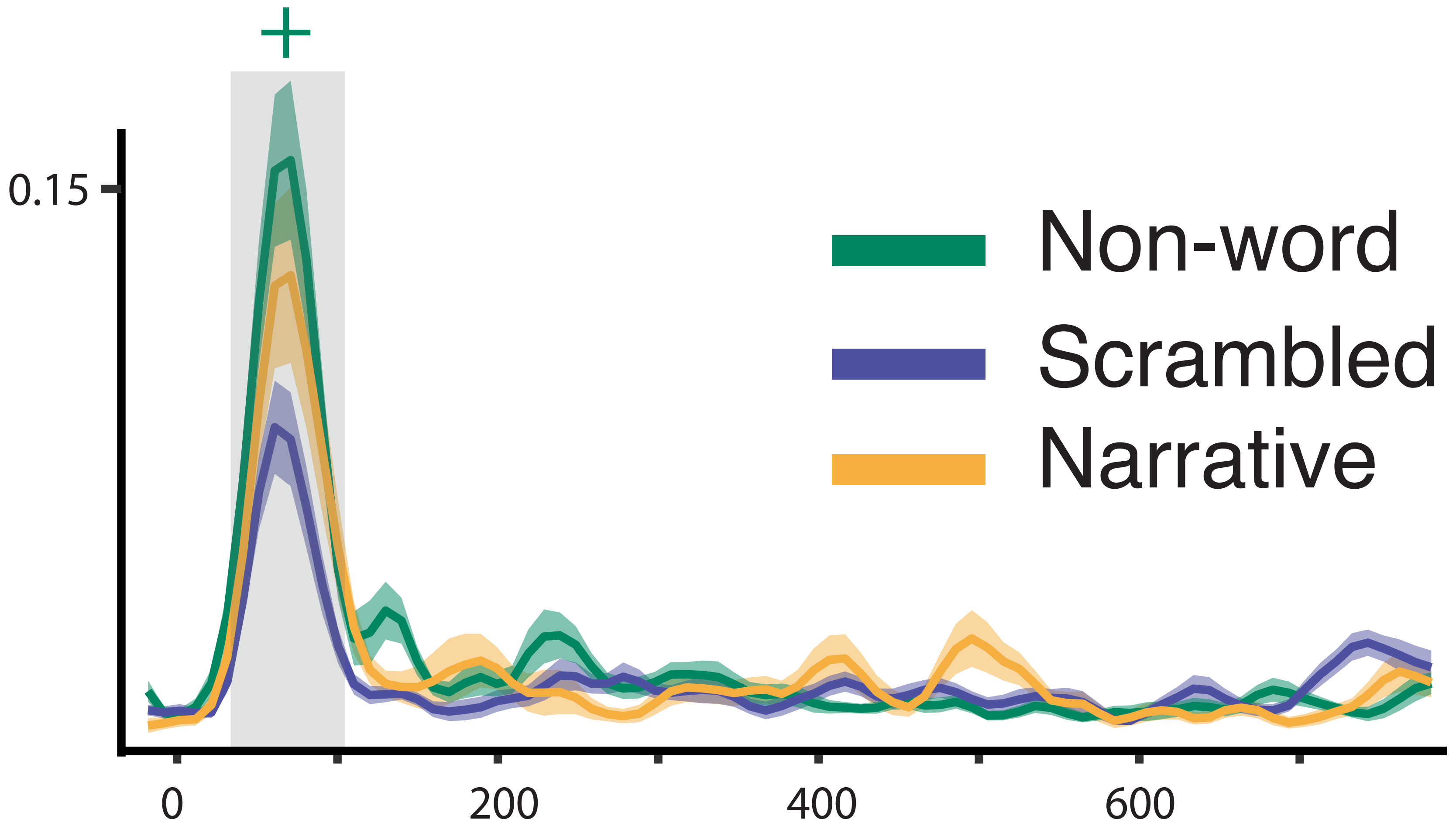

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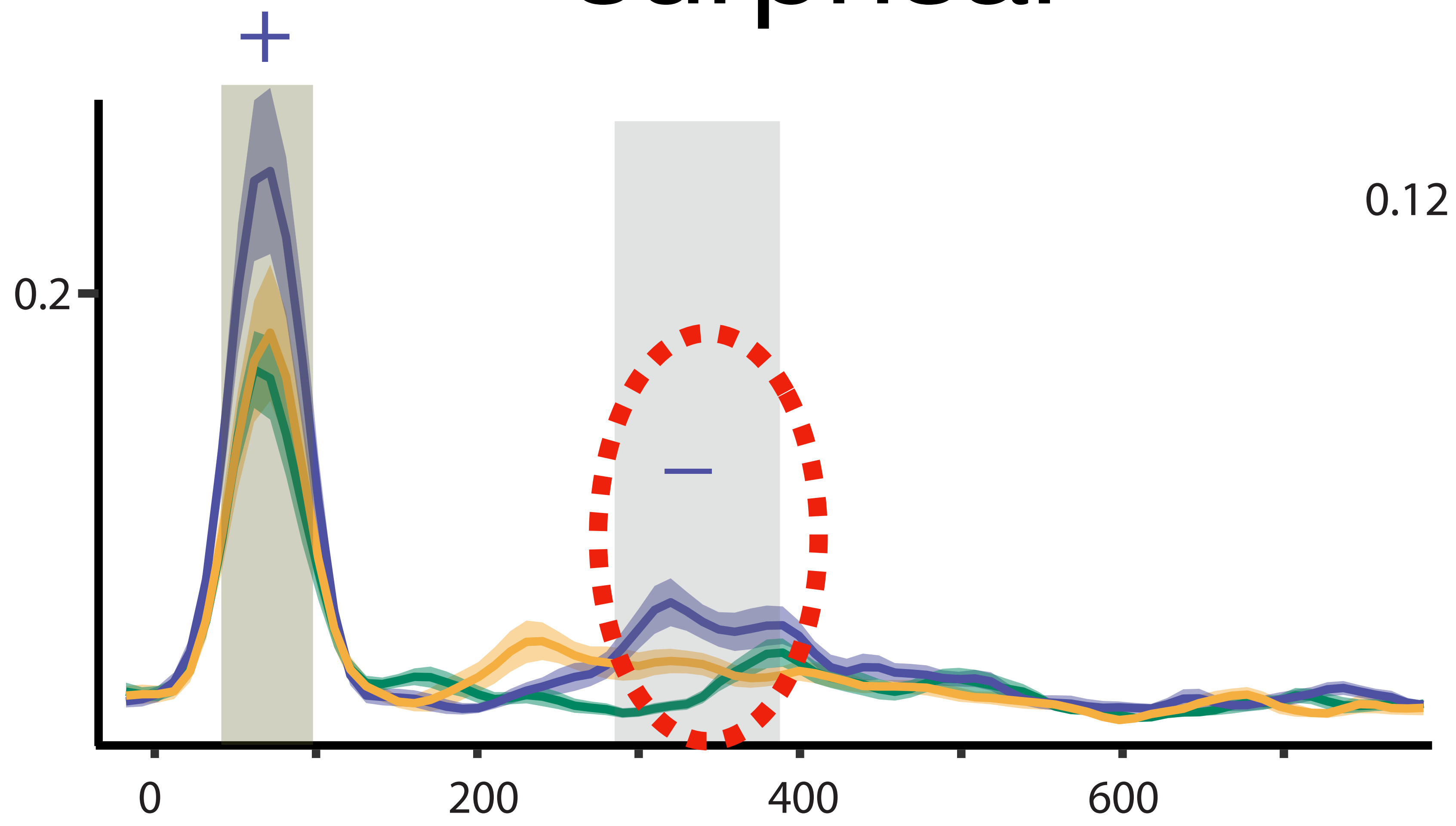

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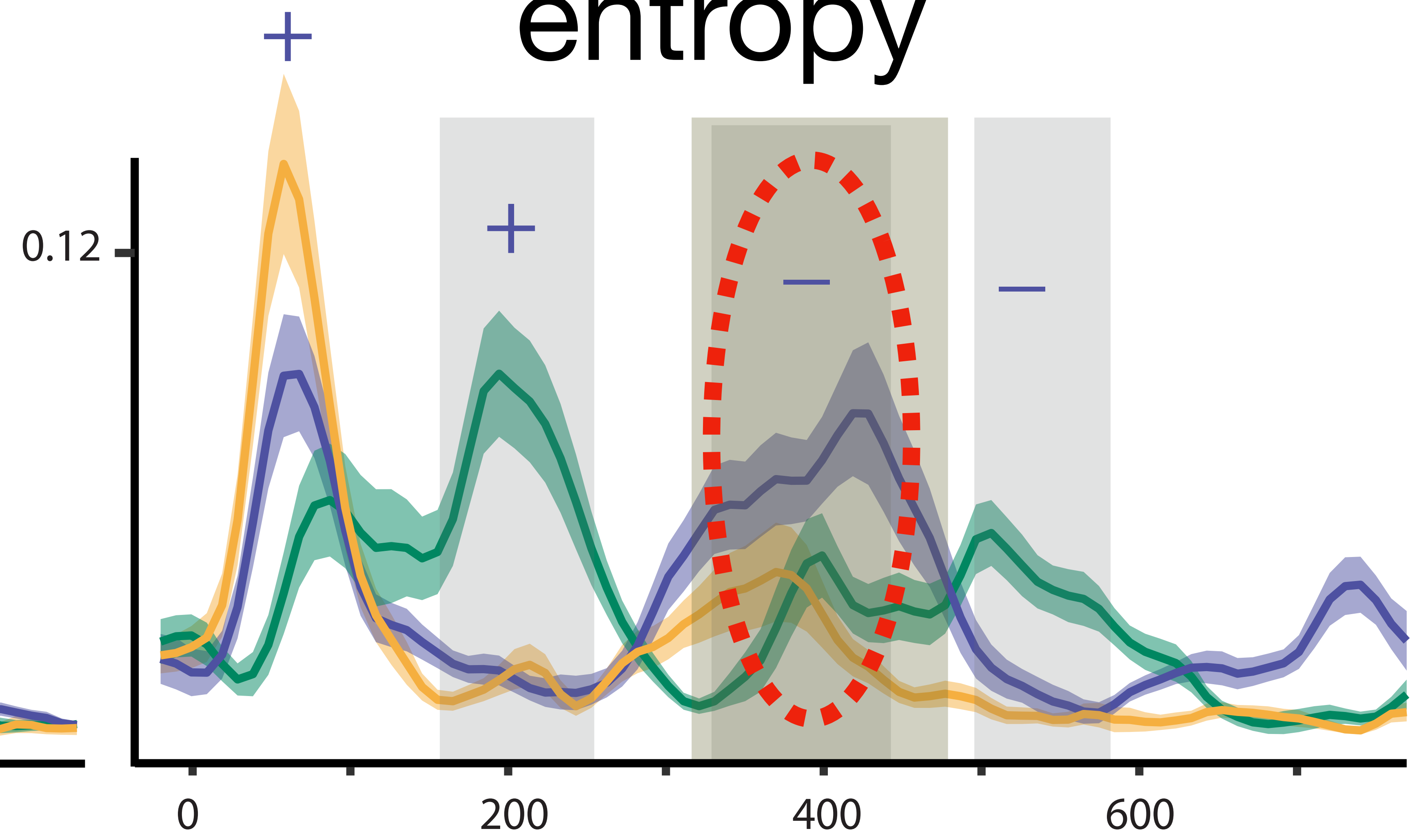

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phoneme onset | phoneme surprisal | cohort entropy

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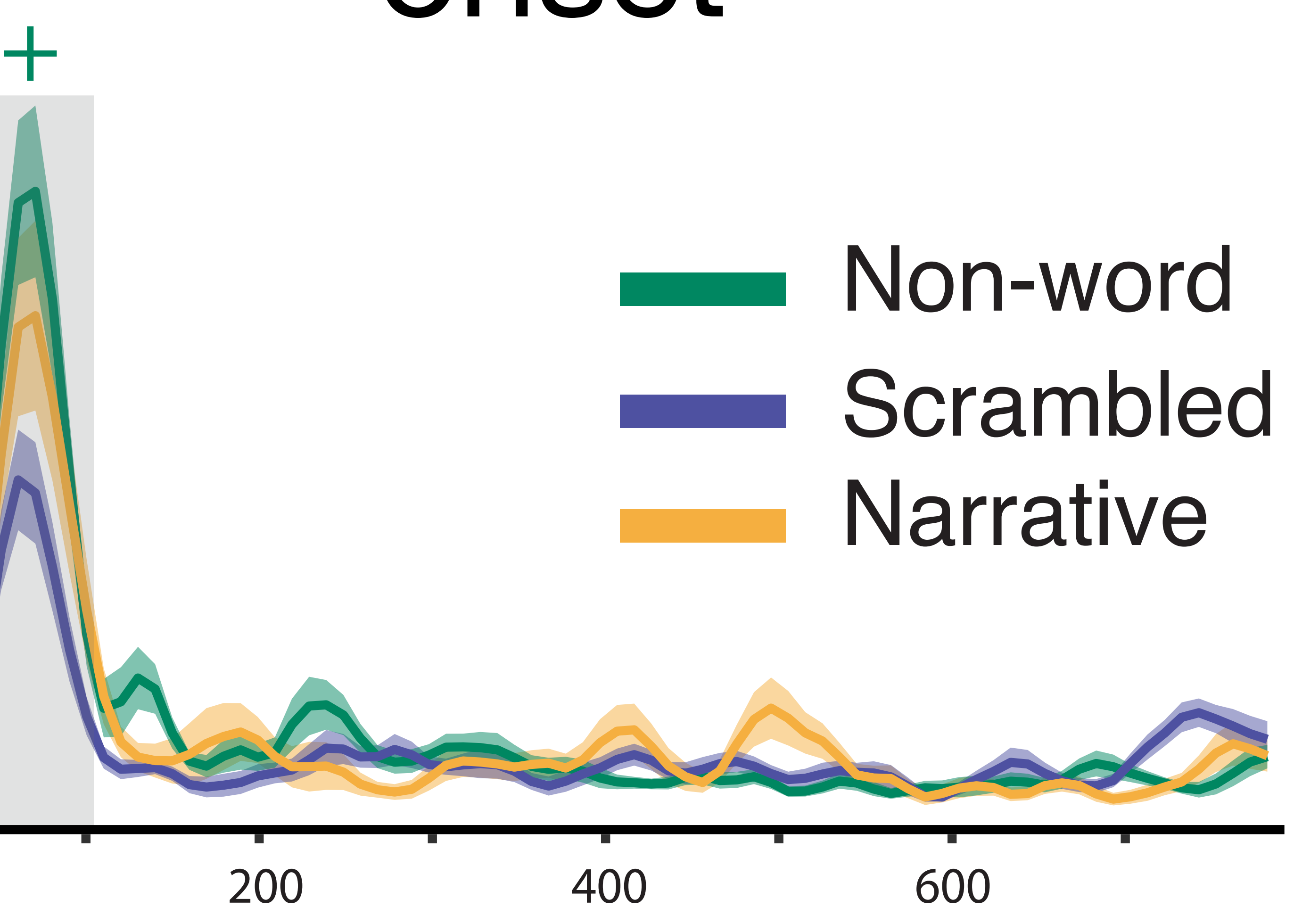

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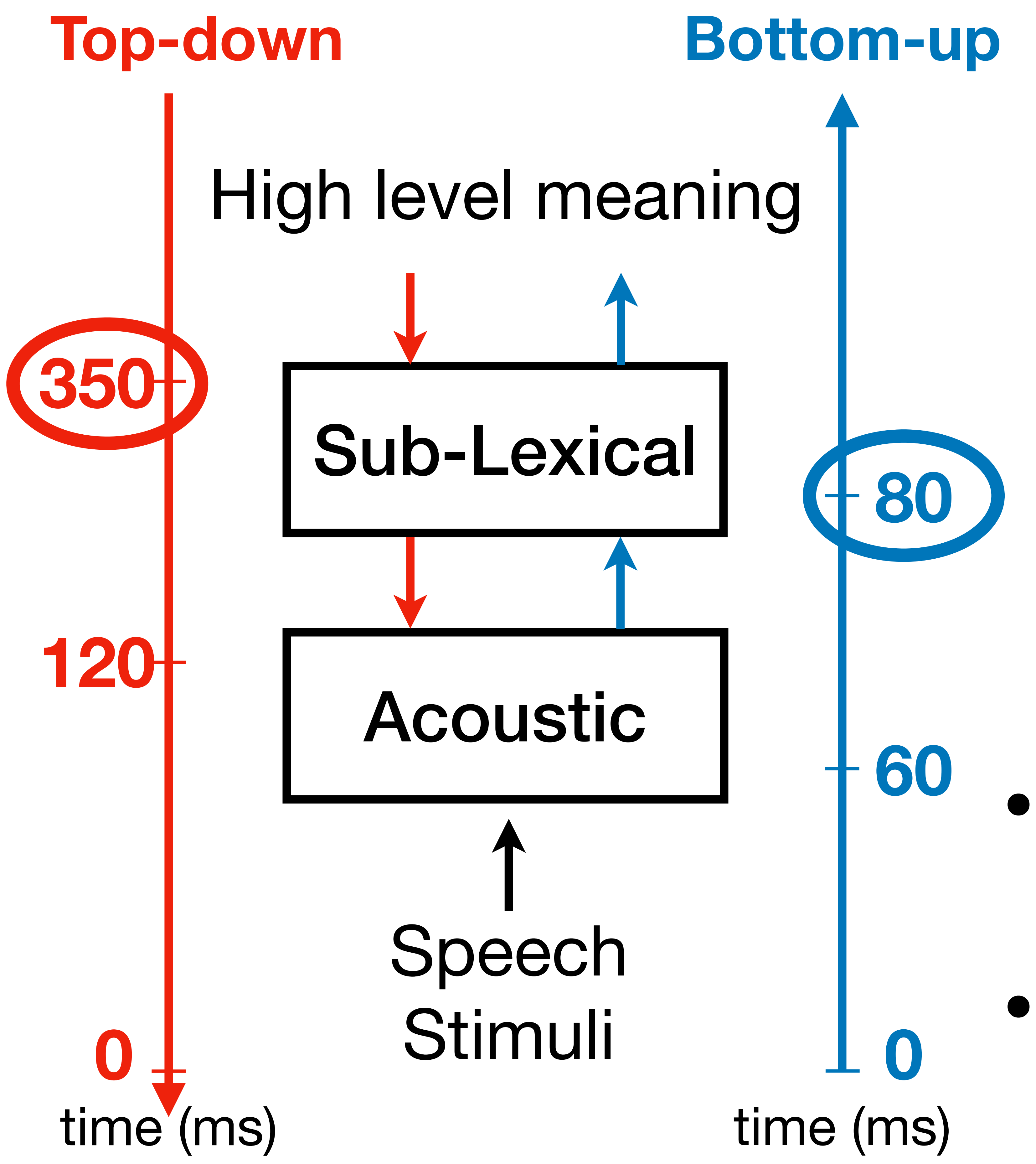

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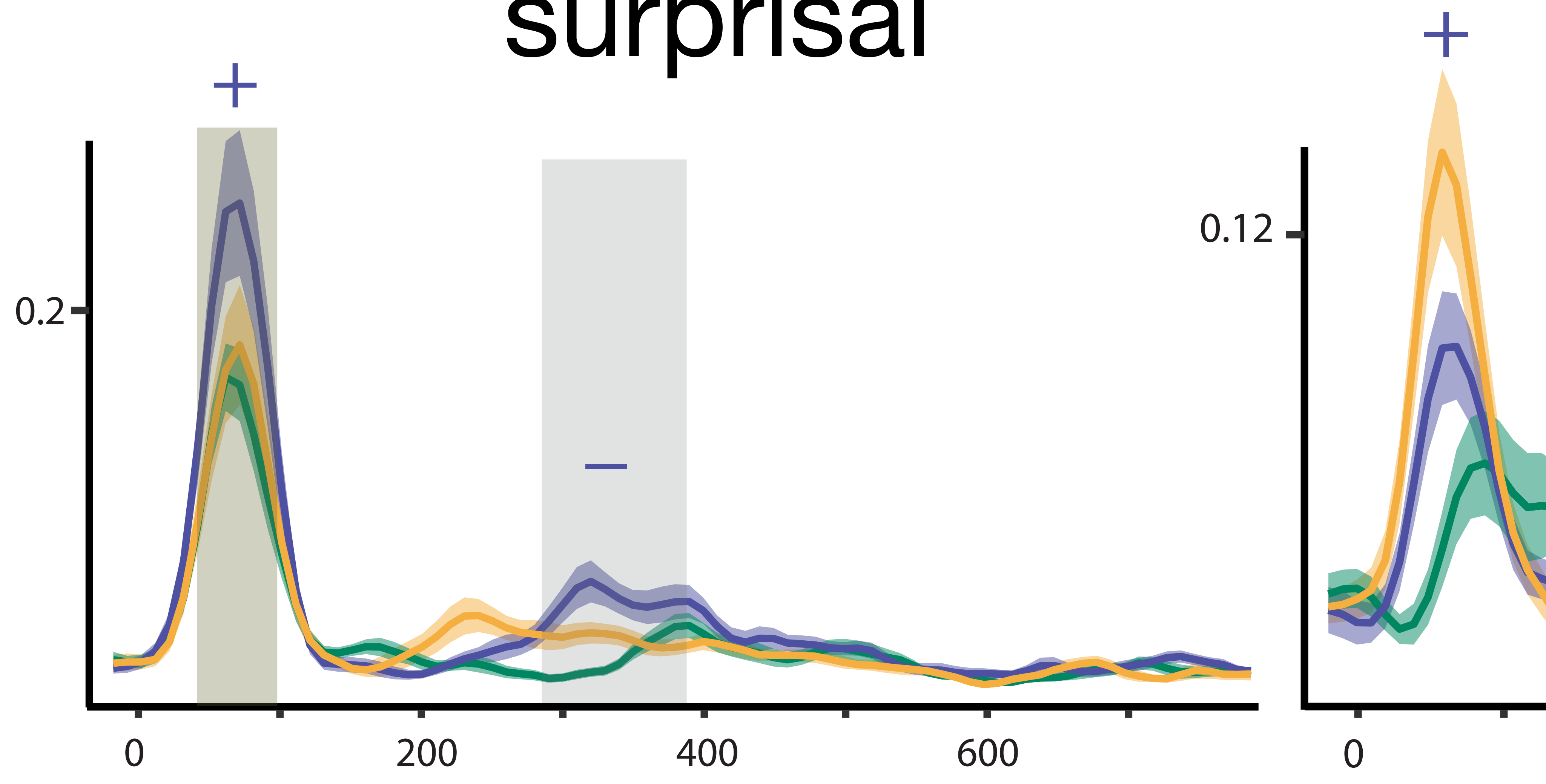

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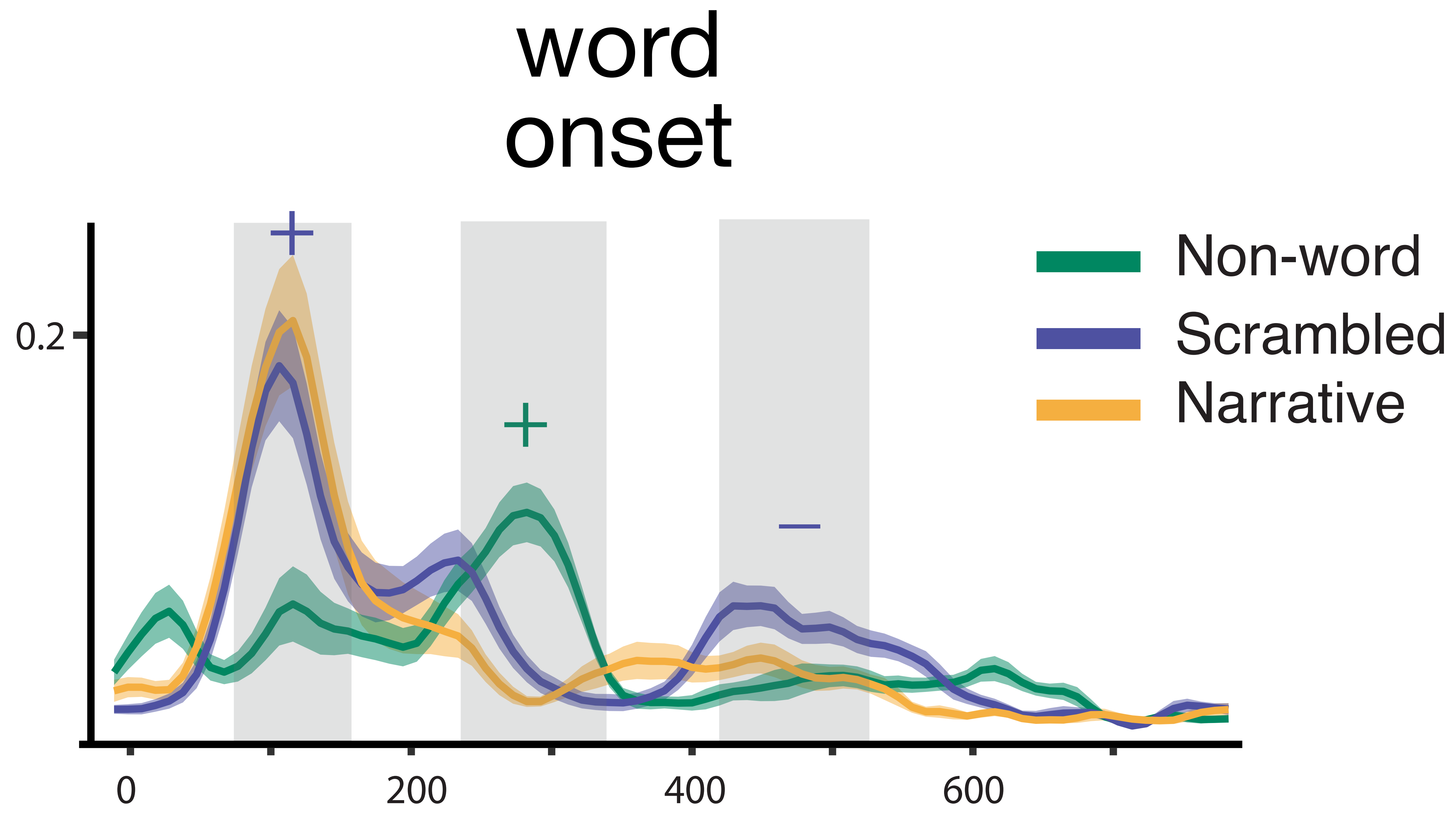
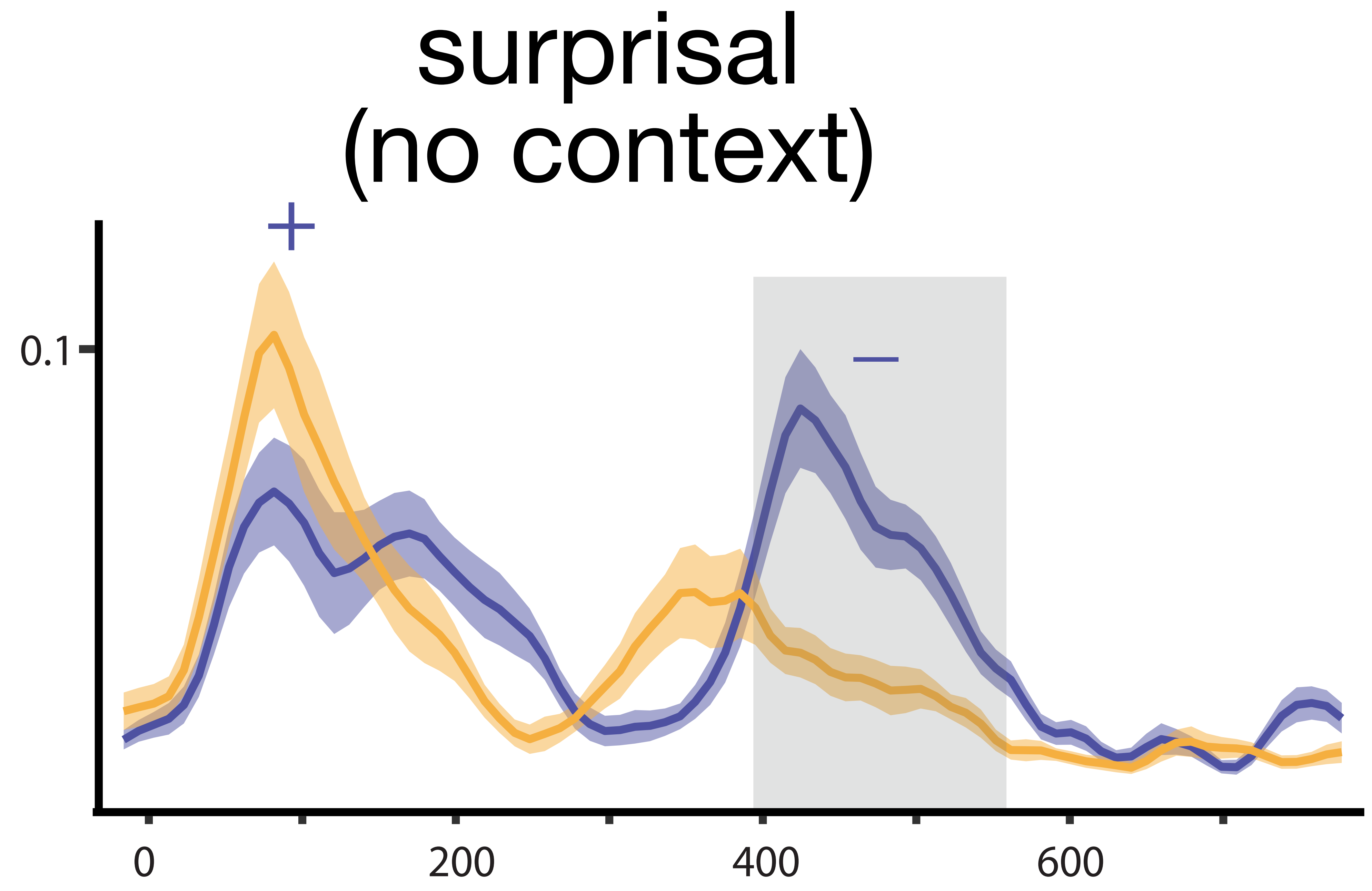
Word-based TRF Results





- Scrambled ≈ narrative for rapid processing
- Scrambled words > narrative at ~450 ms
- words: Left hemi > Right (non-words: L ≈ R)

- N400 like response
- Reduction in surprisal when context
- Left hemi > Right hemi
- Right hemisphere: Scrambled ≈ Narrative

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

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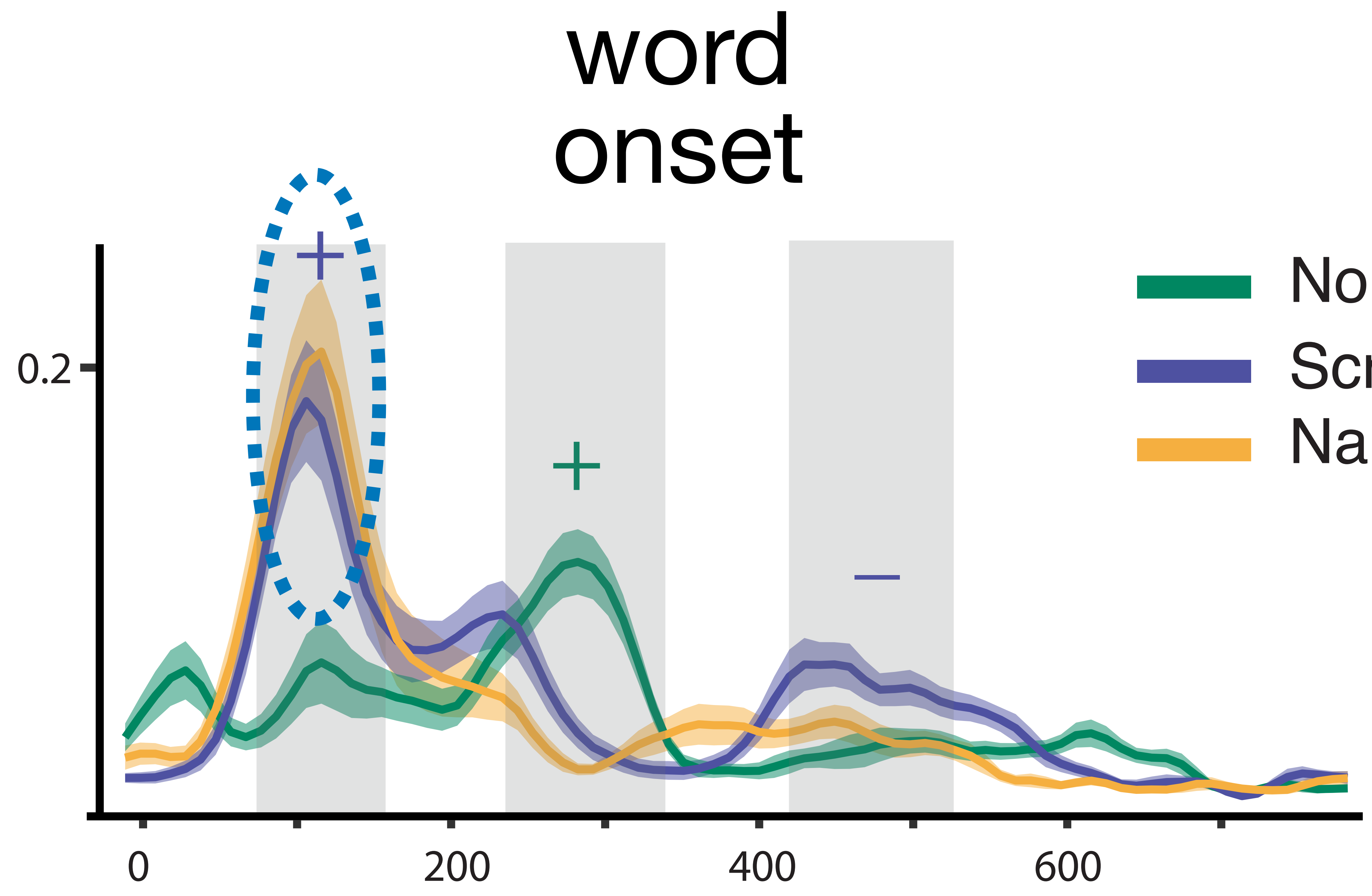

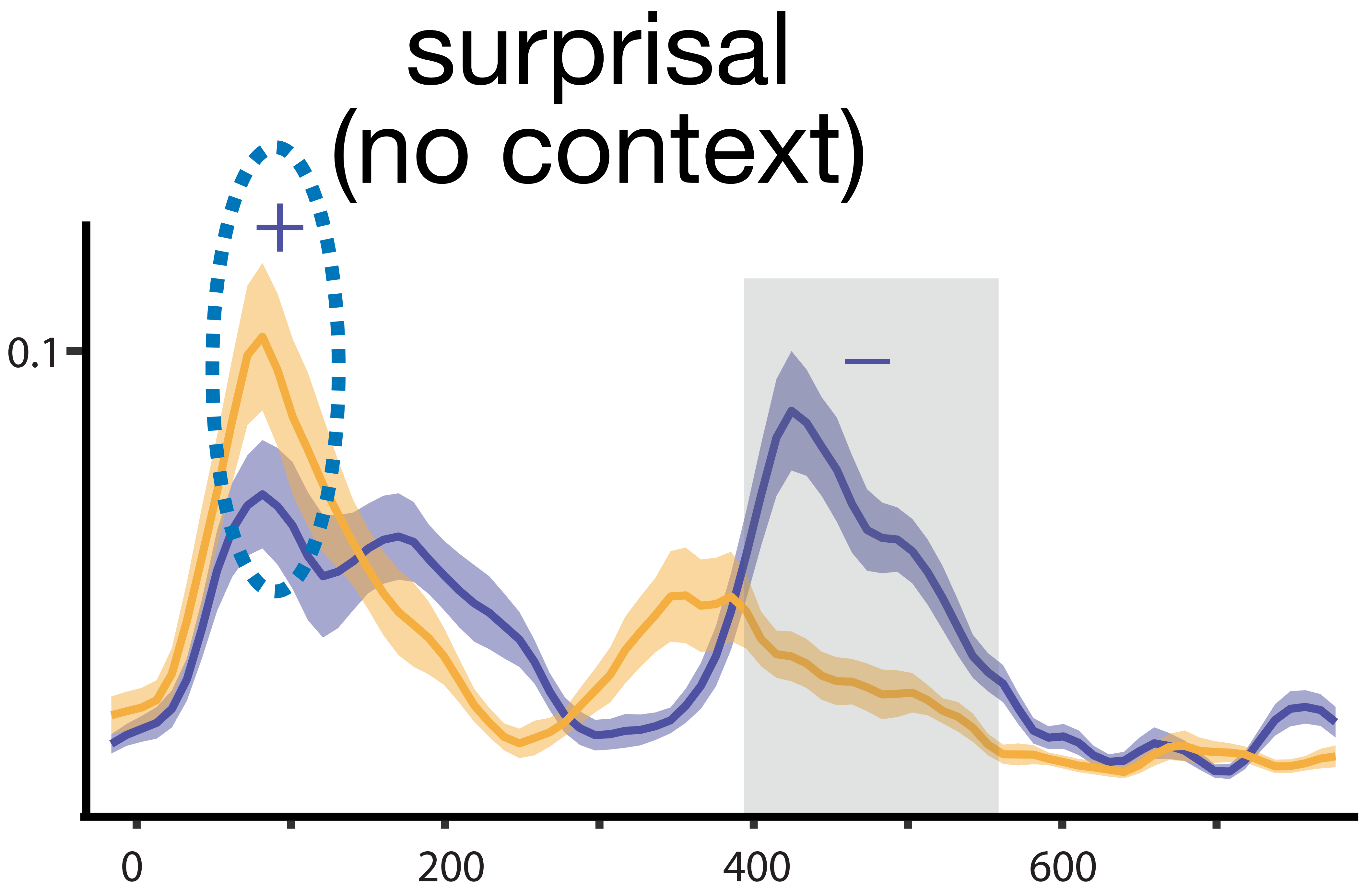

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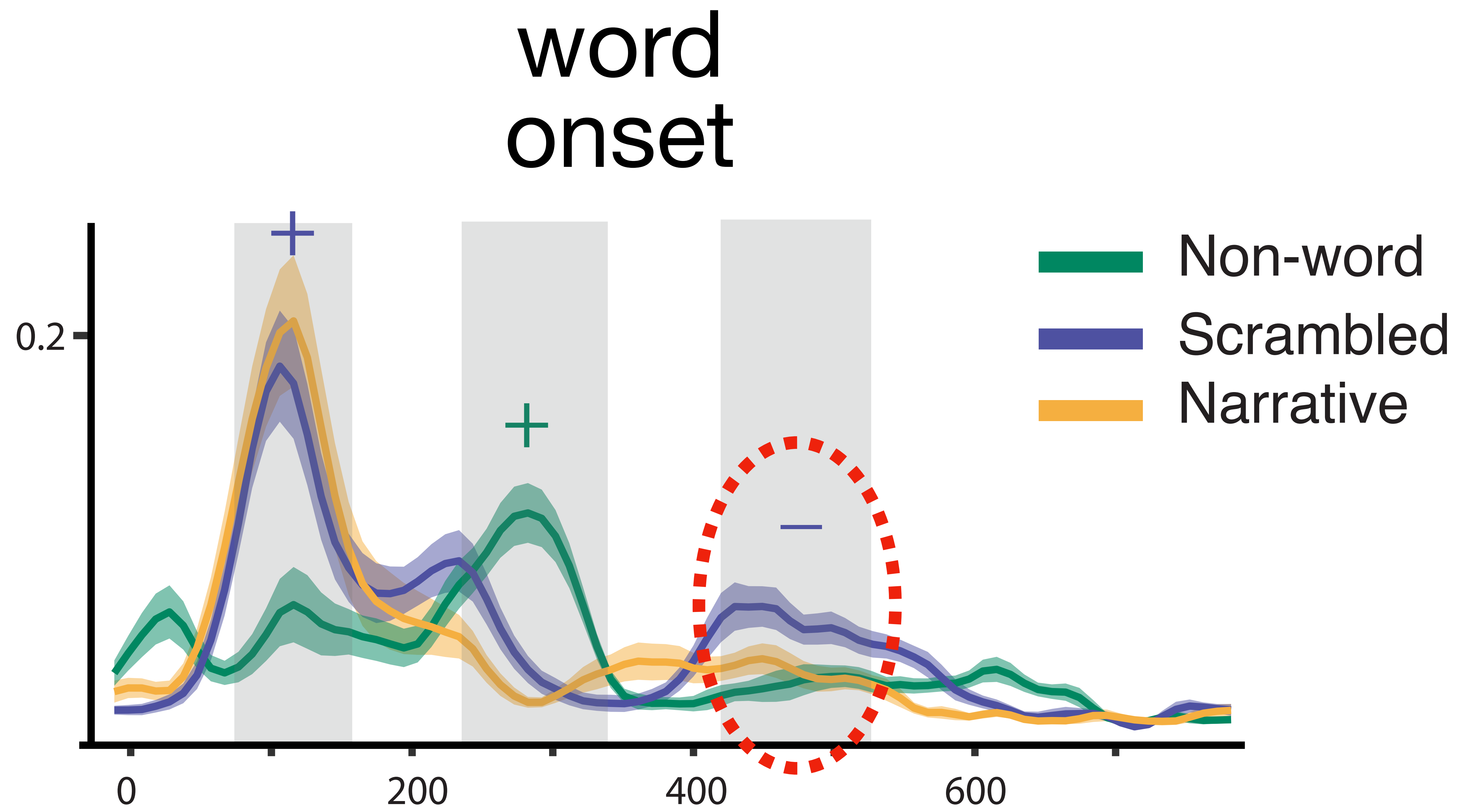

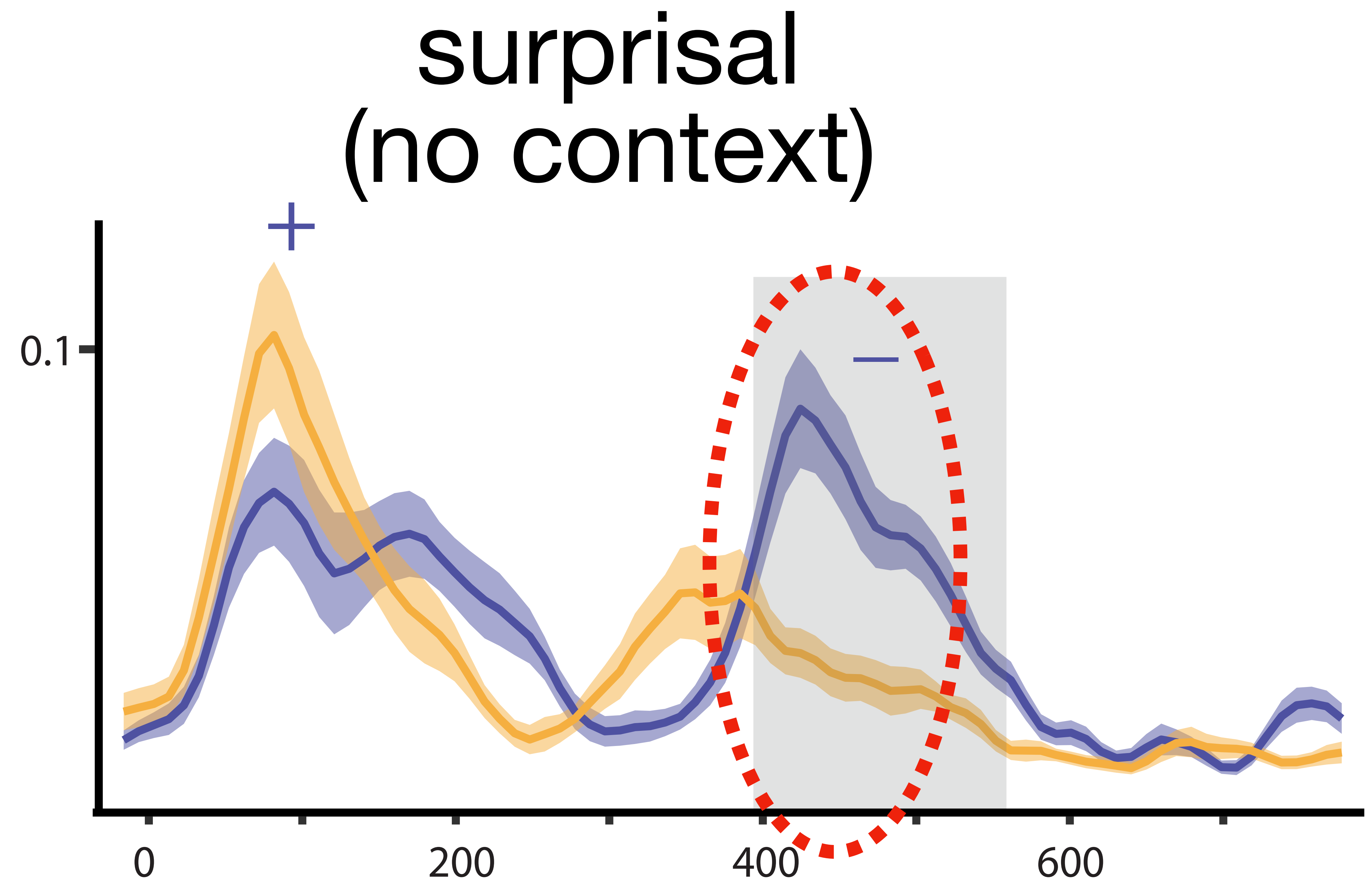

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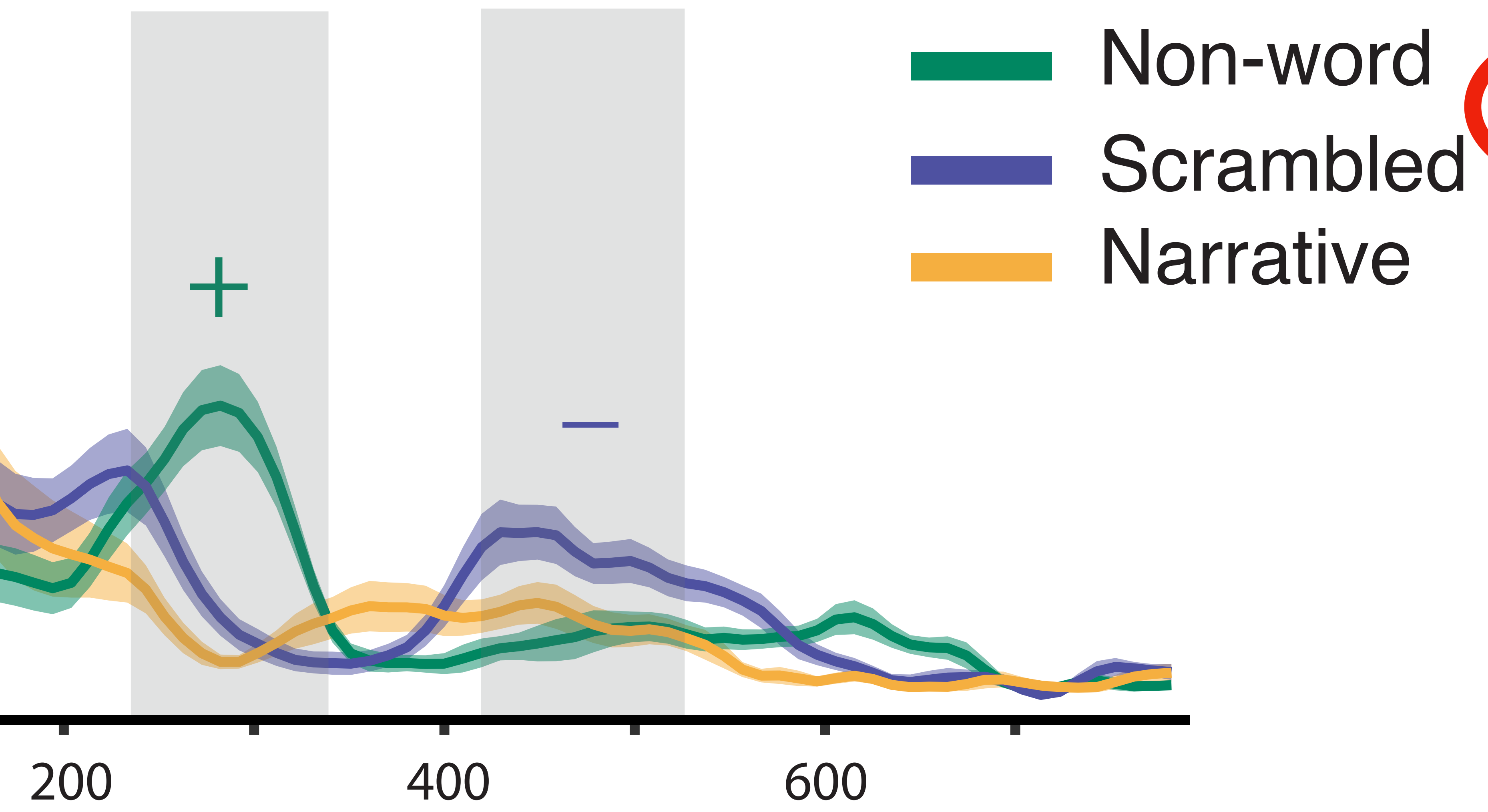
100 ms: simple word processing
450 ms: “error” correction processing

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

Word-based TRF Results

word onset



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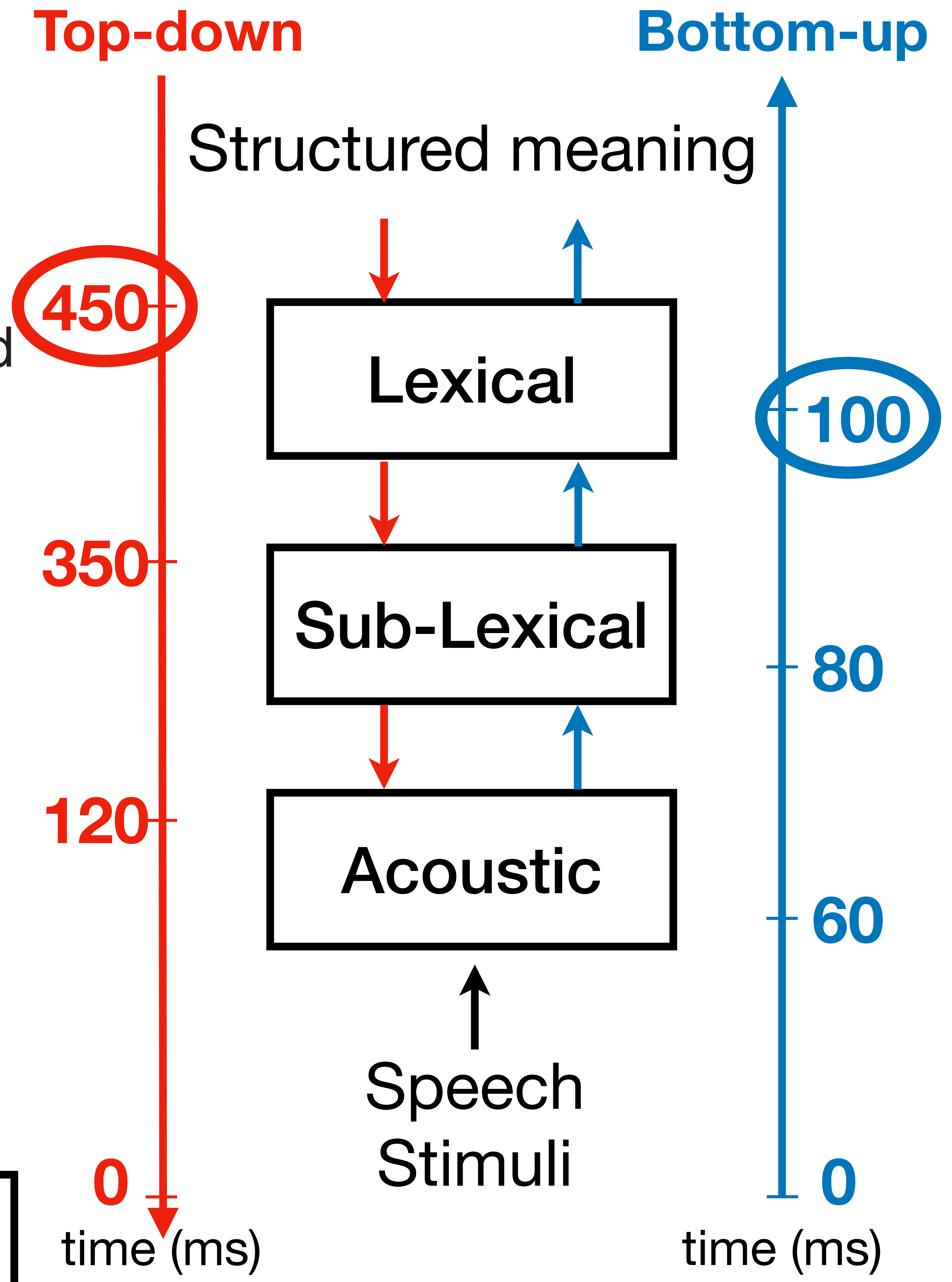
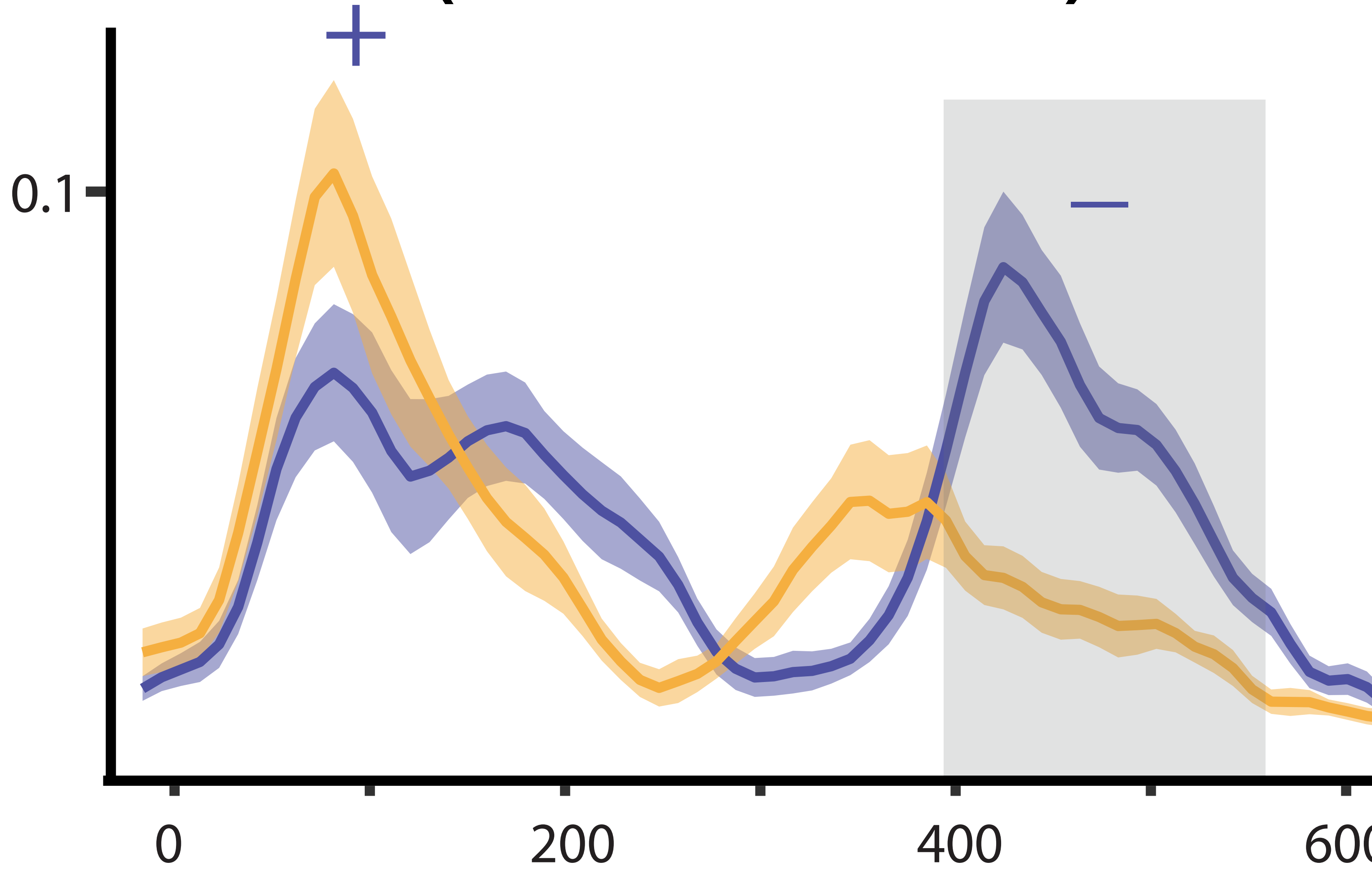
simple word processing
ror" correction processing



surprisal (no context)



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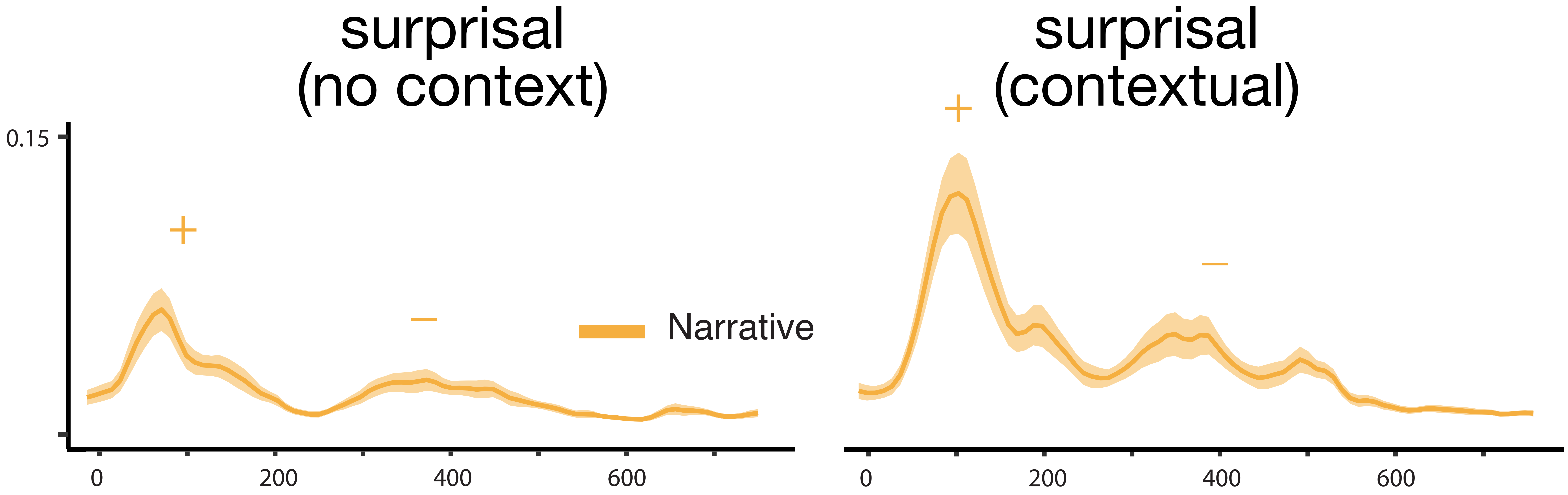
(right much weaker except for non-word onset)

Contextual Word Surprisal Results

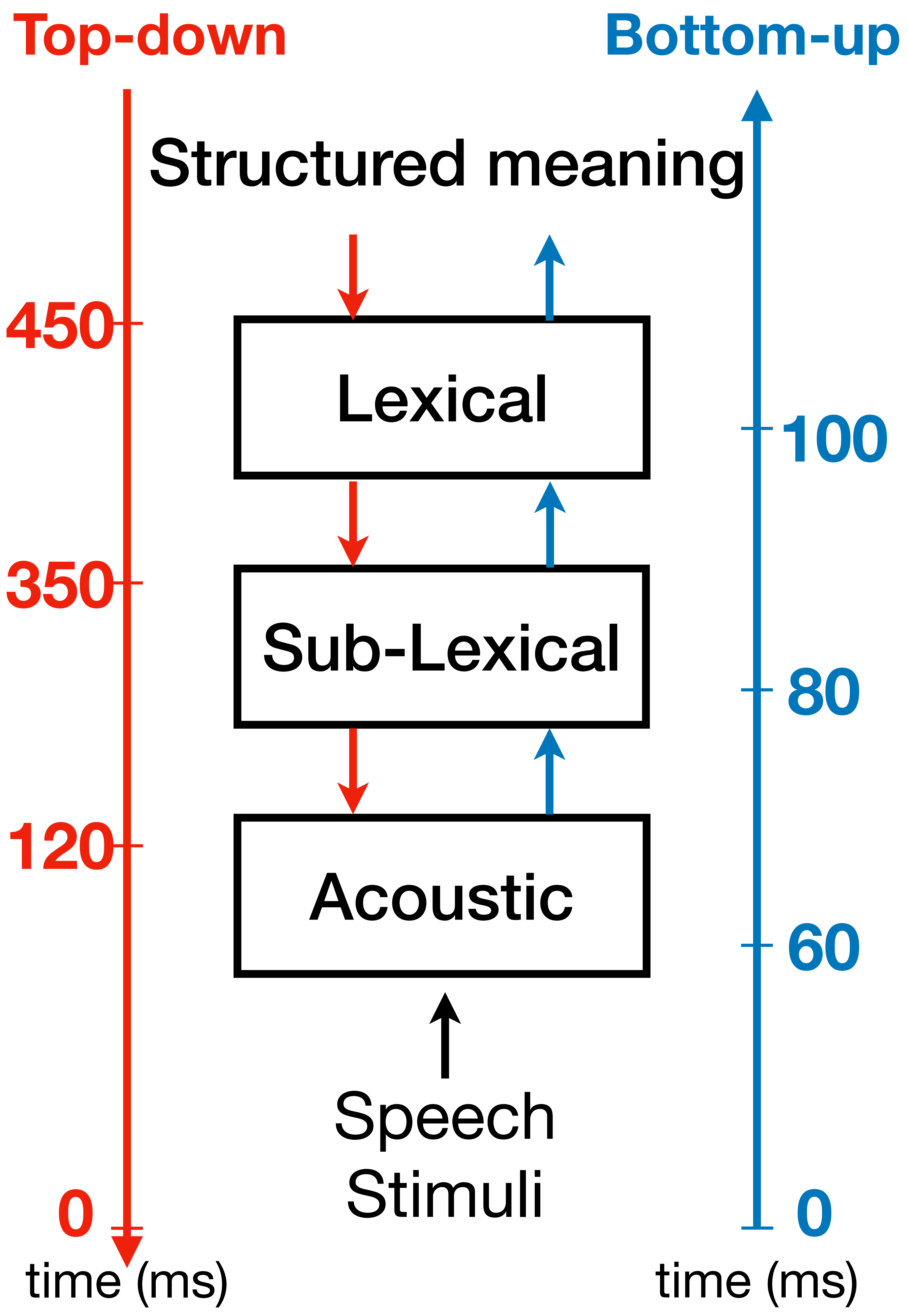


- When context helps, context-based surprisal is better tracked than raw surprisal
- N400 like response in both predictors

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
- Higher level processing / top-down mechanisms may affect lower level speech processing
- Linguistic features are processed when the linguistic boundaries are intelligible
- Lower-level acoustic feature responses are bilateral but right lateralized whereas, context based responses are strongly left lateralized



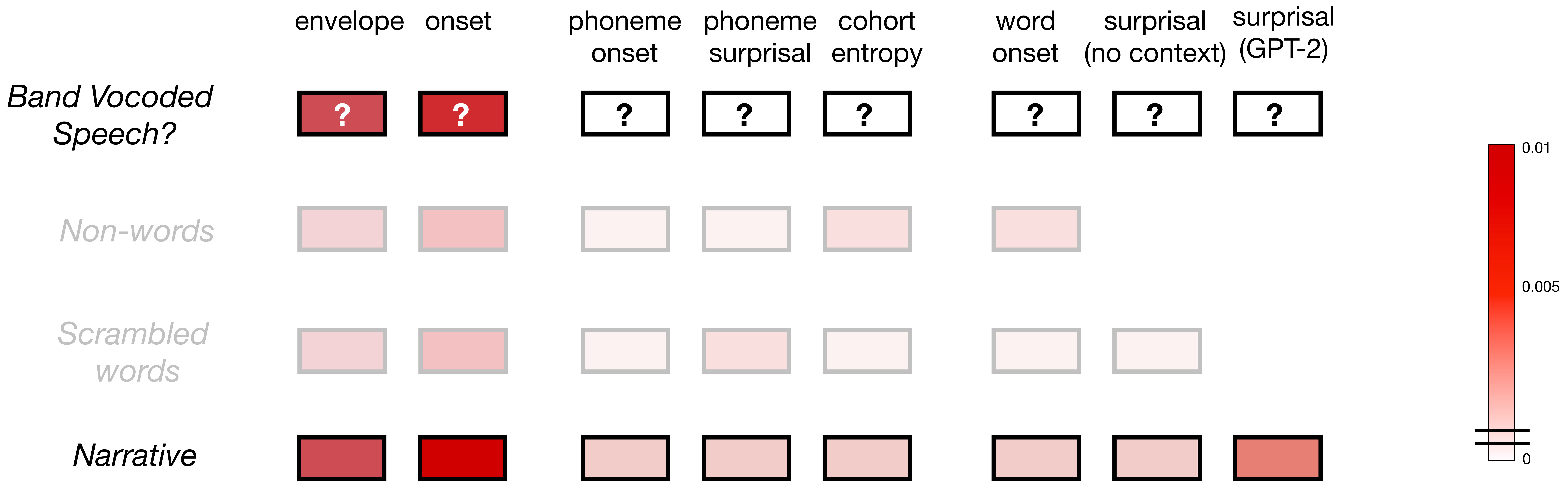
Karunathilake et al. (2024) *Neural Dynamics of the Processing of Speech Features* … bioRxiv

Outline

- Introduction—Cortical representations of continuous speech
- *Early & fast* cortical representation of continuous speech
- *Progression* of representations of continuous speech through cortex (bottom-up and top-down)
- Objective measures of speech *intelligibility*

Previous Neural Prediction Results

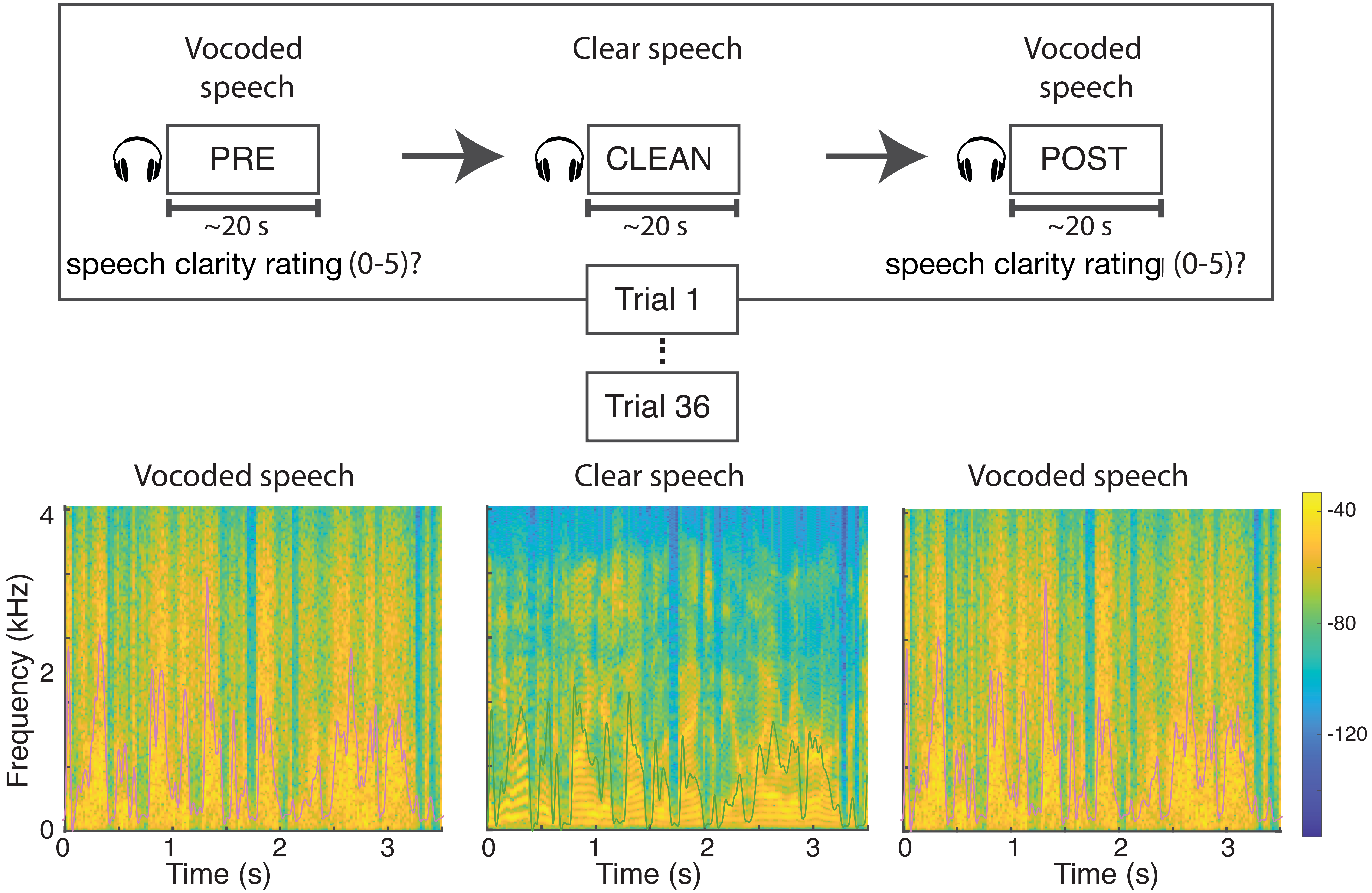
Possible Neural Prediction Results



Karunathilake et al. (2023) *Neural Tracking Measures of Speech Intelligibility…*, PNAS

Intelligibility Experimental Design

- Manipulate intelligibility but keep acoustics unchanged
  - Speech acoustics: three-band noise-vocoded speech
  - Intelligibility manipulated via priming
- Hypothesized intelligibility measure(s)
  - word boundaries



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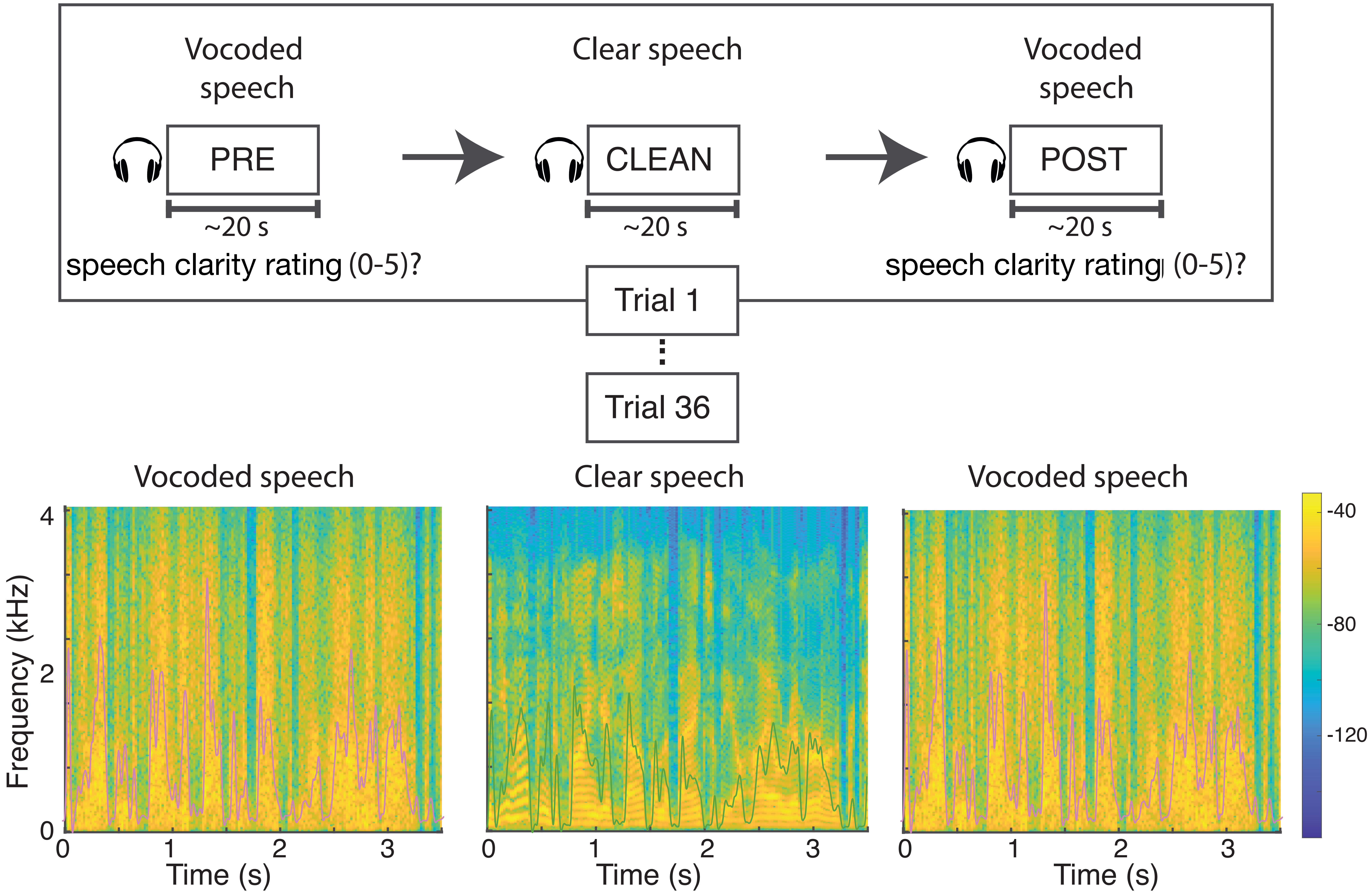

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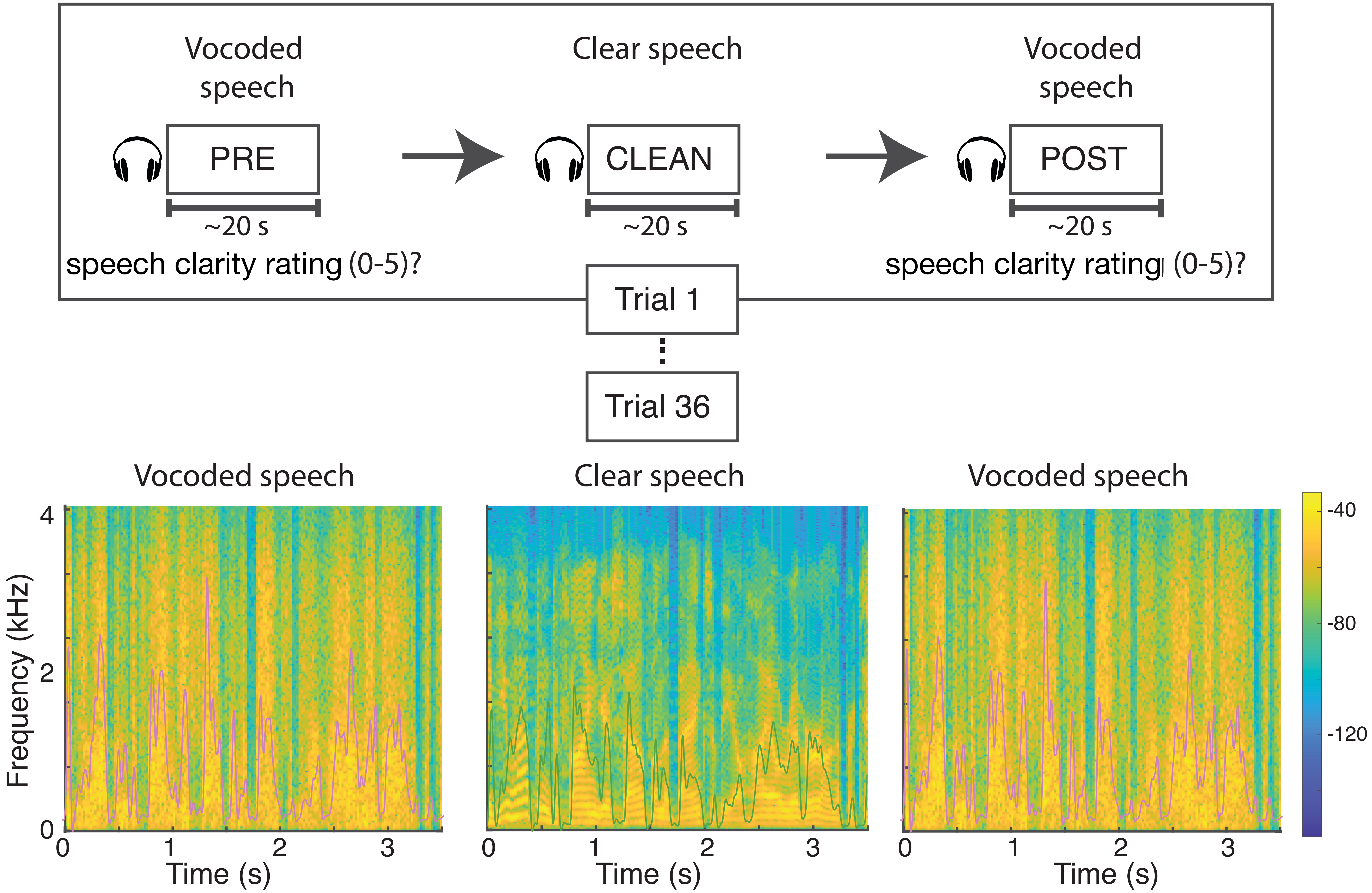

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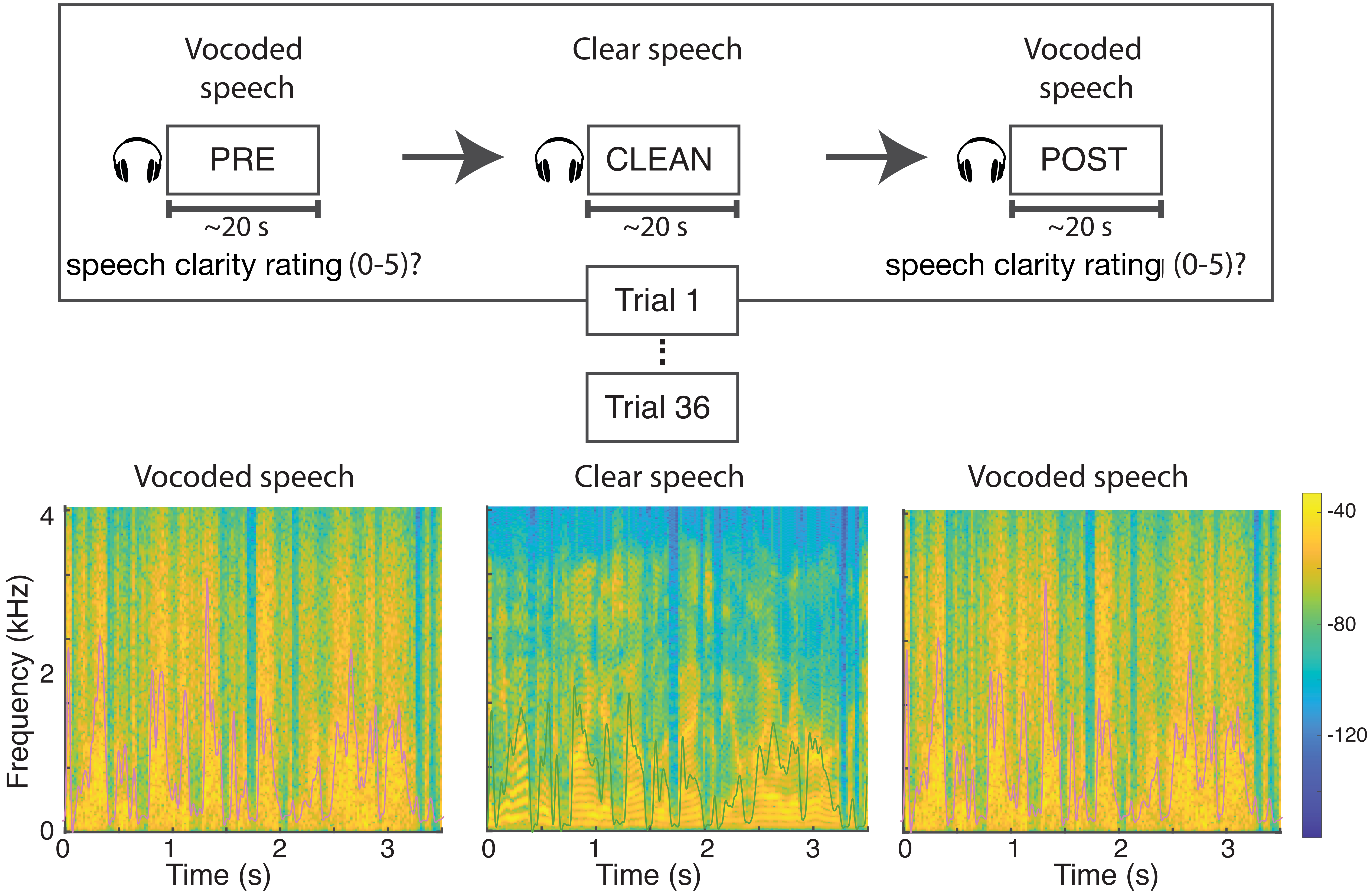

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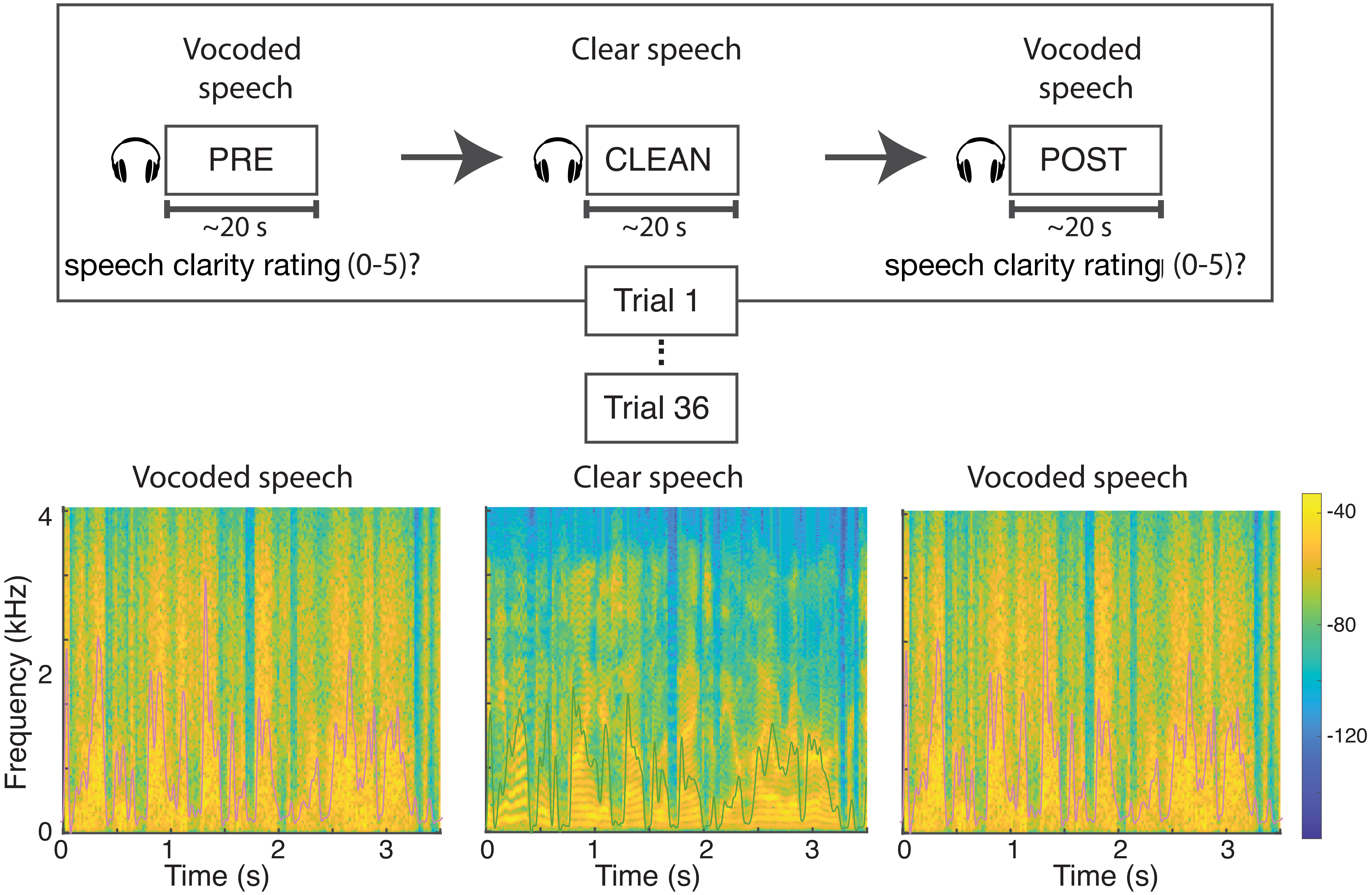

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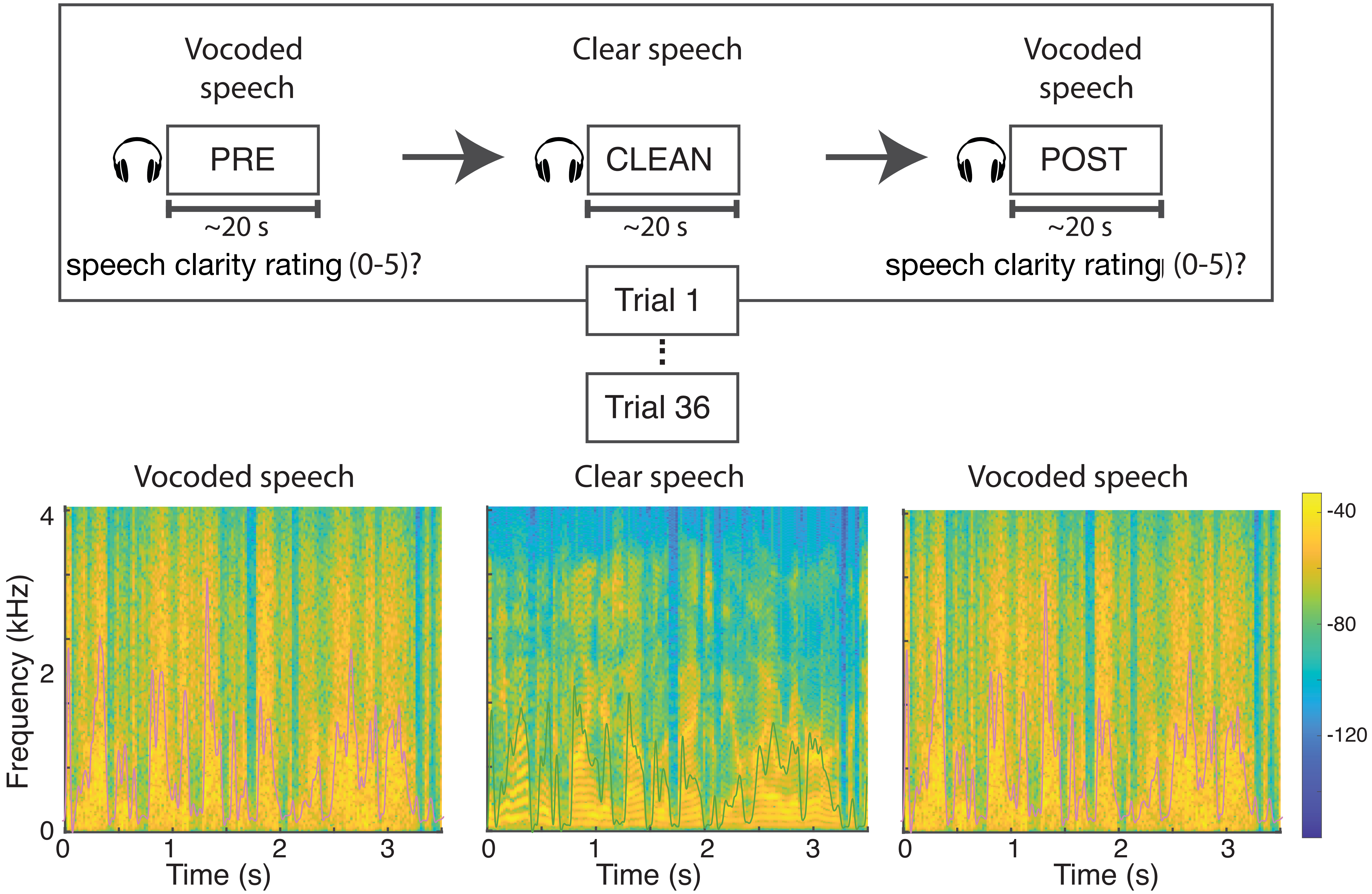

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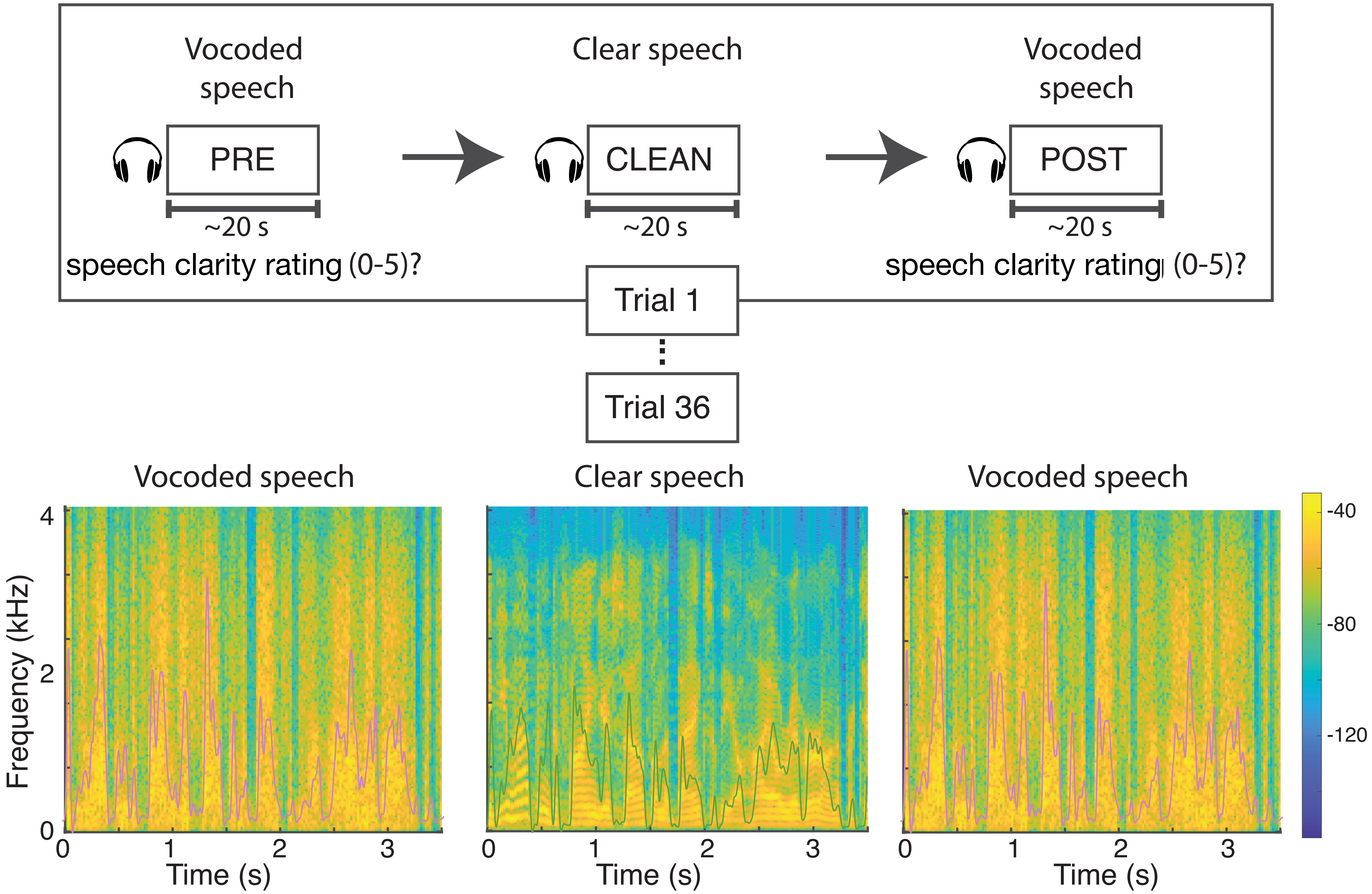

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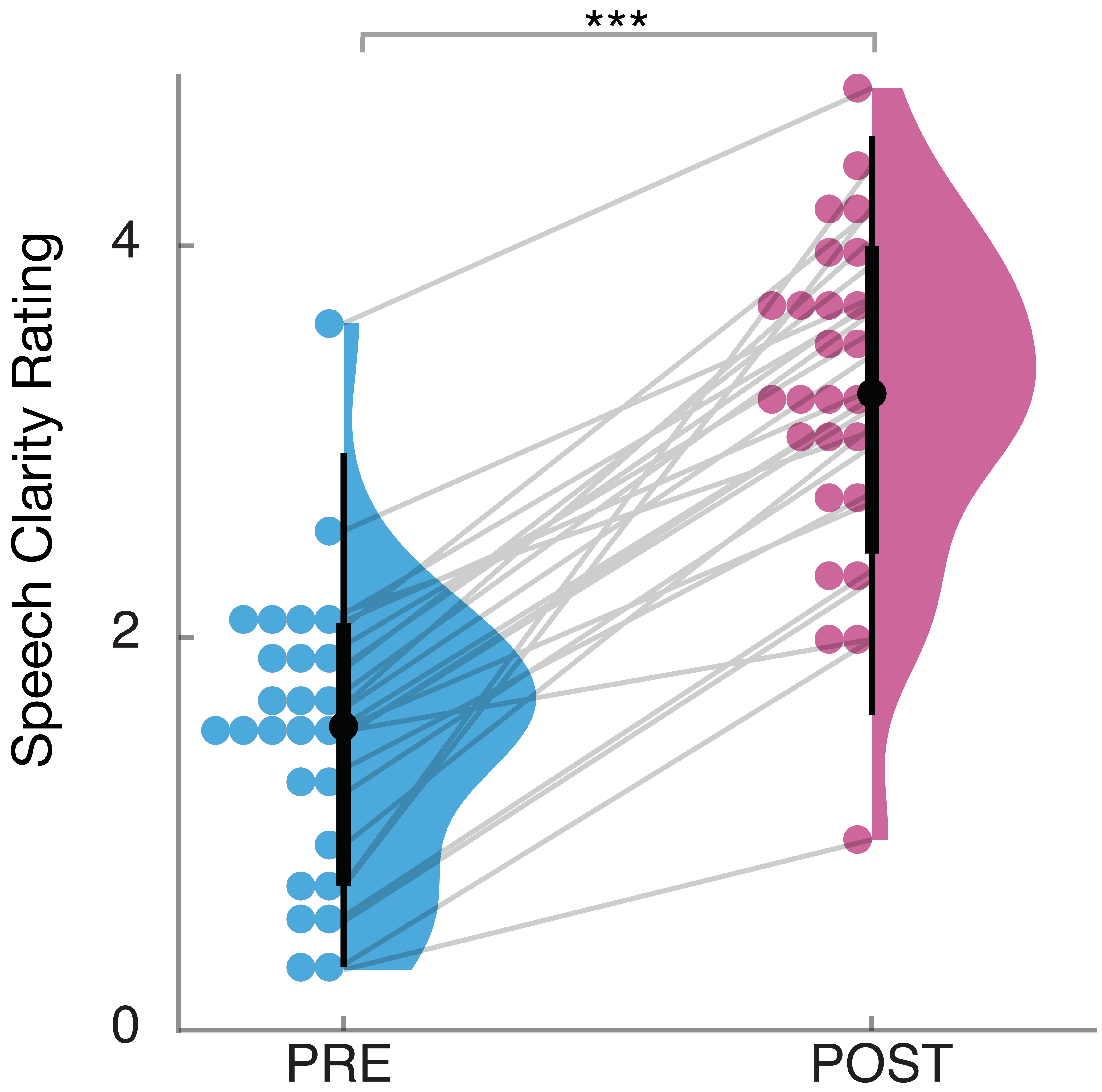
Intelligibility Behavioral Results

Speech Clarity **increases** from PRE condition to POST condition



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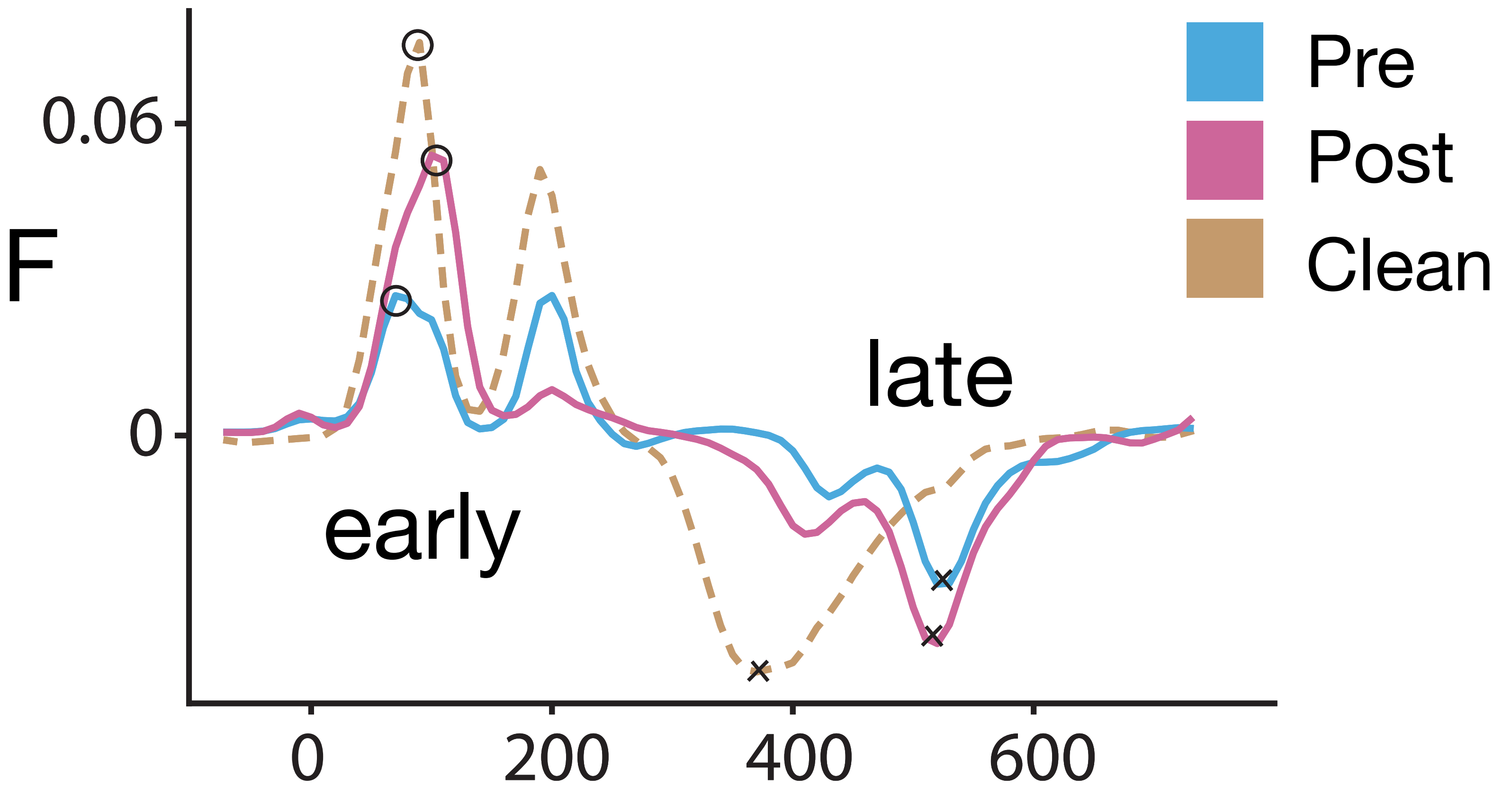
(b)

Intelligibility Neural Results

- Word onset TRF shows both early (+) and late (-) processing stages

Word onset TRF

single subject



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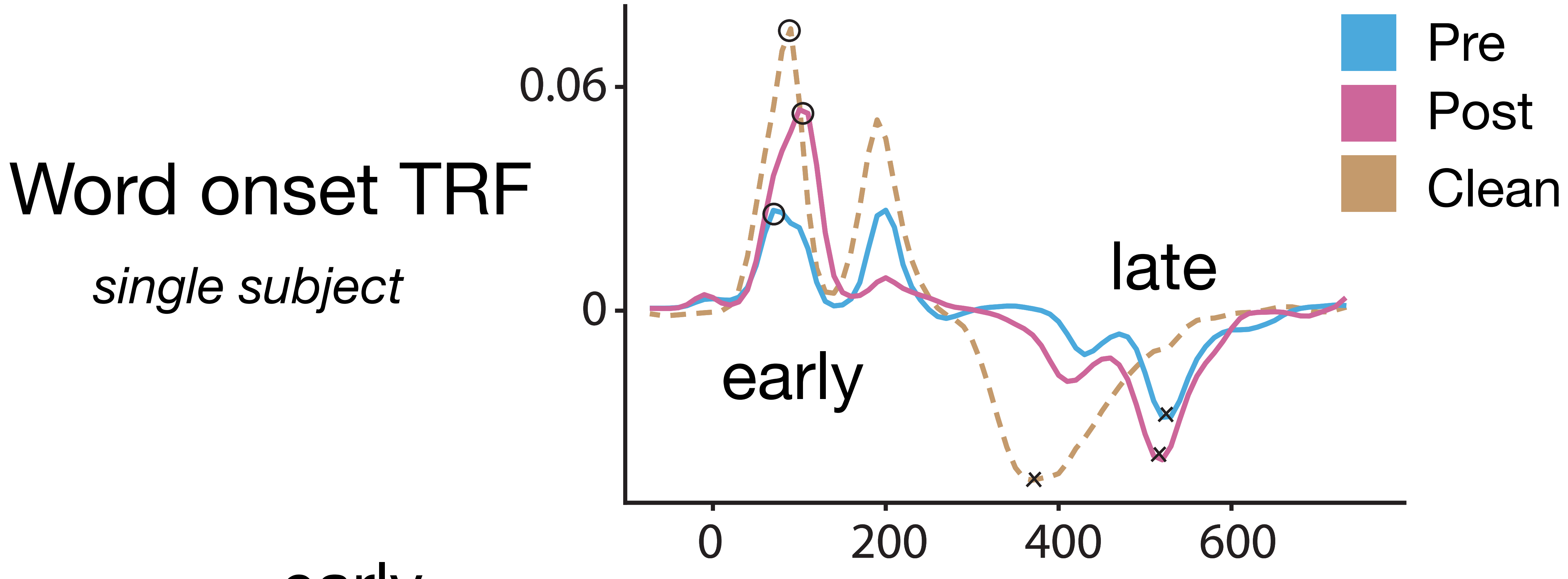
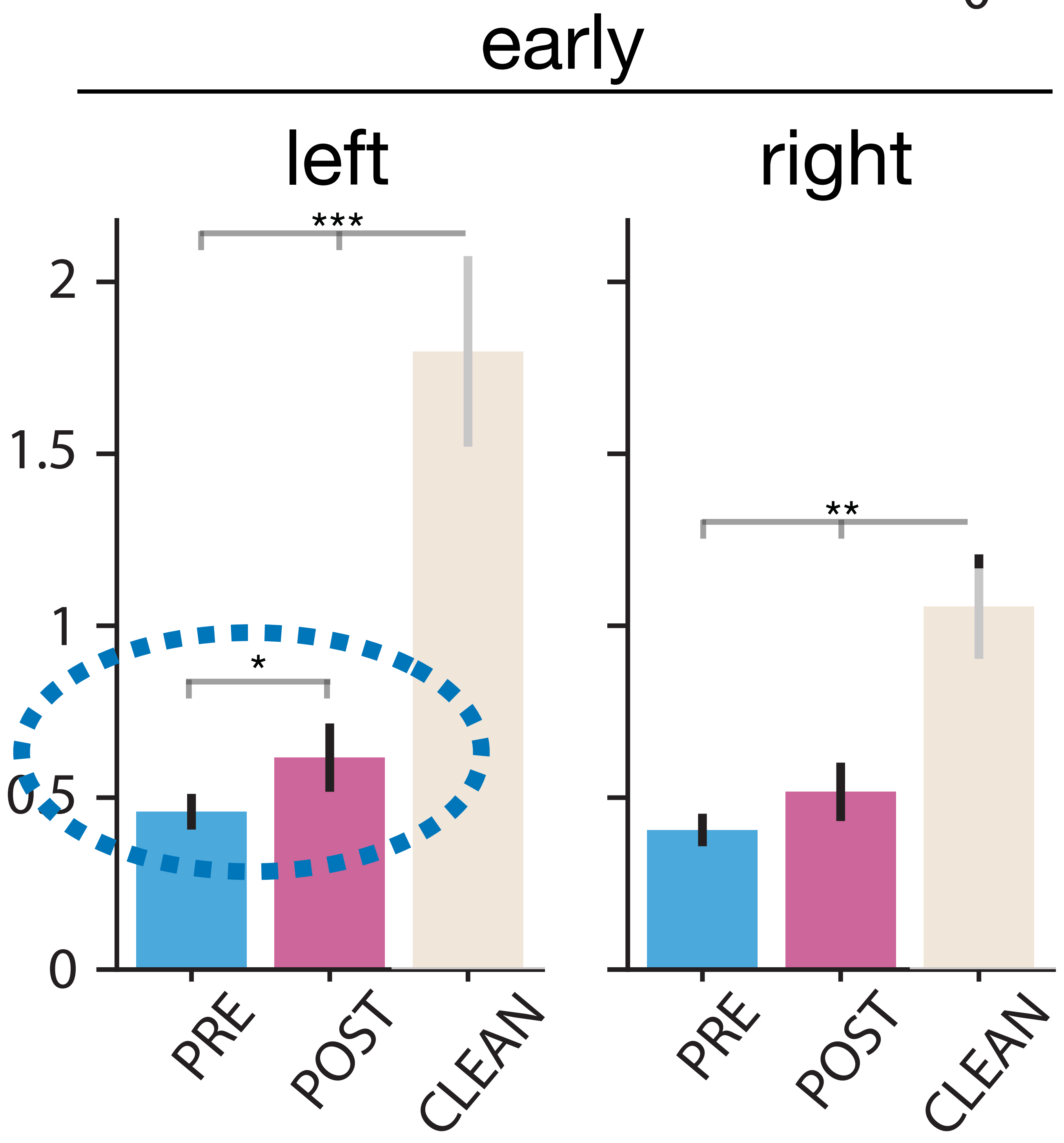
Intelligibility Neural Results

- Word onset TRF shows both early (+) and late (-) processing stages
- Response increases Pre→Post
  - Only in left hemisphere





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- Word onset TRF shows both early (+) and late (-) processing stages
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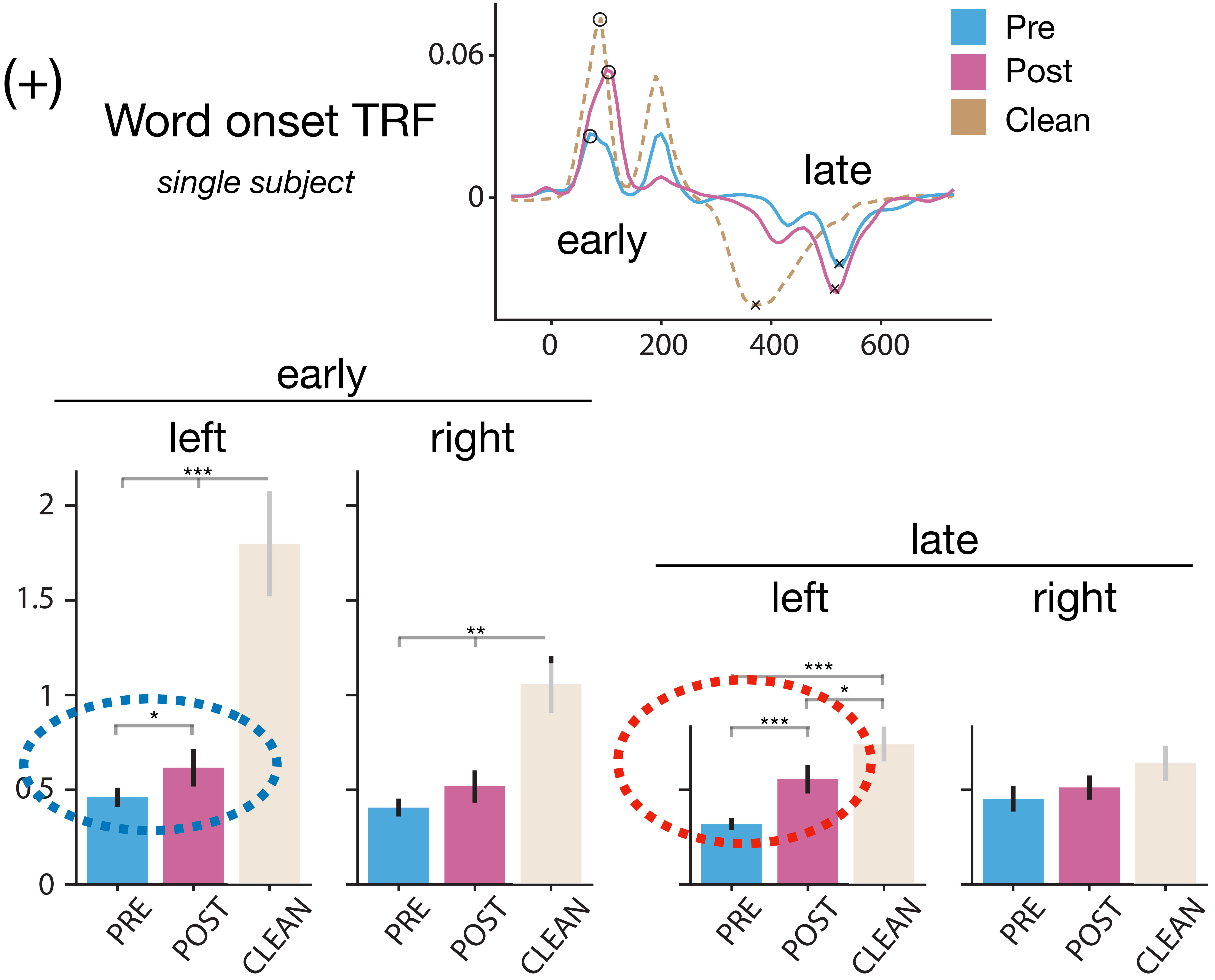
  - Late processing stage shows larger change than early



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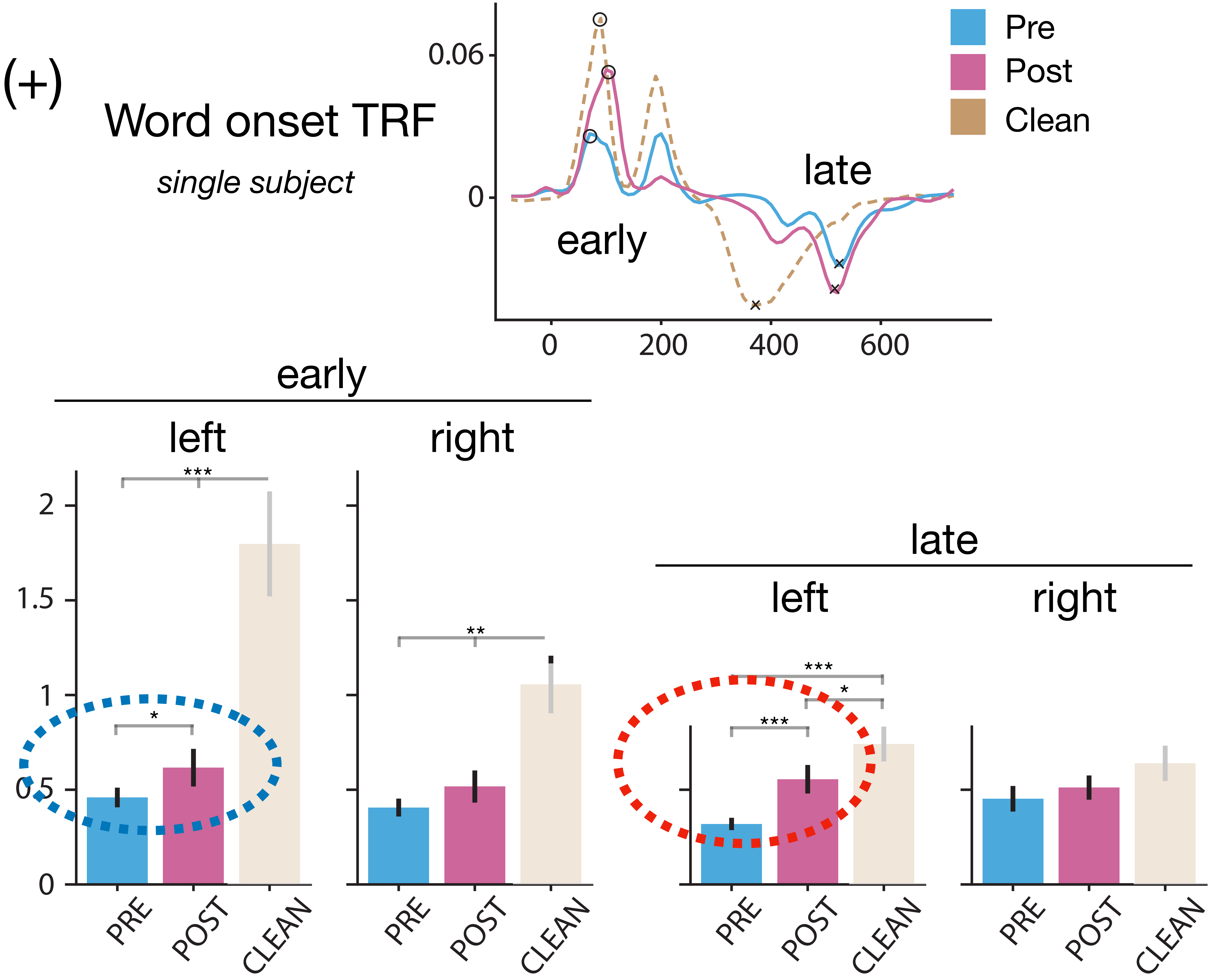
Intelligibility Neural Results

- Word onset TRF shows both early (+) and late (-) processing stages
- Response increases Pre→Post
  - Only in left hemisphere
  - Late processing stage shows larger change than early
- Response to Word Onset: *Objective measure of intelligibility*
- Acoustic responses: no change
- Response to Word Surprisal: *Additional intelligibility measure*



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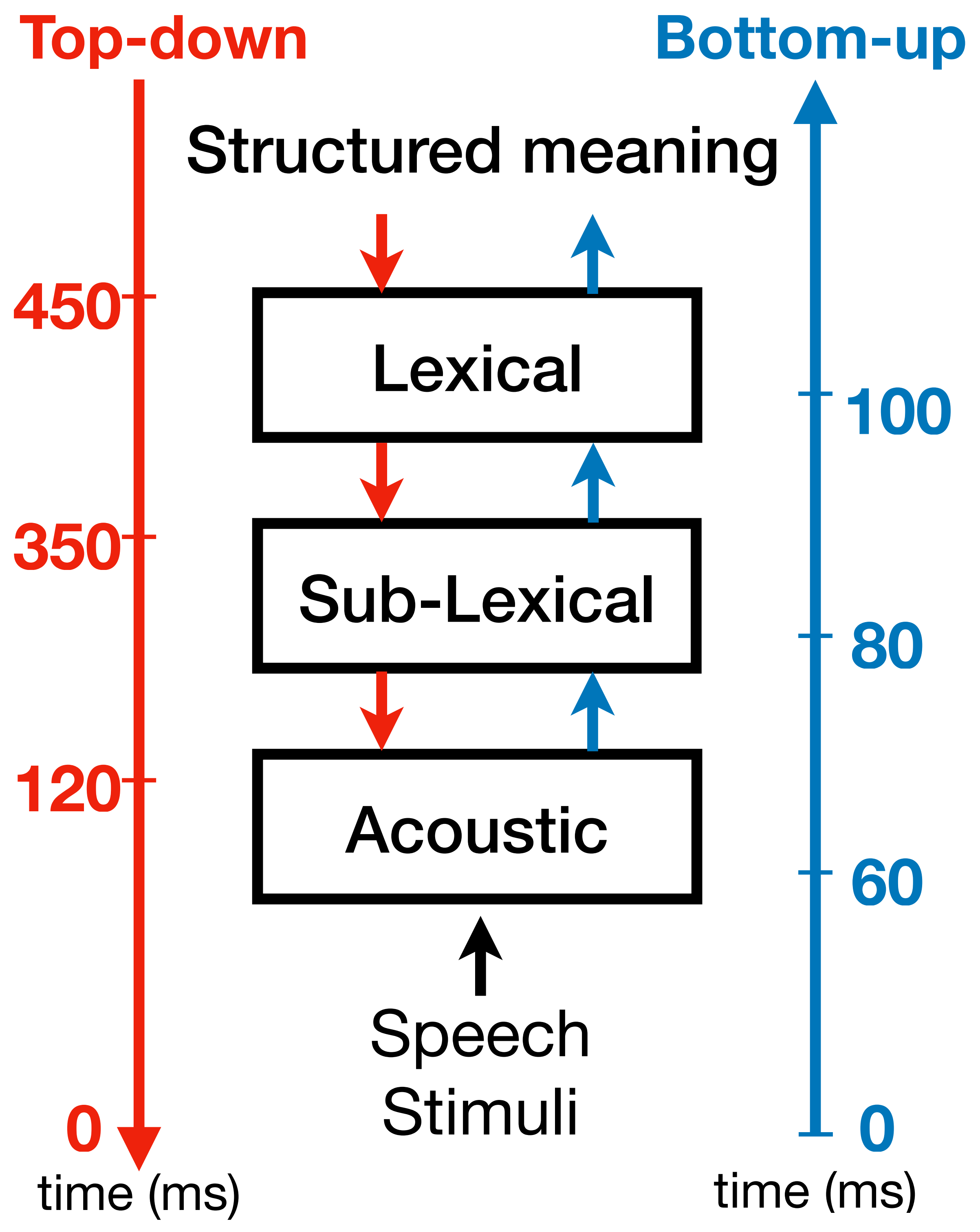
Final Summary

*temporal **neural** patterns* ⇆ *temporal patterns in **speech acoustics***
*temporal patterns in **speech perception***
*temporal patterns in **language perception***
*temporal patterns in **understanding***

- Cortical responses time-lock to emergent features
- Higher level processing / top-down mechanisms may affect lower level
- Linguistic features processed only when linguistic boundaries intelligible
- Acoustic responses: bilateral but right lateralized; context-based responses strongly left lateralized



thank you

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