Neural Encoding of Speech in Auditory Cortex

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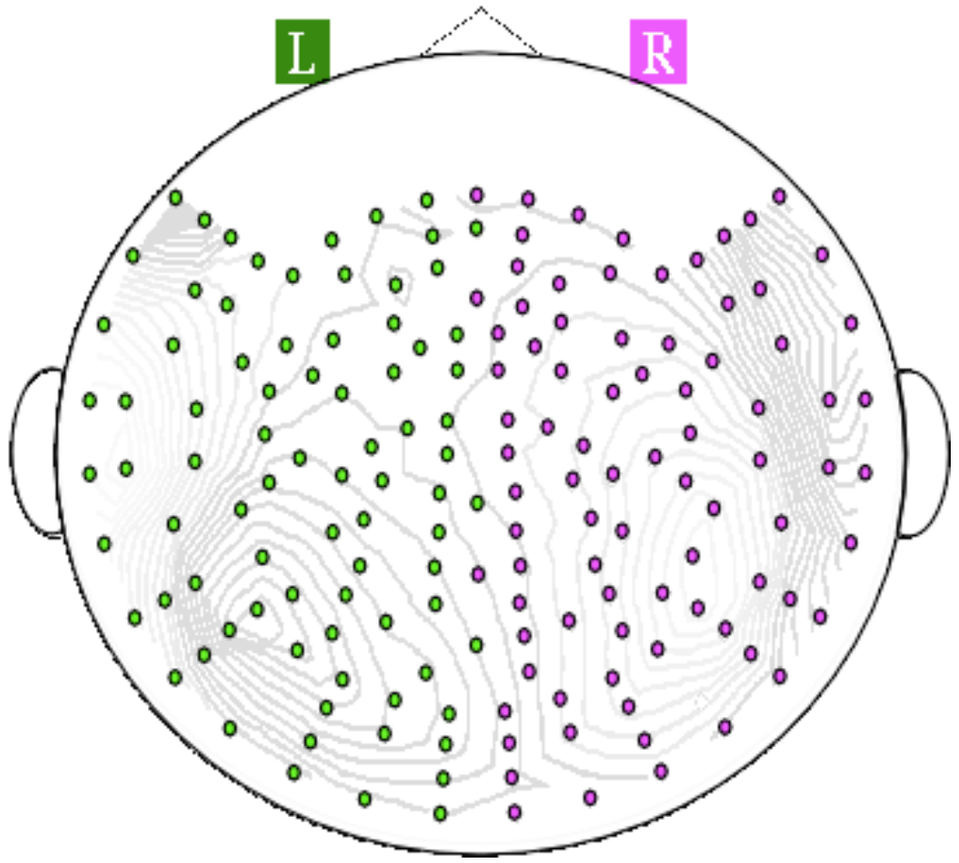
Outline

- Magnetoencephalography (MEG)
- Cortical Representations of Speech
  - Encoding vs. Decoding
  - Attended vs. Unattended Speech
- Work in Progress
  - Attentional Dynamics
  - Aging and the Cocktail Party Problem
  - Foreground vs. Background

Magnetoencephalography

- Non-invasive, Passive, Silent Neural Recordings
- Simultaneous Whole-Head Recording (~200 sensors)
- Sensitivity
  - high: ~100 fT (10^{-13} Tesla)
  - low: ~10^4 – ~10^6 neurons
- Temporal Resolution: ~1 ms
- Spatial Resolution
  - coarse: ~1 cm
  - ambiguous



Neural Signals & MEG

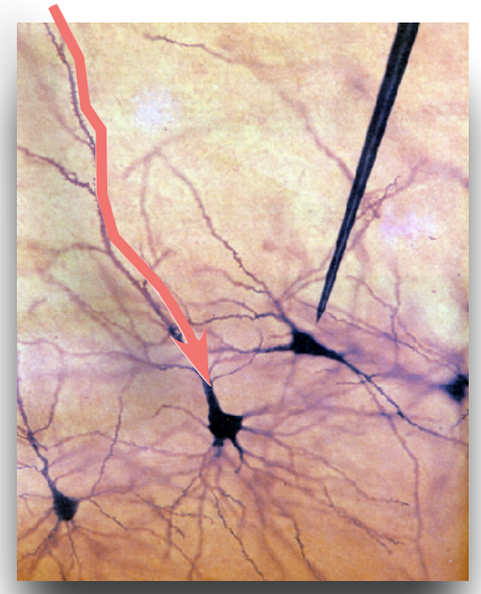
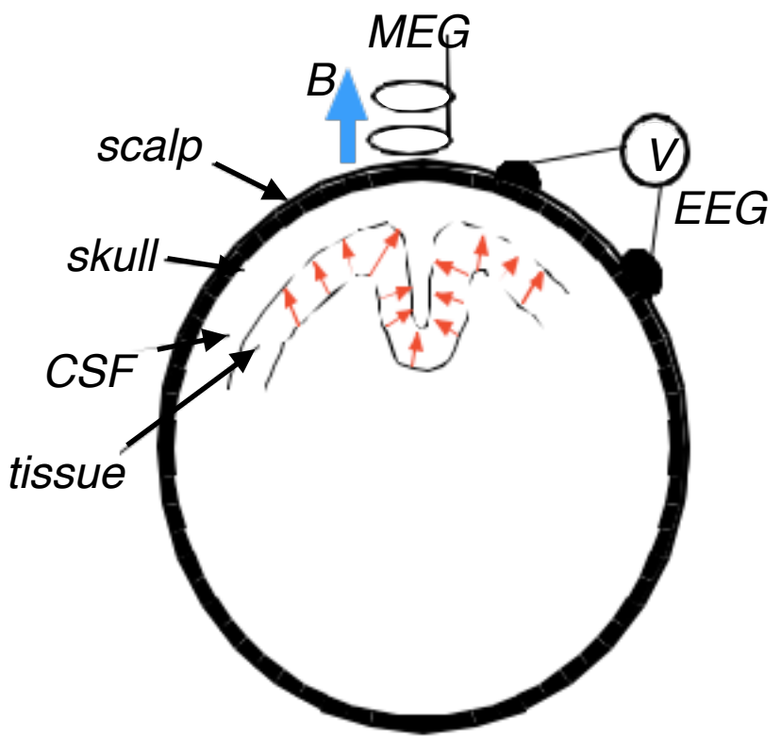
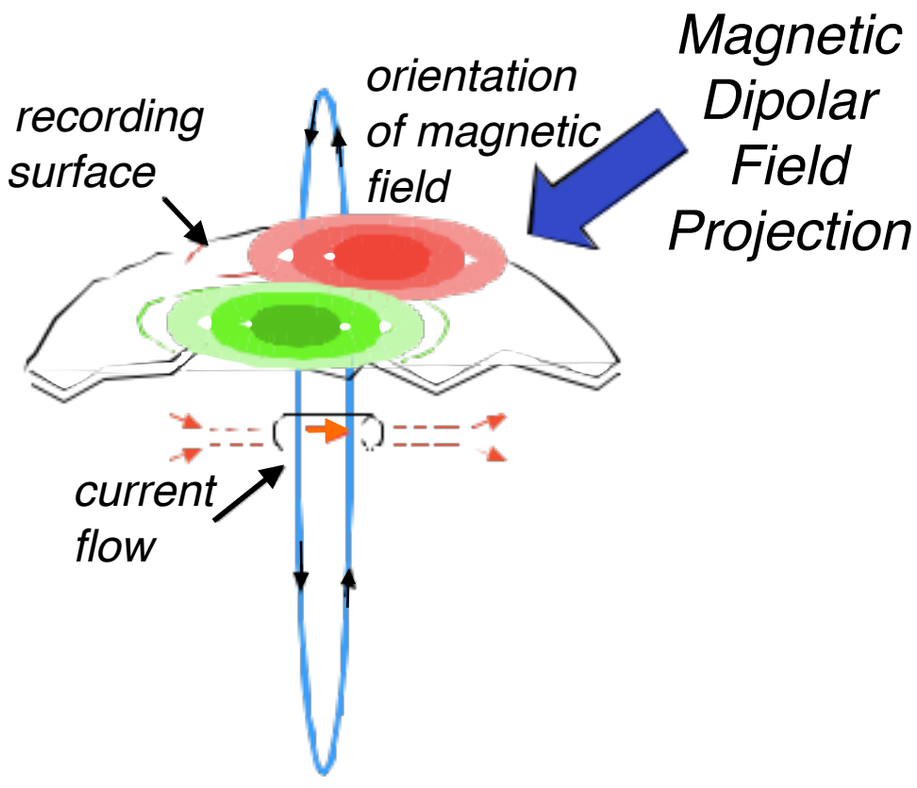


Photo by Fritz Goro

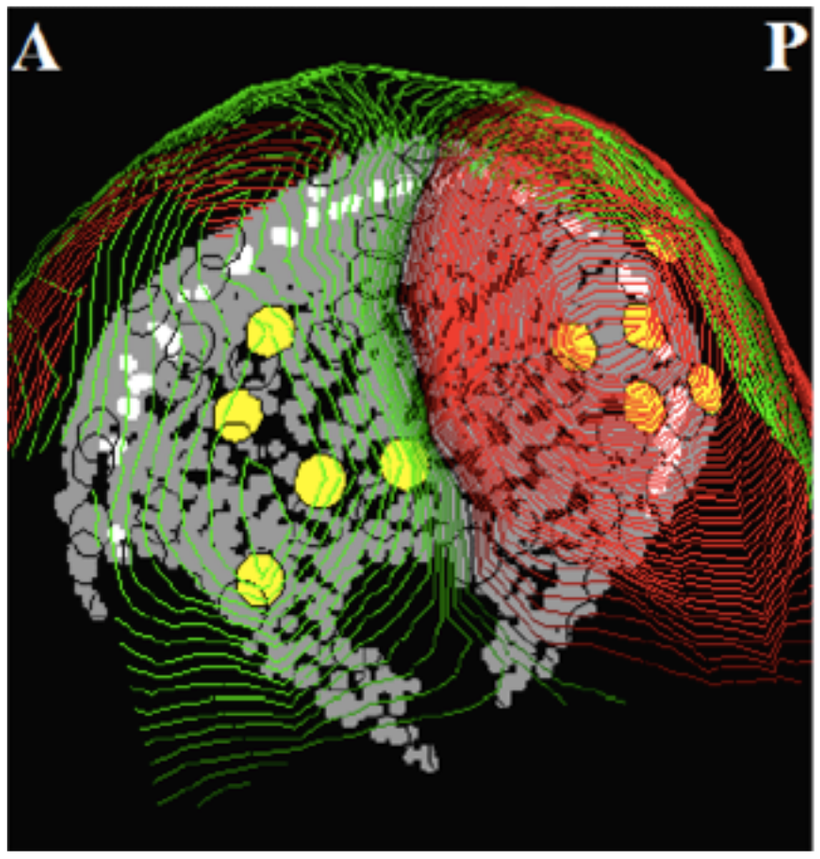




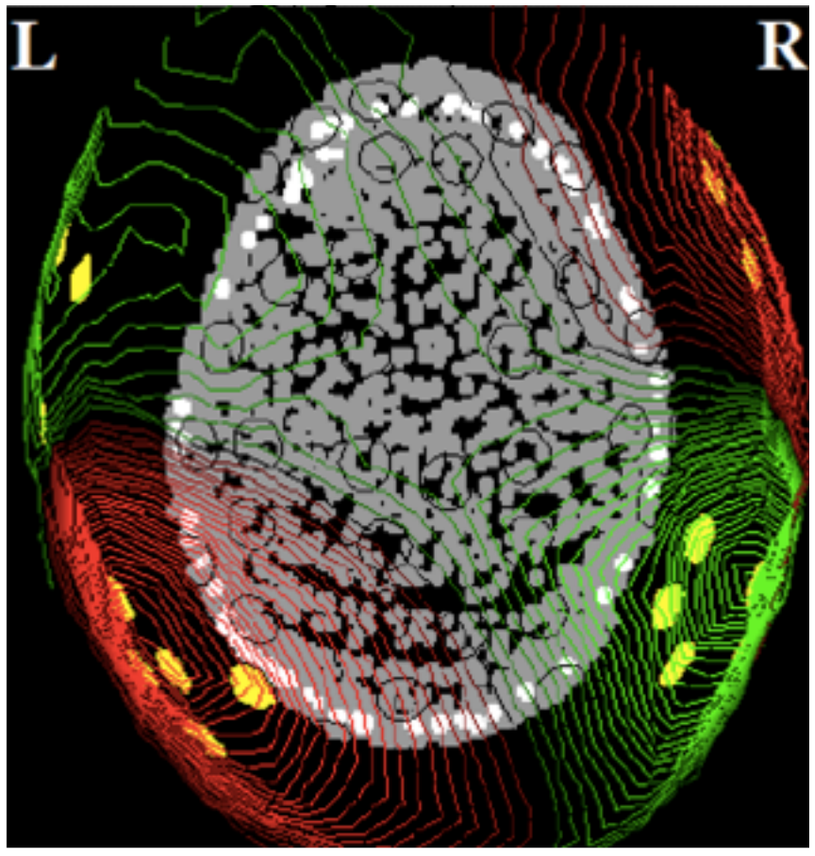
- Direct electrophysiological measurement
  - not hemodynamic
  - real-time
- No unique solution for distributed source

- Measures spatially synchronized cortical activity
- Fine temporal resolution (~ 1 ms)
- Moderate spatial resolution (~ 1 cm)

MEG Auditory Field



Sagittal View

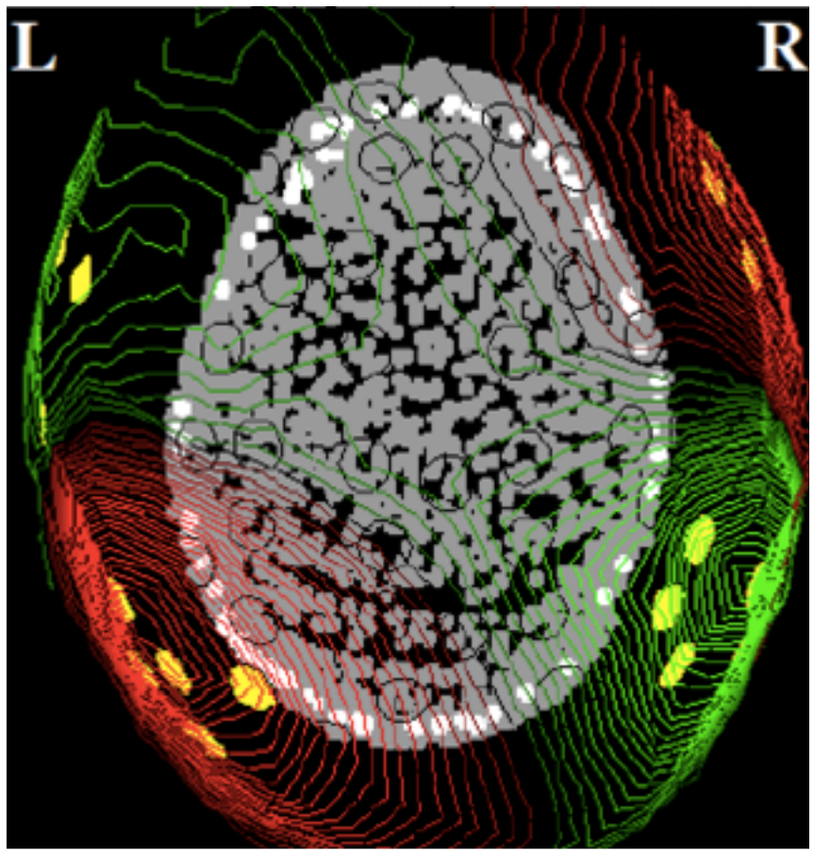


Axial View

Strongly
Lateralized

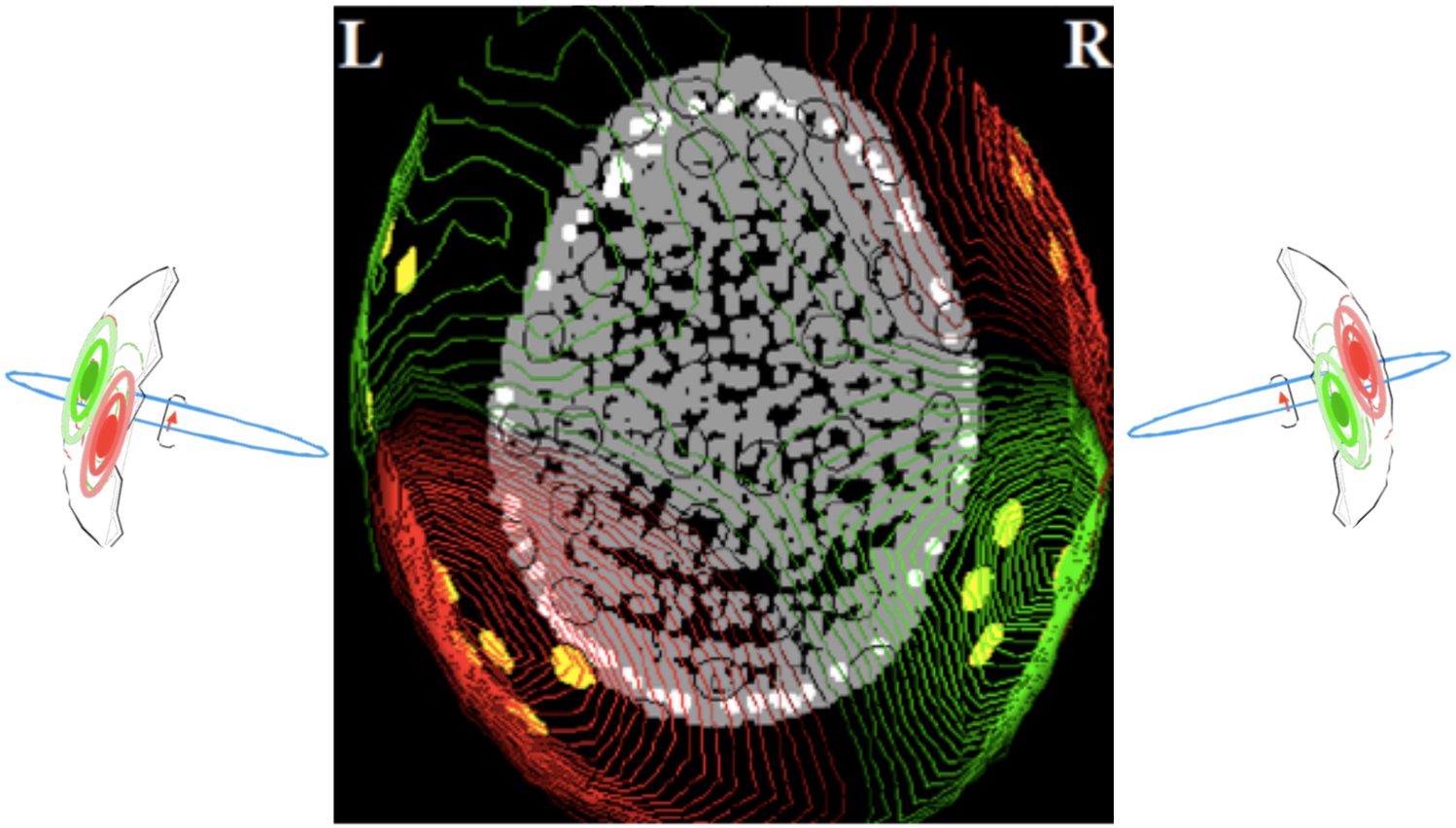
Chait, Poeppel and Simon, Cerebral Cortex (2006)

MEG Auditory Field



Chait et al., Cerebral Cortex (2006)

MEG Auditory Field

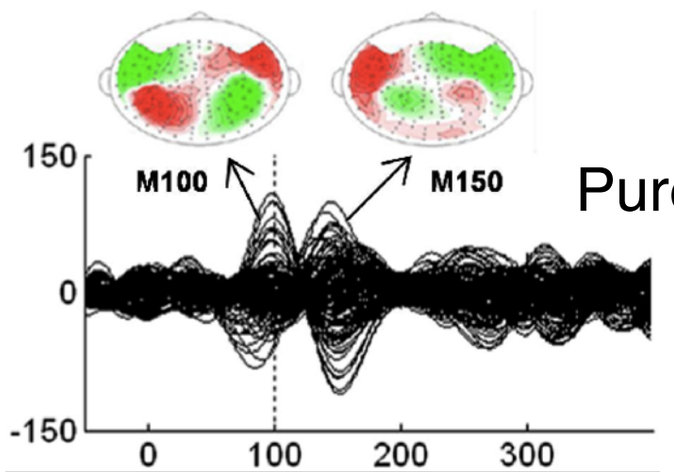


Chait et al., Cerebral Cortex (2006)

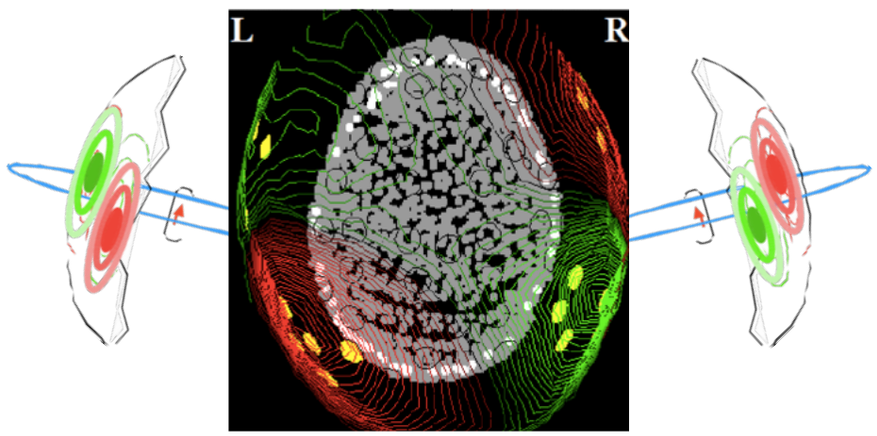
Time Course of MEG Responses

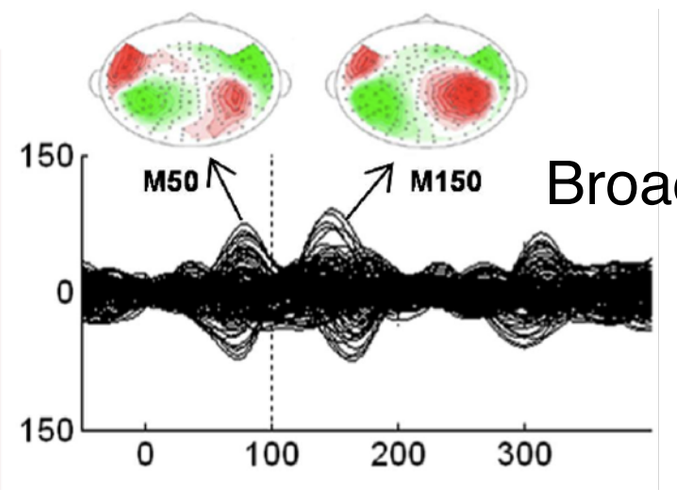
Auditory Evoked Responses

- MEG Response Patterns Time-Locked to Stimulus Events
- Robust
- Strongly Lateralized



Pure Tone





Broadband Noise

MEG Component Analysis

- Data driven spatial filtering:
  many available methods—ICA, PCA, DSS

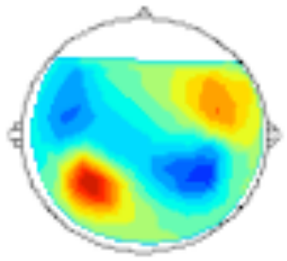
- Generate spatial filters & their outputs (“components”)

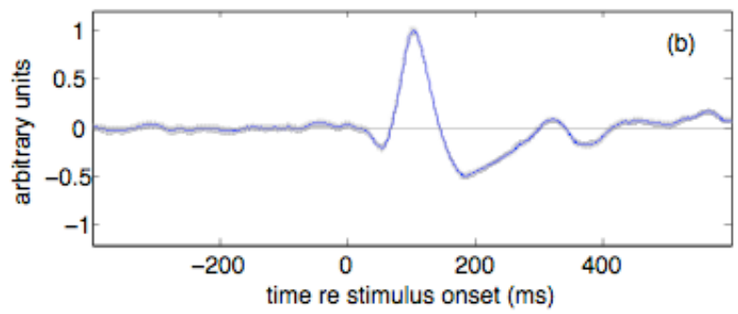
- DSS: Denoising Source Separation:
  Särelä & Valpola (2005)

- DSS components ordered by reproducibility
  - 1st component “maximally reproducible” = most stimulus driven

Component Analysis

- Each component has both spatial and temporal profile



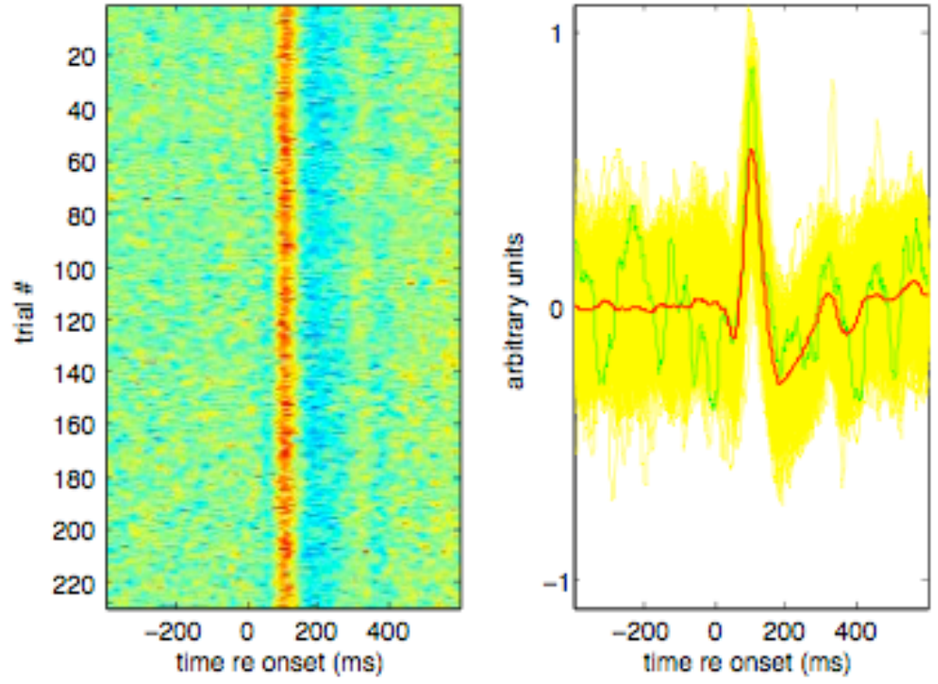


- Data driven, e.g., PCA, ICA, DSS

- DSS: ordered by trial-to-trial reproducibility

- → Spatial Filter, e.g. for single trials

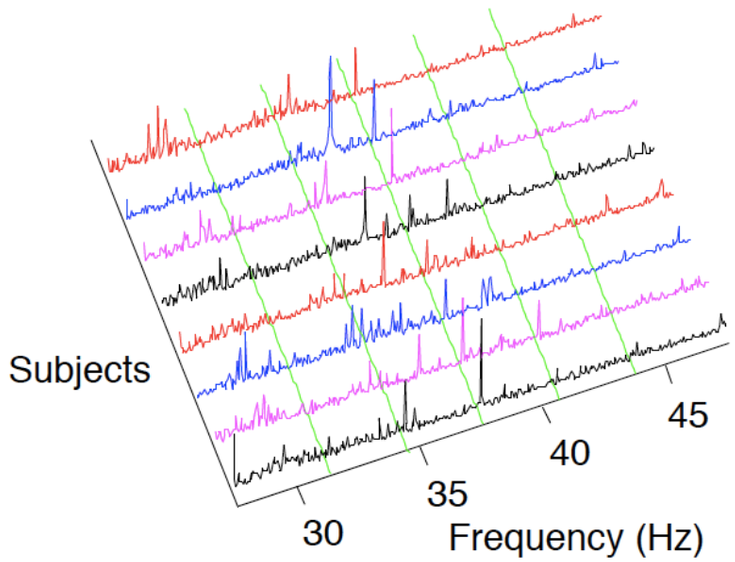
- **Can analyze temporal processing separately from anatomical origin**



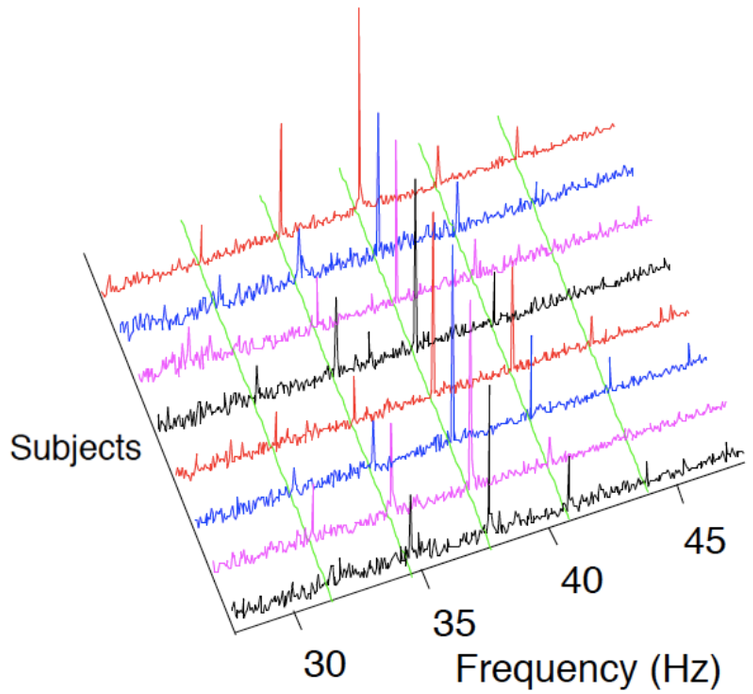
Särelä & Valpola (2005)
de Cheveigné & Simon, J. Neurosci. Methods (2008)

DSS Example: Spectral

Frequency Spectrum before DSS

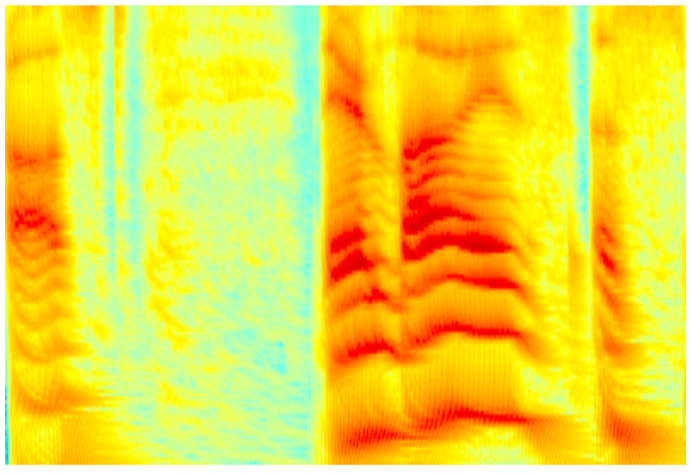


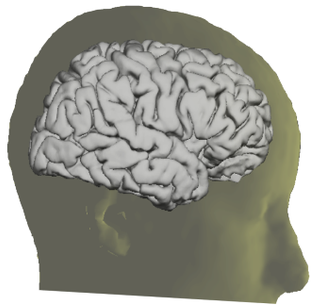
Frequency Spectrum after DSS



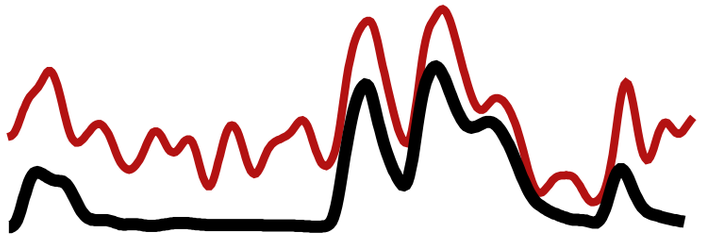
Ding & Simon, J. Neurophysiol (2009)

MEG Responses to Speech Modulations

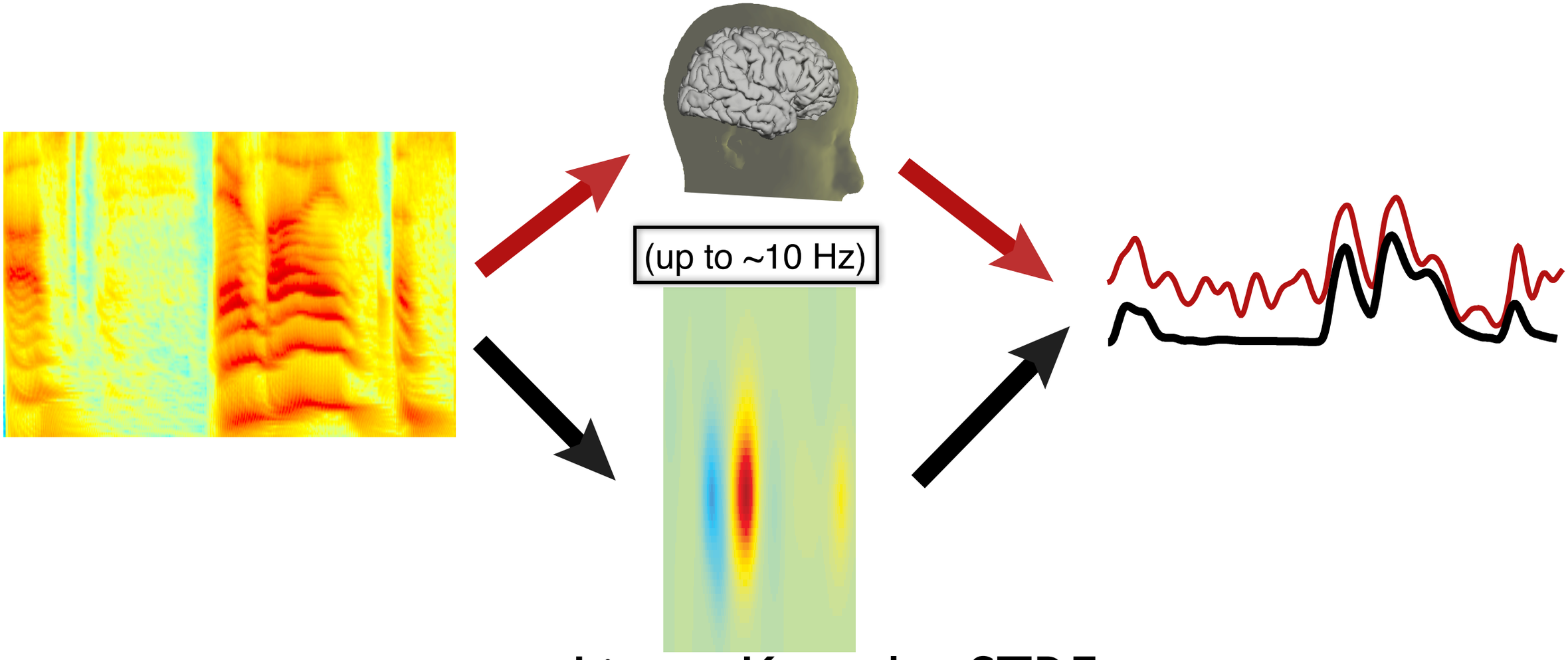




Auditory Model



MEG Responses Predicted by STRF Model

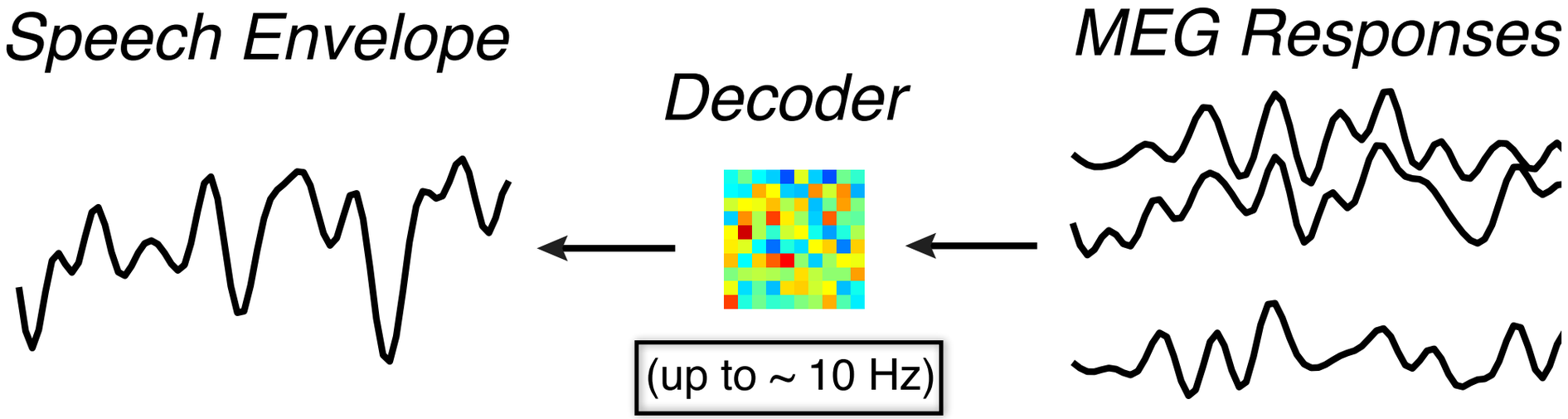


Linear Kernel = STRF

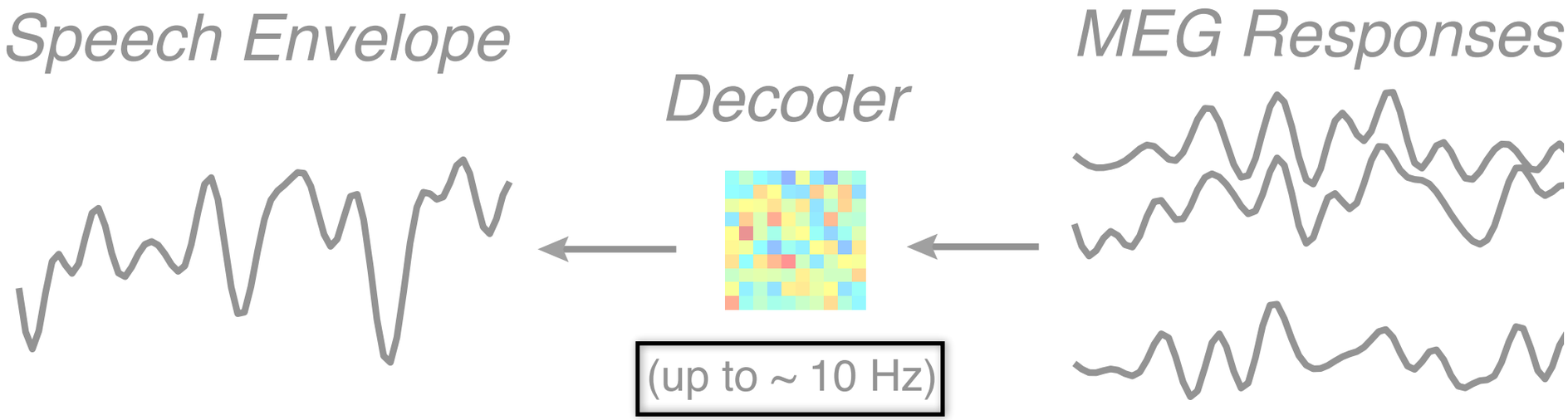
"Spectro-Temporal Response Function"

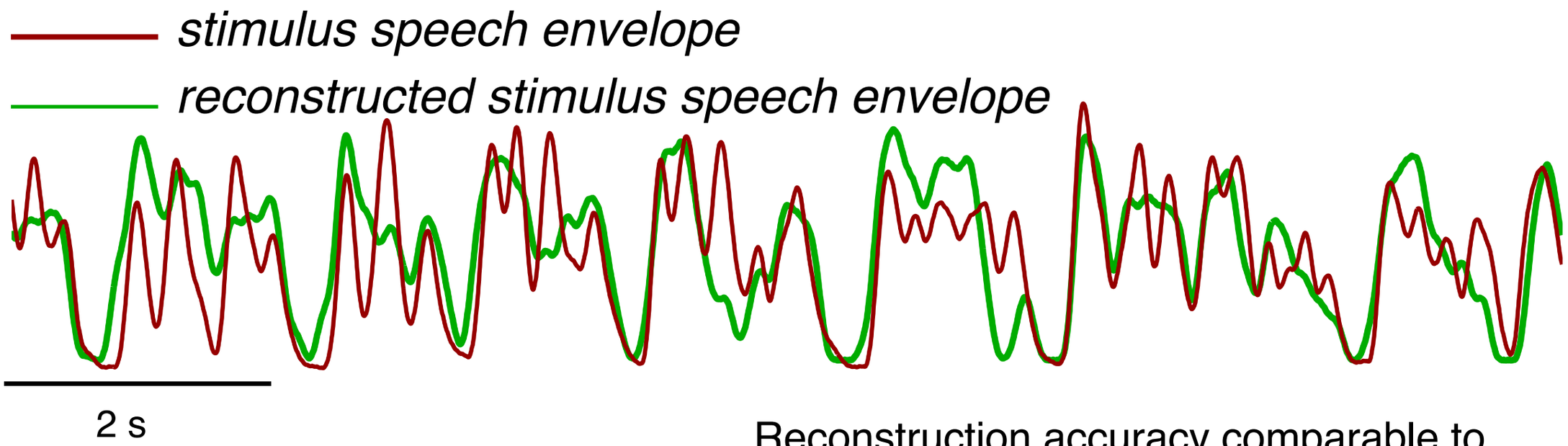
Ding & Simon, J Neurophysiol (2012)

Neural Reconstruction of Speech Envelope



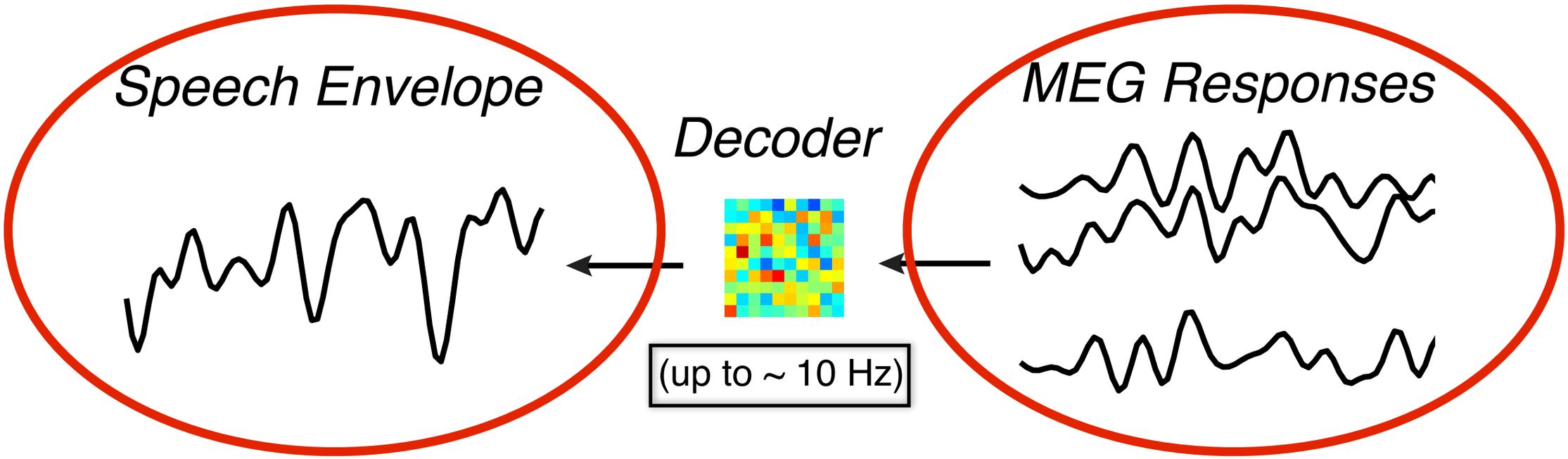
Neural Reconstruction of Speech Envelope



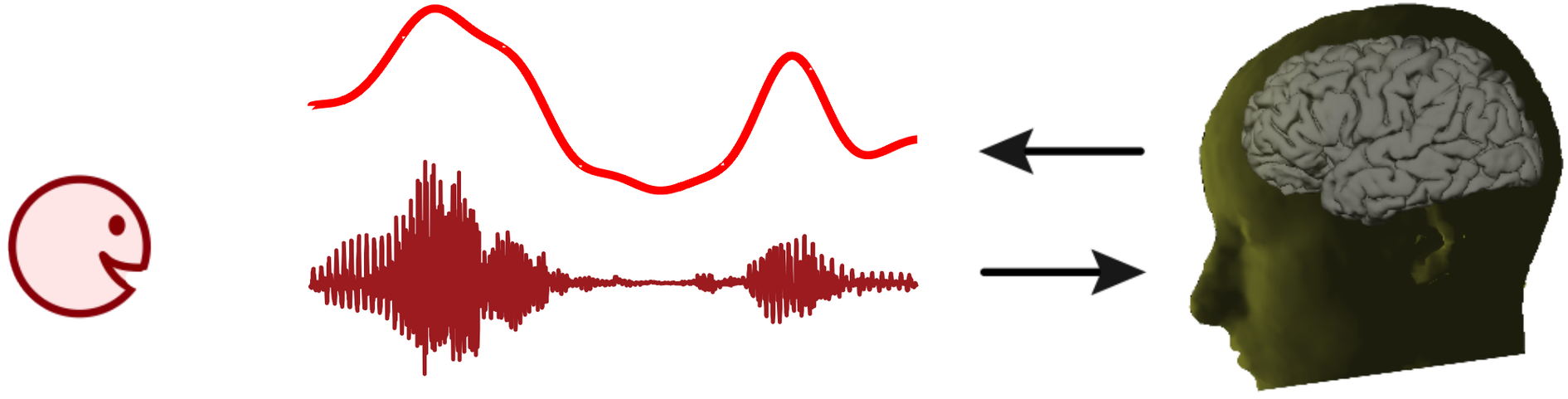


Reconstruction accuracy comparable to single unit & ECoG recordings

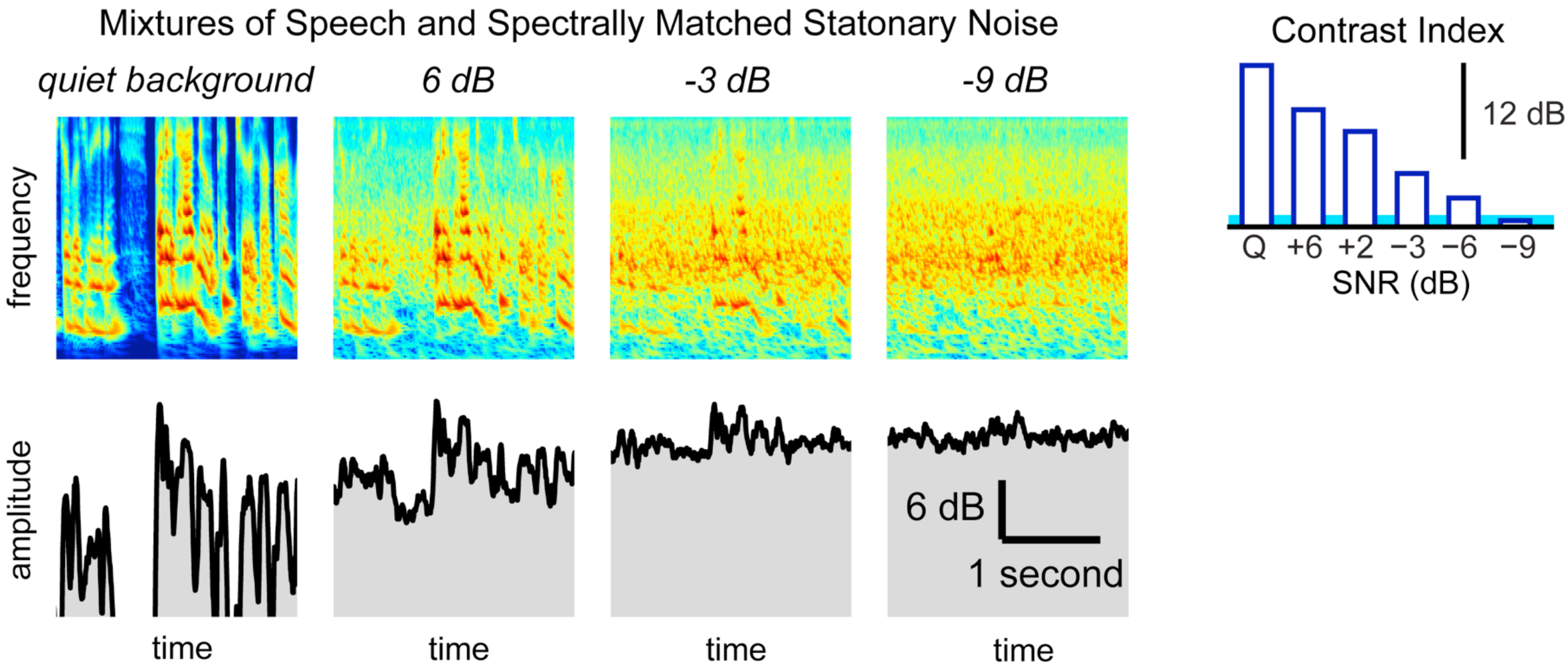
Ding & Simon, J Neurophysiol (2012)
Zion-Golumbic et al., Neuron (2013)


Speech Envelope
Decoder
MEG Responses
(up to ~ 10 Hz)

Neural Representation of Speech: Temporal

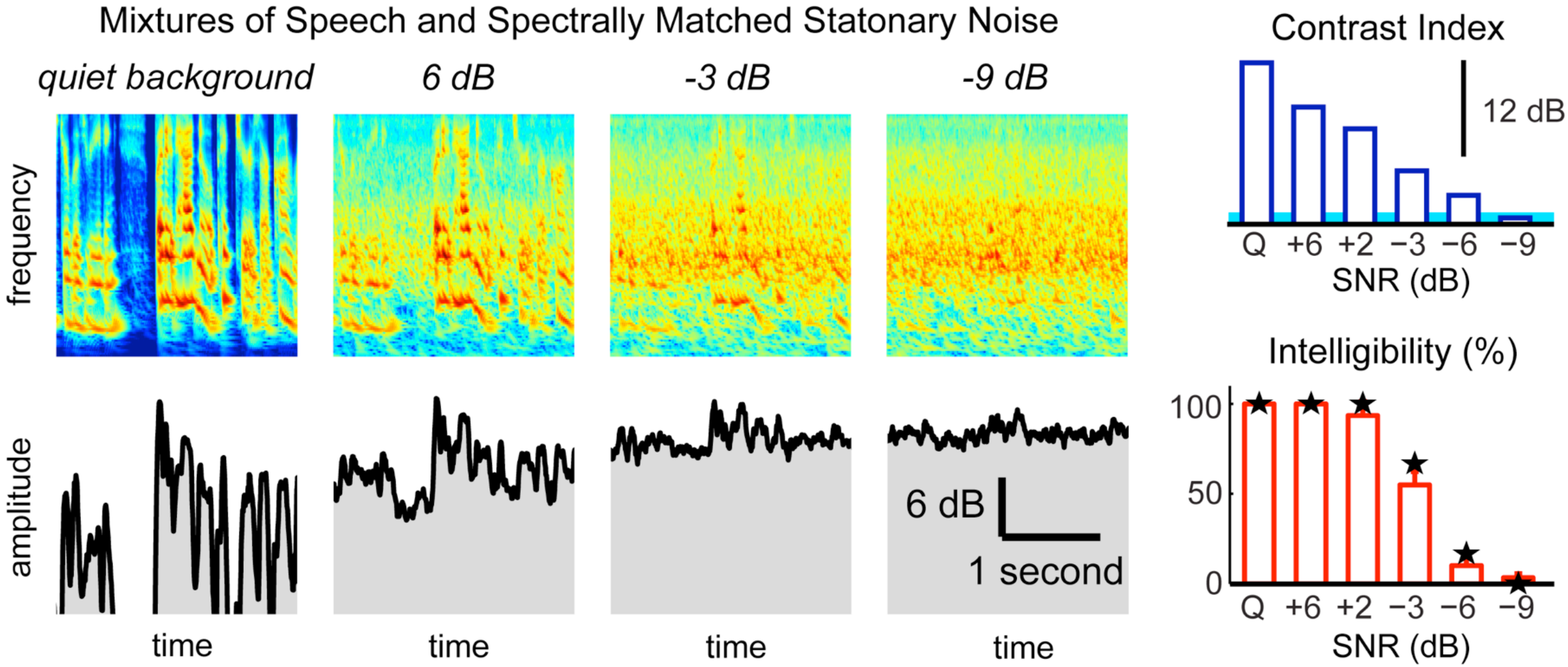


Speech in Noise



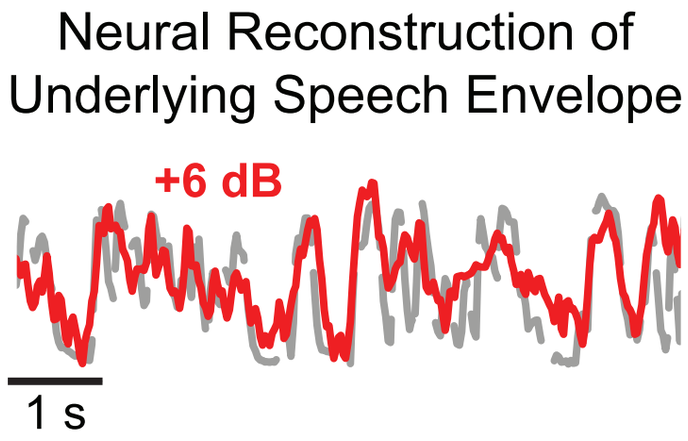
Ding & Simon, J Neuroscience (2013)

Speech in Noise



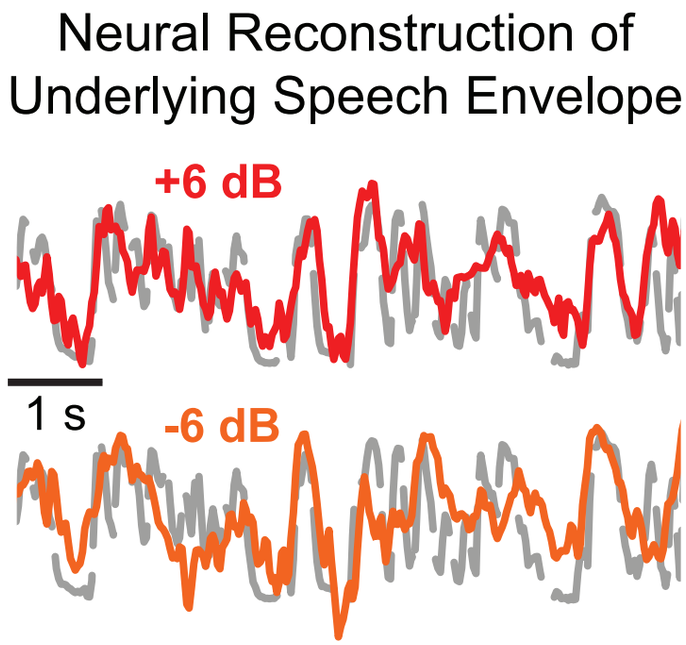
Ding & Simon, J Neuroscience (2013)

Speech in Noise: Results



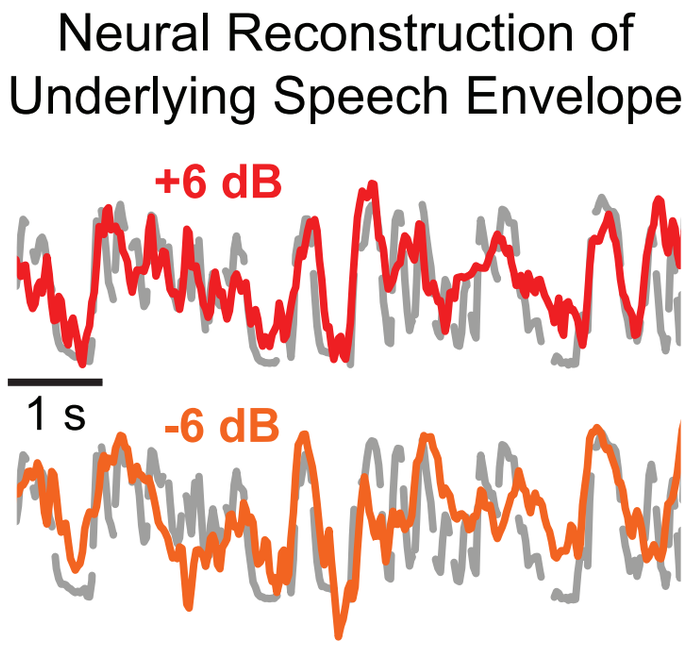
Ding & Simon, J Neuroscience (2013)

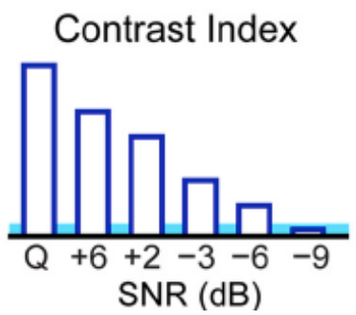
Speech in Noise: Results



Ding & Simon, J Neuroscience (2013)

Speech in Noise: Results





Ding & Simon, J Neuroscience (2013)

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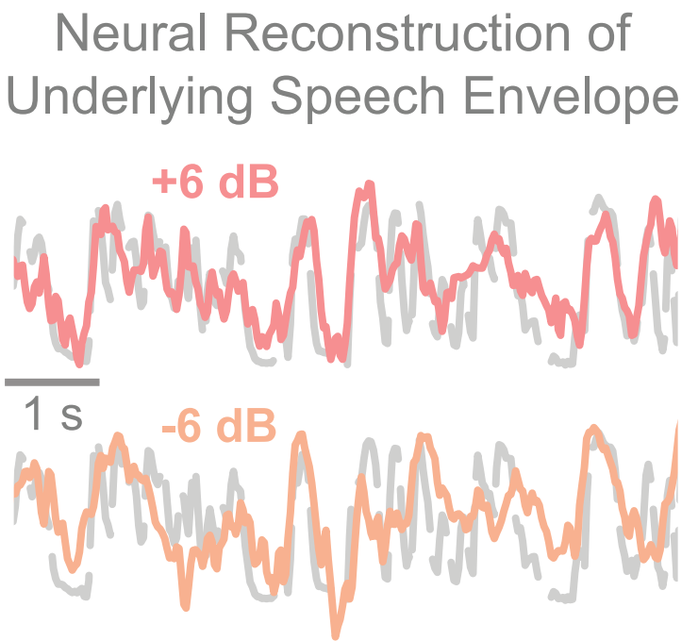
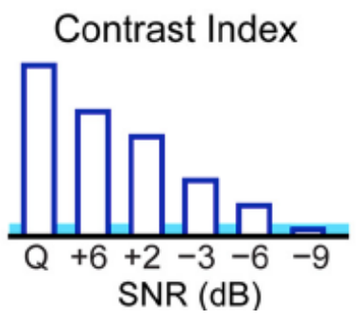
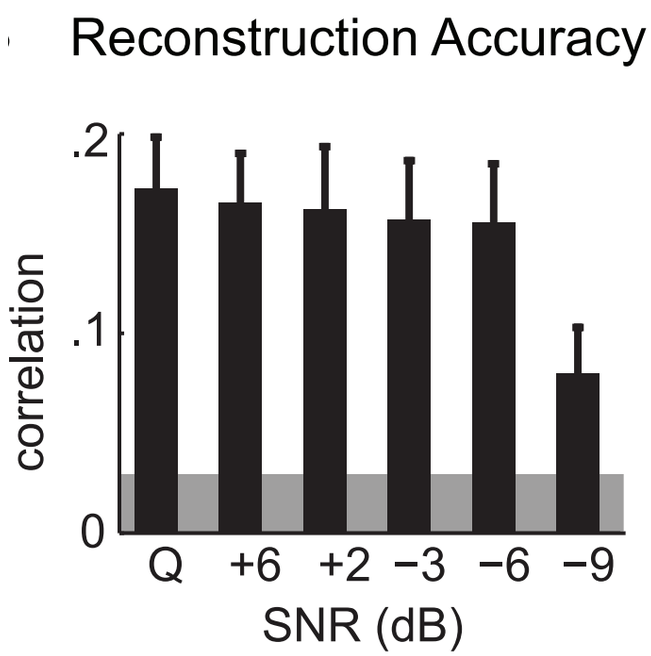
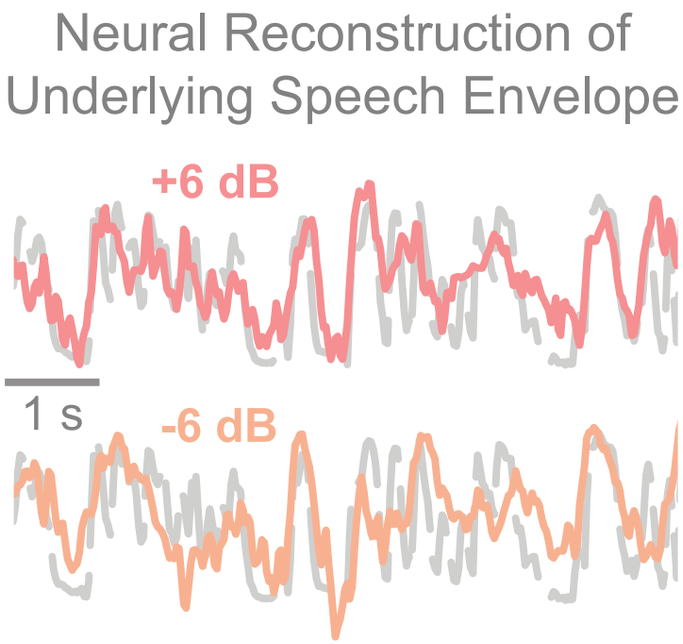


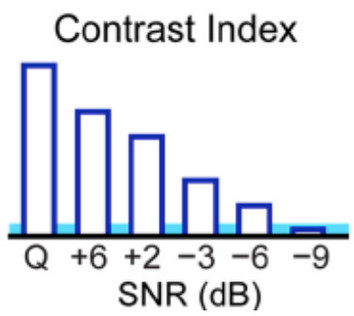


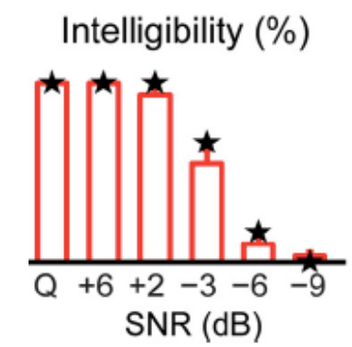


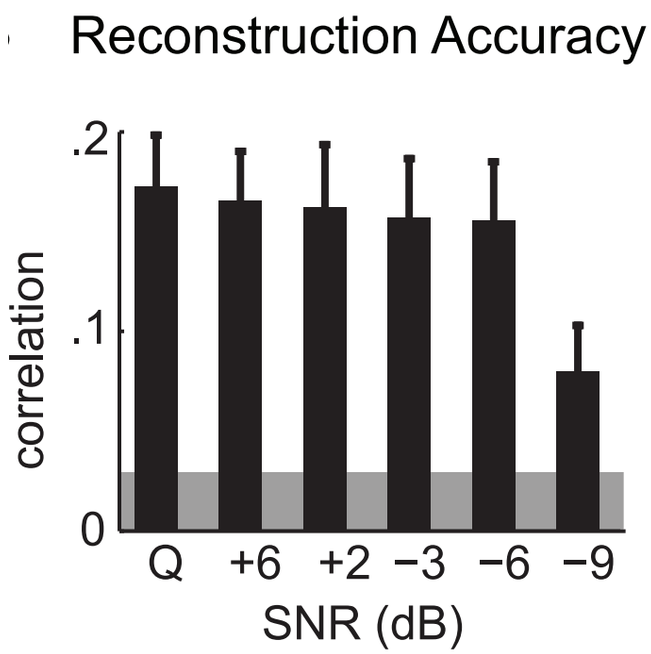
Ding & Simon, J Neuroscience (2013)

Speech in Noise: Results









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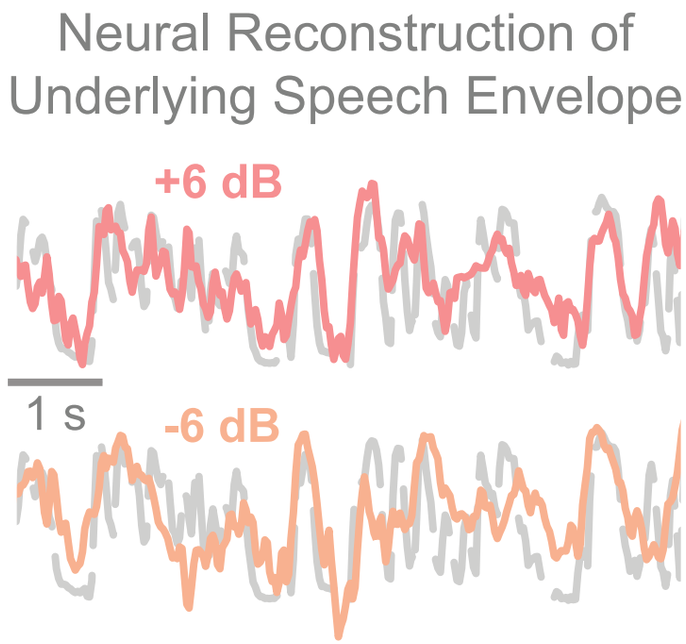

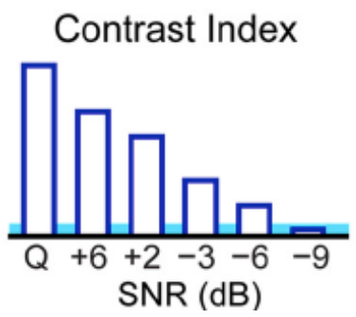

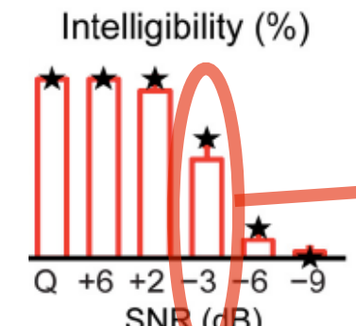

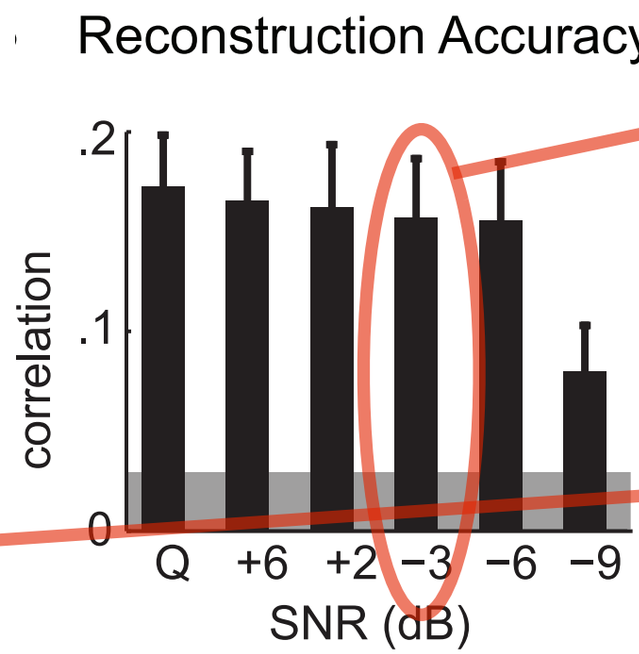

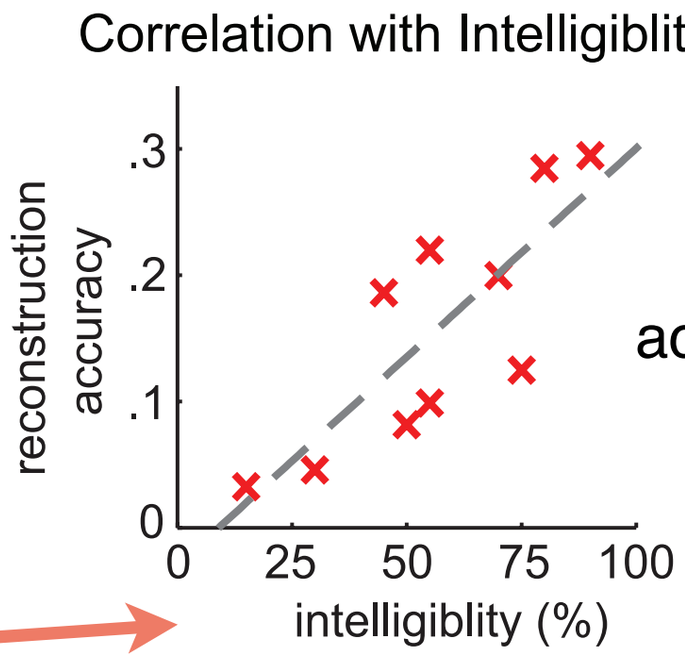

across Subjects

Ding & Simon, J Neuroscience (2013)

Cortical Speech Representations

- Neural Representations: Encoding & Decoding
- Linear models: Useful & Robust
- Speech **Envelope** only (as seen by MEG)
- Envelope Rates: ~ 1 - 10 Hz

The Cocktail Party

Alex Katz,
The Cocktail Party

The Cocktail Party

Alex Katz,
The Cocktail Party

The Cocktail Party

Alex Katz,
The Cocktail Party

The Cocktail Party

Alex Katz,
The Cocktail Party

The Cocktail Party

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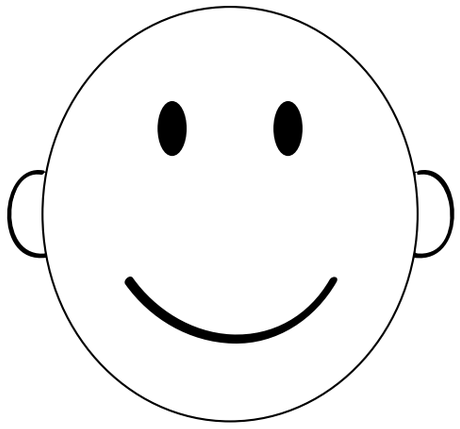
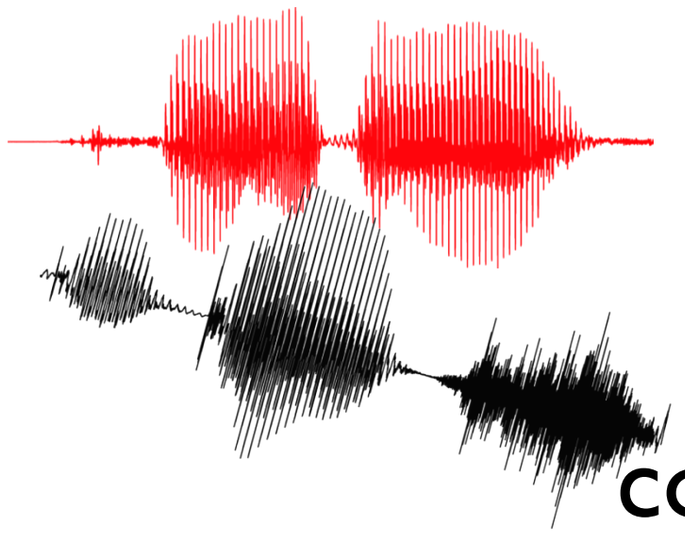
The Cocktail Party

Experiments

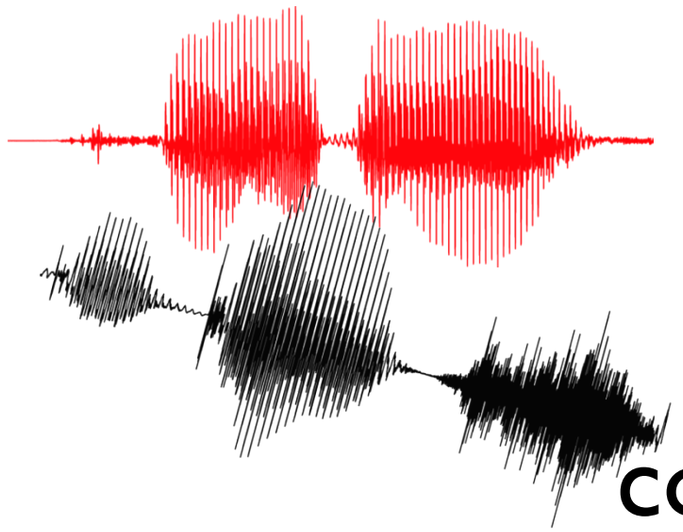




speech

competing speech

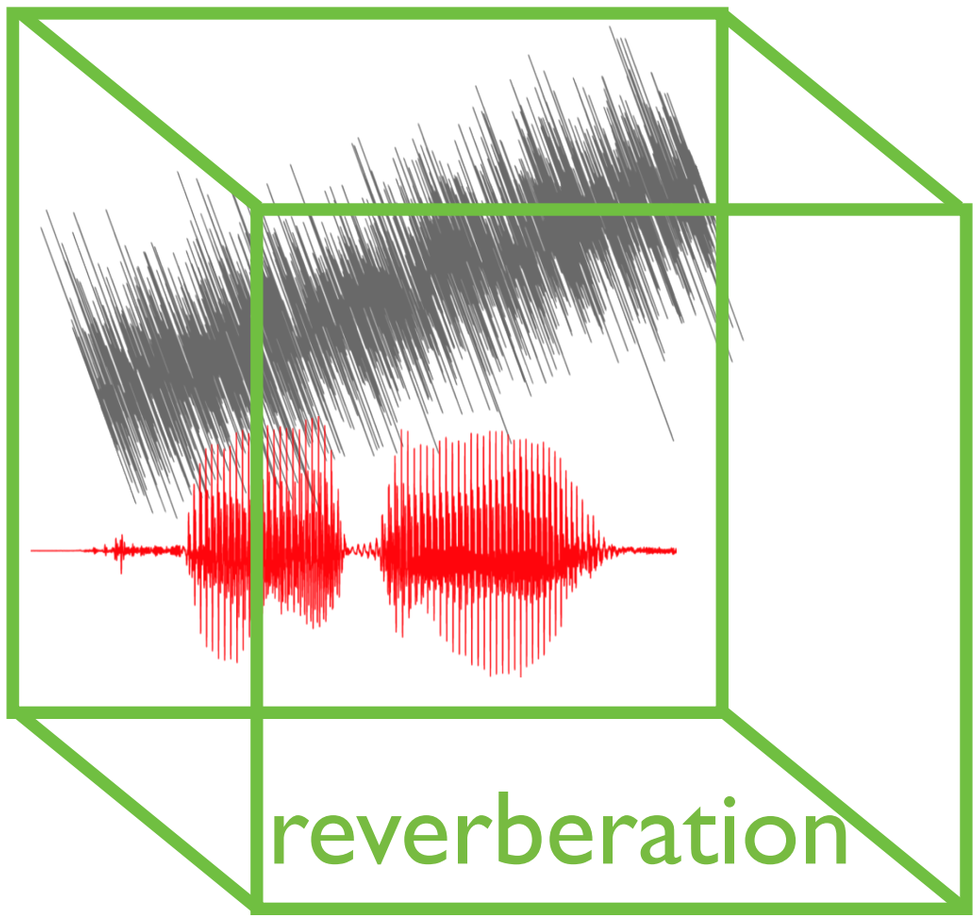
Experiments



speech

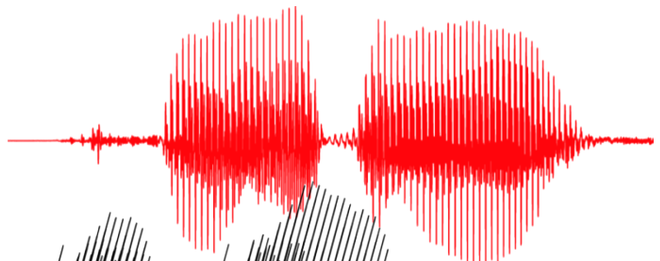
competing speech

Experiments in Progress

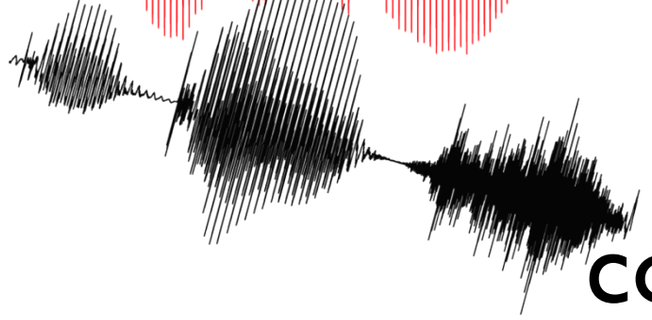


Experiments in Progress

older listener

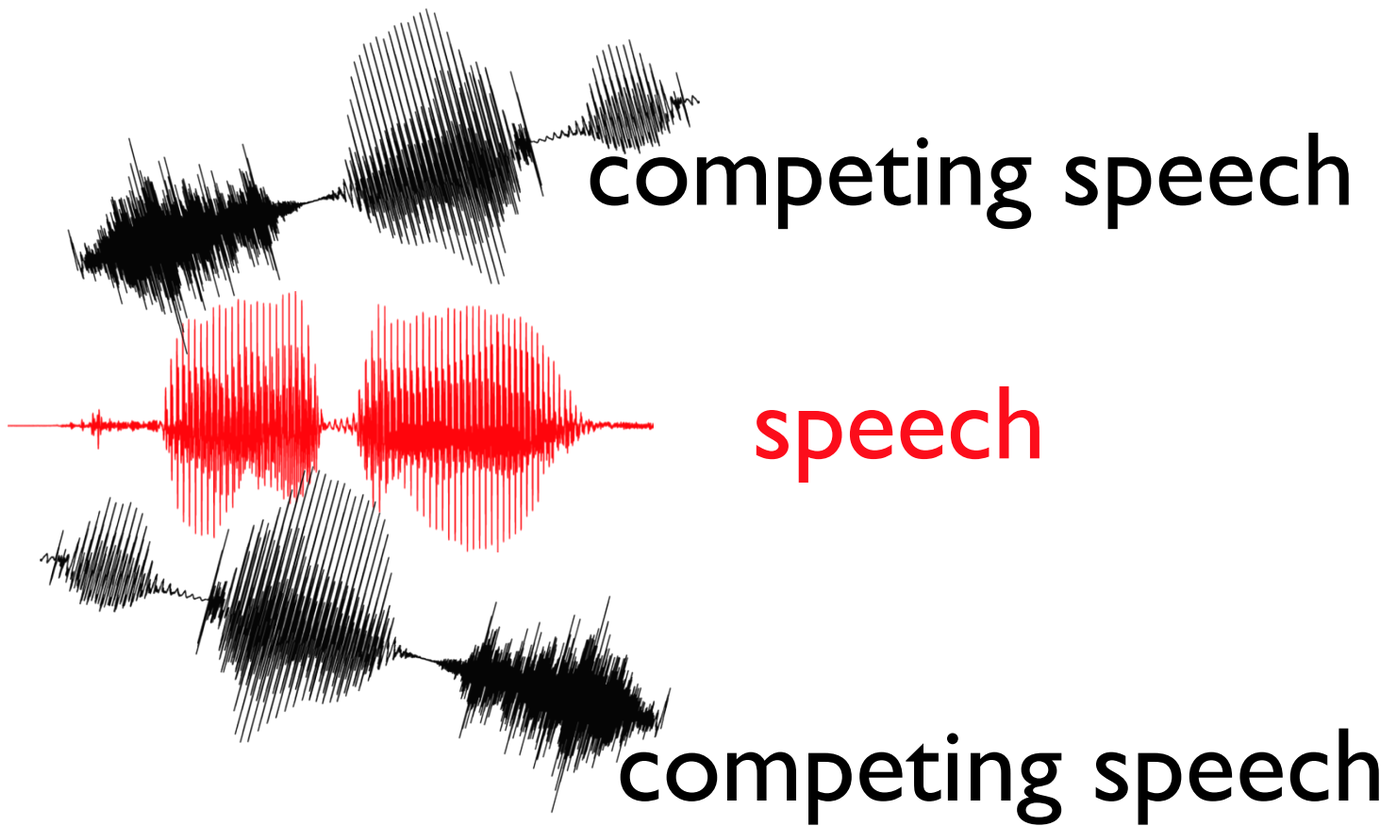


speech

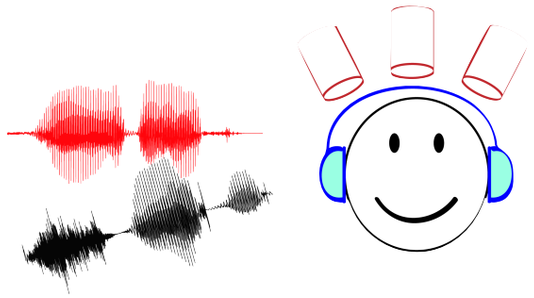


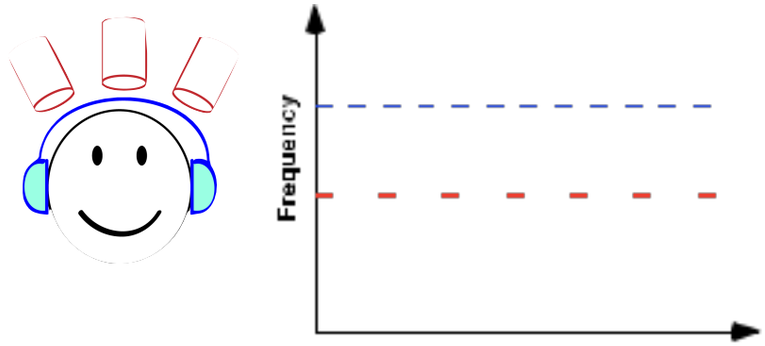
competing speech

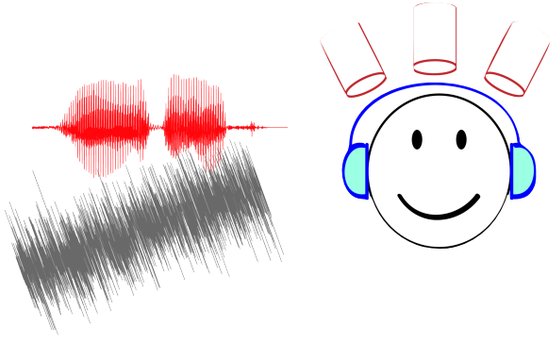
Experiments in Progress

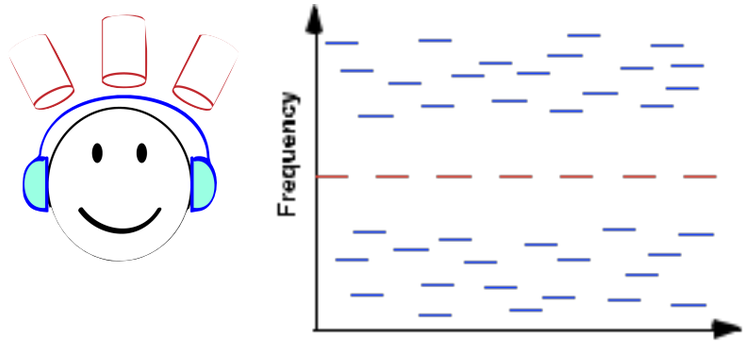


Experiments

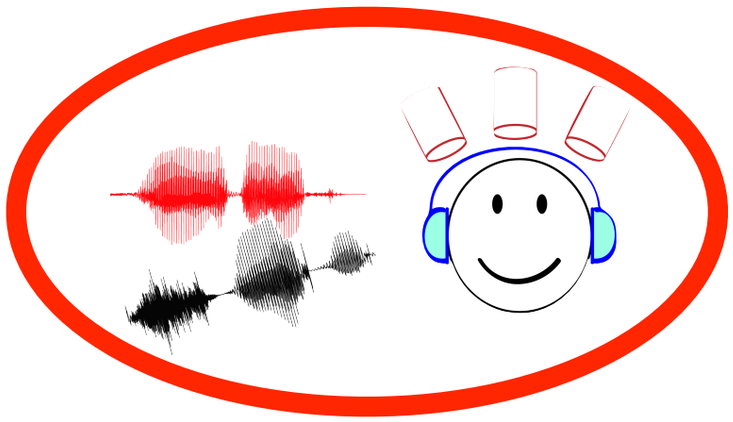


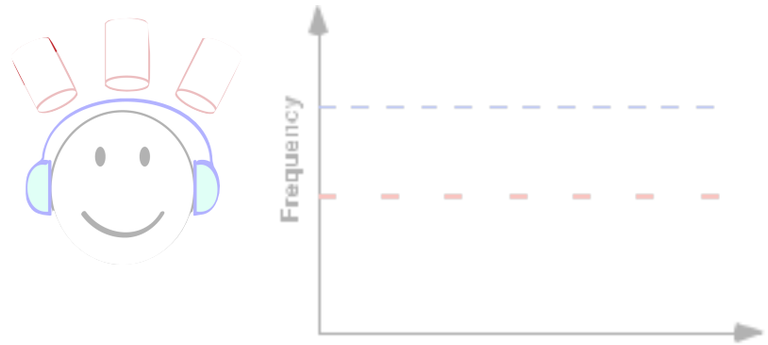


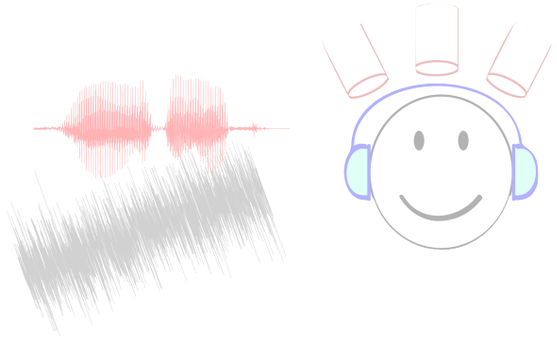


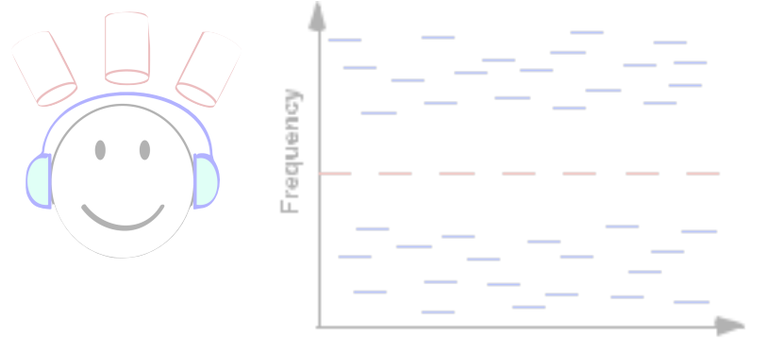


Experiments



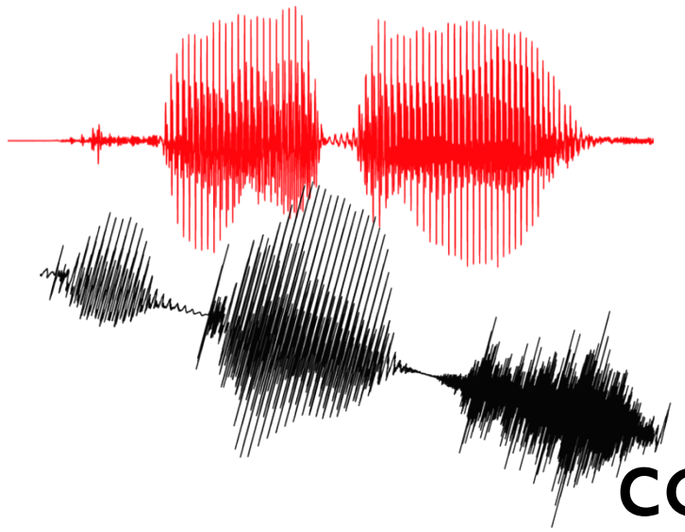






Ding & Simon, PNAS (2012)

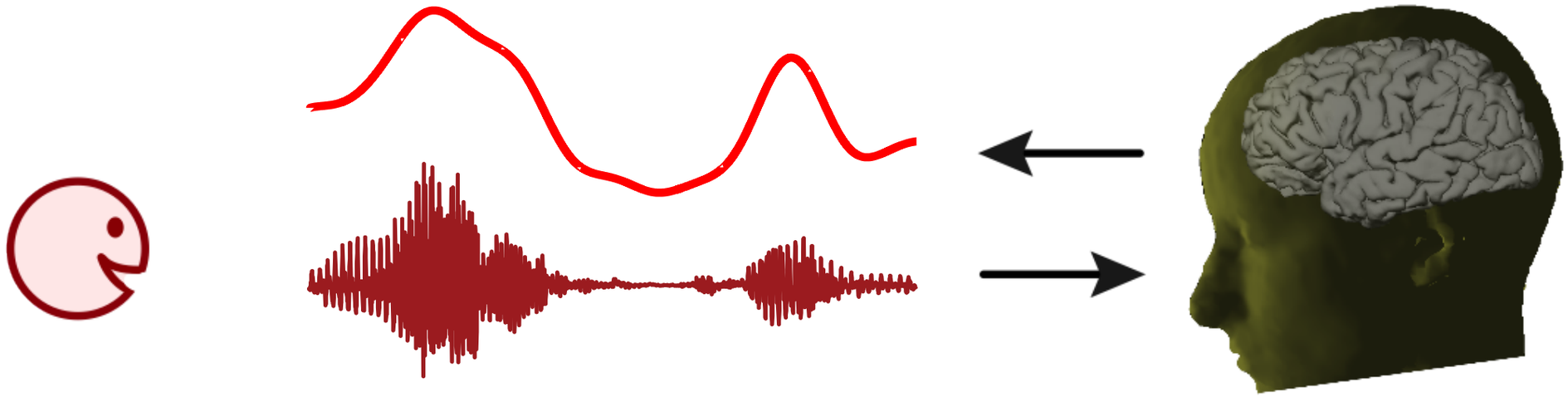
Two Competing Speakers



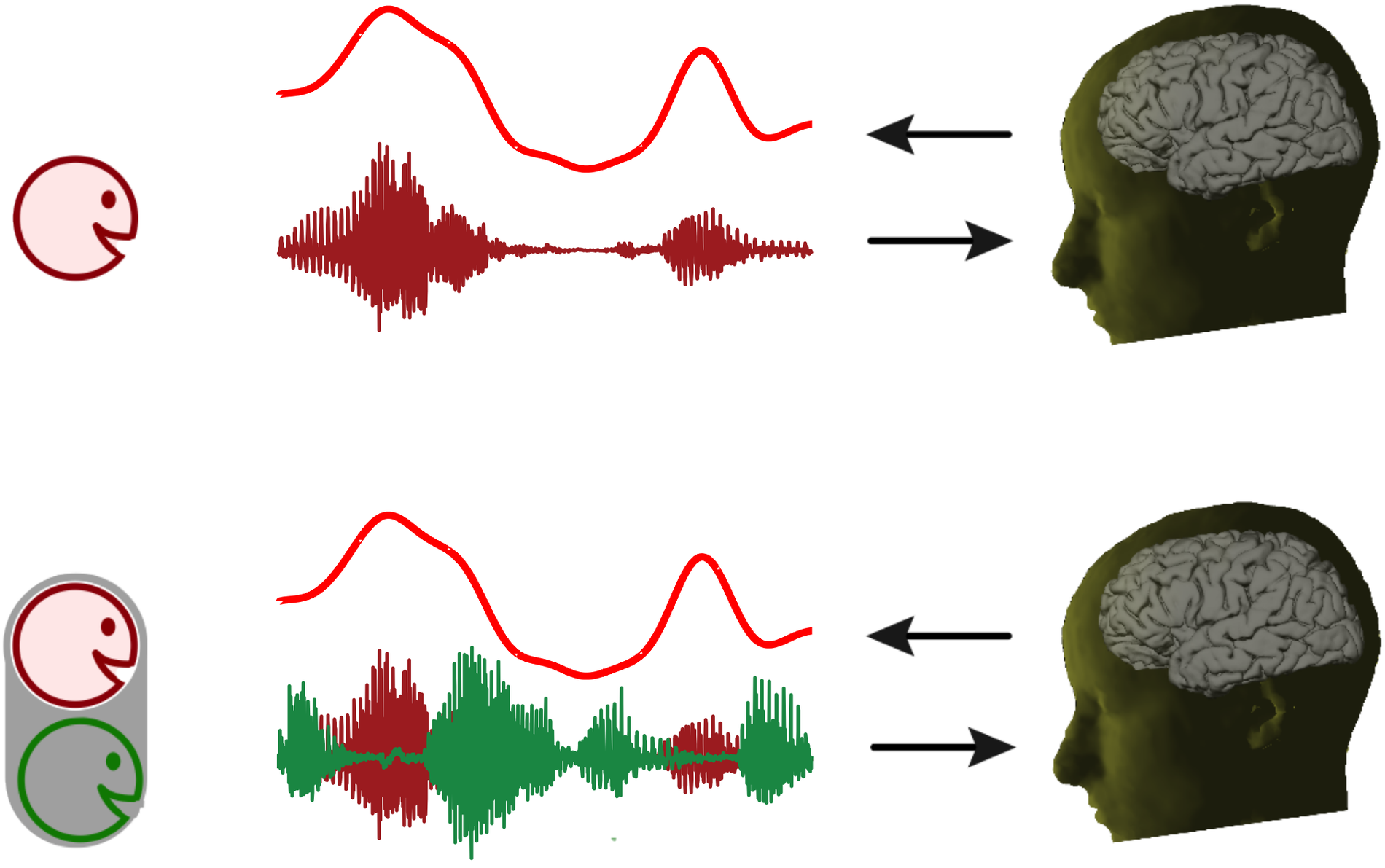
speech

competing speech

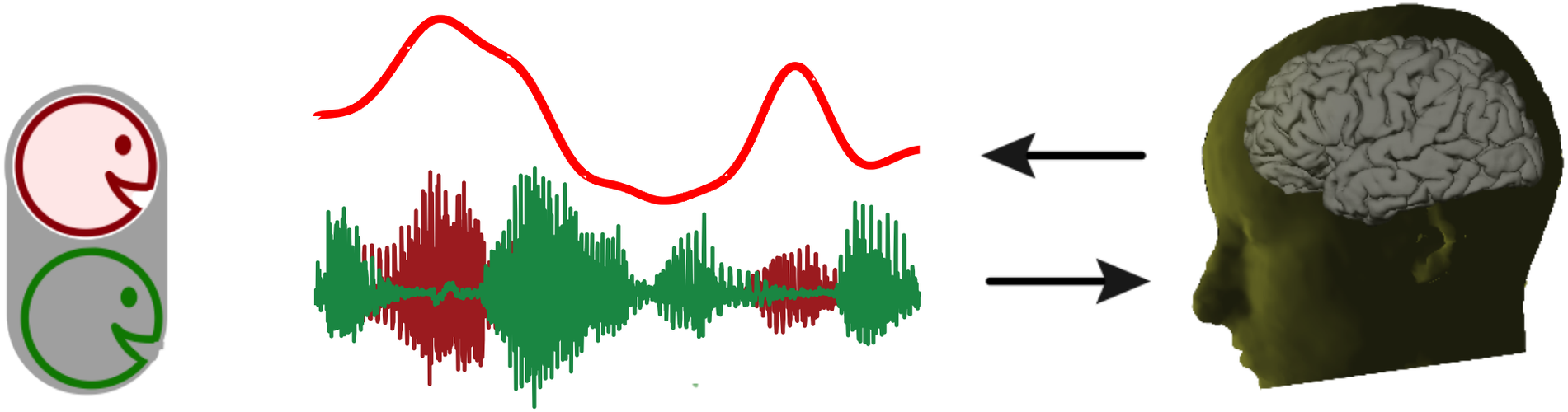
Selective Neural Encoding



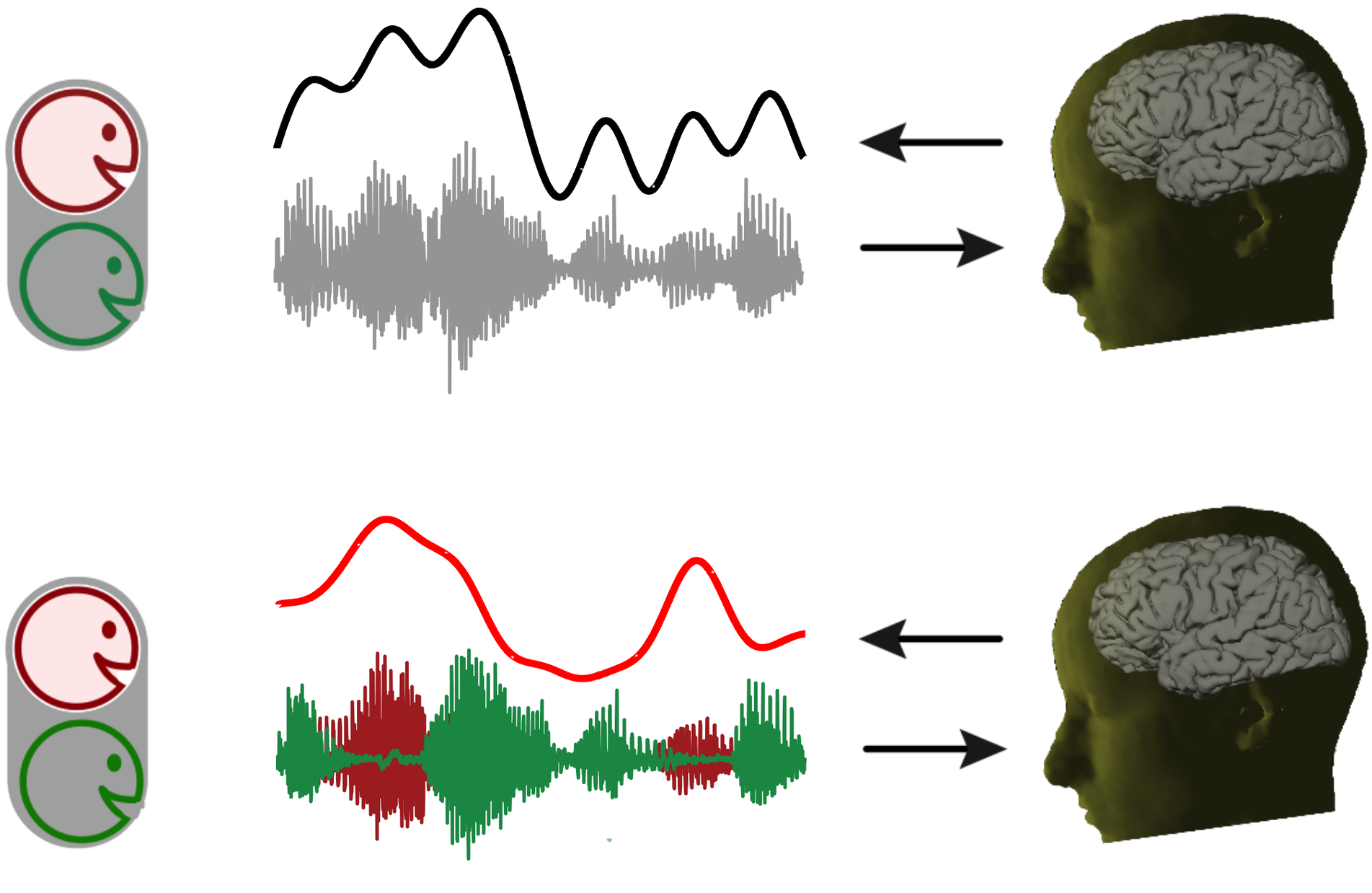
Selective Neural Encoding



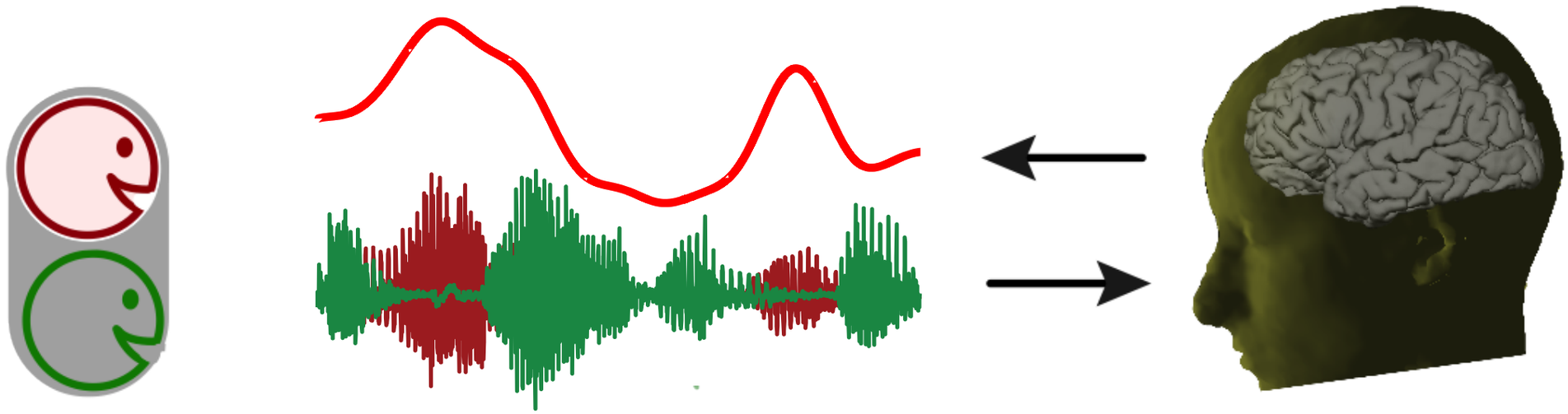
Selective Neural Encoding



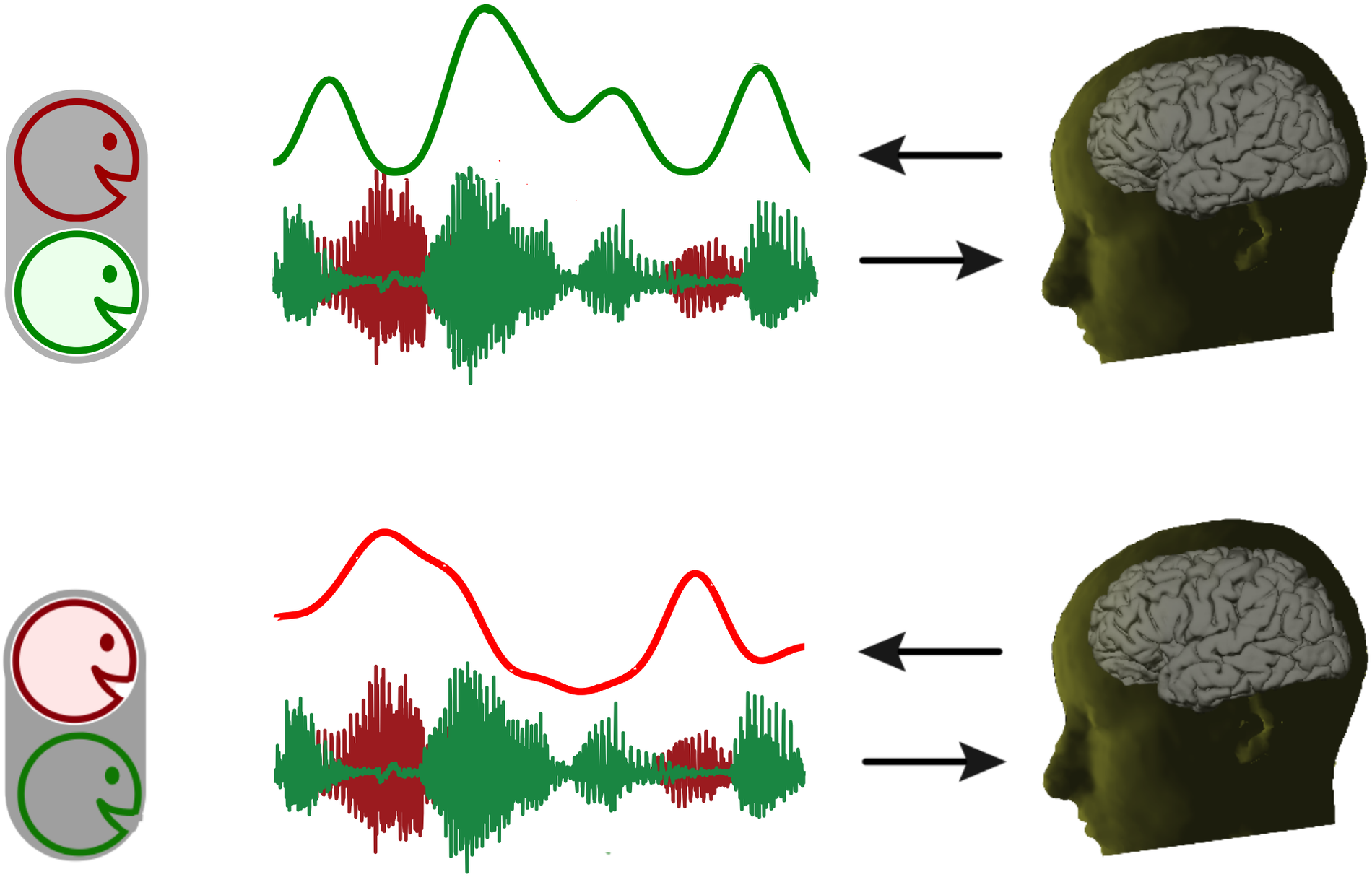
Unselective vs. Selective Neural Encoding



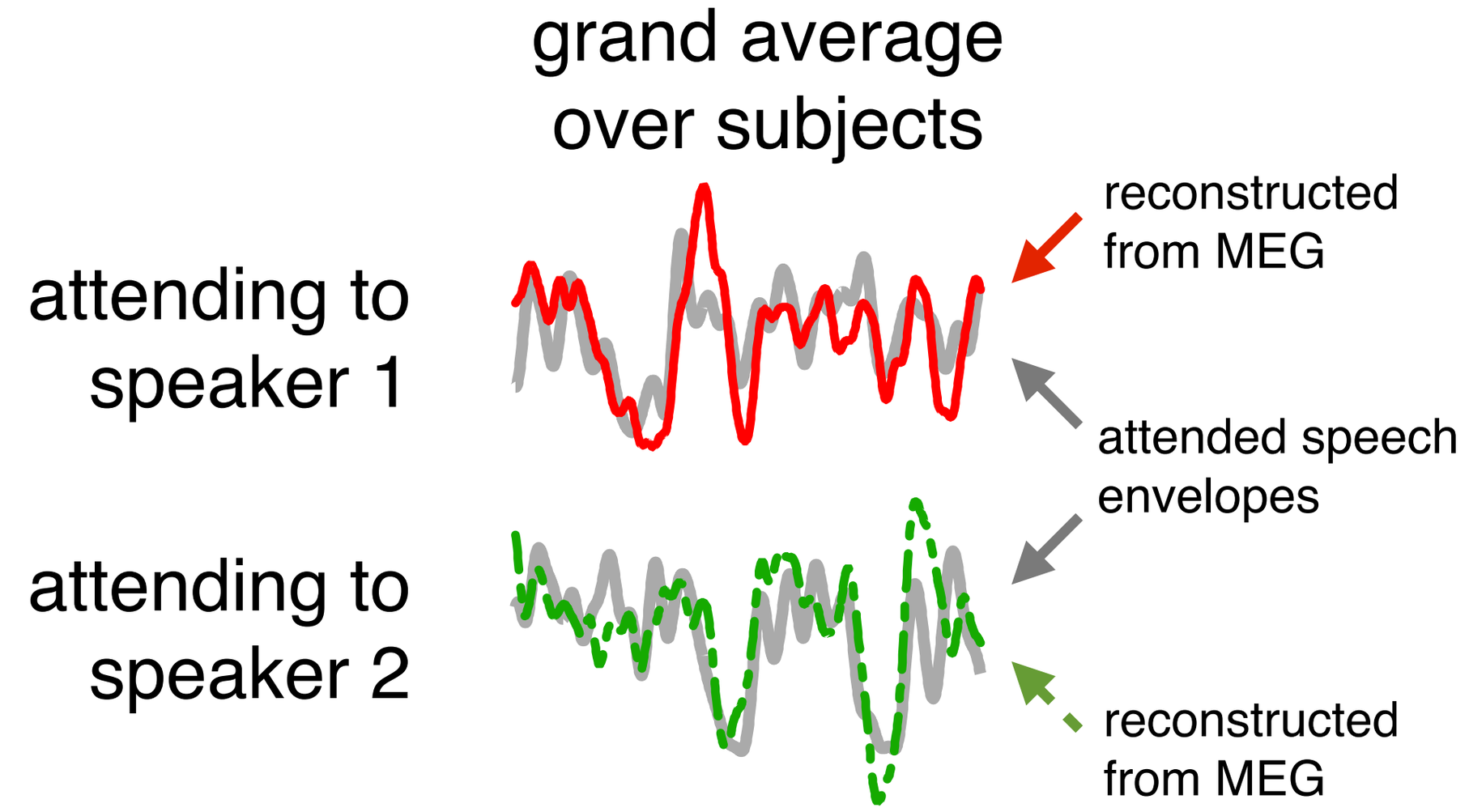
Unselective vs. Selective Neural Encoding



Selective Neural Encoding



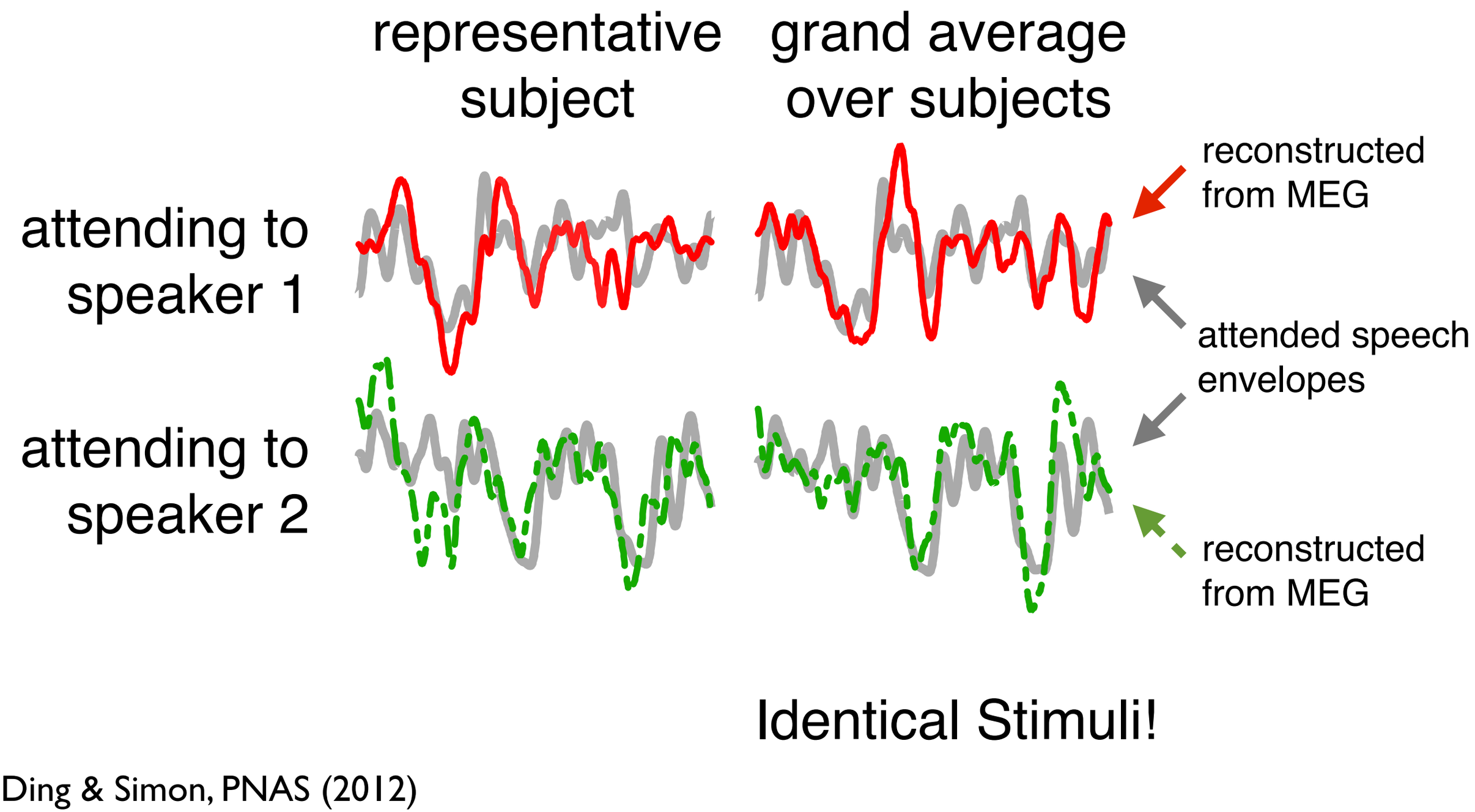
Stream-Specific Representation



Identical Stimuli!

Ding & Simon, PNAS (2012)

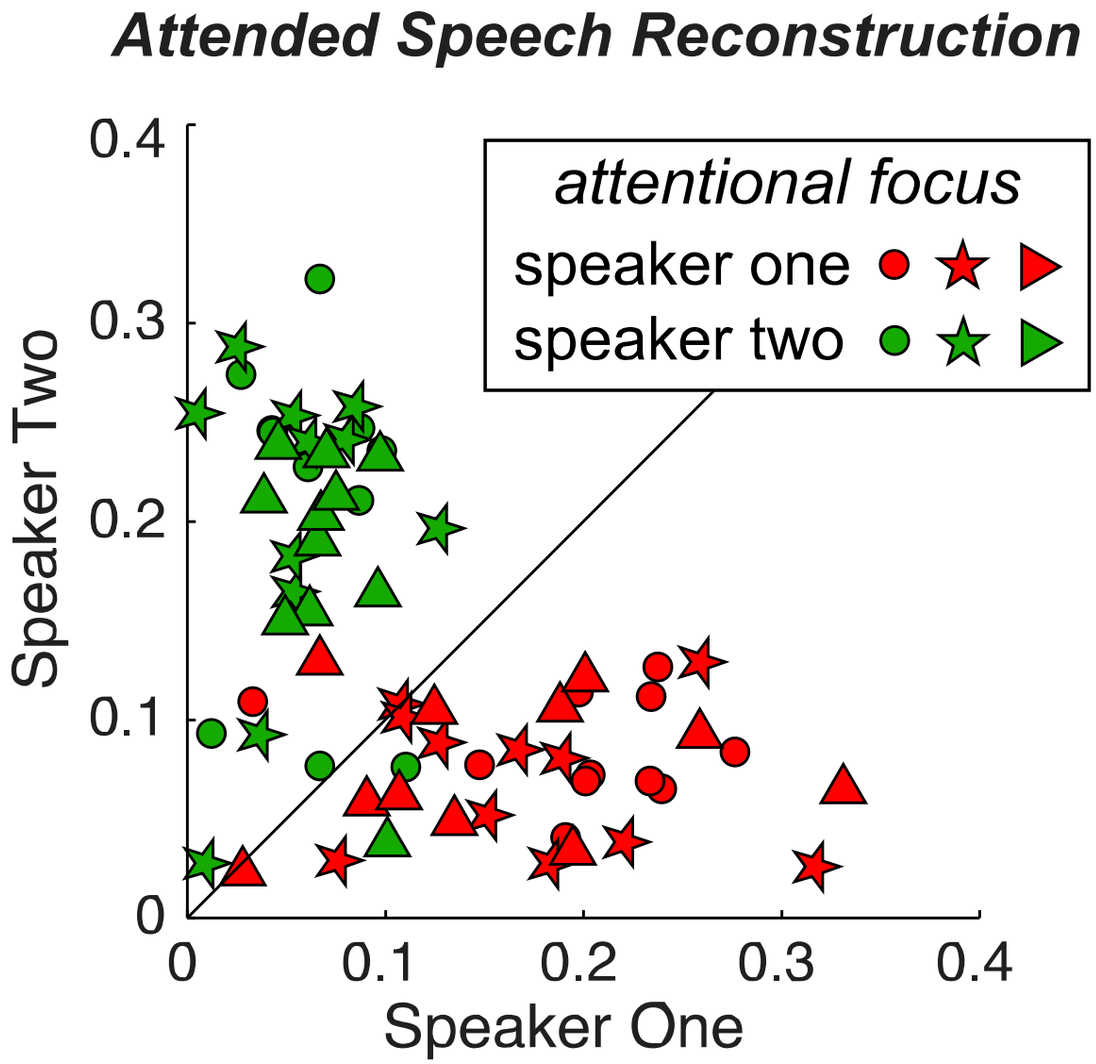
Stream-Specific Representation



Identical Stimuli!

Ding & Simon, PNAS (2012)

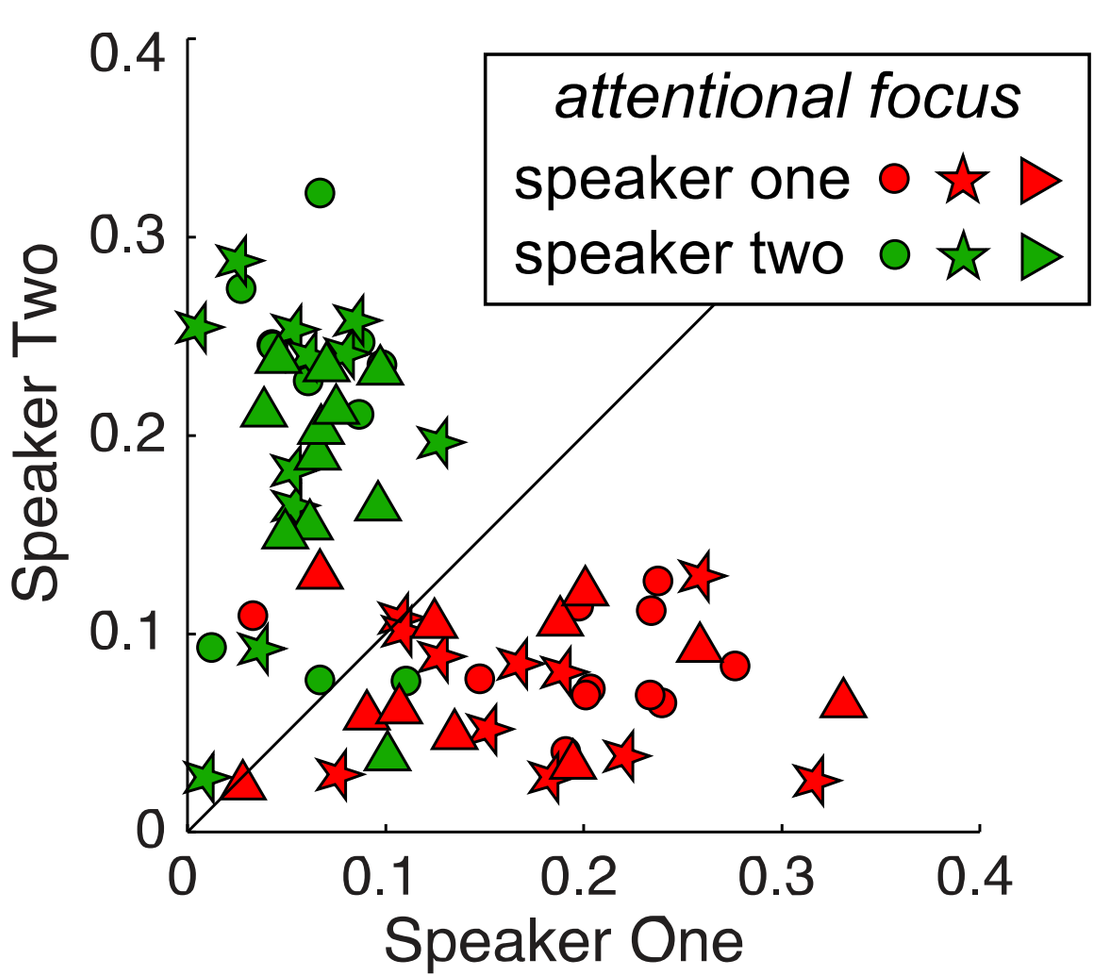
Single Trial Speech Reconstruction



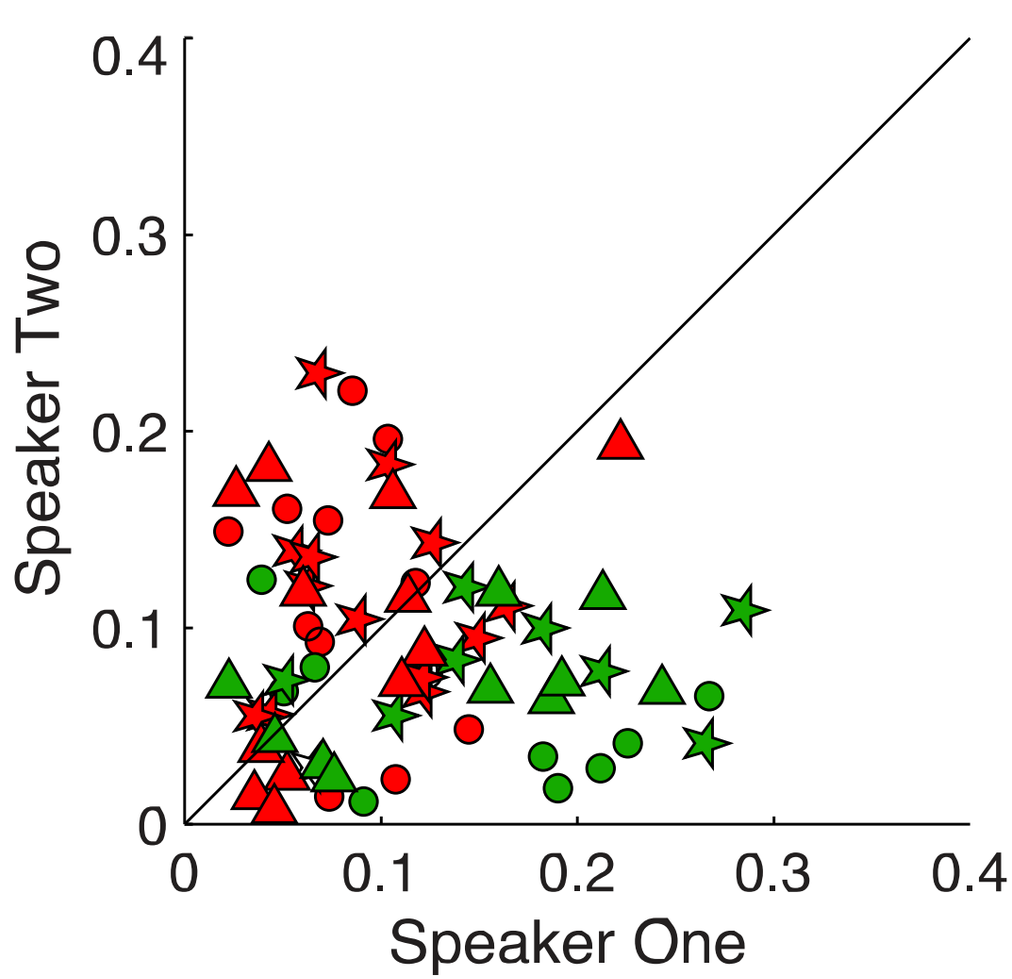
Ding & Simon, PNAS (2012)

Single Trial Speech Reconstruction

Attended Speech Reconstruction

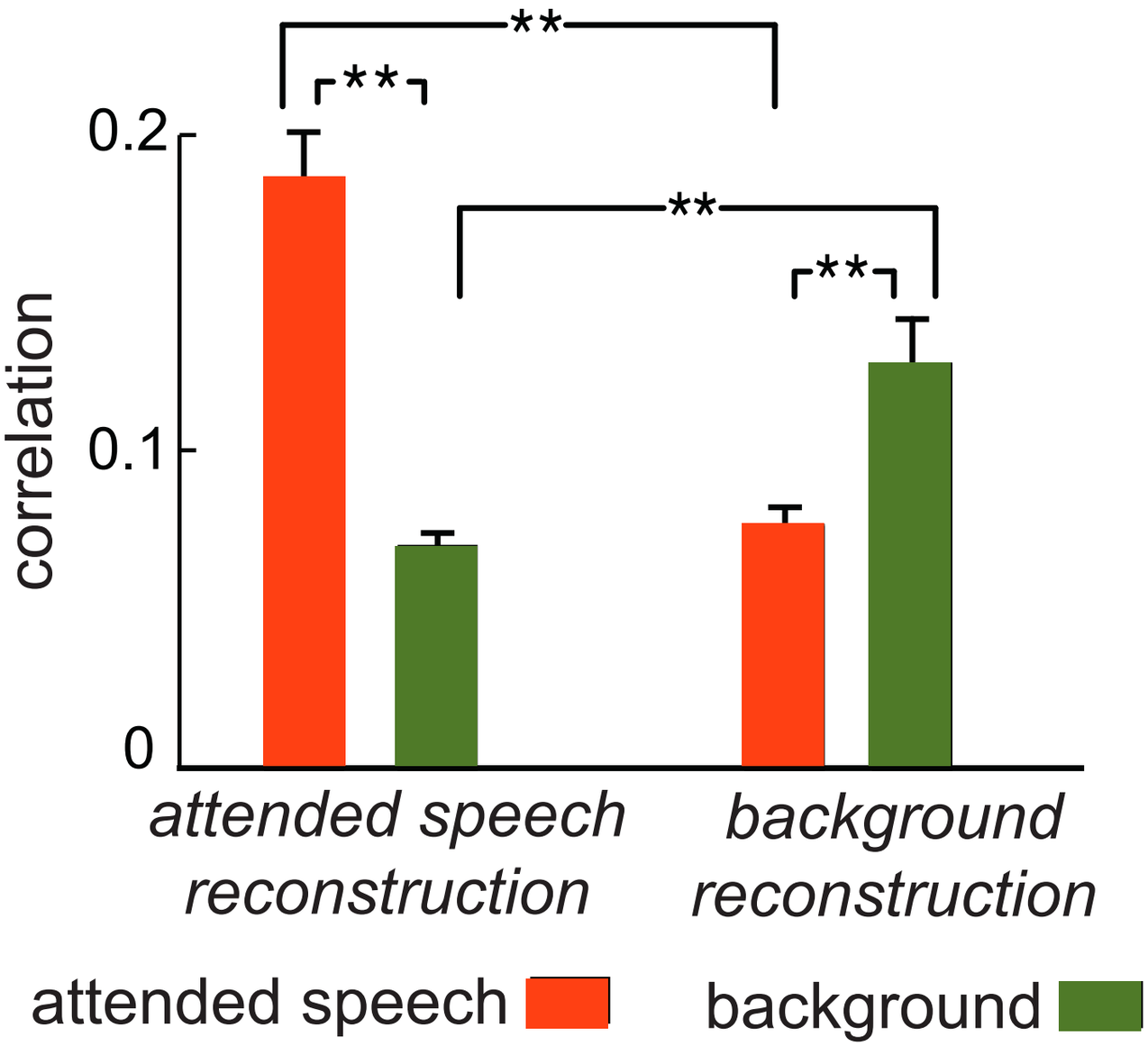


Background Speech Reconstruction



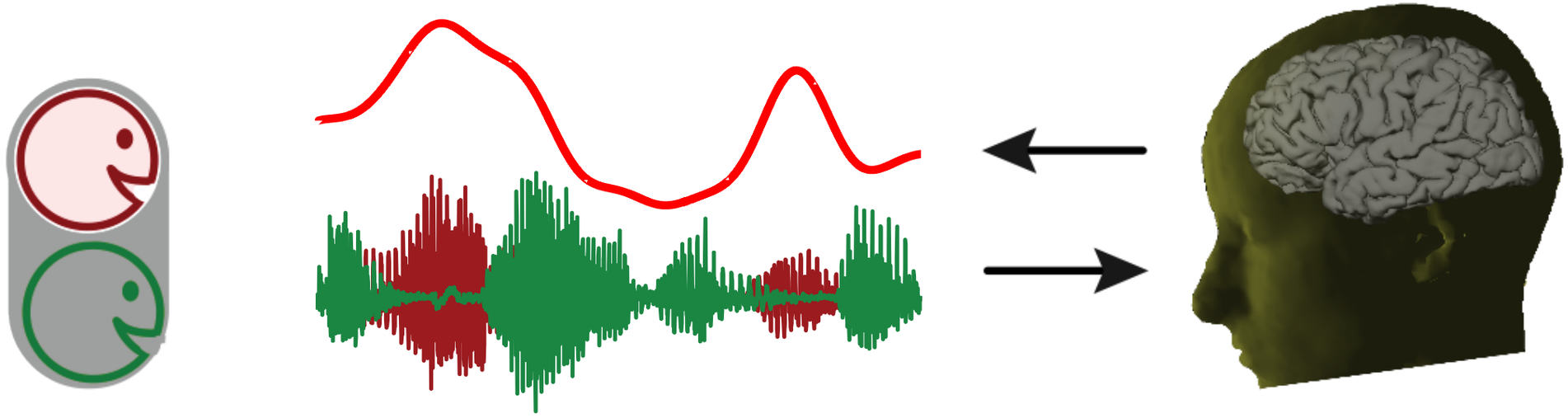
Ding & Simon, PNAS (2013)

Overall Speech Reconstruction

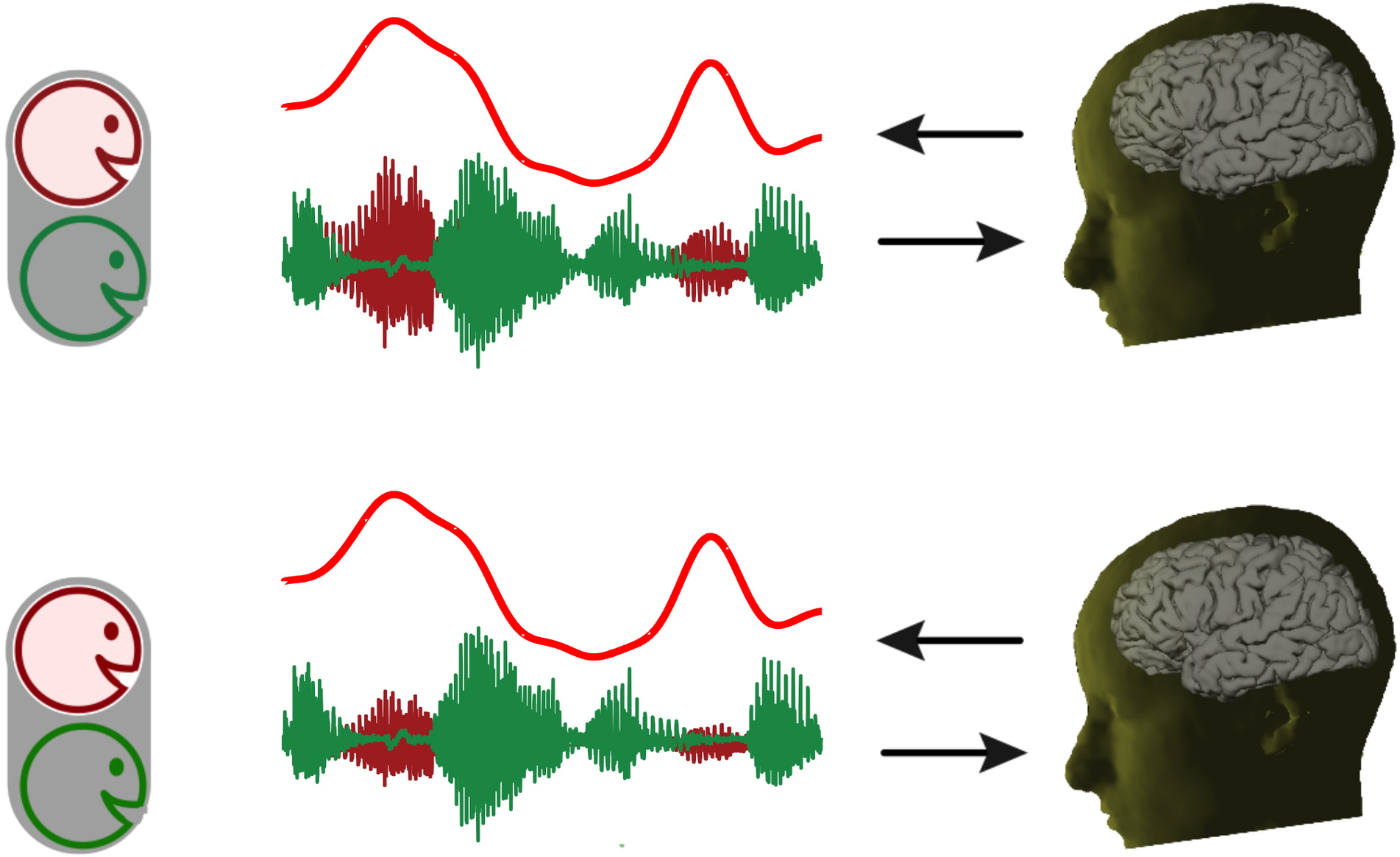


Distinct neural representations for different speech streams

Invariance Under Relative Loudness Change?

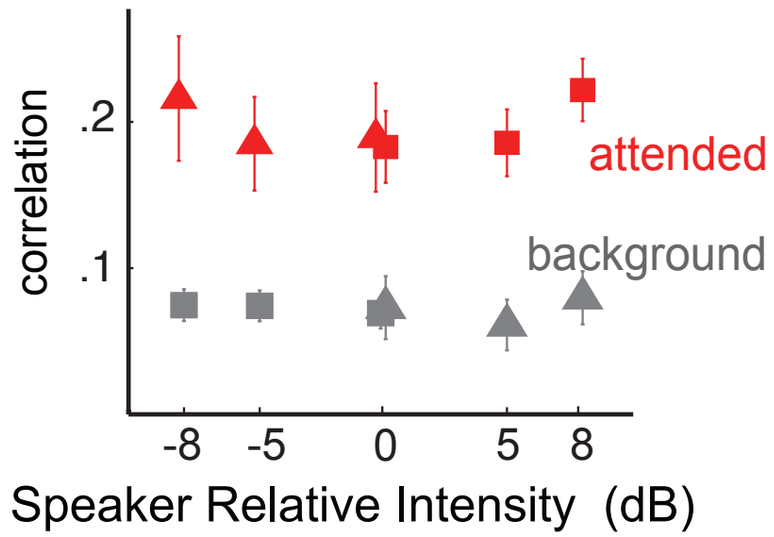


Invariance Under Relative Loudness Change?



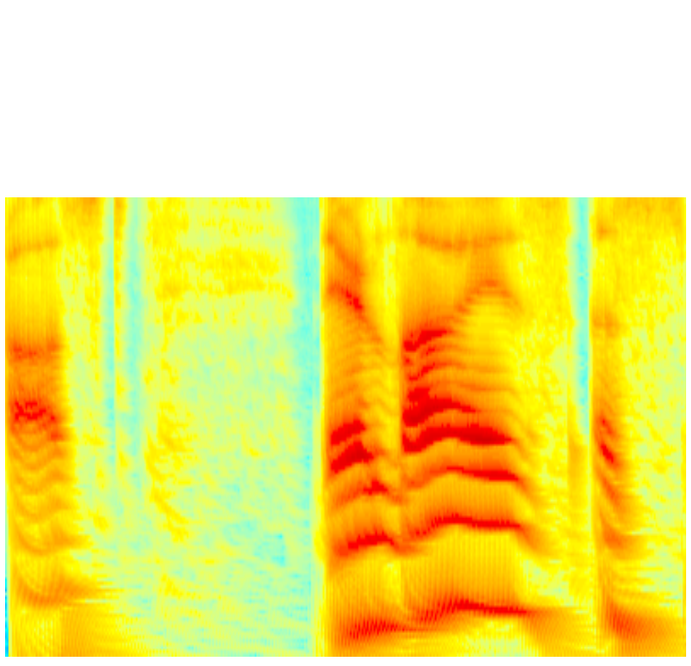
Invariance under Relative Loudness Change

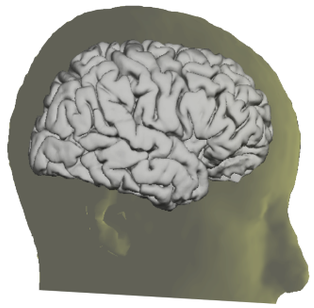
Neural Results

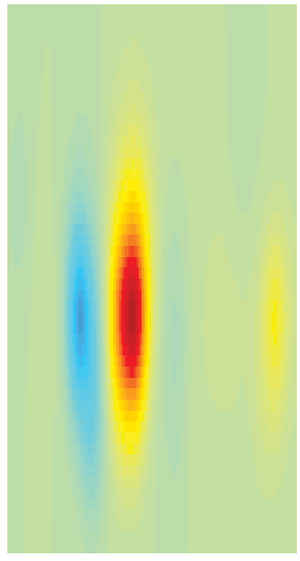


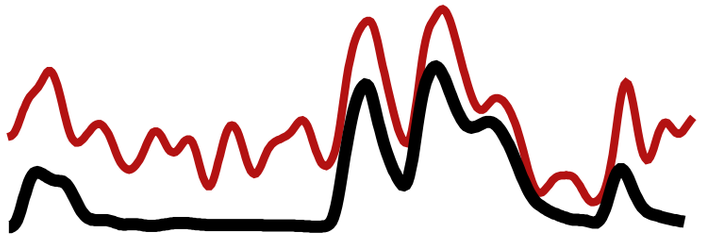
- Neural representation invariant to relative loudness change
- Stream-based Gain Control, not stimulus-based

Forward STRF Model



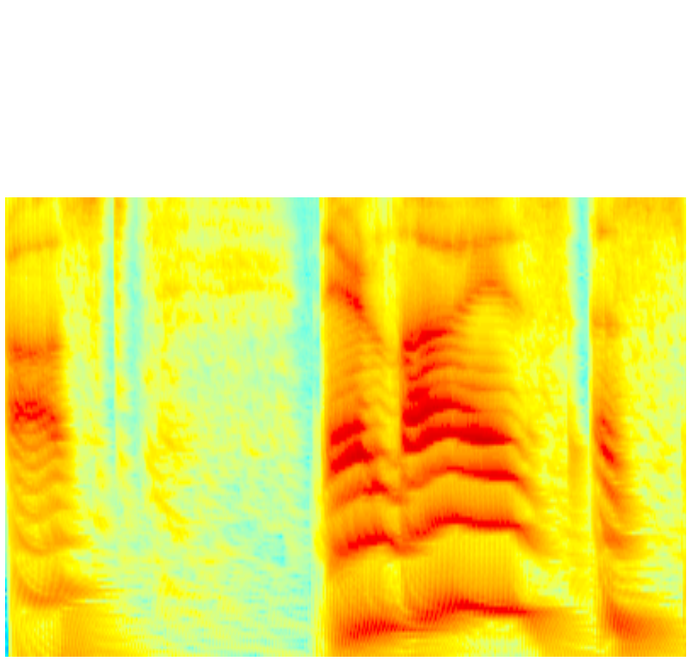


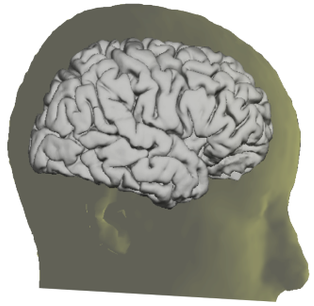


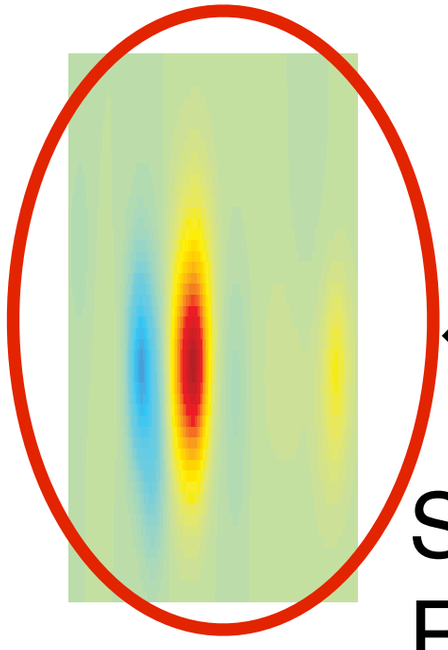


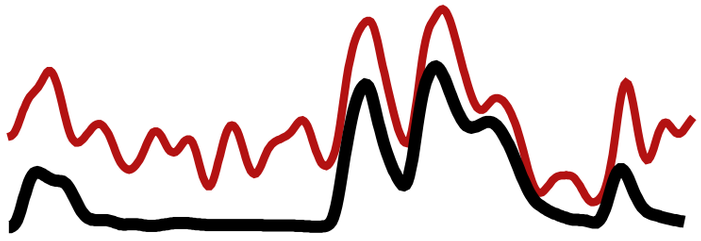
Spectro-Temporal Response Function (STRF)

Forward STRF Model



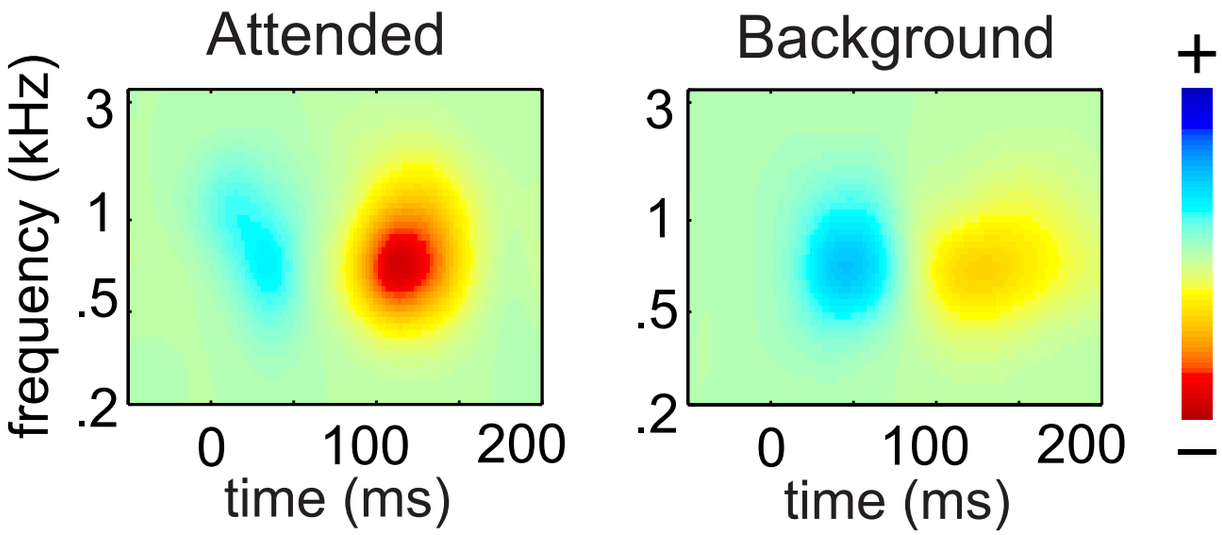






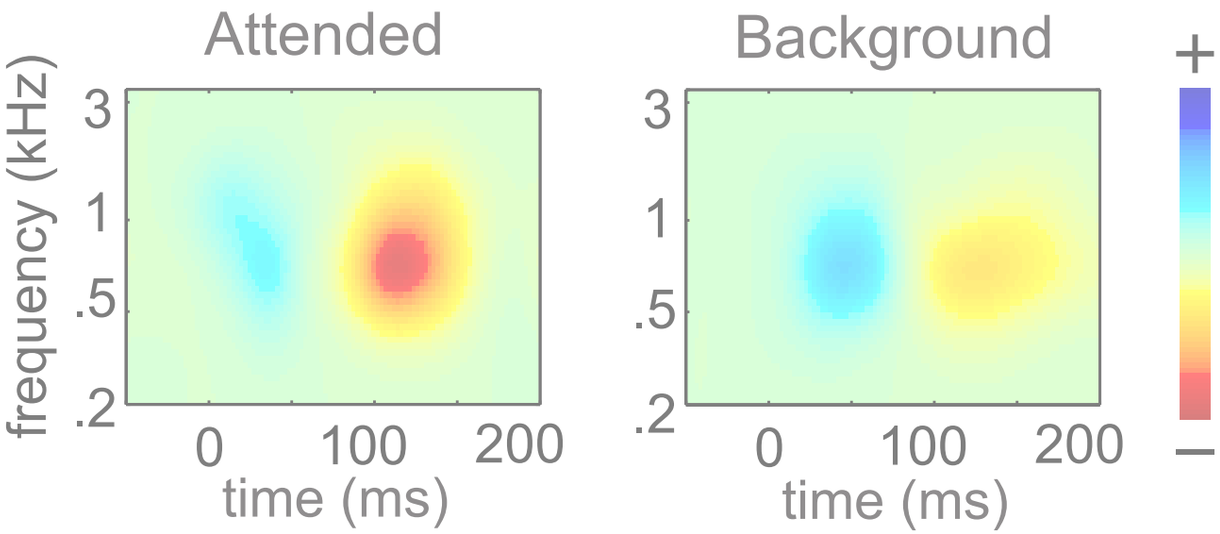
Spectro-Temporal
Response Function
(STRF)

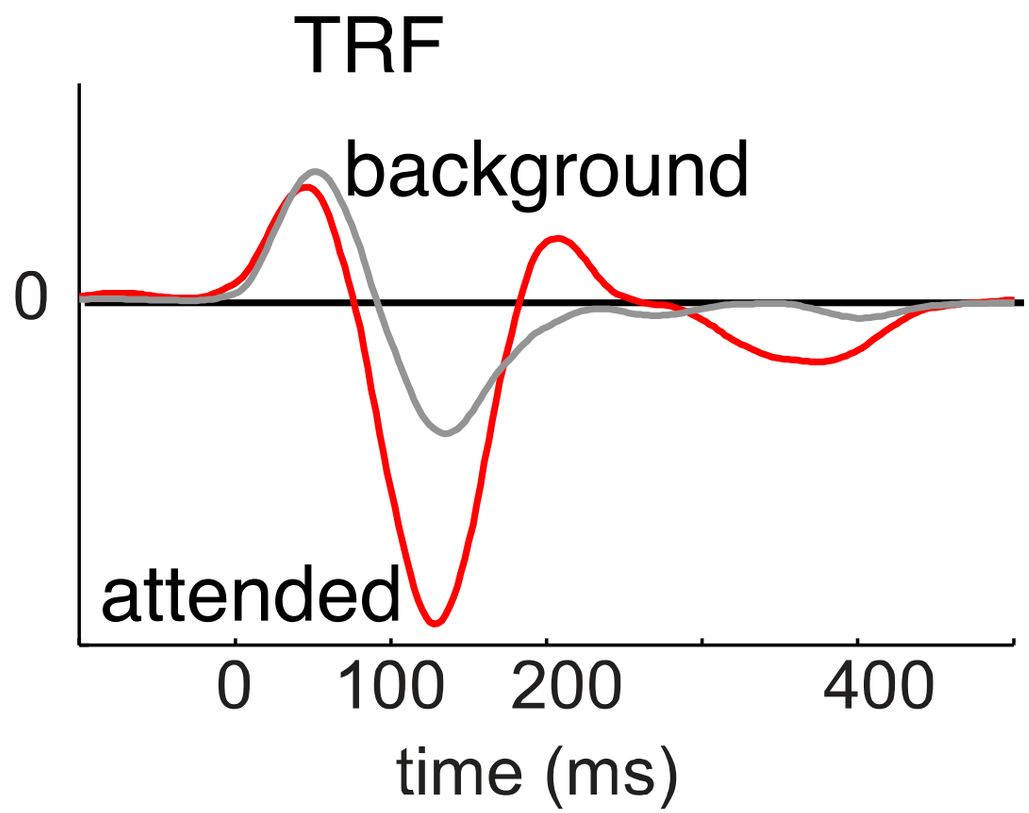
STRF Results



- STRF separable (time, frequency)
- 300 Hz - 2 kHz dominant carriers
- $M50_{STRF}$ positive peak
- $M100_{STRF}$ negative peak

STRF Results





- STRF separable (time, frequency)
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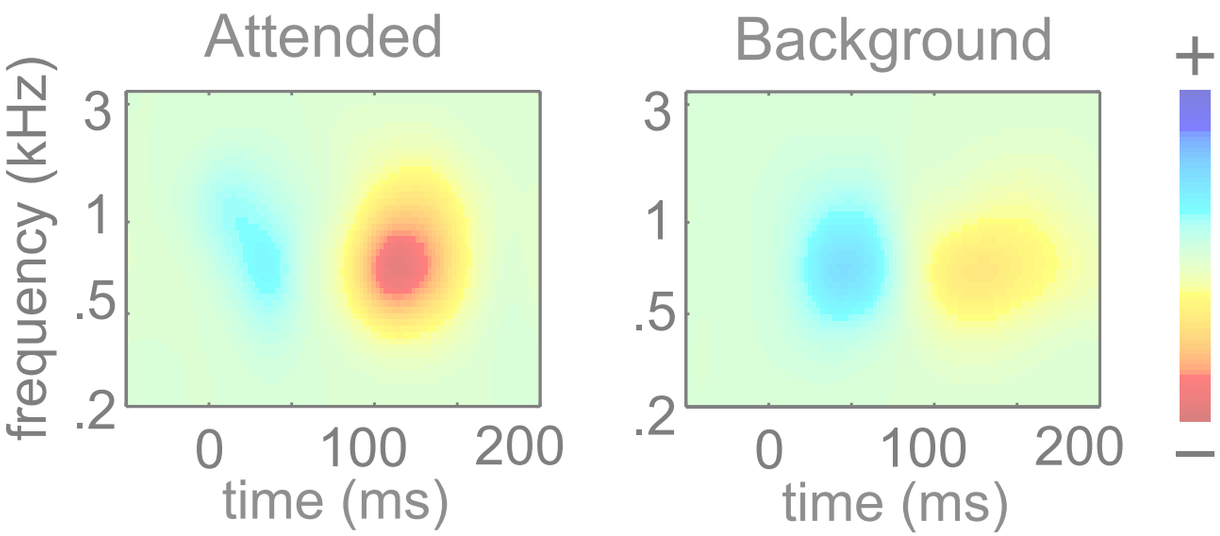
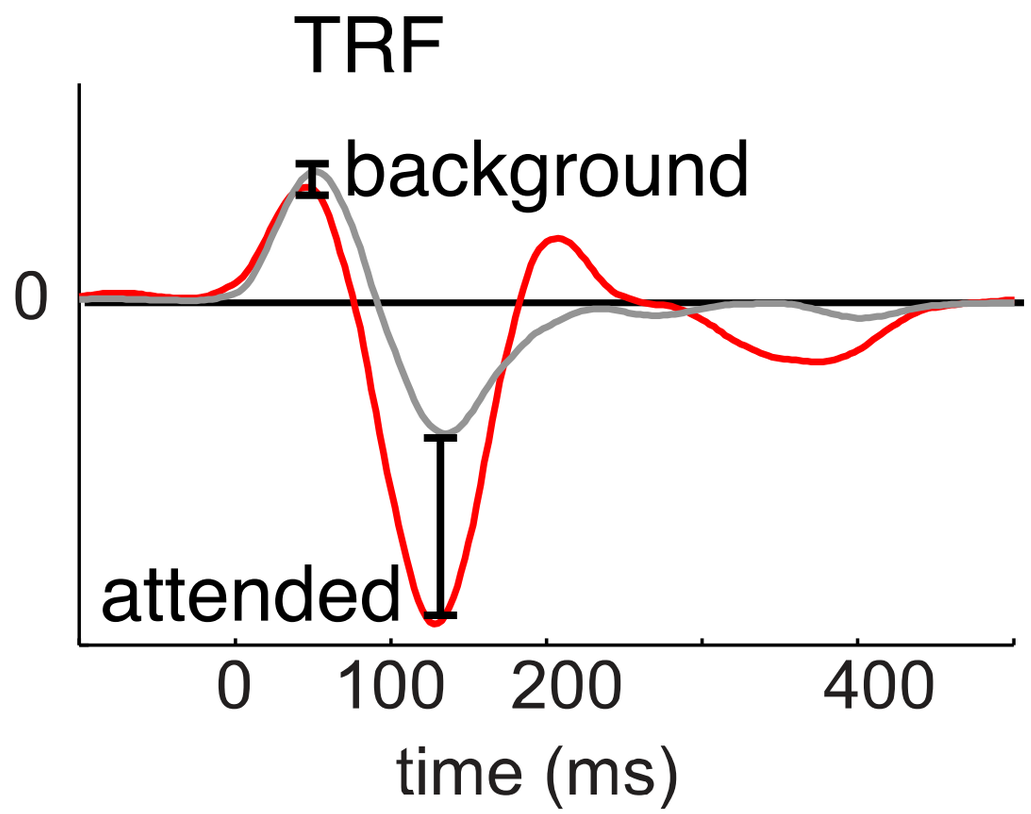
STRF Results





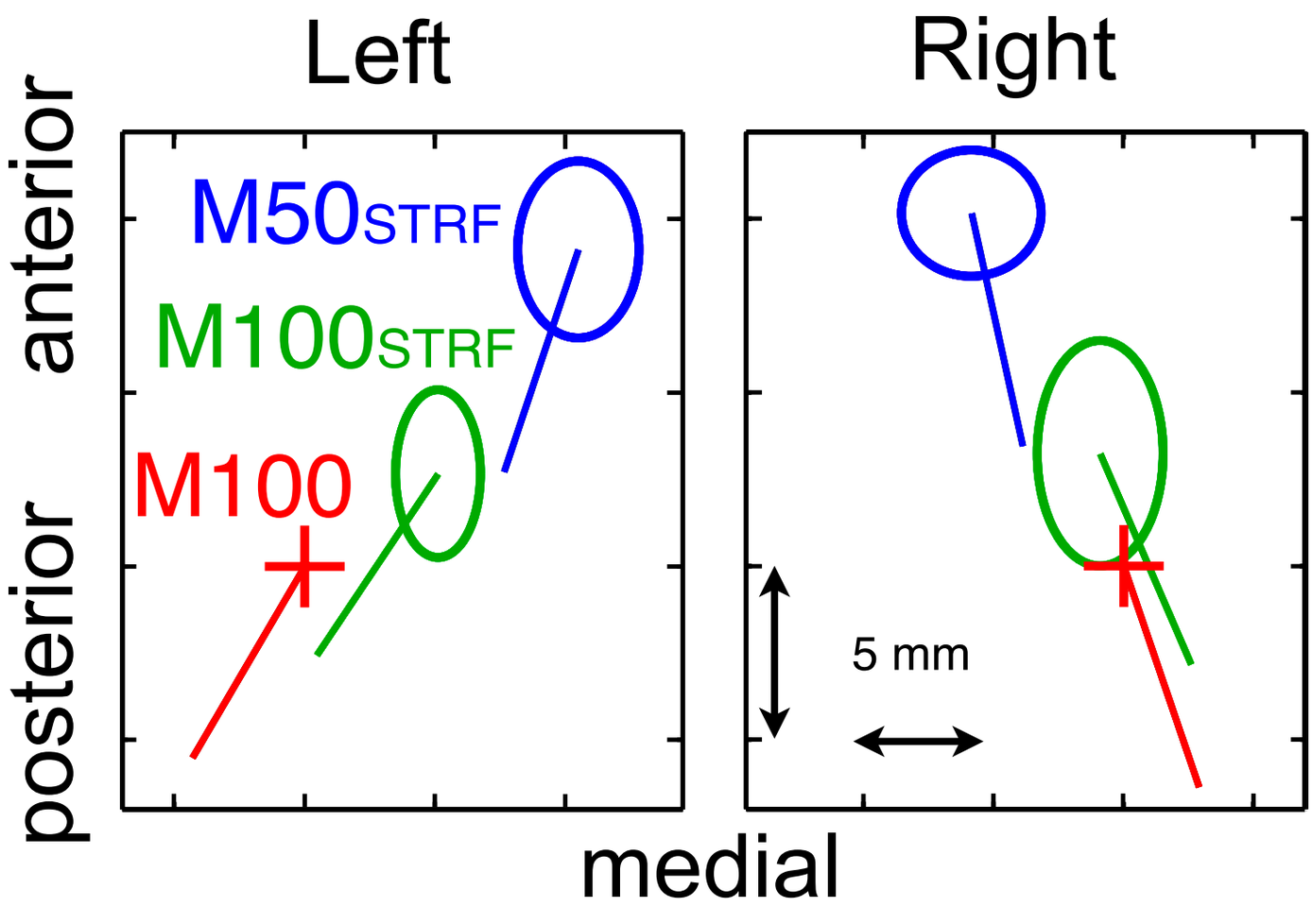
- STRF separable (time, frequency)
- 300 Hz - 2 kHz dominant carriers
- $M50_{STRF}$ positive peak
- $M100_{STRF}$ negative peak
- **$M100_{STRF}$ strongly modulated by attention, *but not $M50_{STRF}$***

Neural Sources

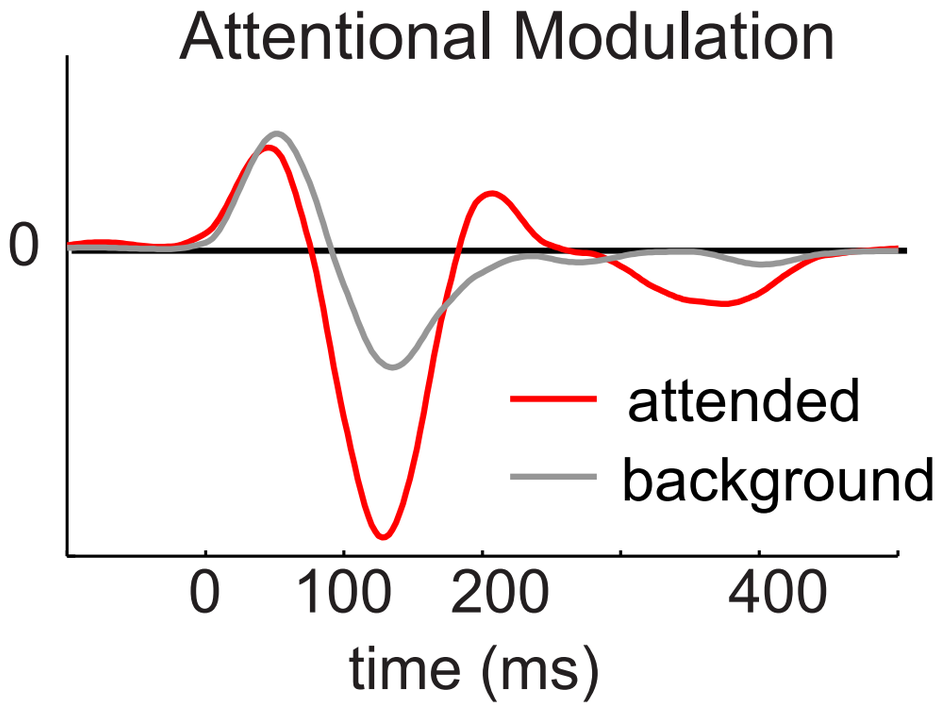
- M100$_{STRF}$ source near (same as?) M100 source: Planum Temporale

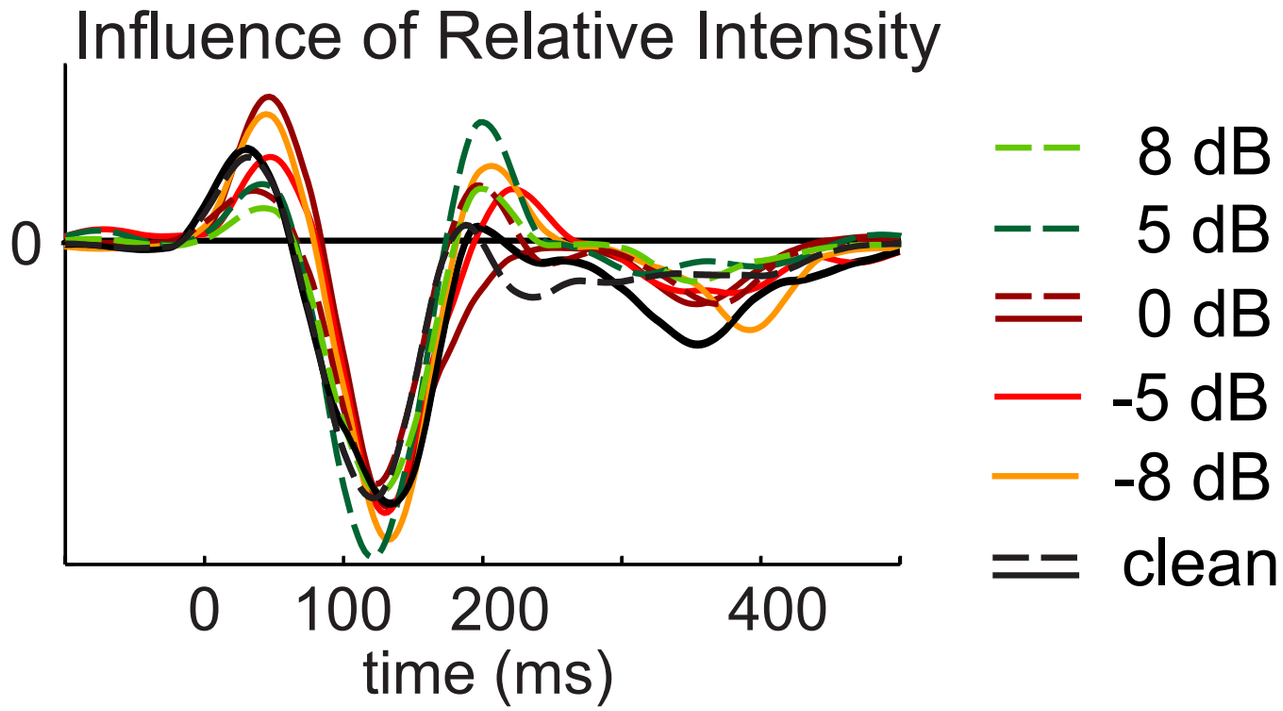
- M50$_{STRF}$ source is anterior and medial to M100 (same as M50?): Heschl's Gyrus

- **PT strongly modulated by attention, *but not HG***



Cortical Object-Processing Hierarchy





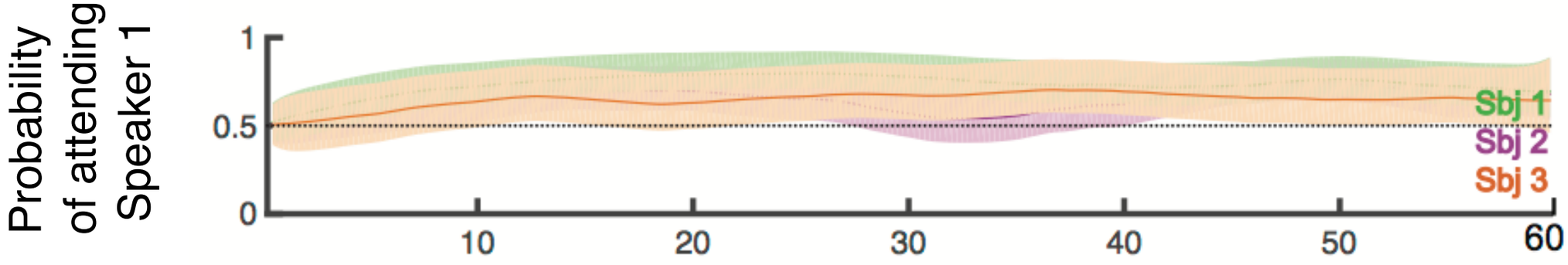
- $M100_{STRF}$ strongly modulated by attention, but not $M50_{STRF}$.
- $M100_{STRF}$ invariant against acoustic changes.
- Objects well-neurally represented at 100 ms, but not 50 ms.

Studies In Progress

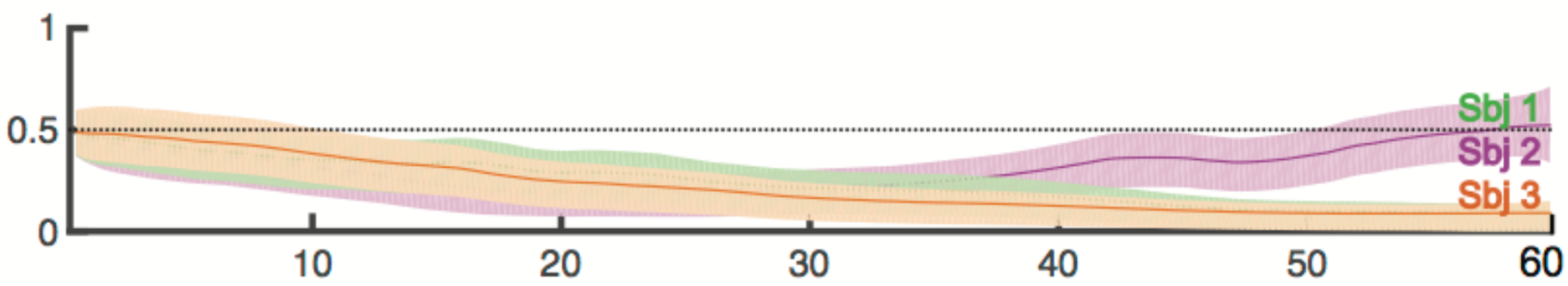
- Attentional Dynamics
- Aging & Neural Representations of Speech
- Neural Representations of the Background

Attentional Dynamics

Attend to Speaker 1

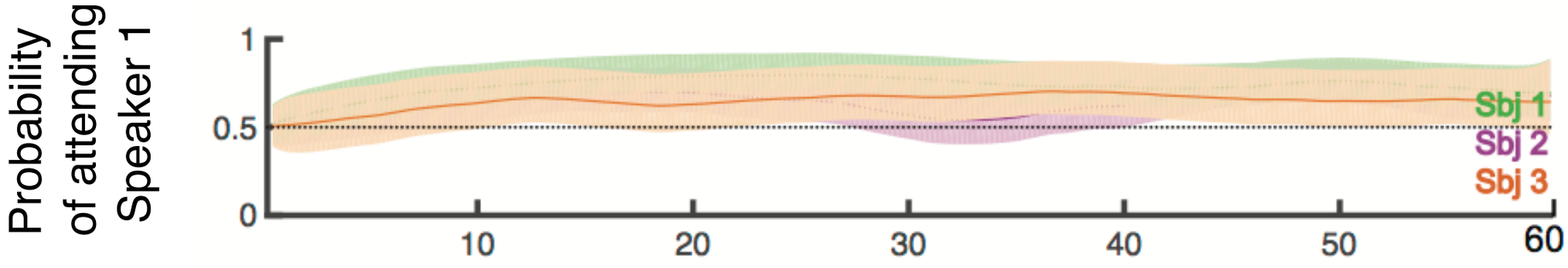


Attend to Speaker 2

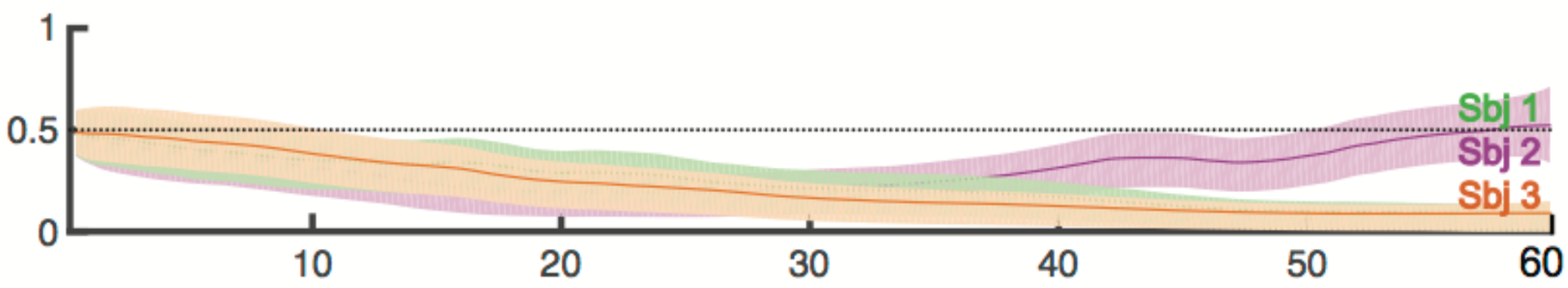


Attentional Dynamics

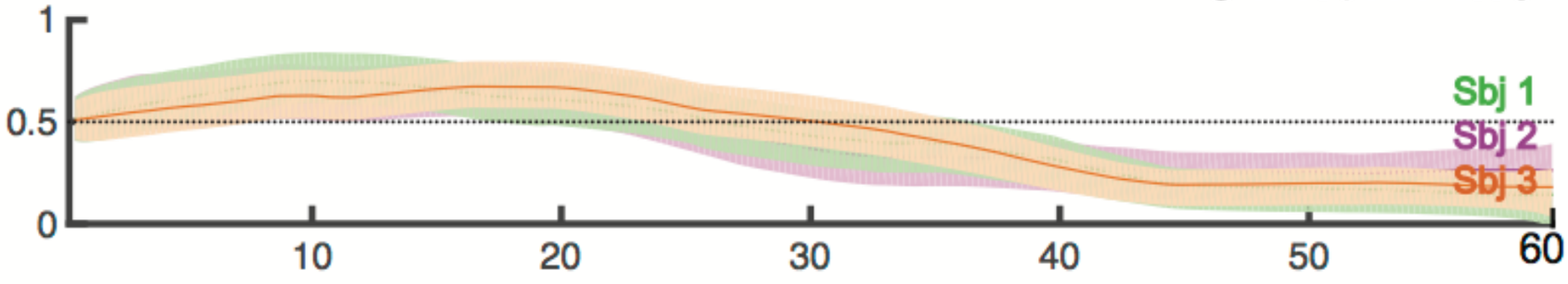
Attend to Speaker 1



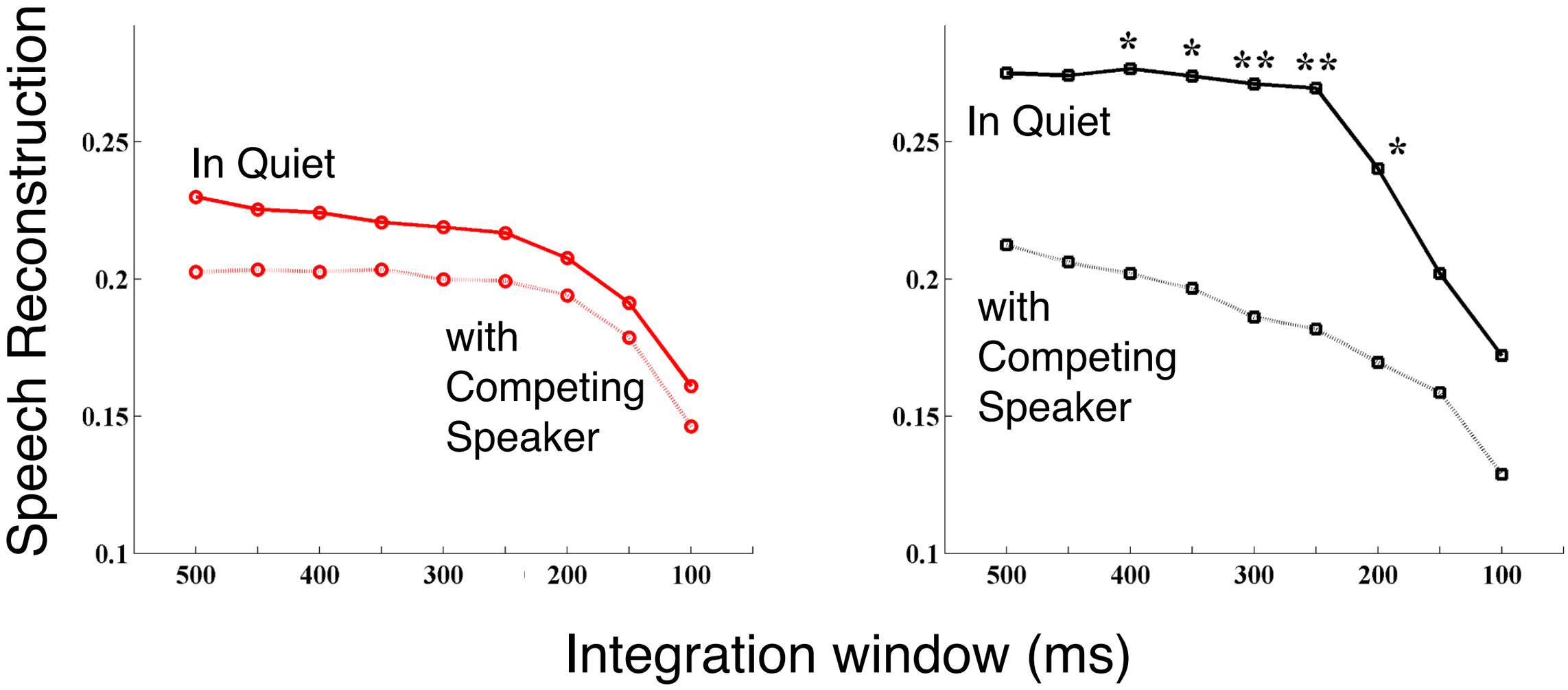
Attend to Speaker 2



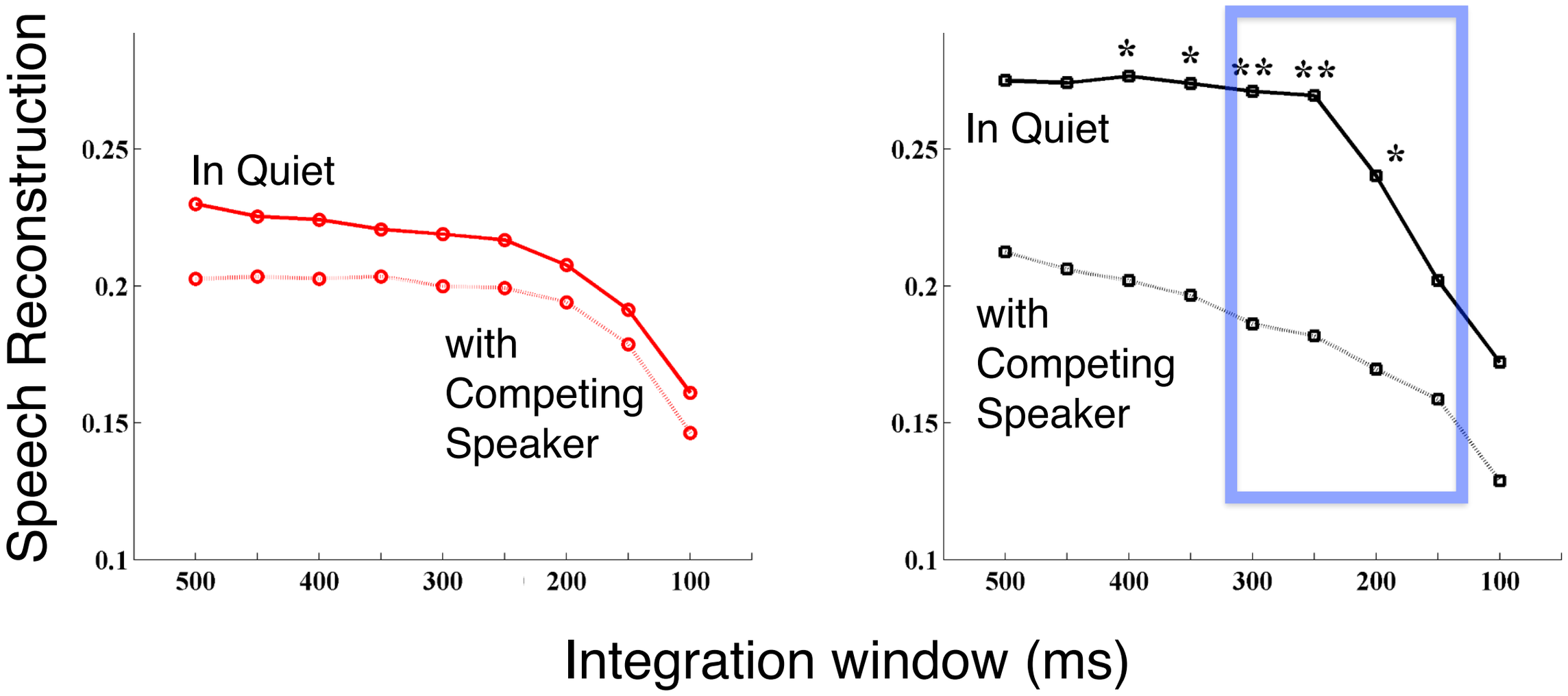
Switch Attention



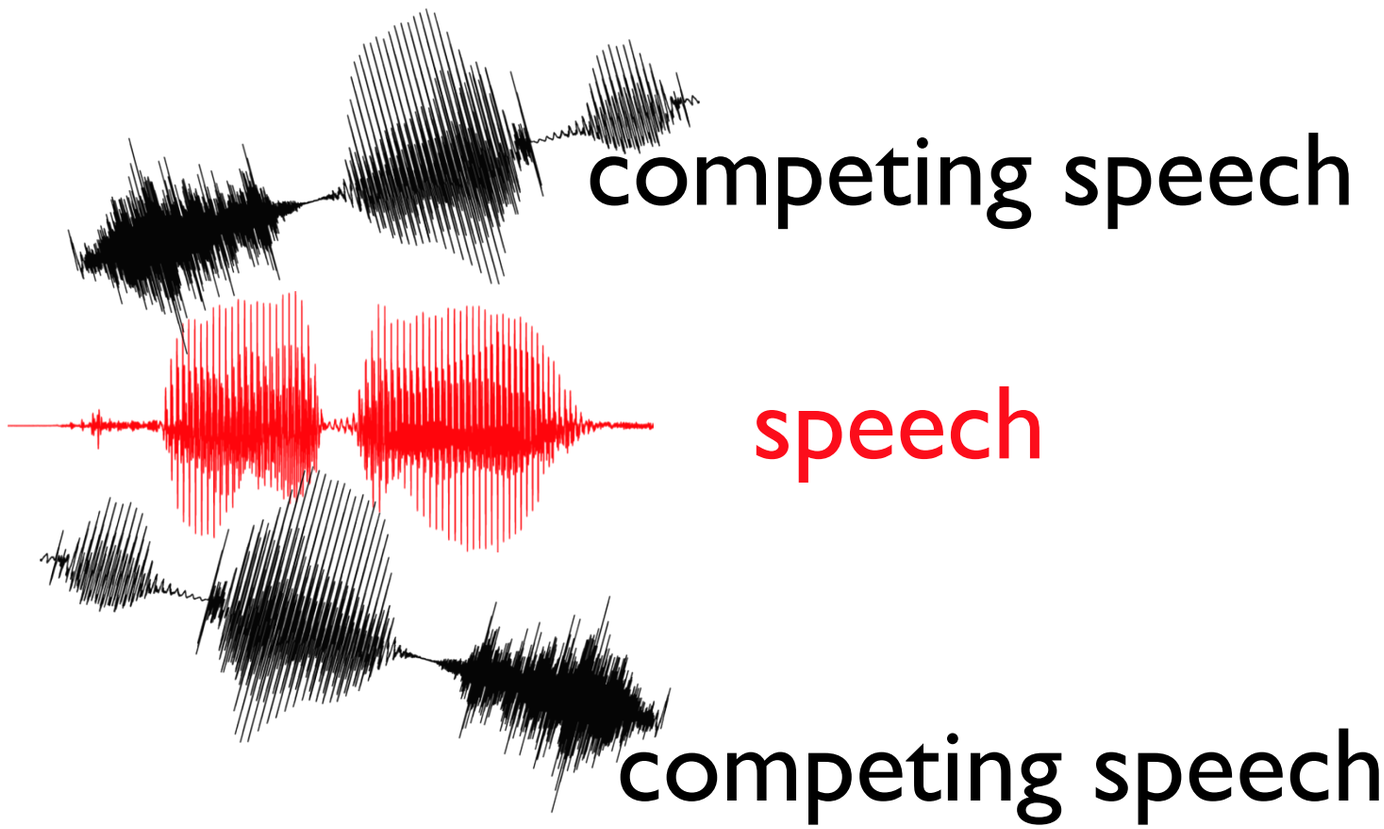
Younger vs. Older Listeners



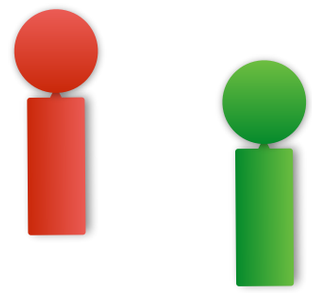
Younger vs. Older Listeners

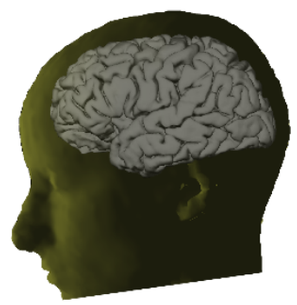


Three Competing Speakers

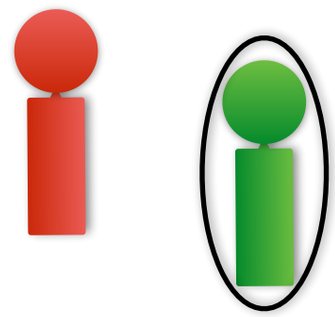


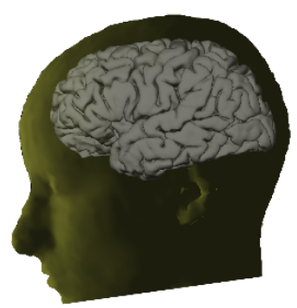
Foreground vs. Background



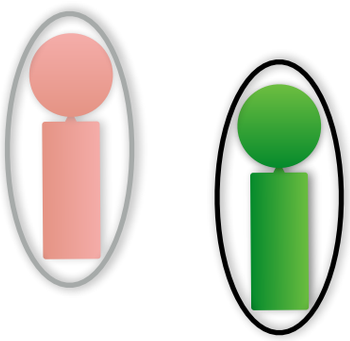


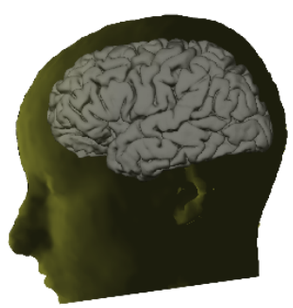
Foreground vs. Background



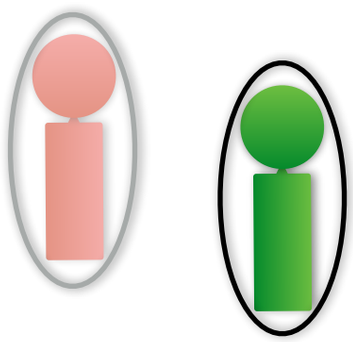


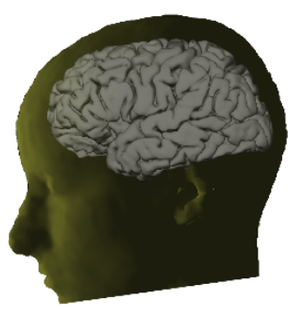
Foreground vs. Background

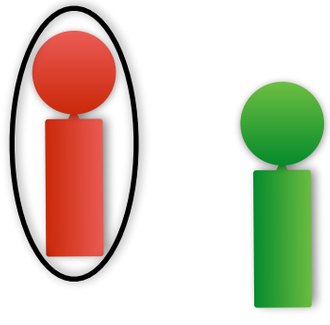




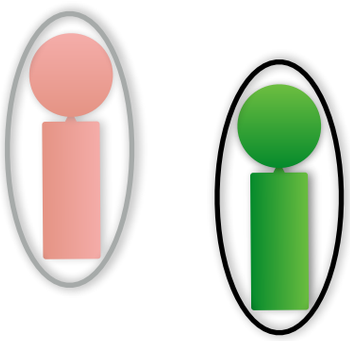
Foreground vs. Background

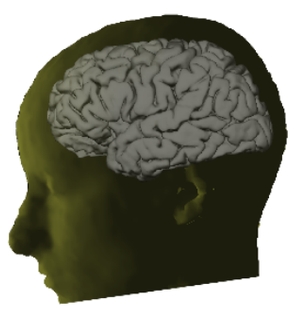


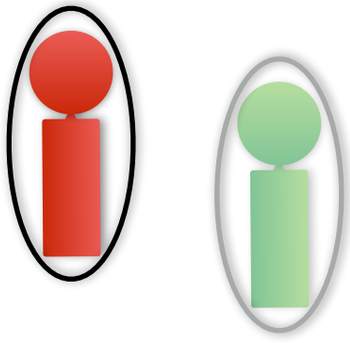




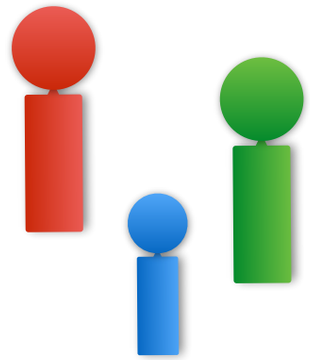
Foreground vs. Background







Foreground vs. Background



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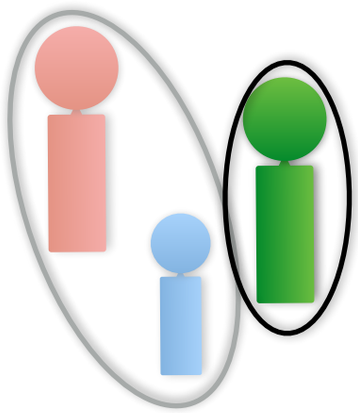

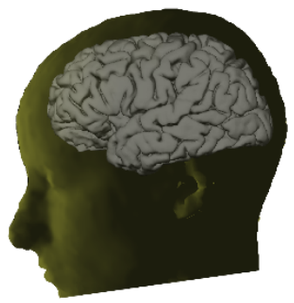

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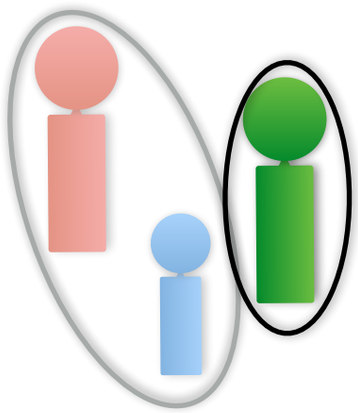
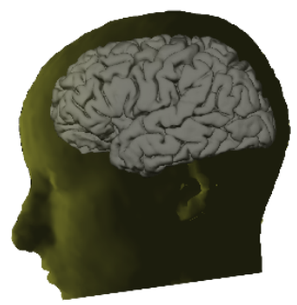
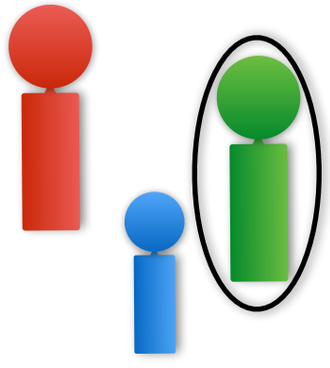
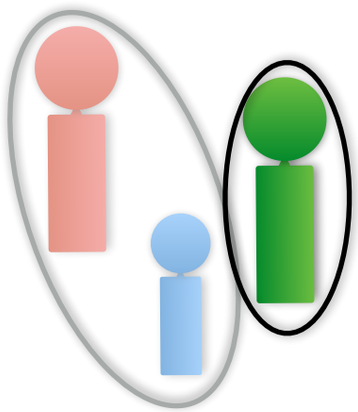
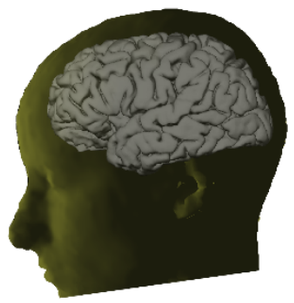


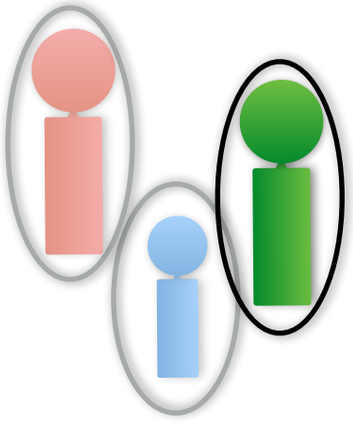




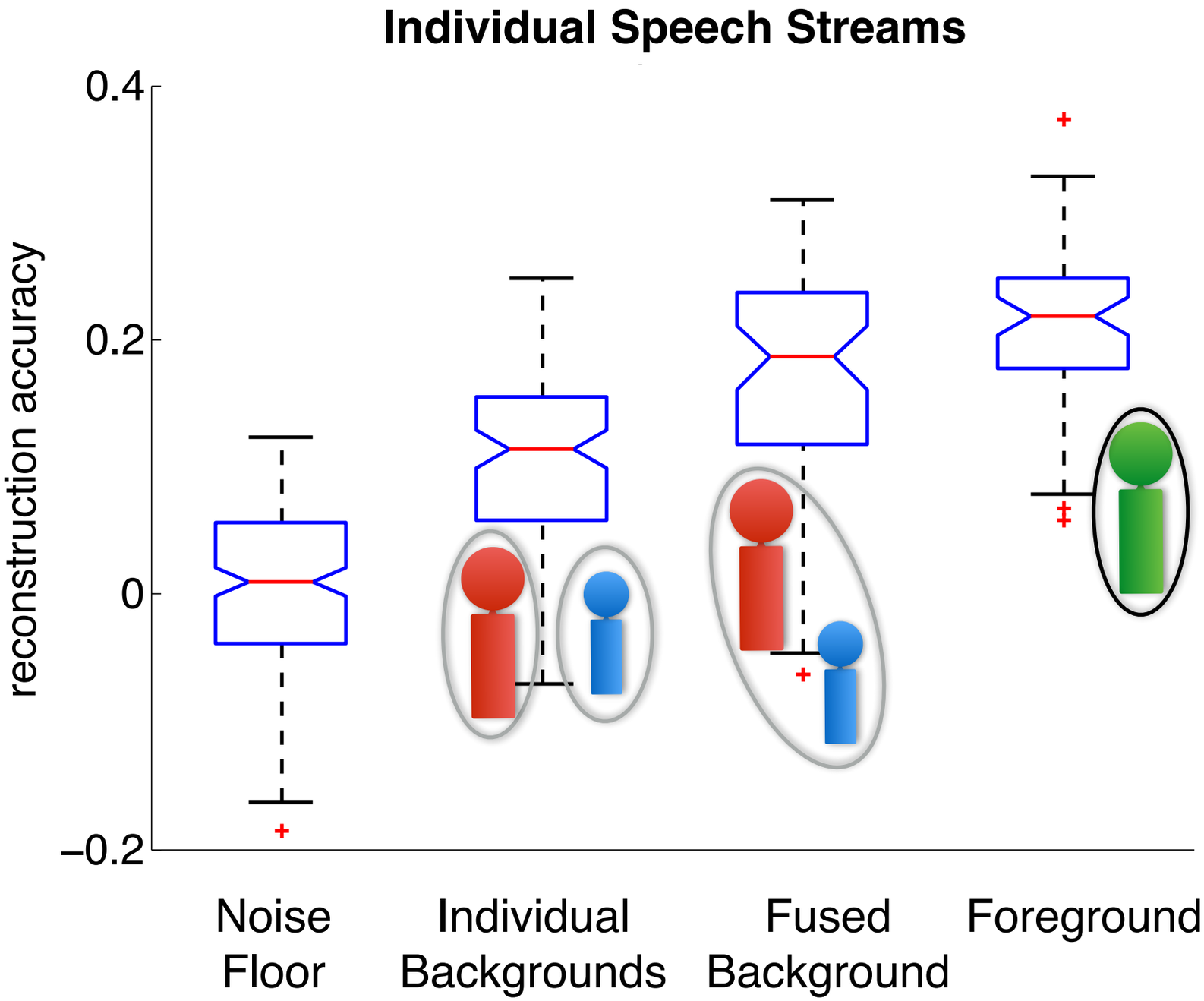
Foreground vs. Background





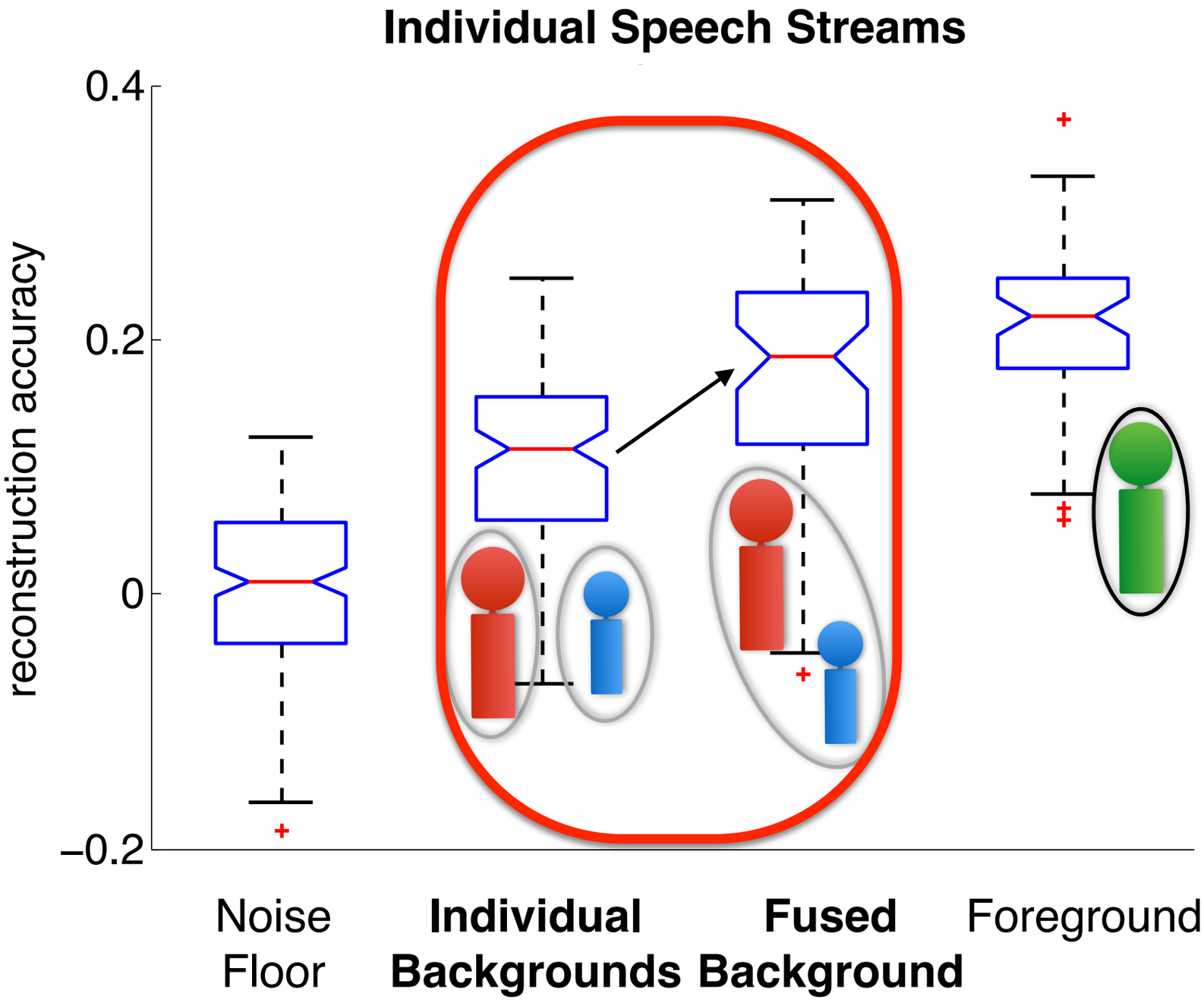


Backgrounds vs. Background



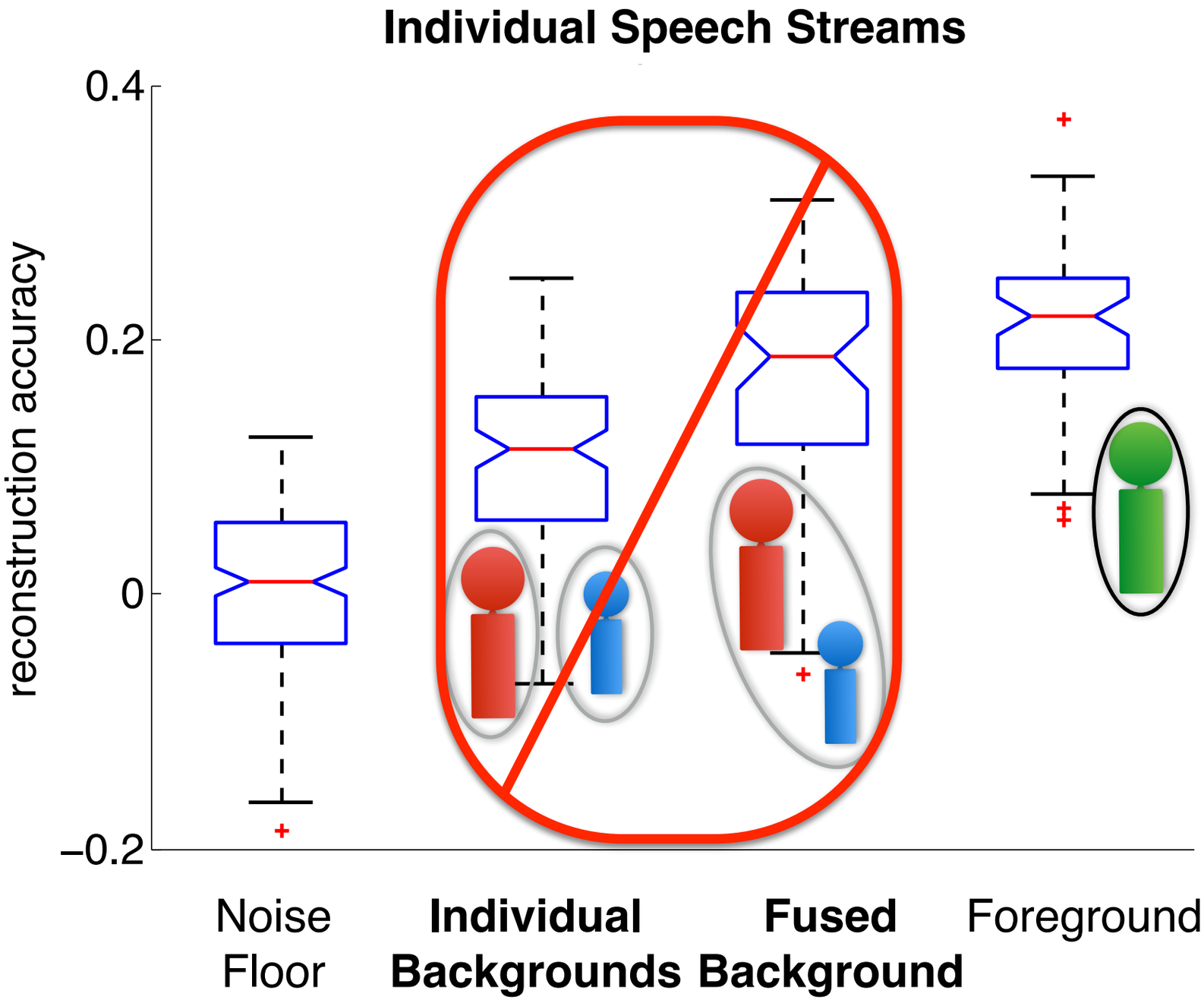
Integration Window over Late Times Only

Backgrounds vs. Background



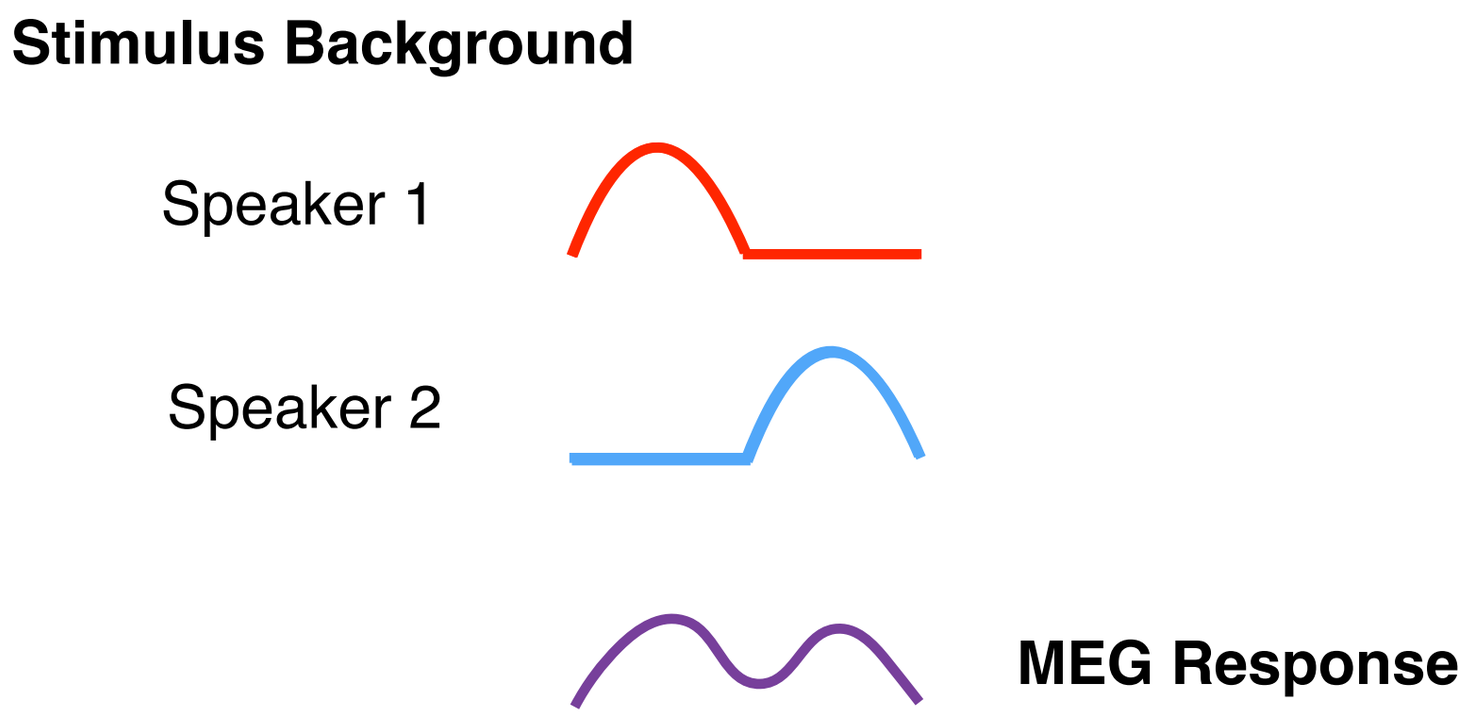
Integration Window over Late Times Only

Backgrounds vs. Background

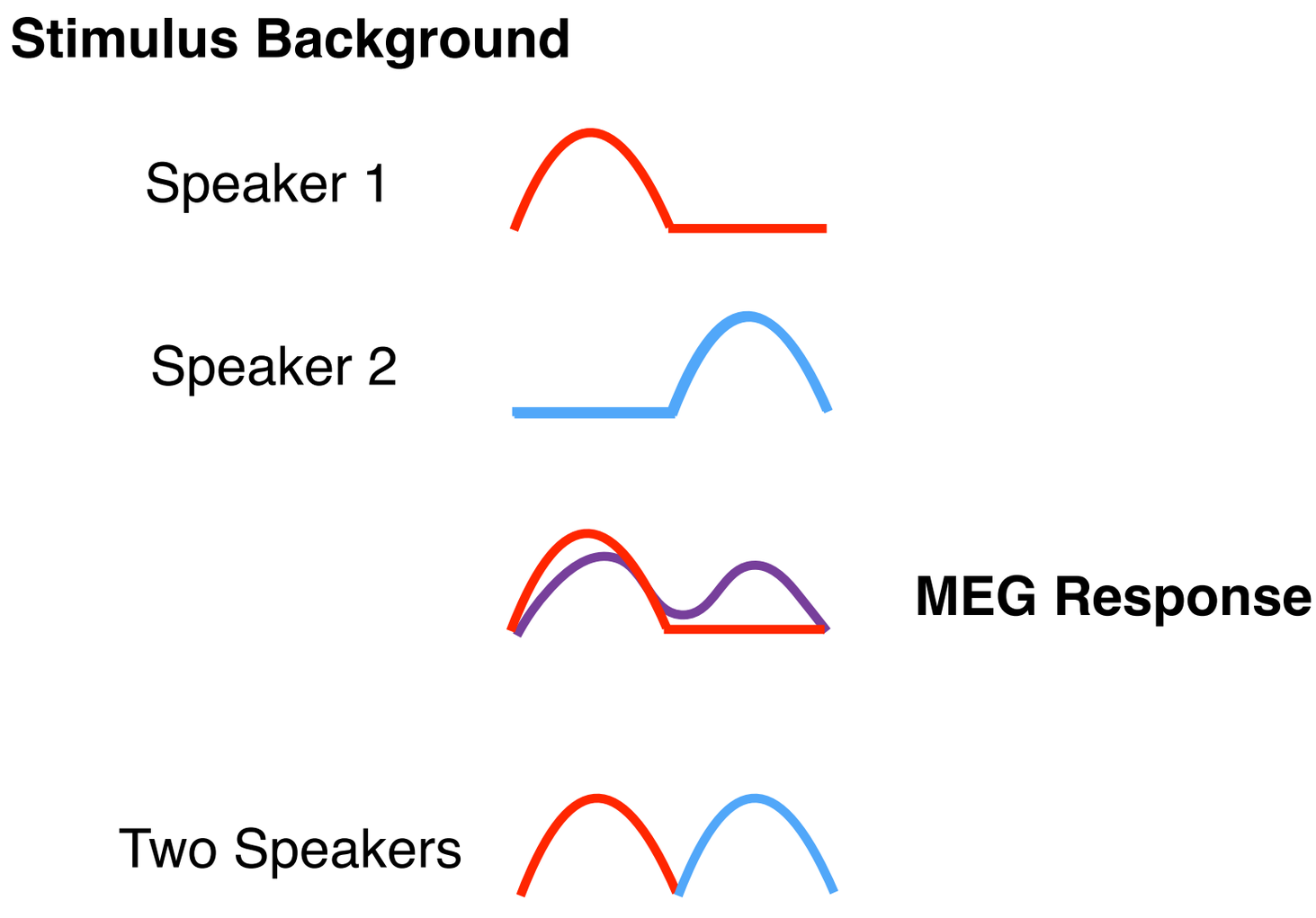


Integration Window over Late Times Only

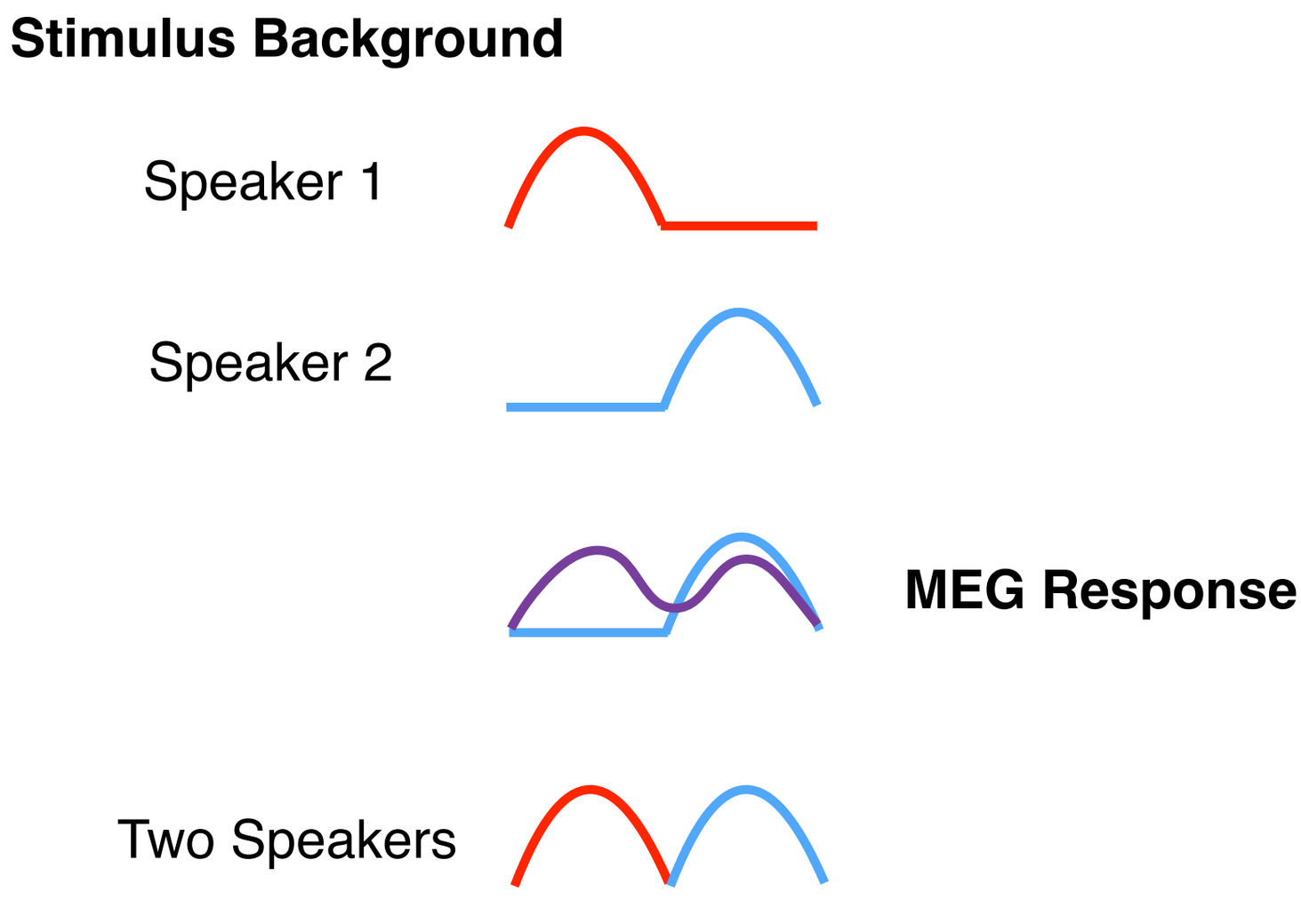
Backgrounds vs. Background
Why not?



Backgrounds vs. Background
Why not?



Backgrounds vs. Background
Why not?

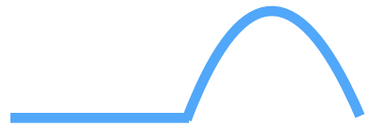


Backgrounds vs. Background
Why not?

Stimulus Background

Speaker 1

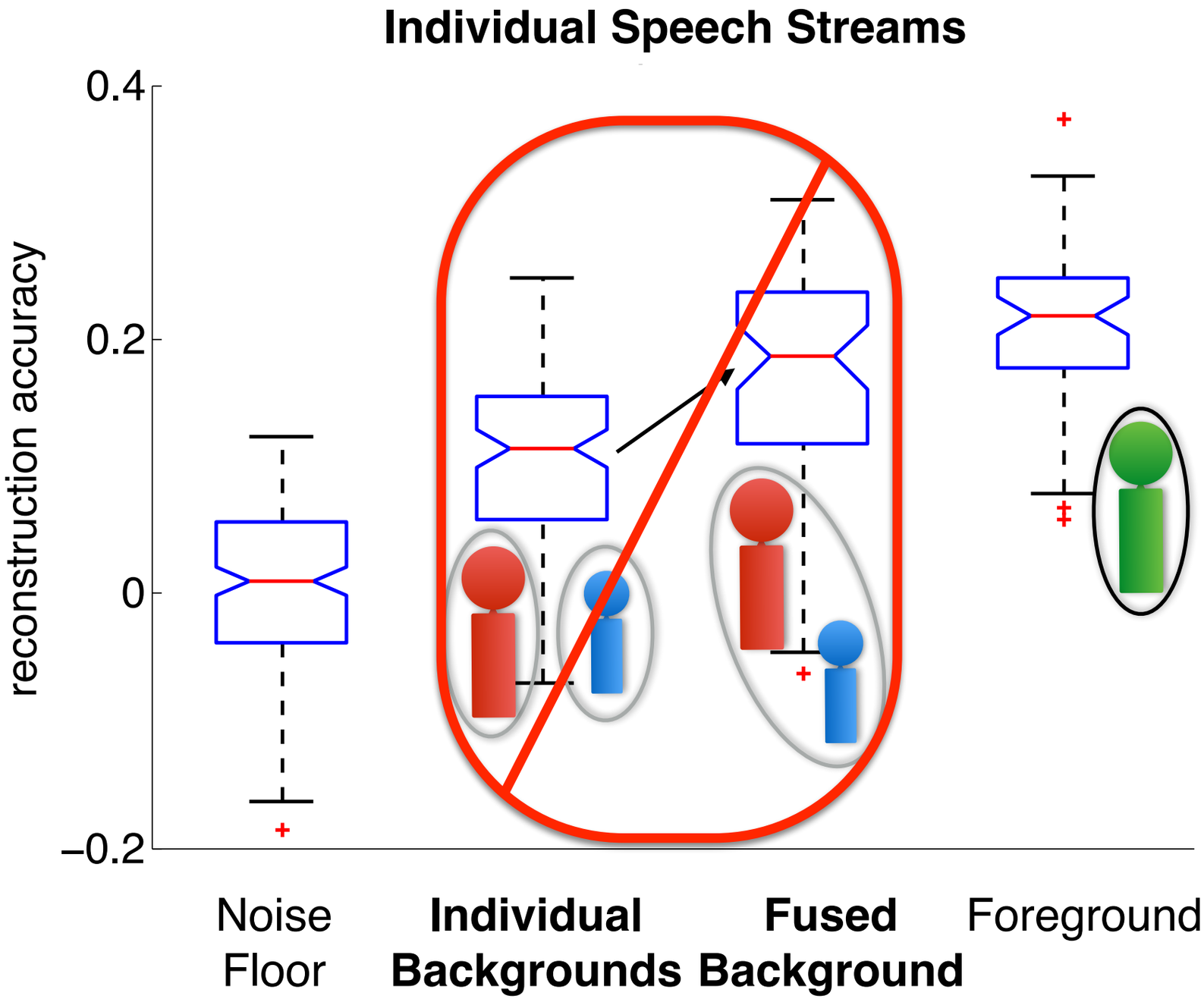
Speaker 2



MEG Response

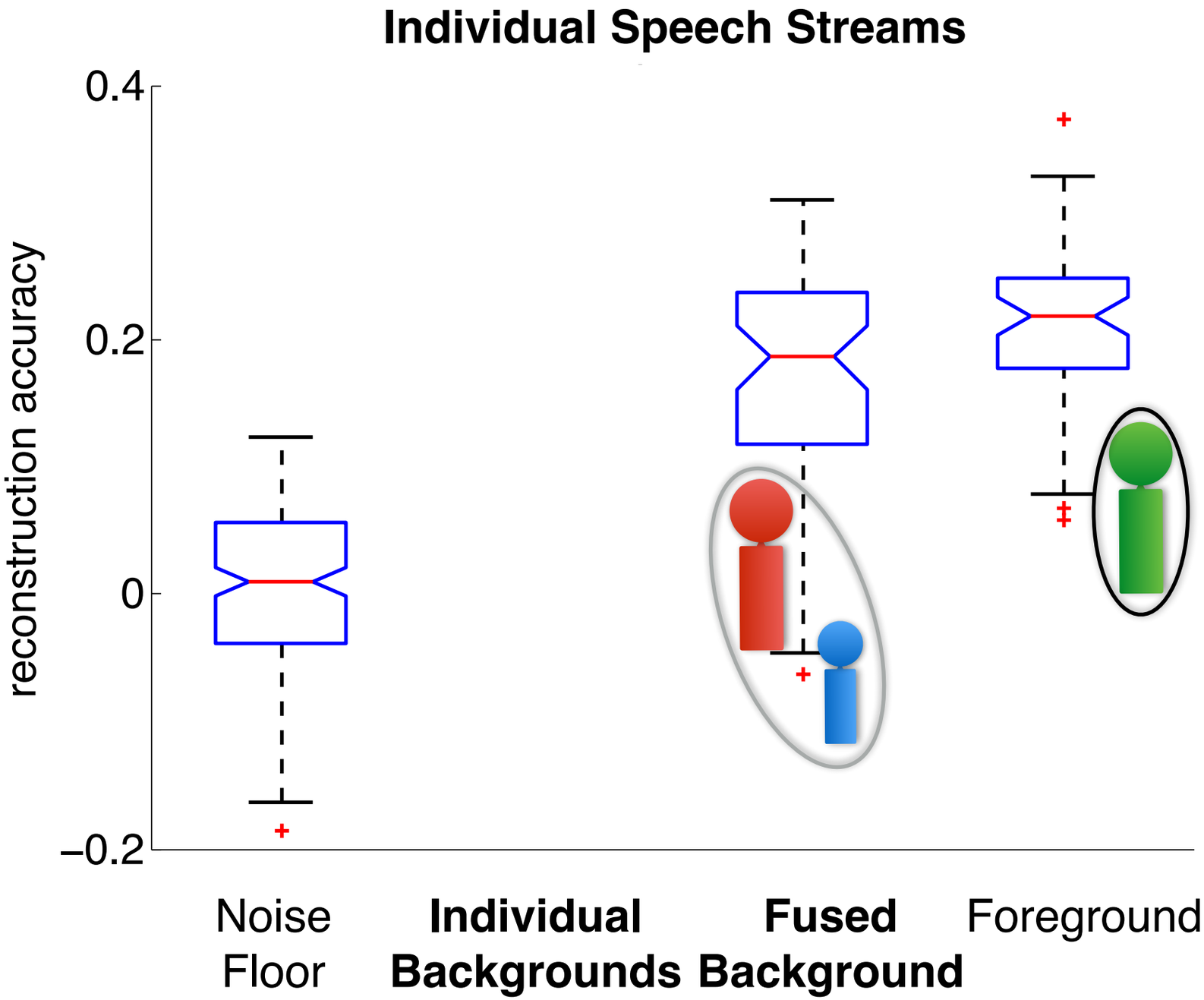
Two Speakers

Backgrounds vs. Background



Integration Window over Late Times Only

Backgrounds vs. Background



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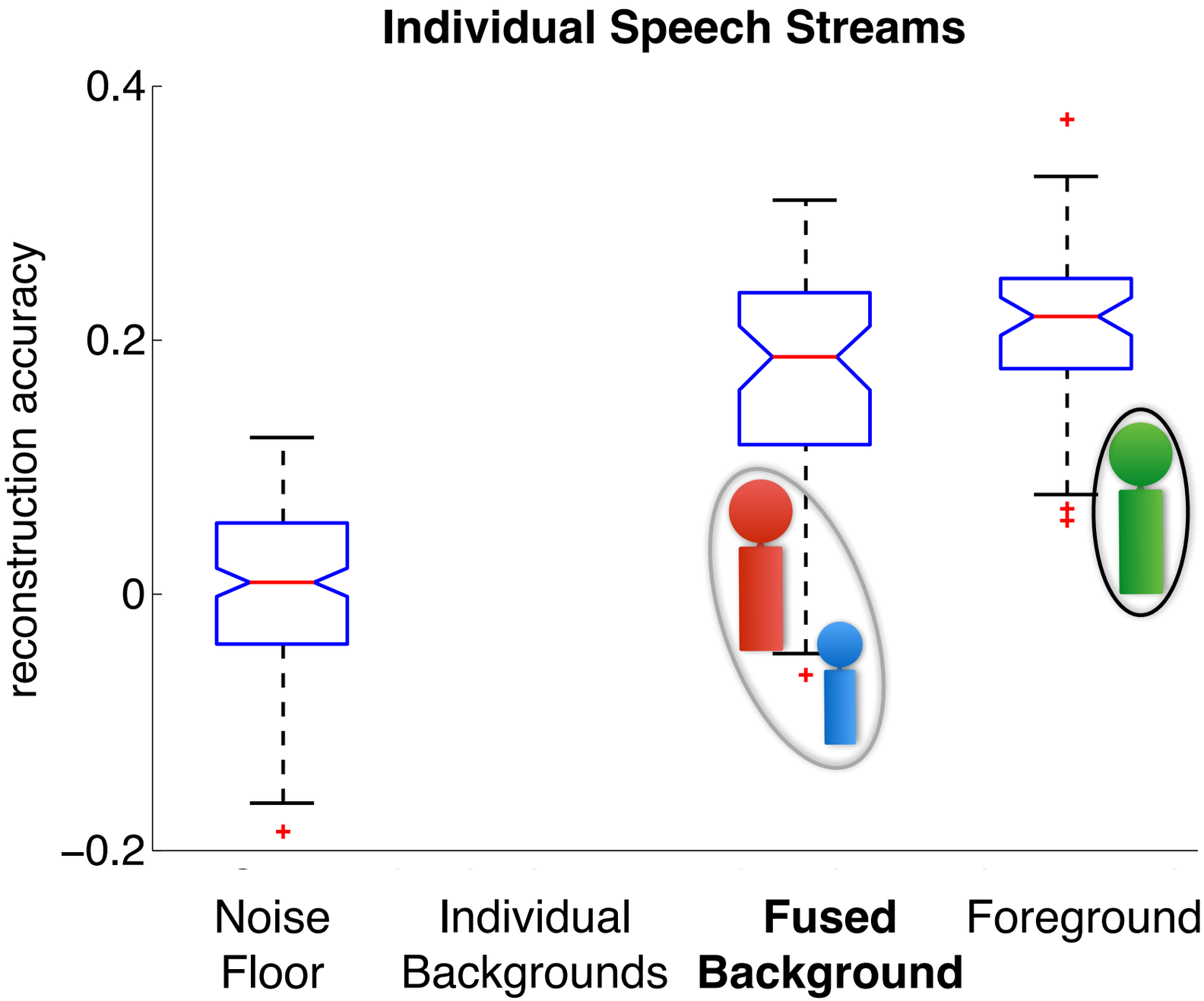
Backgrounds vs. Background



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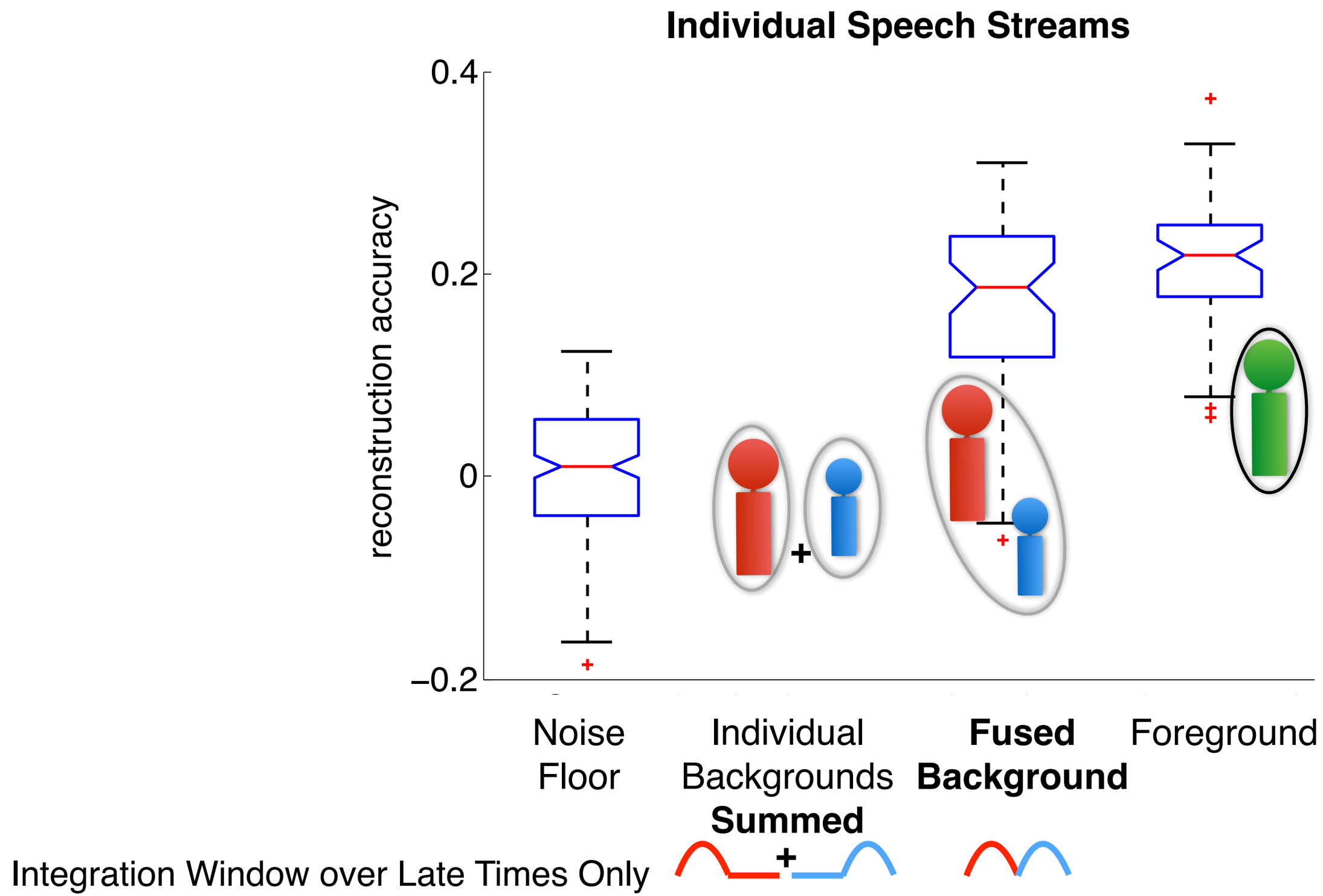
Backgrounds vs. Background



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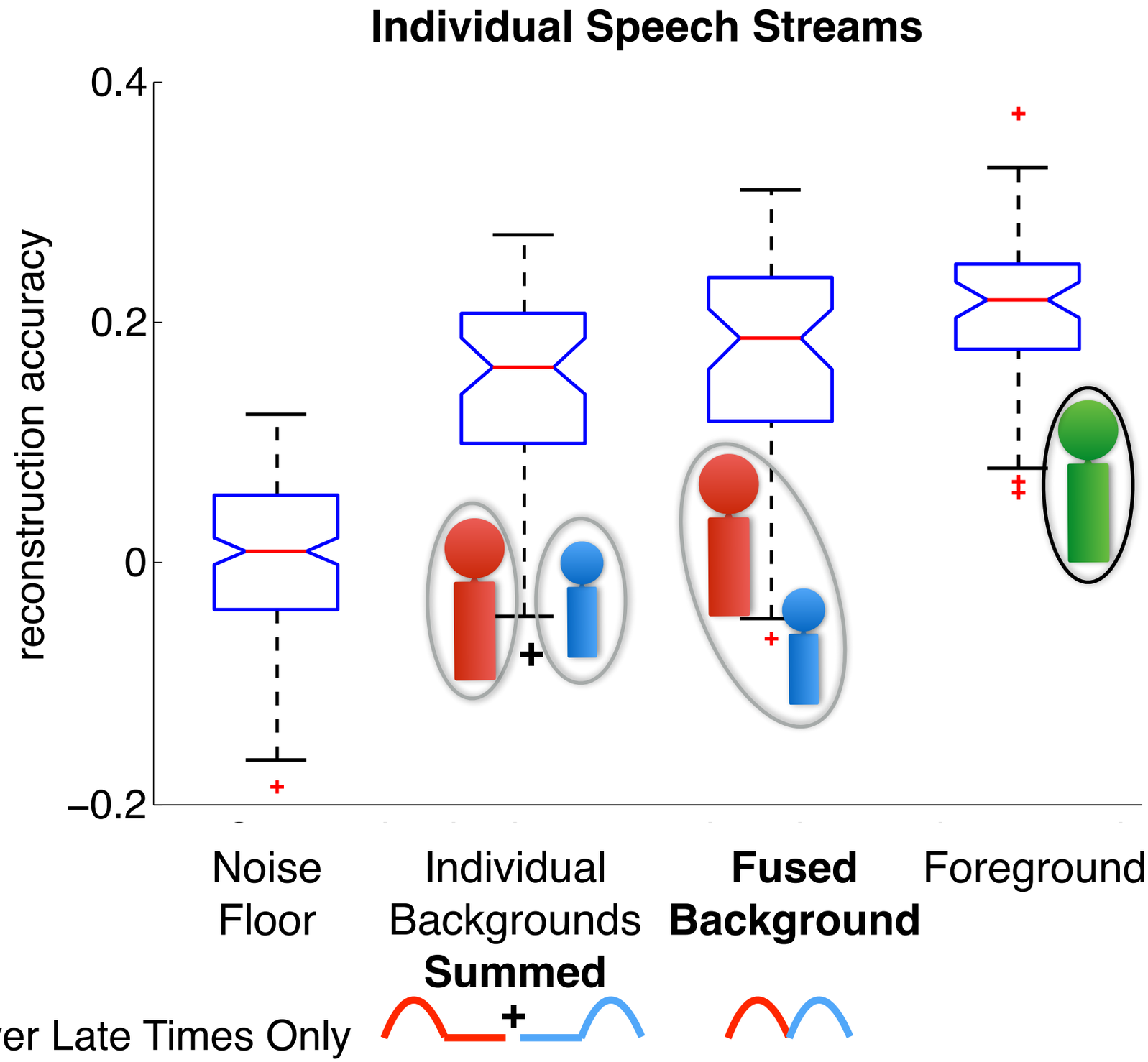

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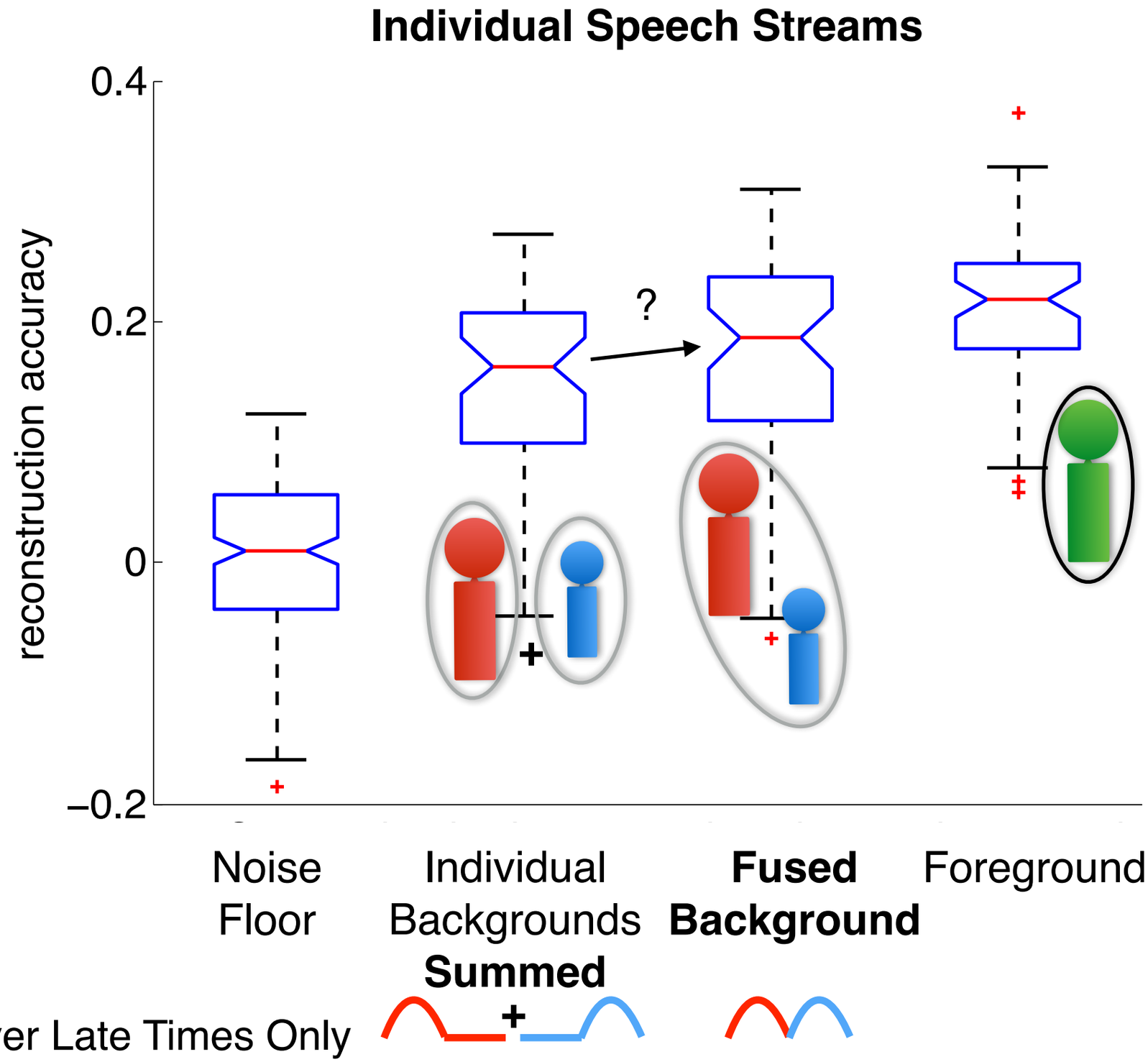
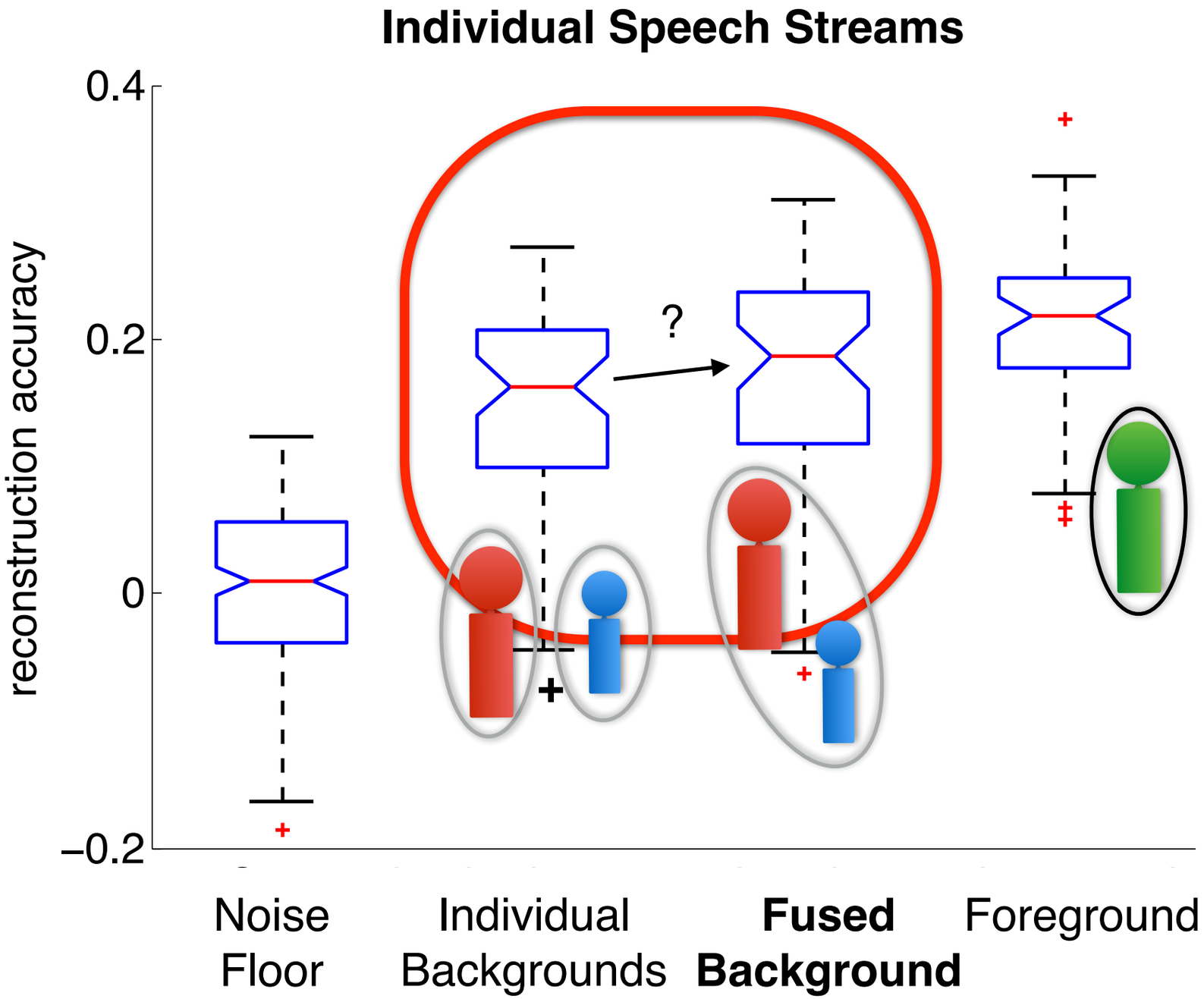


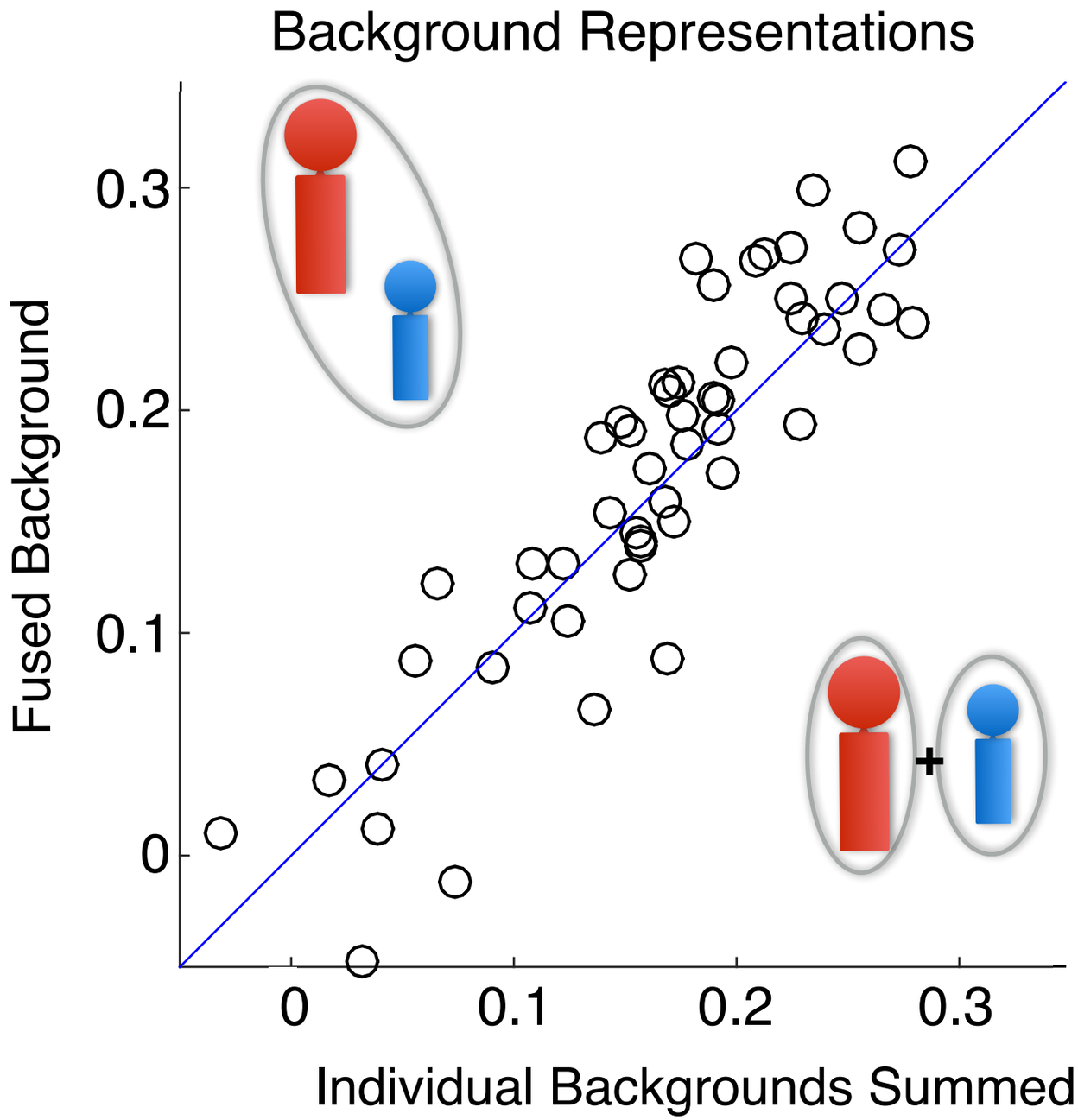
Integration Window over Late Times Only

Backgrounds vs. Background



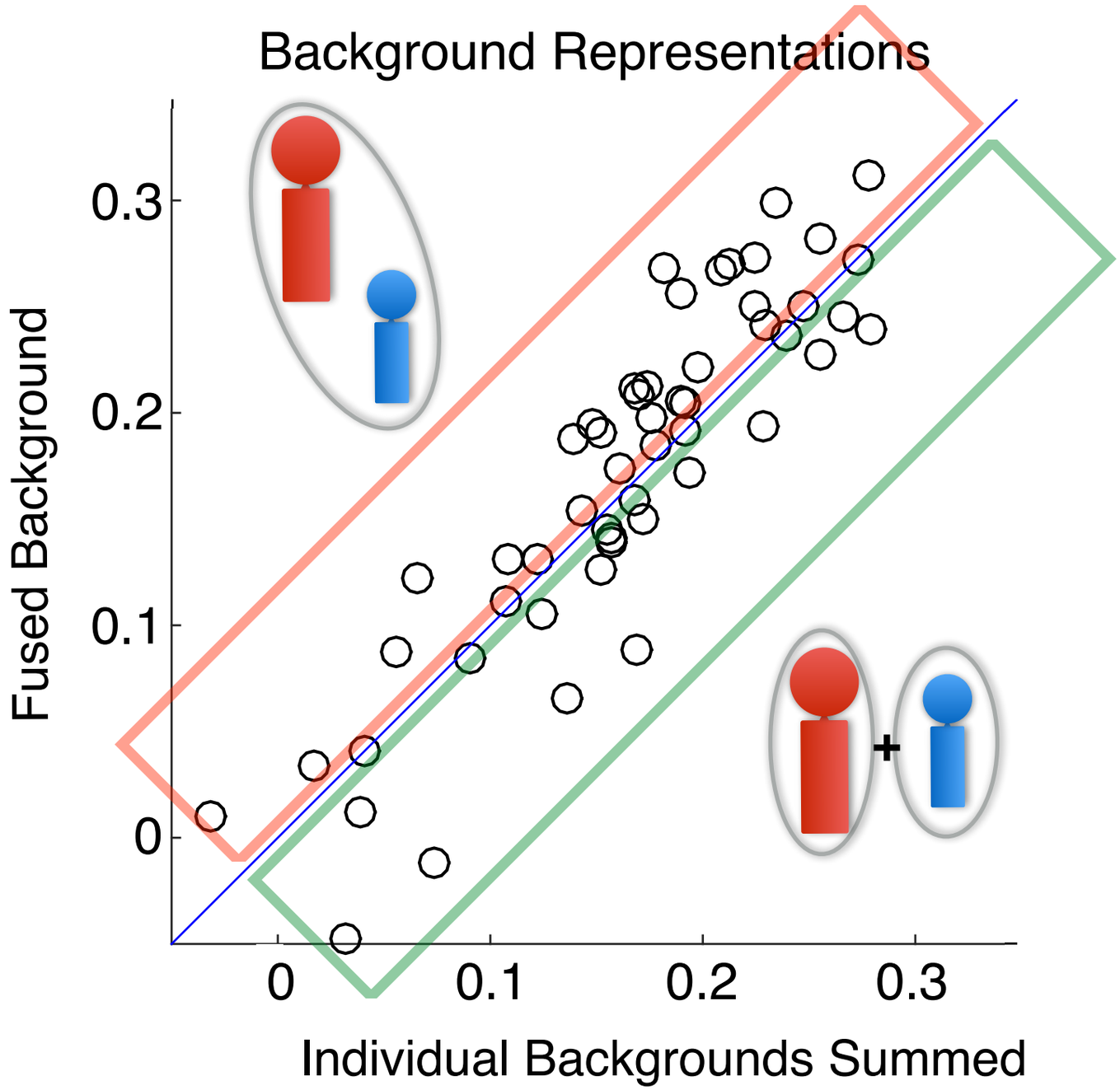
Integration Window over Late Times Only

Backgrounds vs. Background



Integration Window over Late Times Only

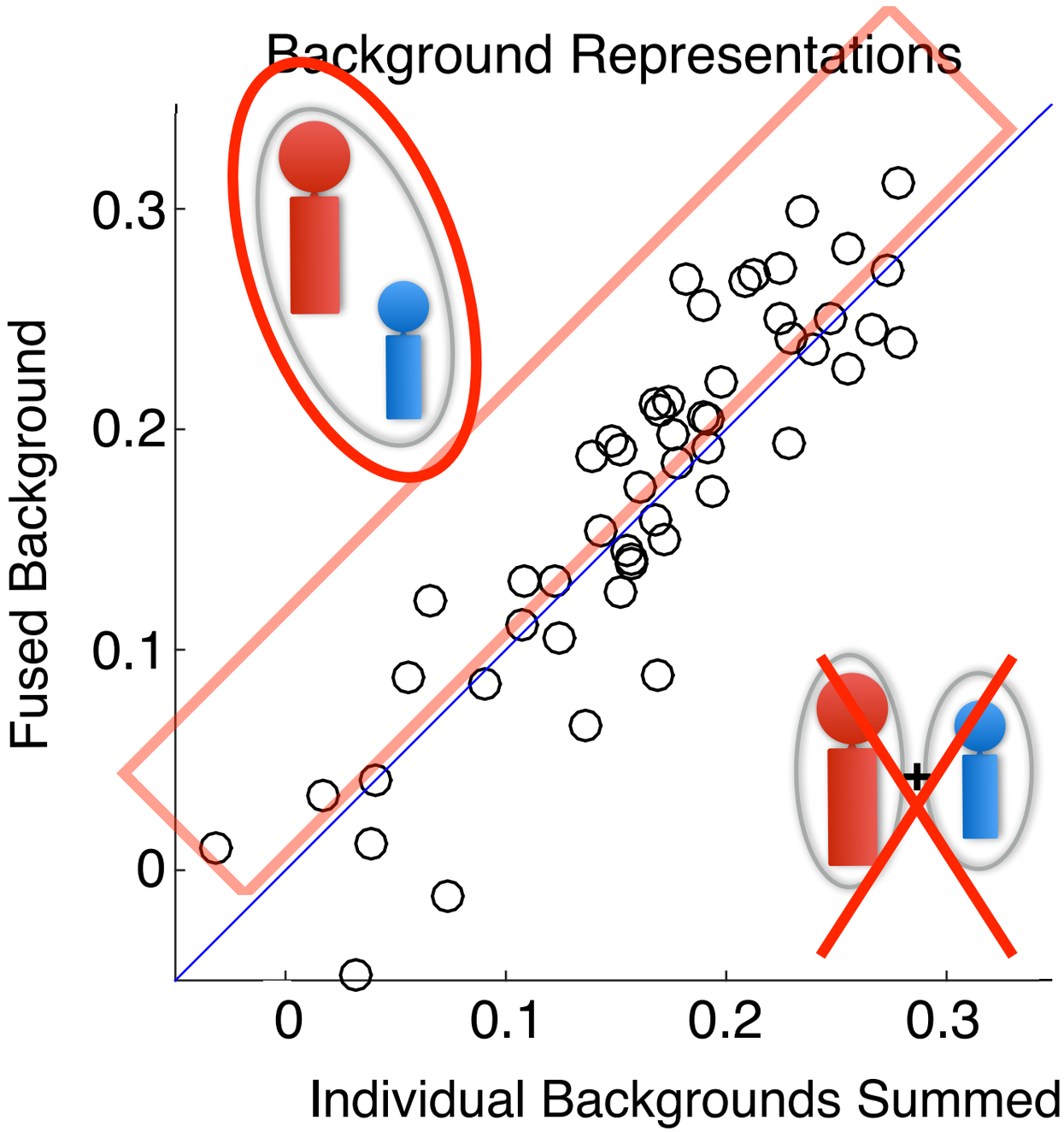
Backgrounds vs. Background



Integration Window over Late Times Only

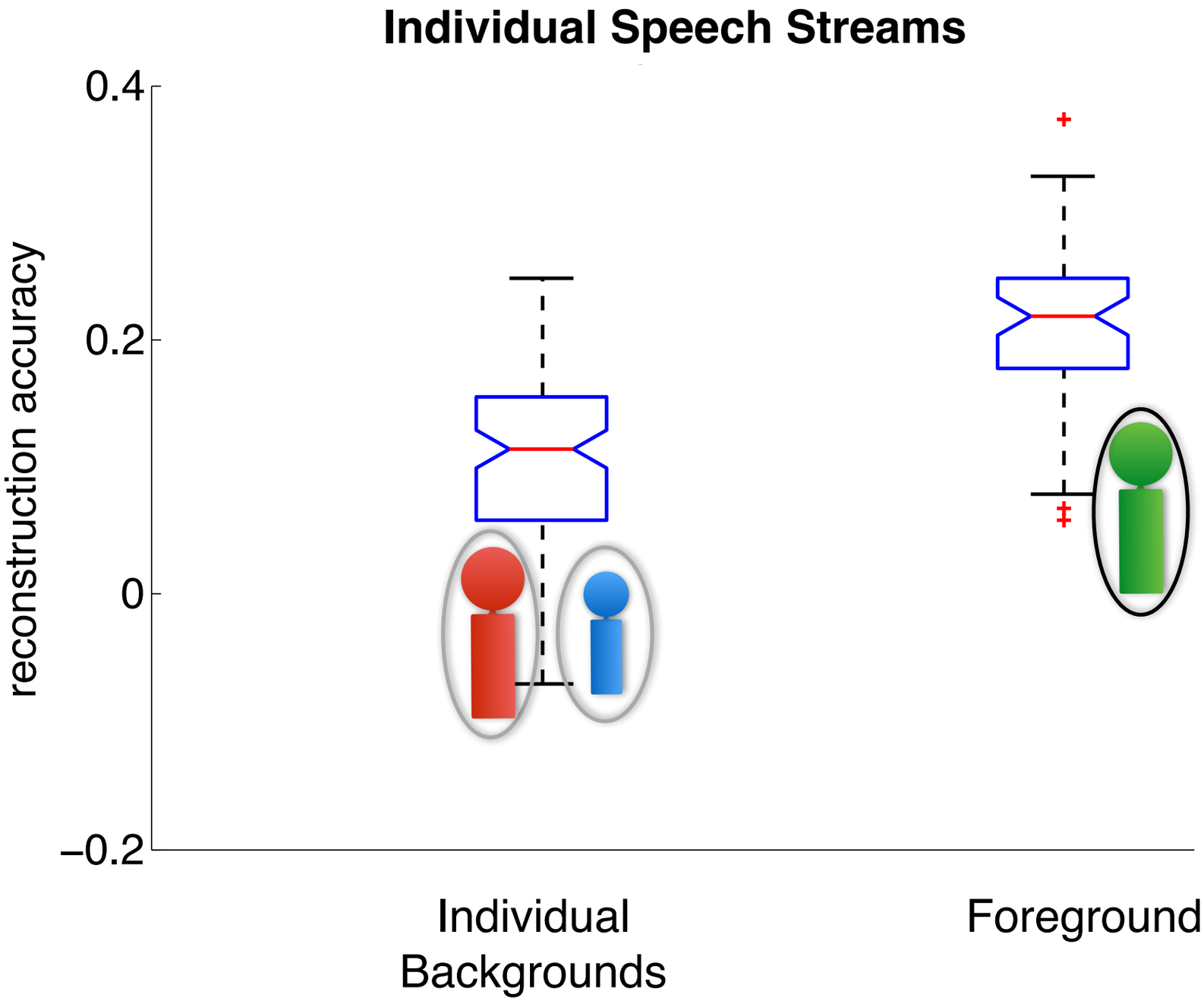
Backgrounds vs. Background

High latency areas (PT) represent ***fused*** background with better fidelity than ***individual*** backgrounds ($p = 0.012$)



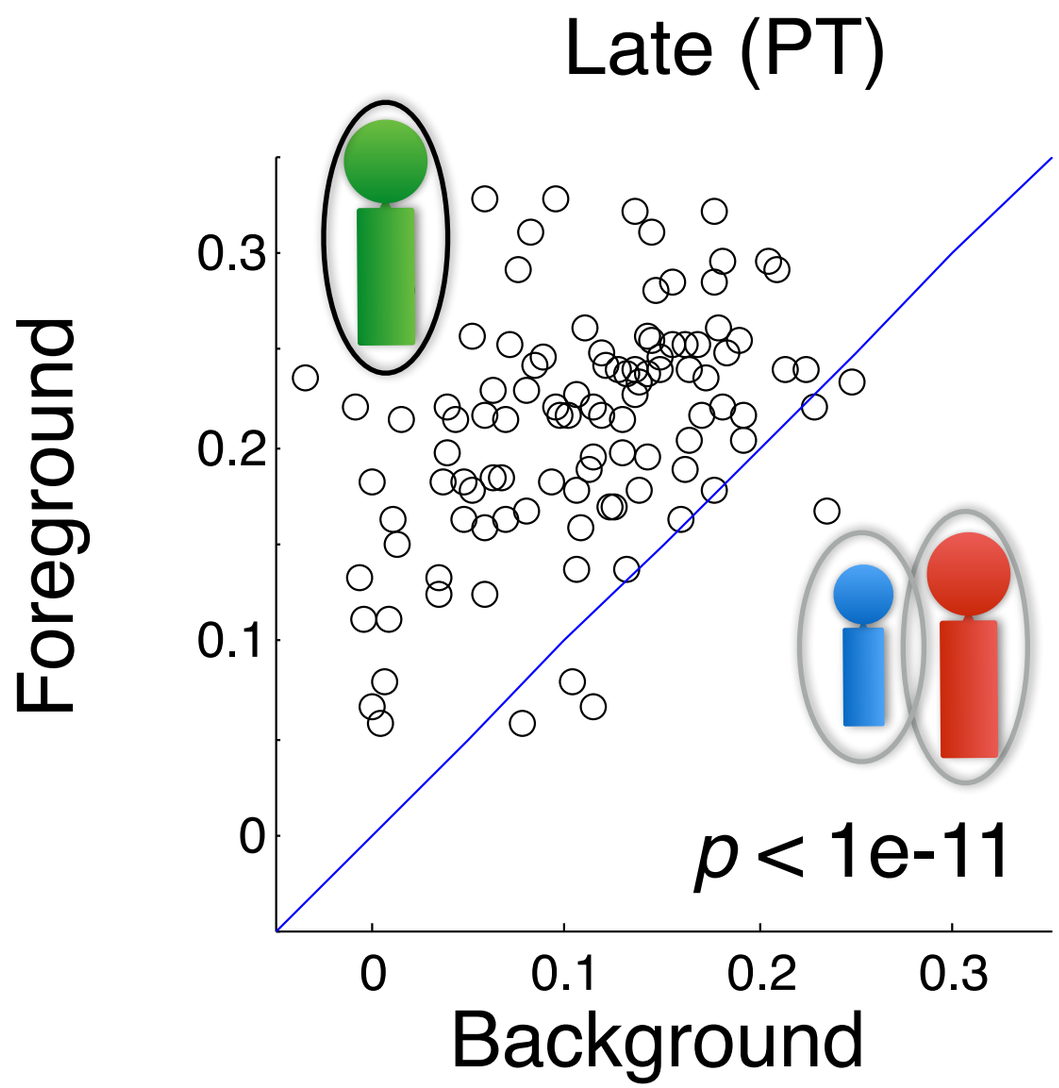
Integration Window over Late Times Only

Foreground vs. Background

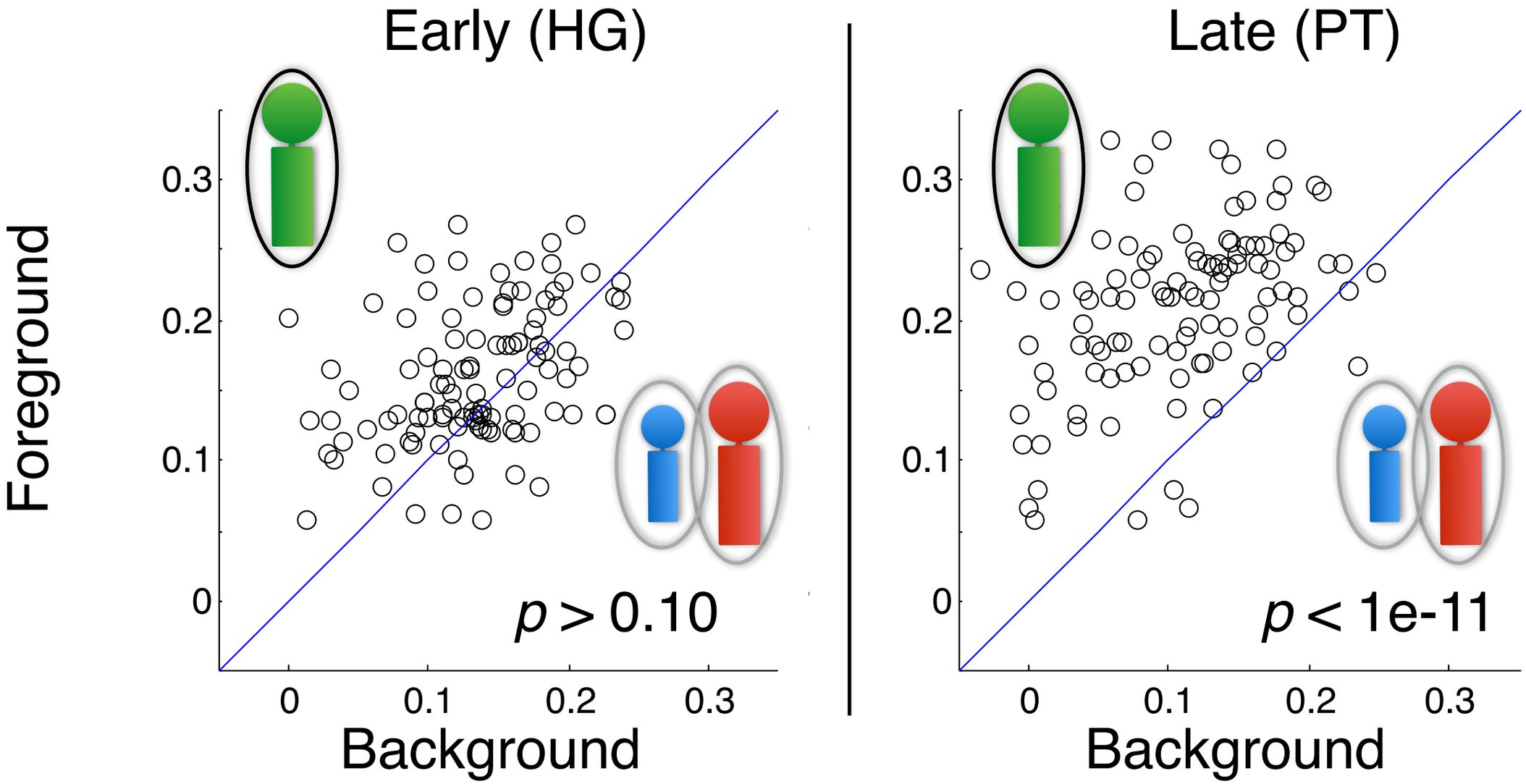


Integration Window over Late Times Only

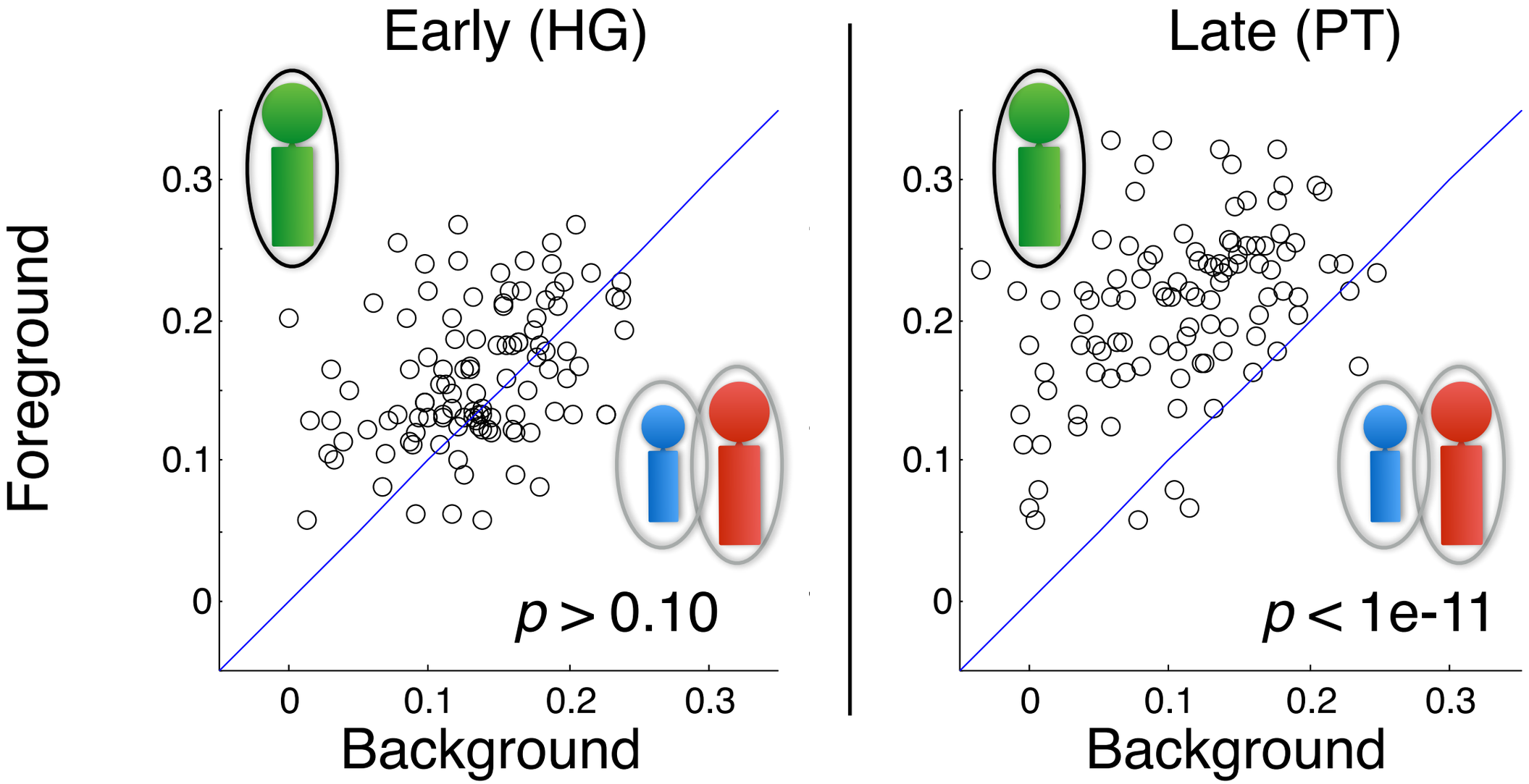
Foreground vs. Background
Early vs. Late



Foreground vs. Background
Early vs. Late



Foreground vs. Background
Early vs. Late



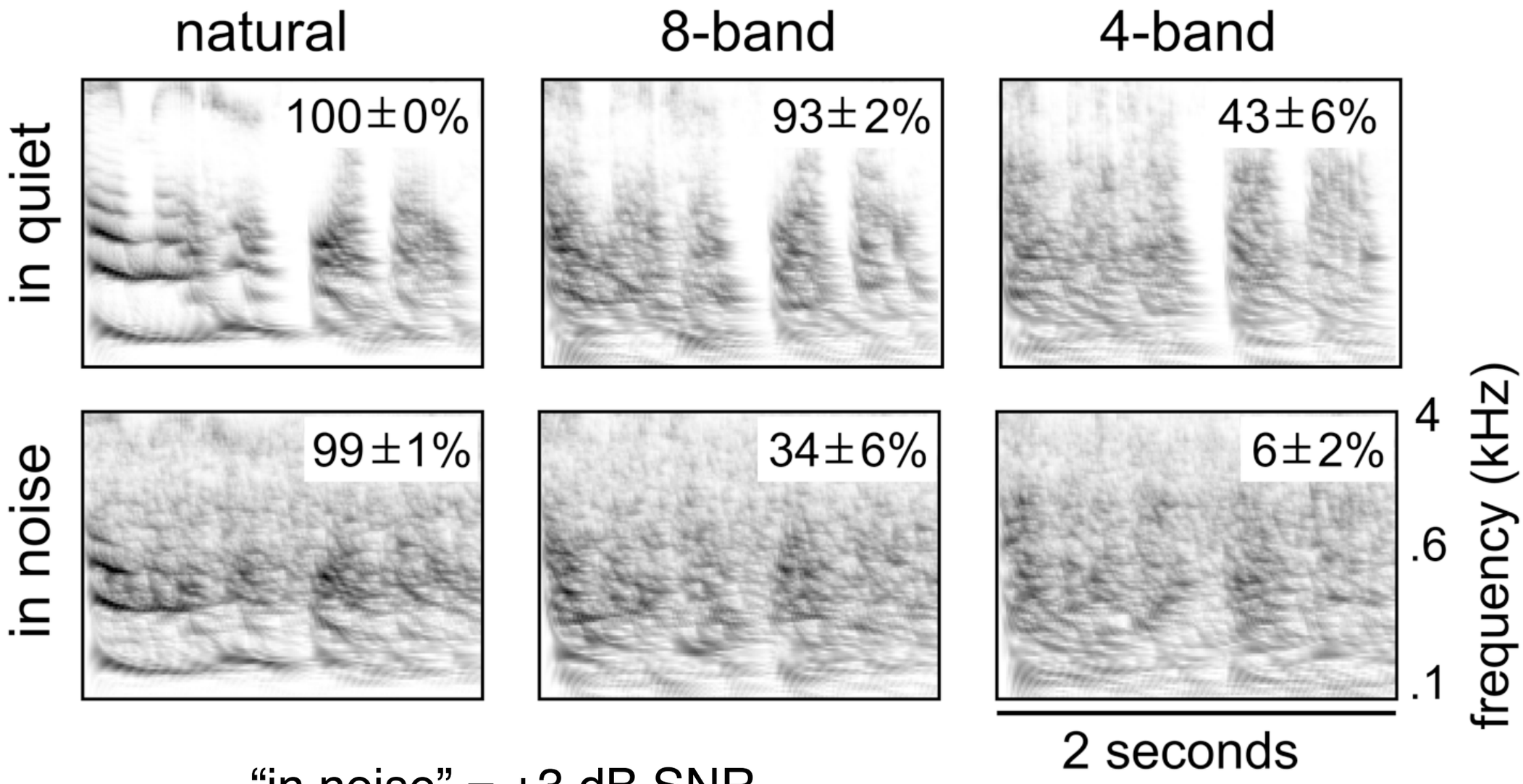
HG represents attended and unattended speech with *almost* equal fidelity

Summary

- Cortical representations of speech
  - representation of envelope (up to ~10 Hz)
- Cortical Processing Hierarchy: Consistent with being neural representation of auditory perceptual object
- Object representation at 100 ms latency (PT), but not by 50 ms (HG)
- Preliminary evidence for
  - PT: additional fused background representation
  - HG: almost equal representations

Thank You

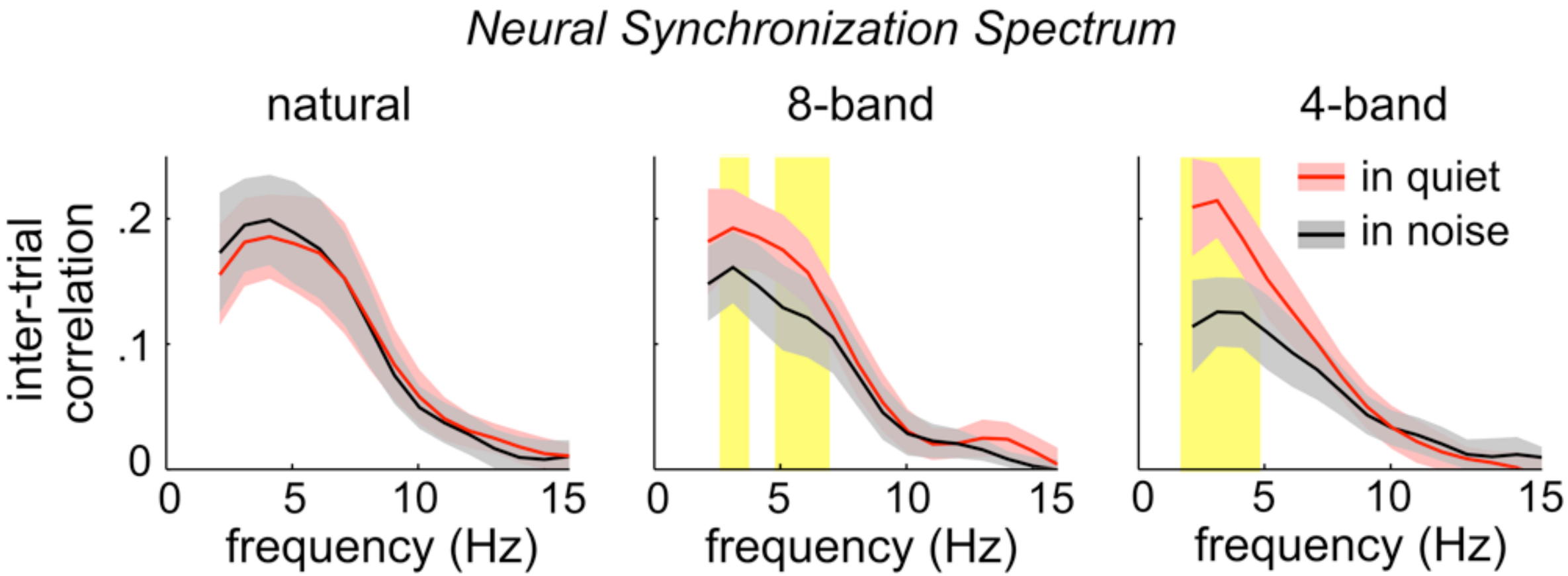
Noise-Vocoded Speech



"in noise" = +3 dB SNR

Ding, Chatterjee & Simon, NeuroImage (2014)

Noise-Vocoded Speech: Results



- Cortical entrainment to natural speech robust to noise
- Cortical entrainment to vocoded speech is not
- Not explainable by passive envelope tracking mechanisms
  - noise vocoding does not directly affect the stimulus envelope

Noise-Vocoded Speech: Results