Neural Representations of Speech in Human Auditory Cortex

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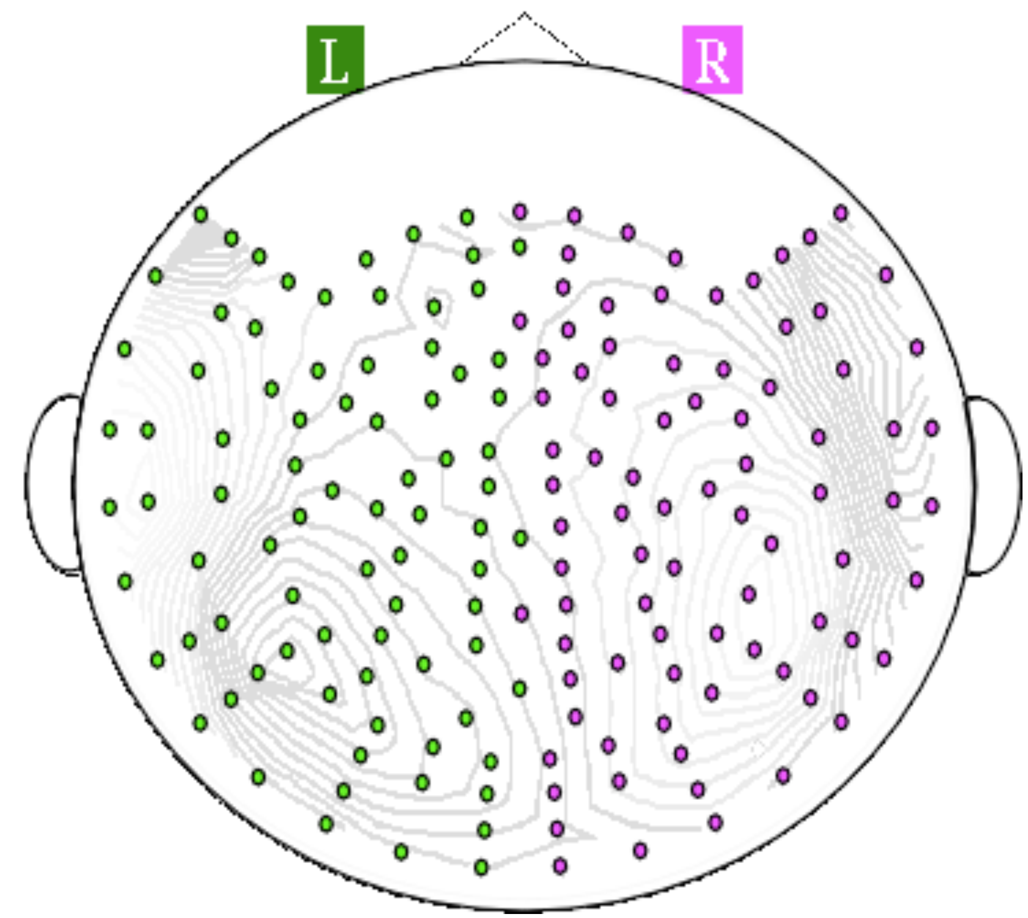
Outline

- Cortical Representations of Speech (via MEG)
  - Encoding vs. Decoding
- Cortical Representations Speech in Noise
- Recent Results
  - Aging & Cortical Representations of Speech
  - Higher Level Interference & Noise
  - Foreground and Background Representations
  - Speech Restoration

Magnetoencephalography (MEG)

- 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

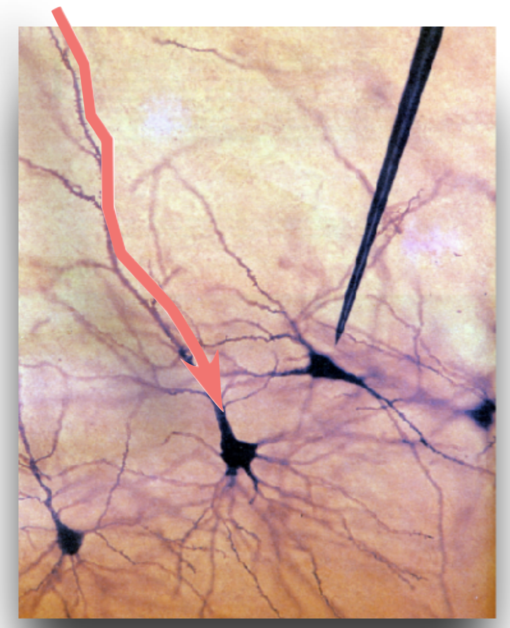
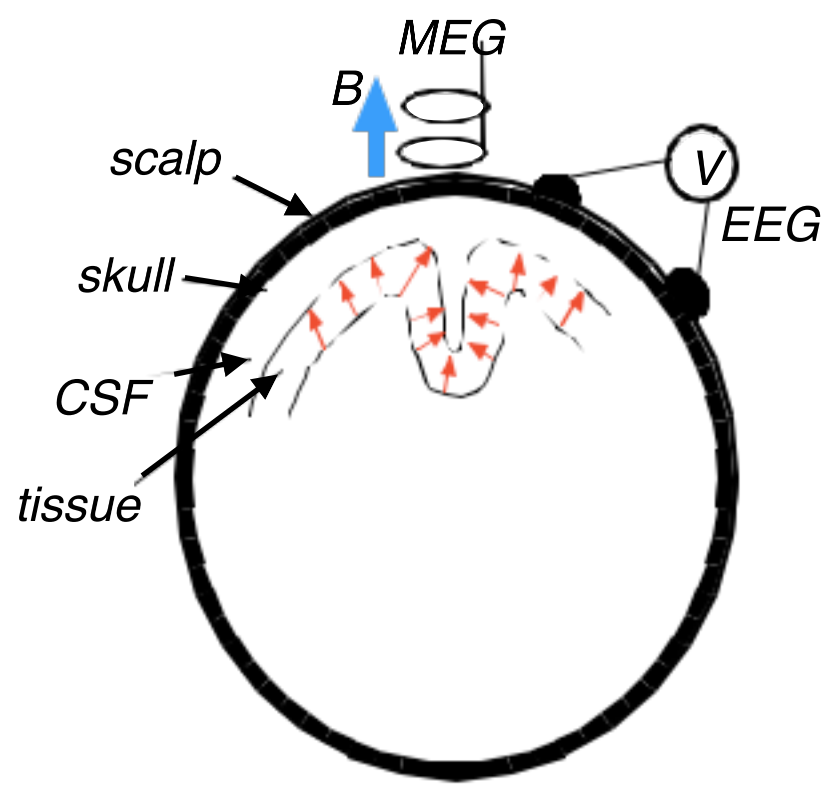
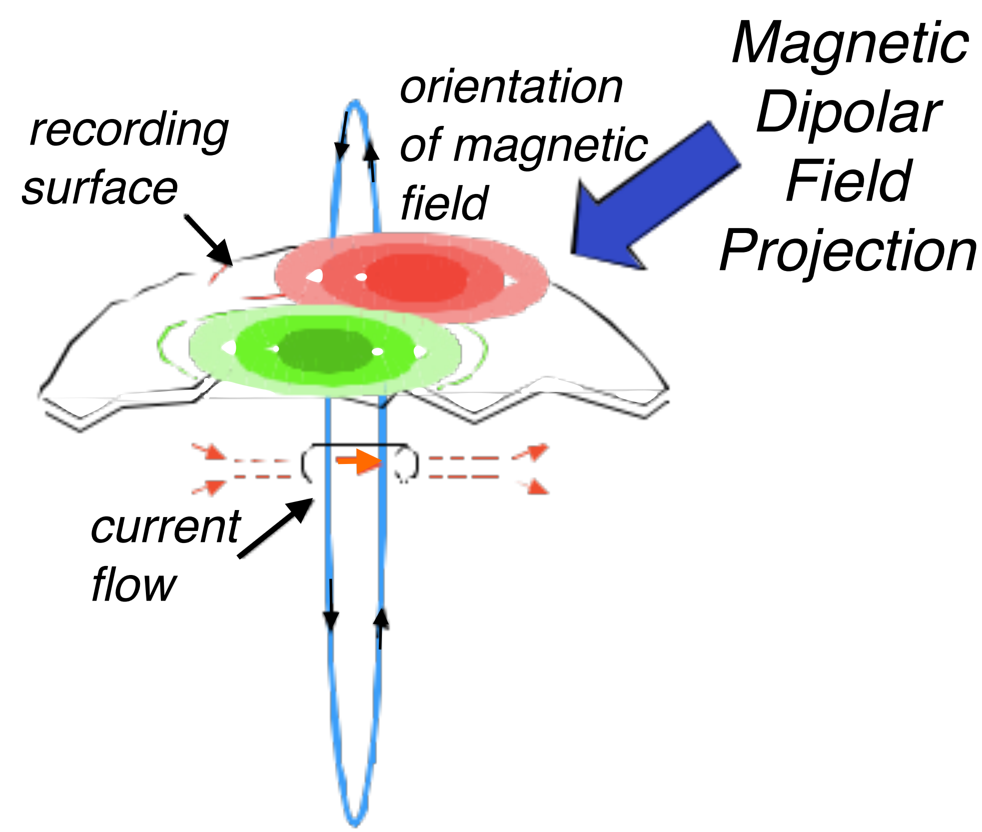


Photo by Fritz Goro



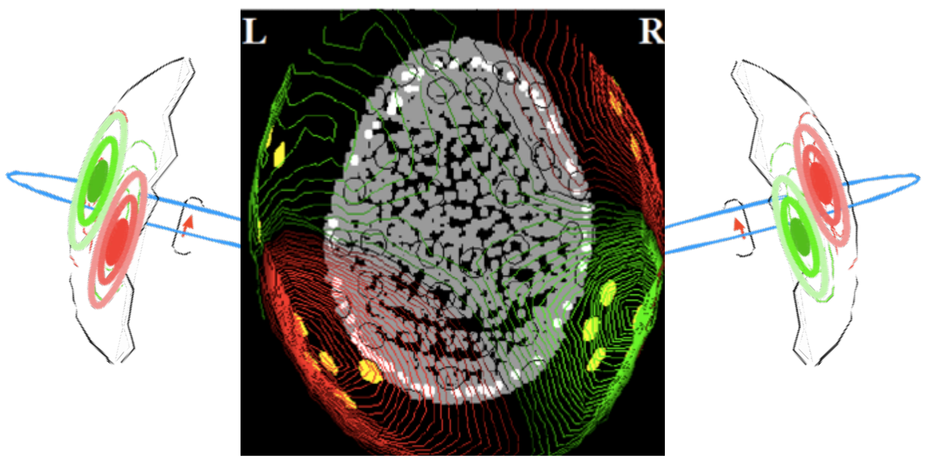


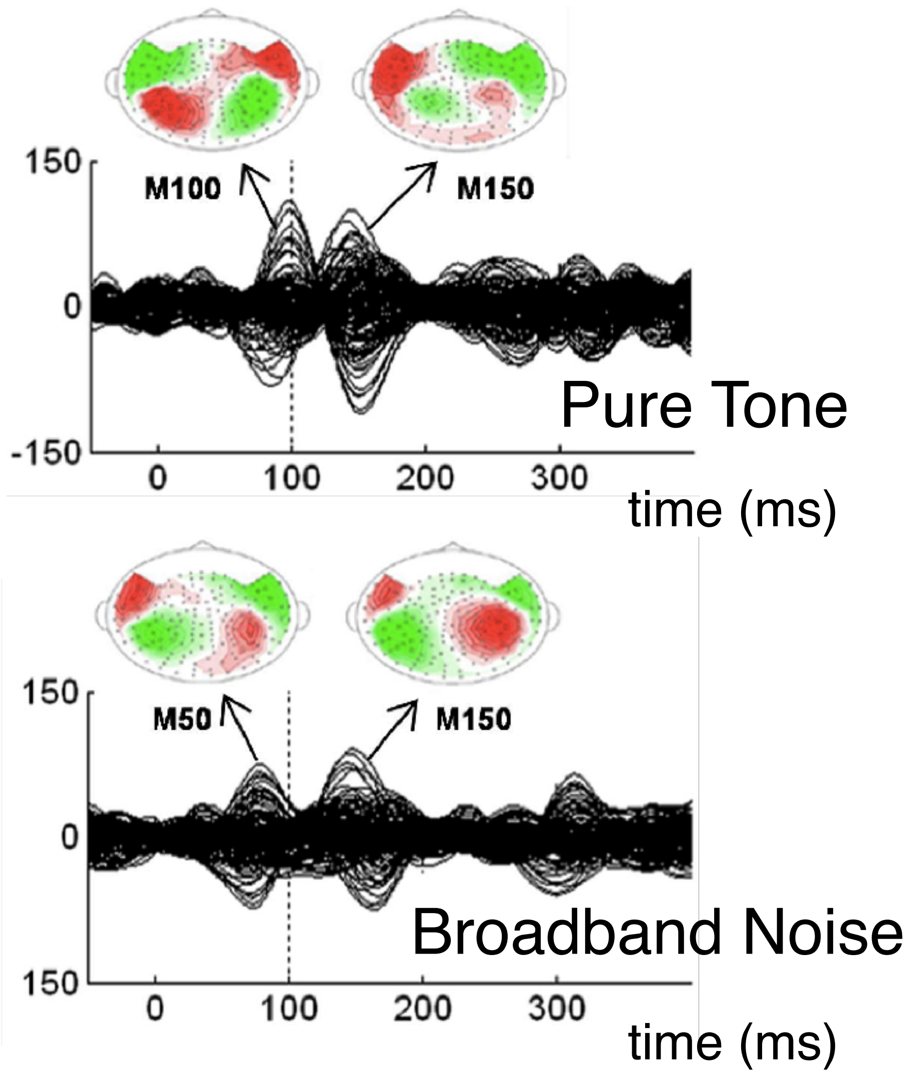
- Direct electrophysiological measurement
  - not hemodynamic
  - real-time
- No unique solution for distributed source

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

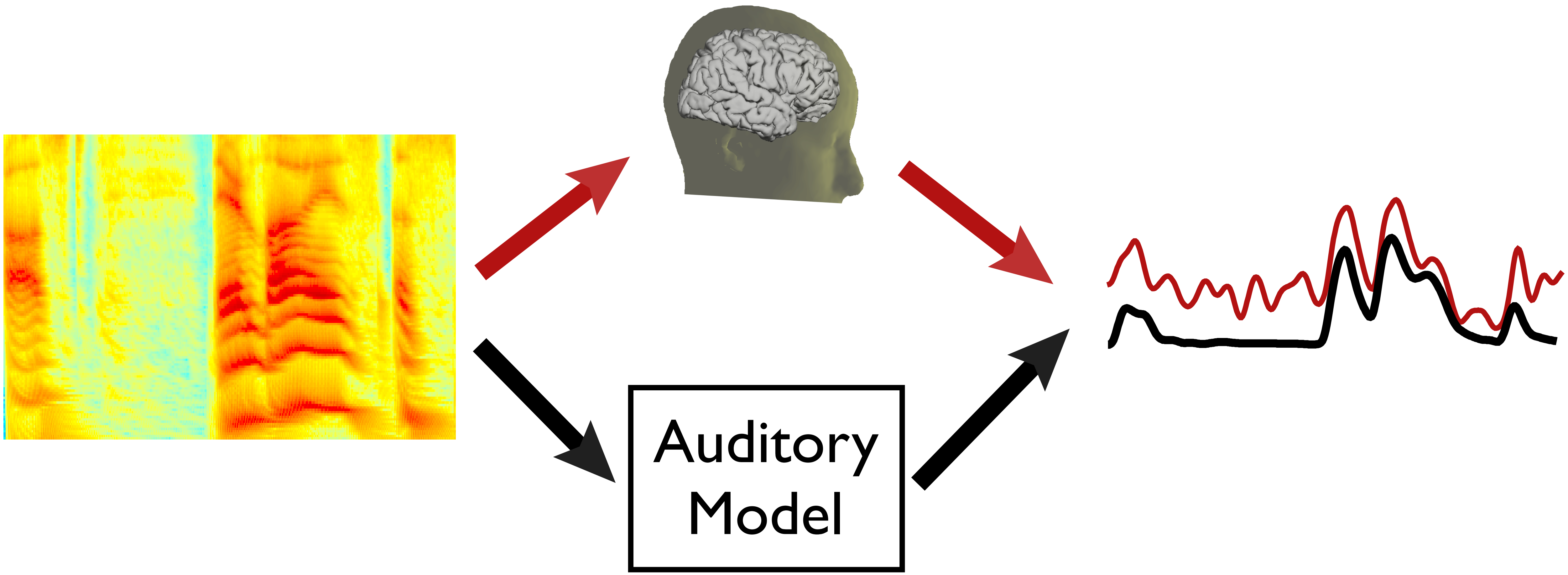
MEG & Auditory Cortex

- Non-invasive, Passive, Silent Neural Recordings
- MEG Response Patterns Time-Locked to Stimulus Events
- Robust
- Strongly Lateralized
- Cortical Origin Only (few exceptions)

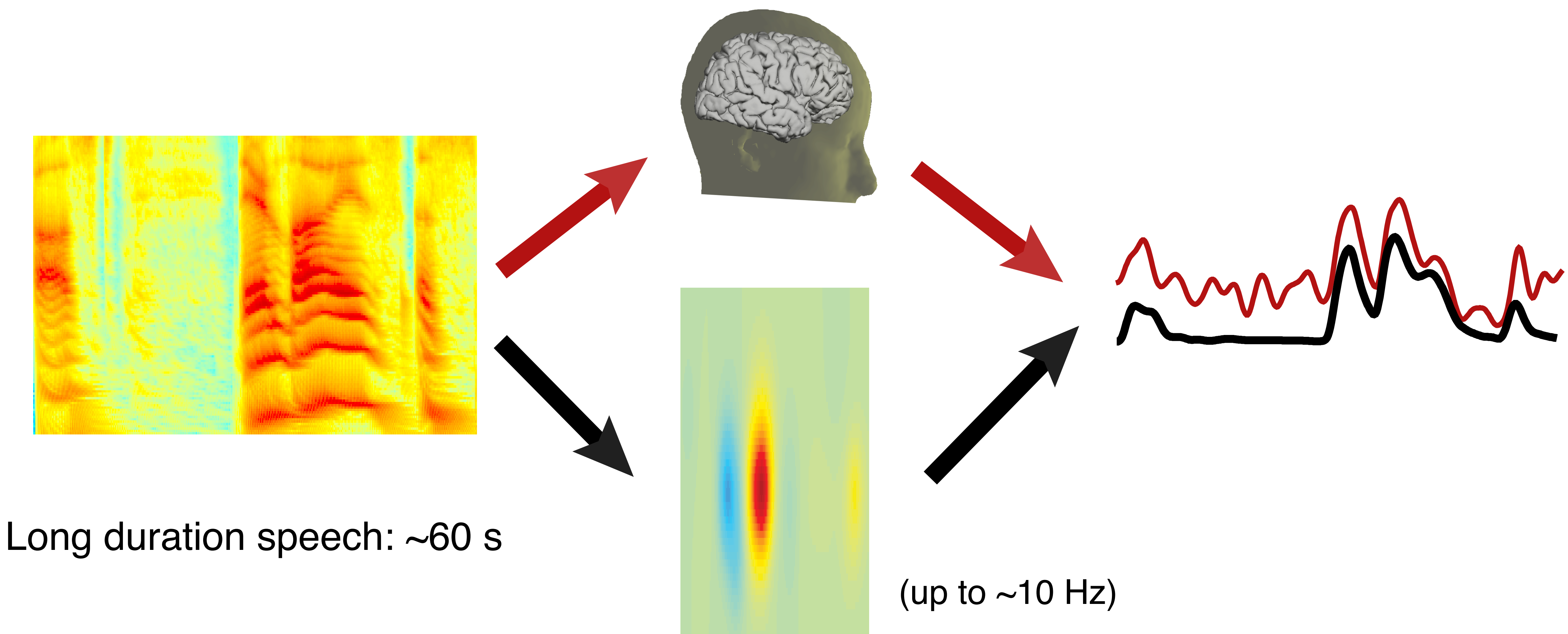




MEG Responses to Speech Modulations



MEG Responses Predicted by STRF Model

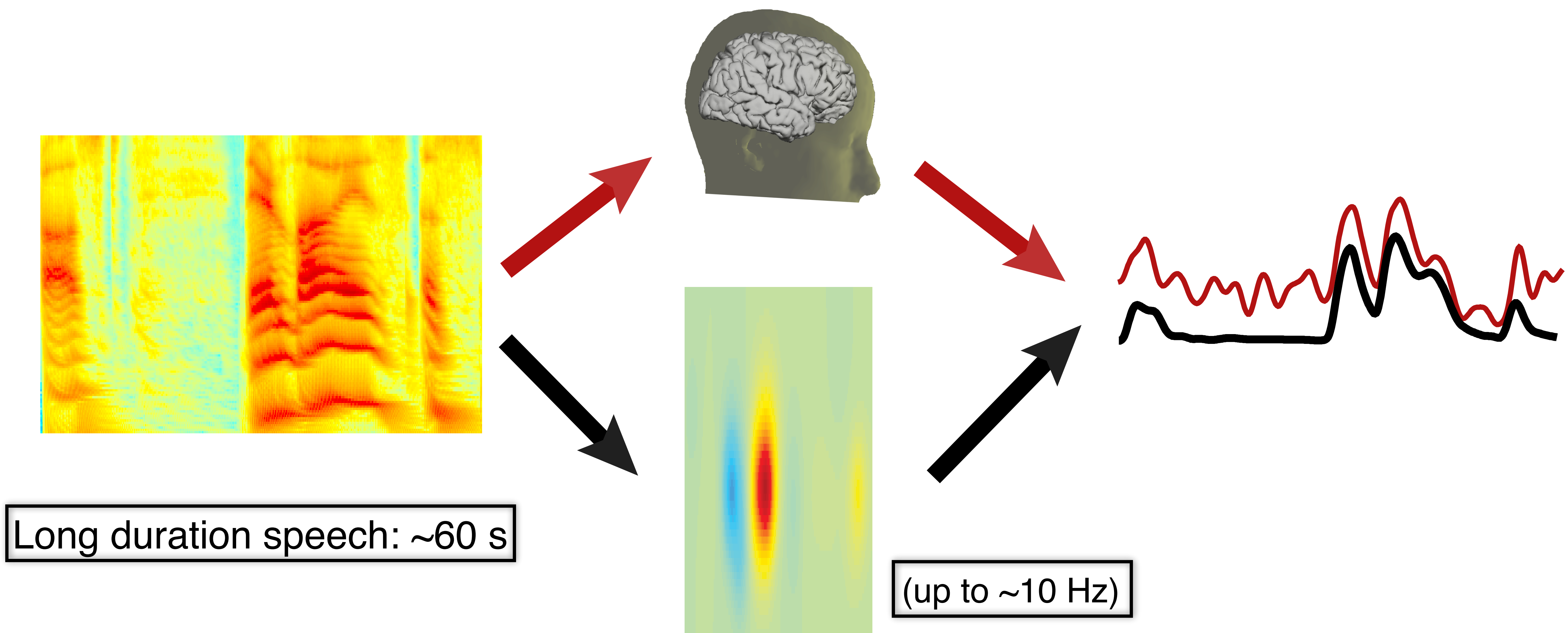


Linear Kernel = STRF

"Spectro-Temporal Response Function"

Ding & Simon, J Neurophysiol (2012)

MEG Responses Predicted by STRF Model

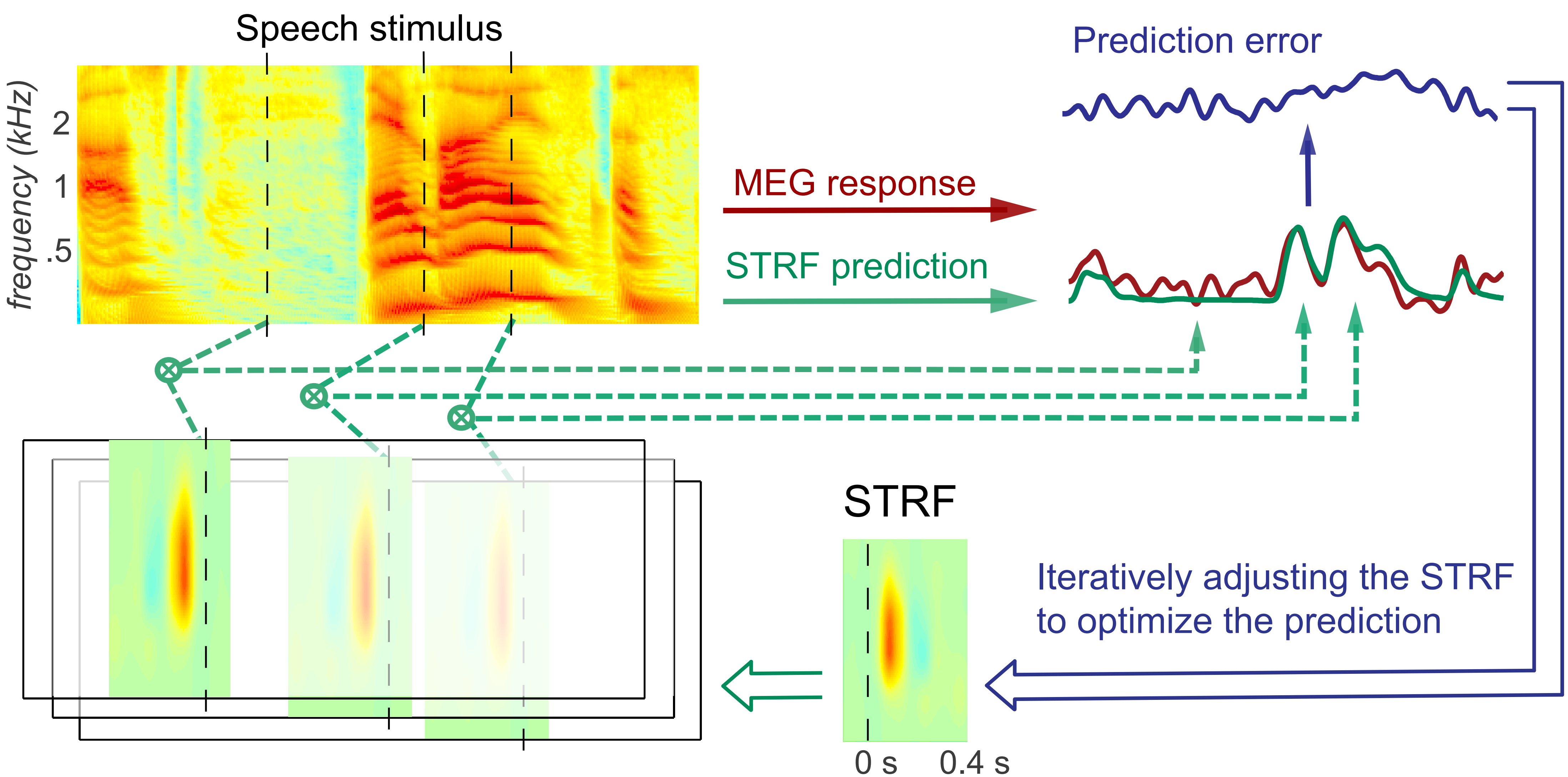


Linear Kernel = STRF

"Spectro-Temporal Response Function"

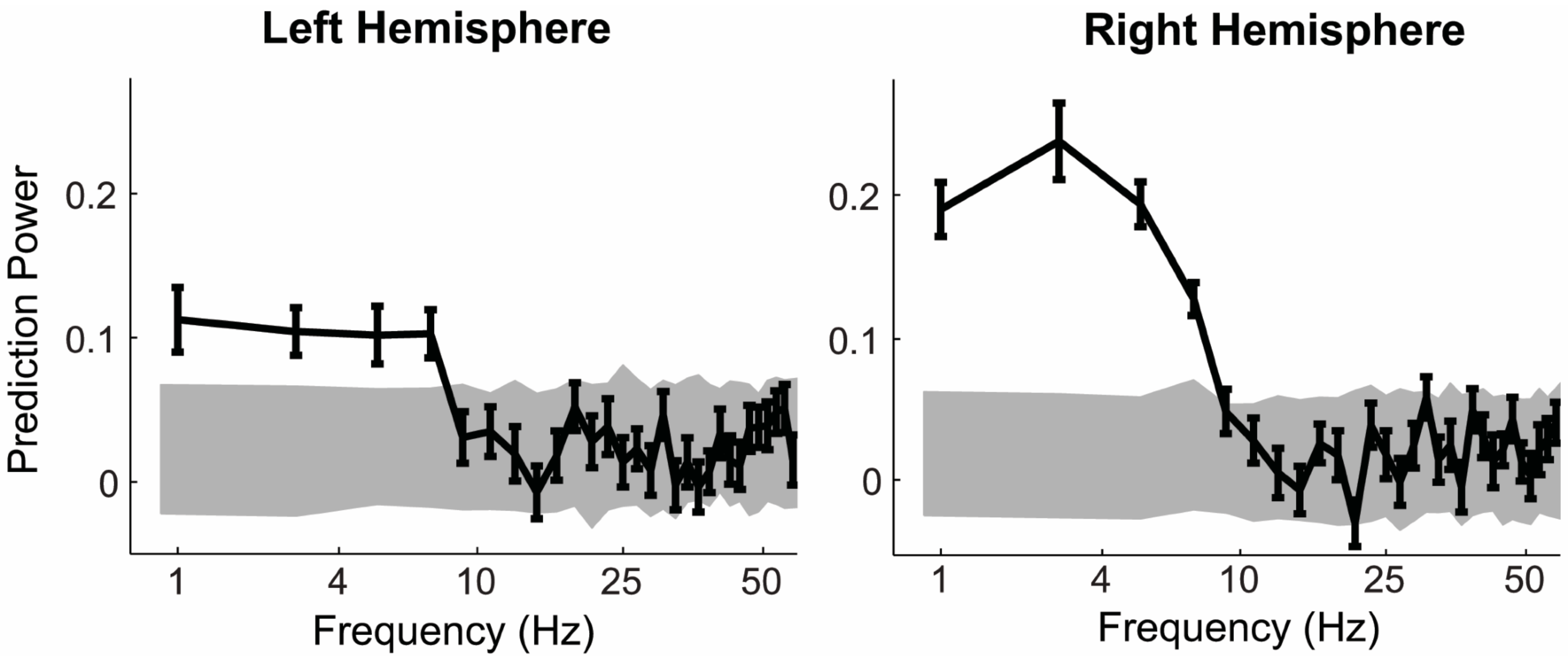
Ding & Simon, J Neurophysiol (2012)

STRF Estimation via Boosting



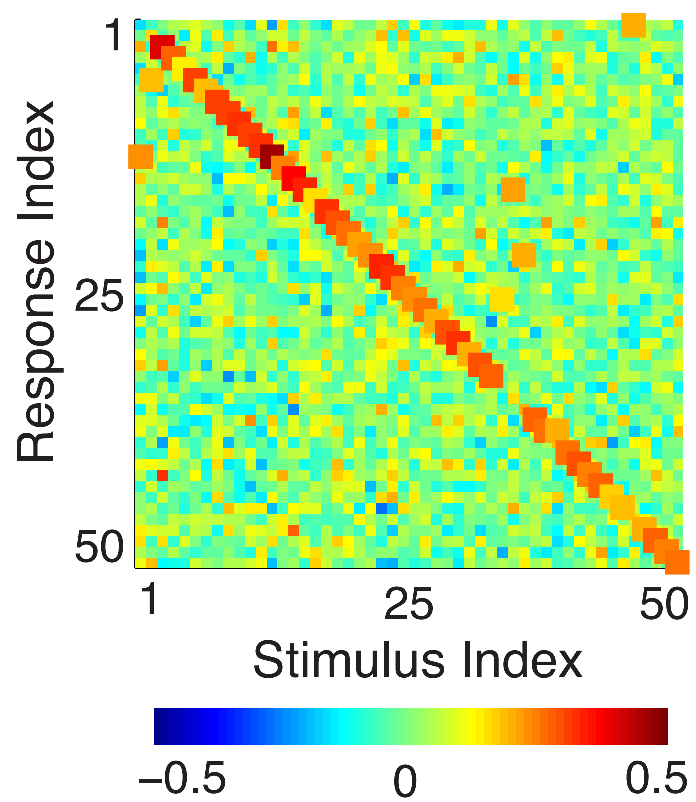
Ding & Simon, J Neurophysiol (2012)

Frequency Dependence of STRF Predictability

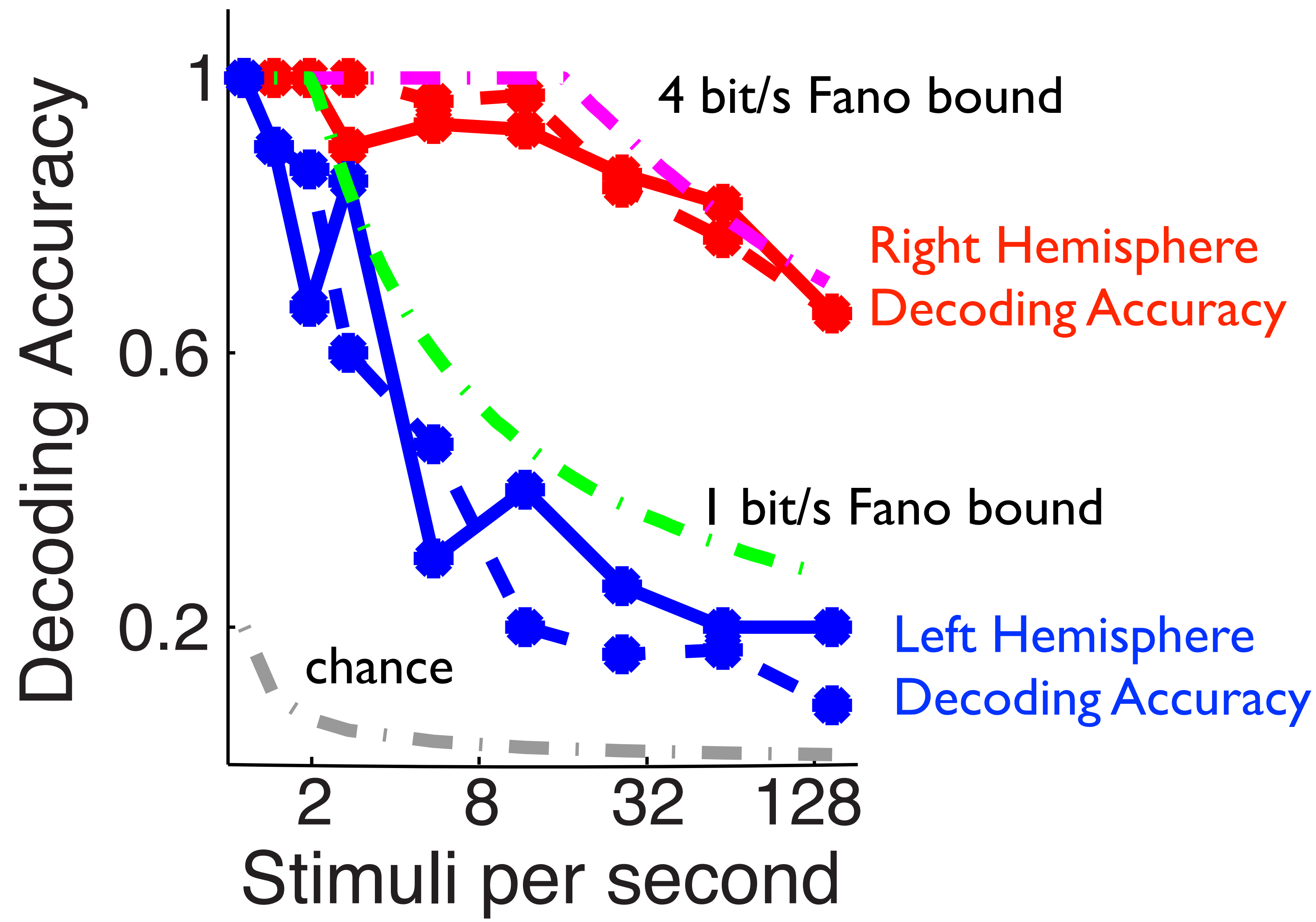


Ding & Simon, J Neurophysiol (2012)

Stimulus Information Encoded in Response

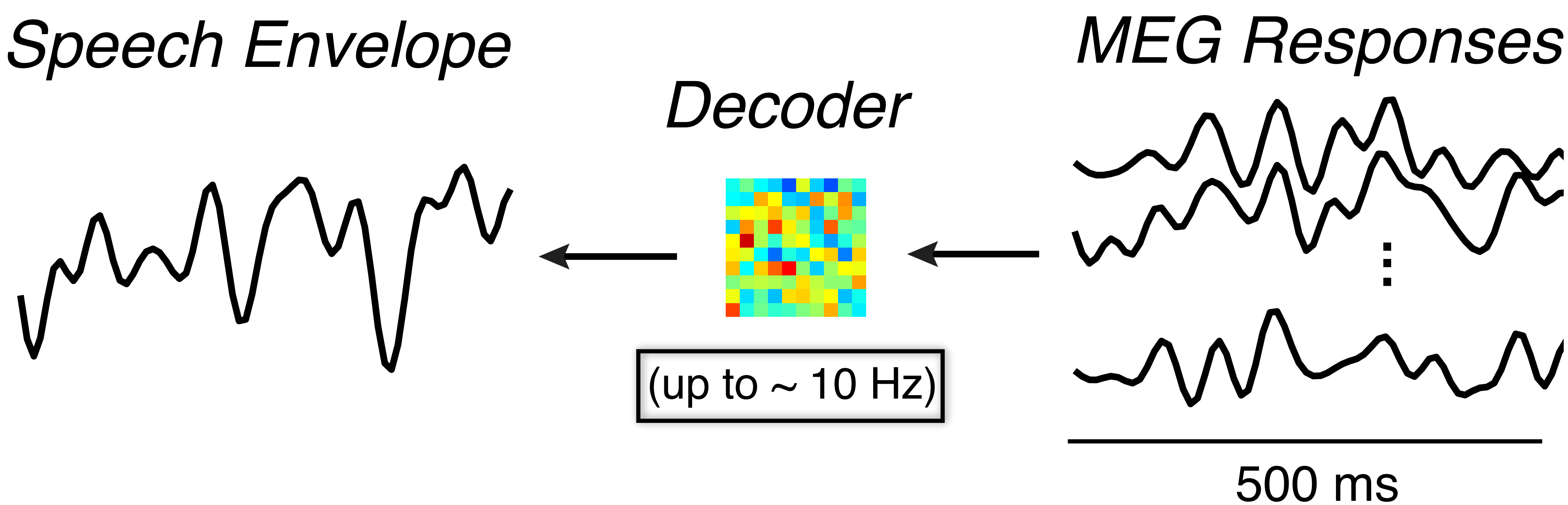


Correlation between stimulus envelope and reconstructed envelope (right hemisphere)



Ding & Simon, J Neurophysiol (2012)

Neural Reconstruction of Speech Envelope



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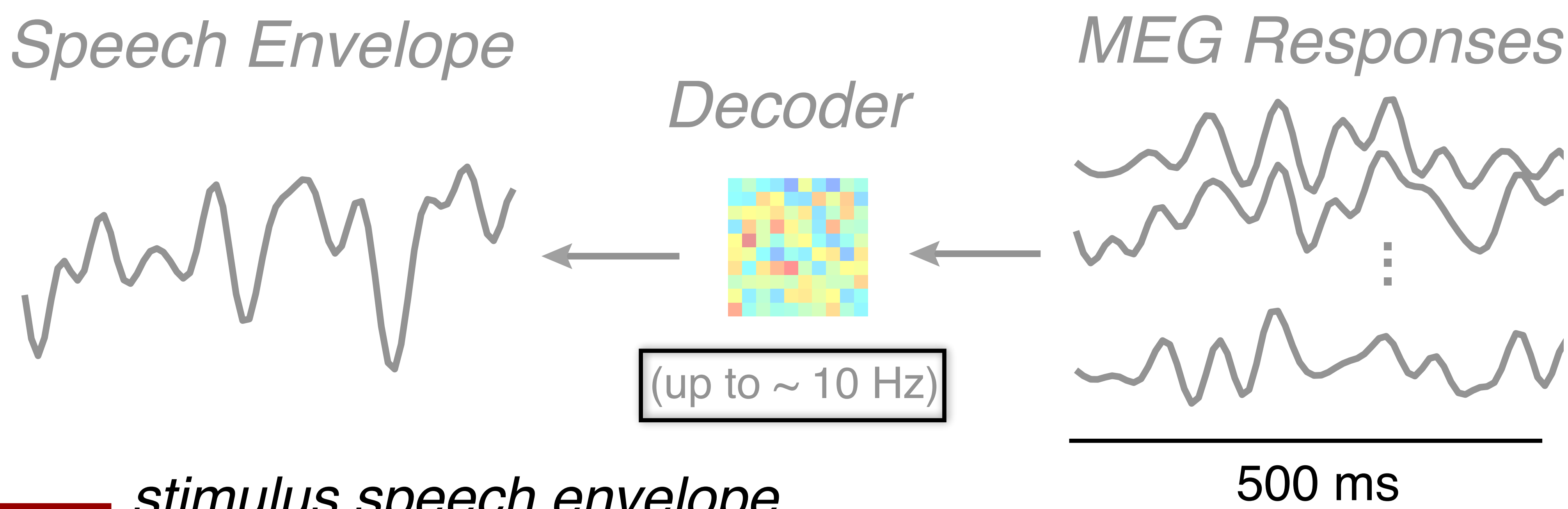
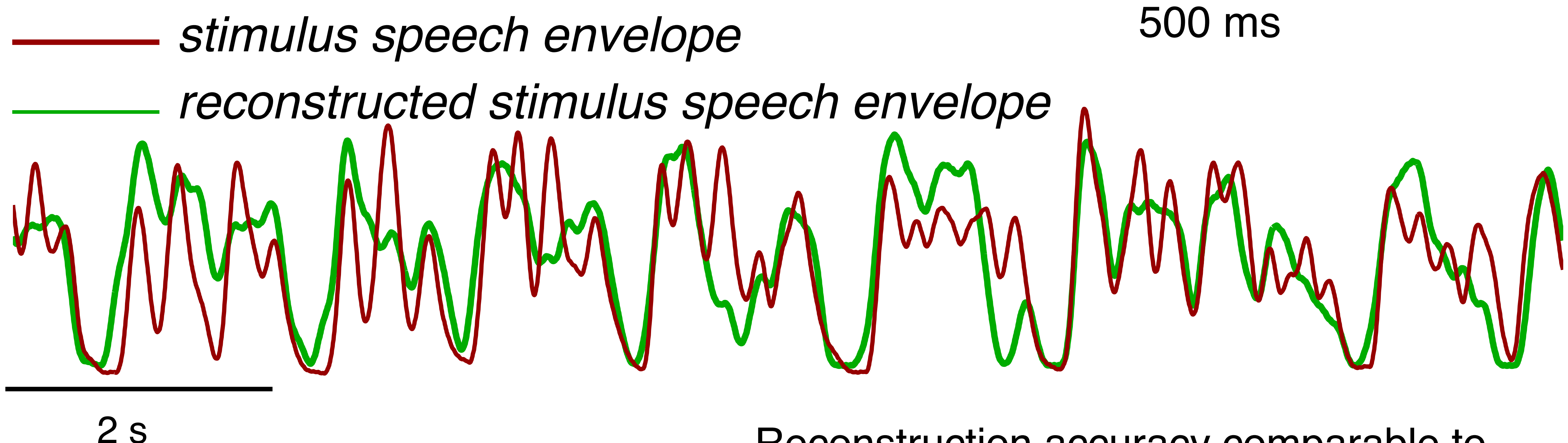
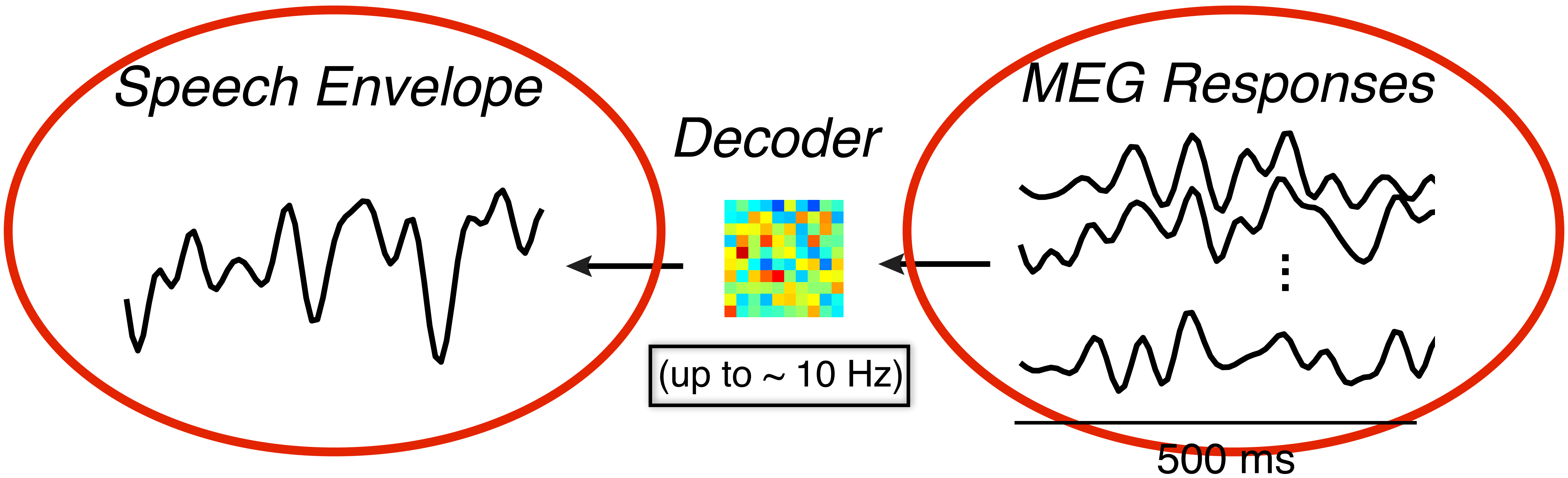




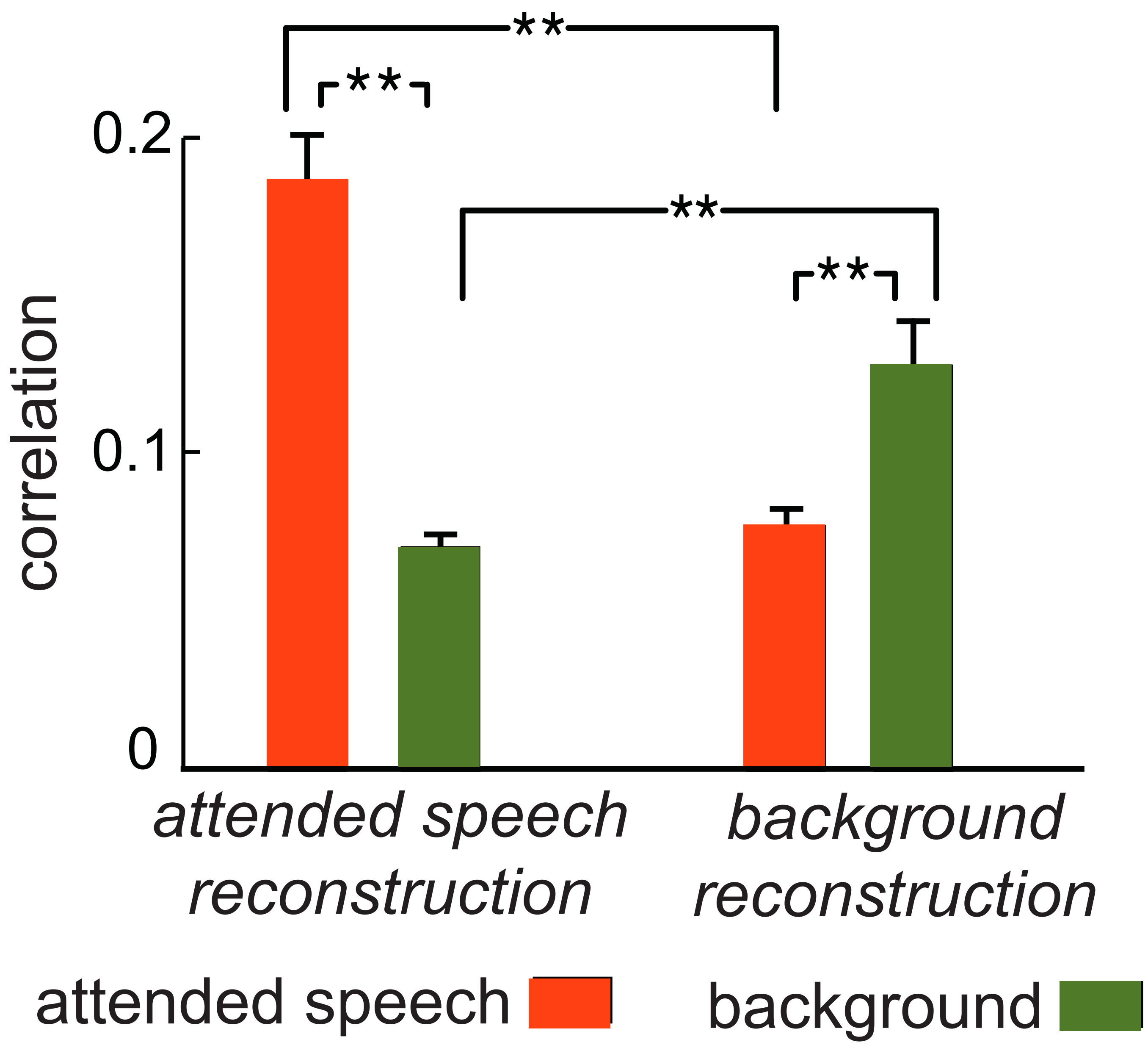
Reconstruction accuracy comparable to single unit & ECoG recordings

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



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

Overall Speech Reconstruction



Distinct neural representations for different speech streams

Ding & Simon, PNAS (2012)

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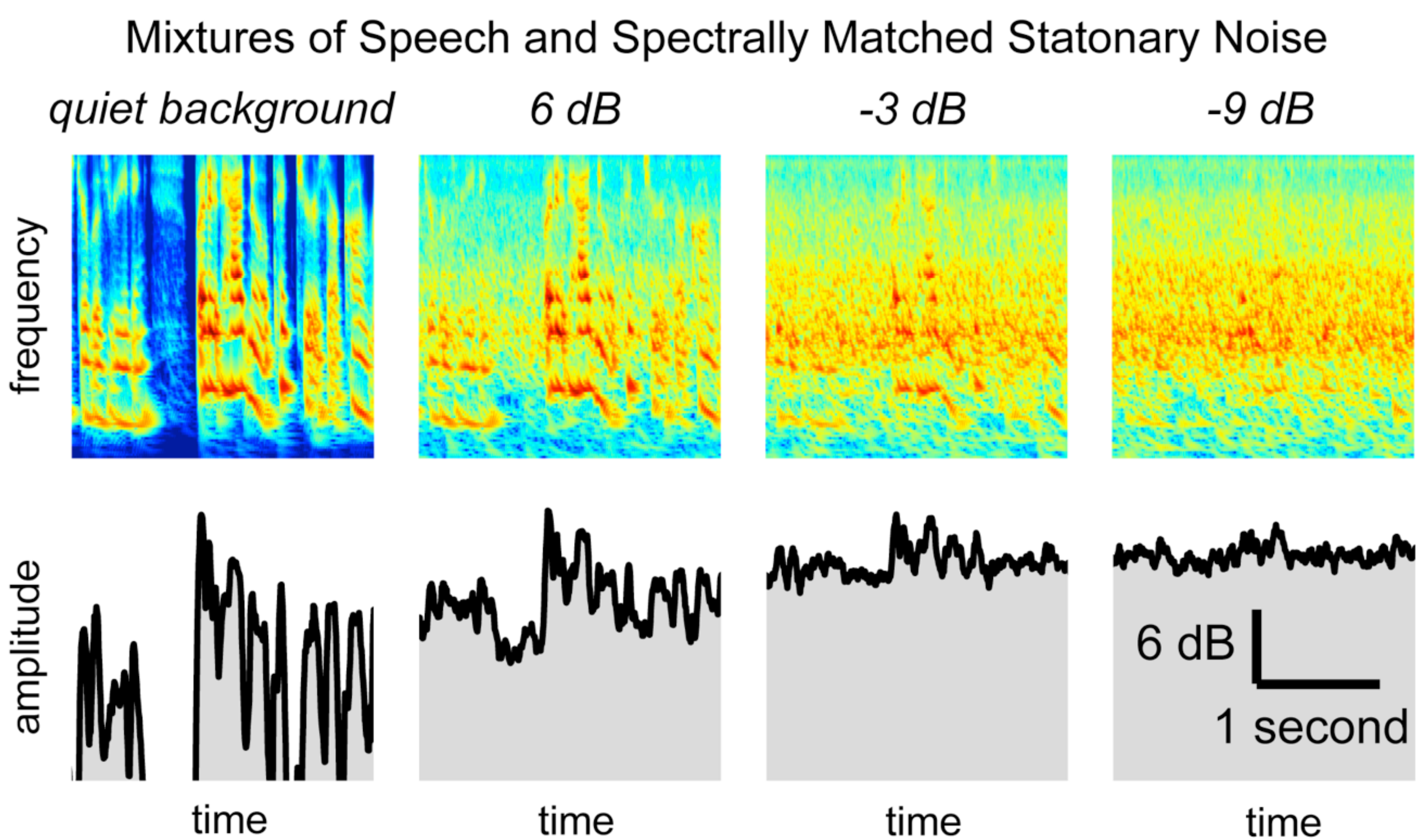
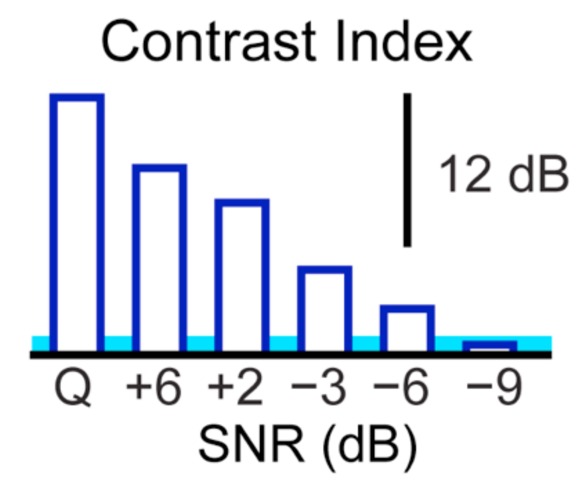
Speech in Stationary Noise





Ding & Simon, J Neuroscience (2013)

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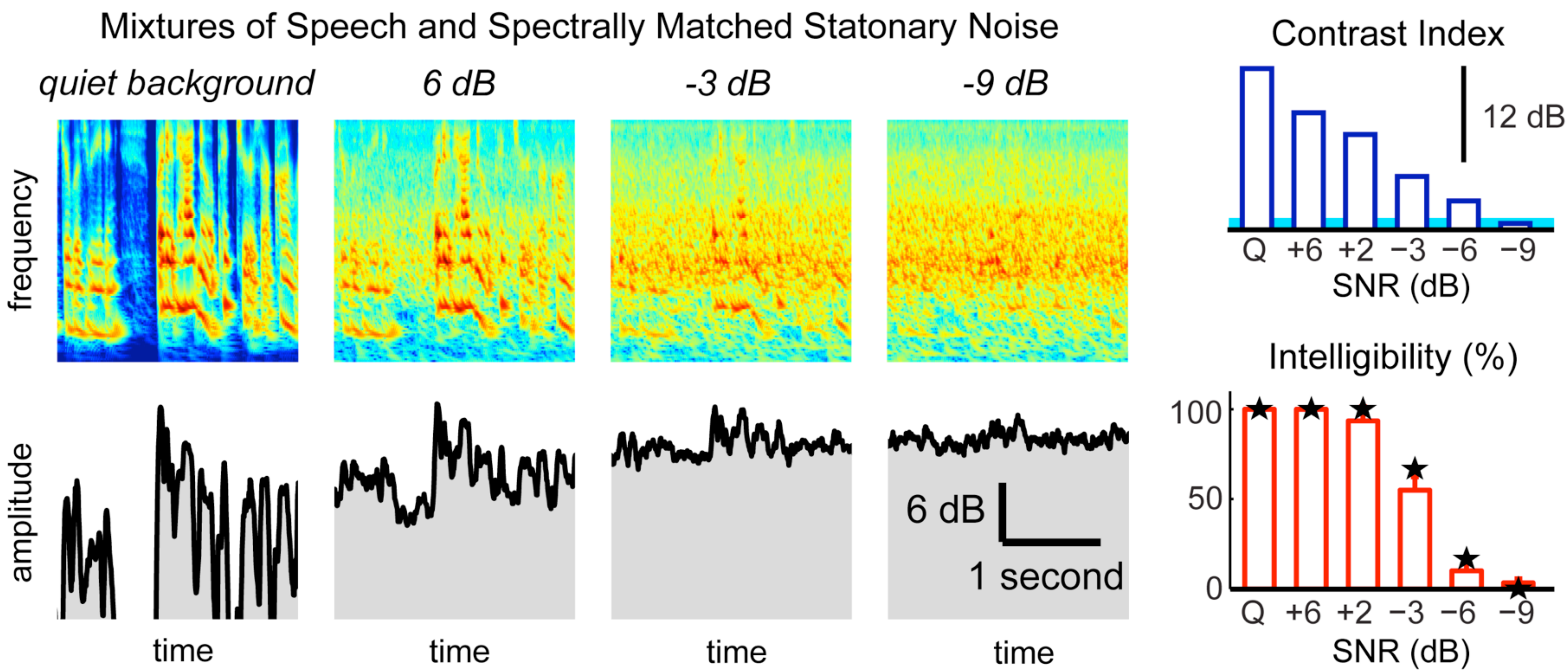
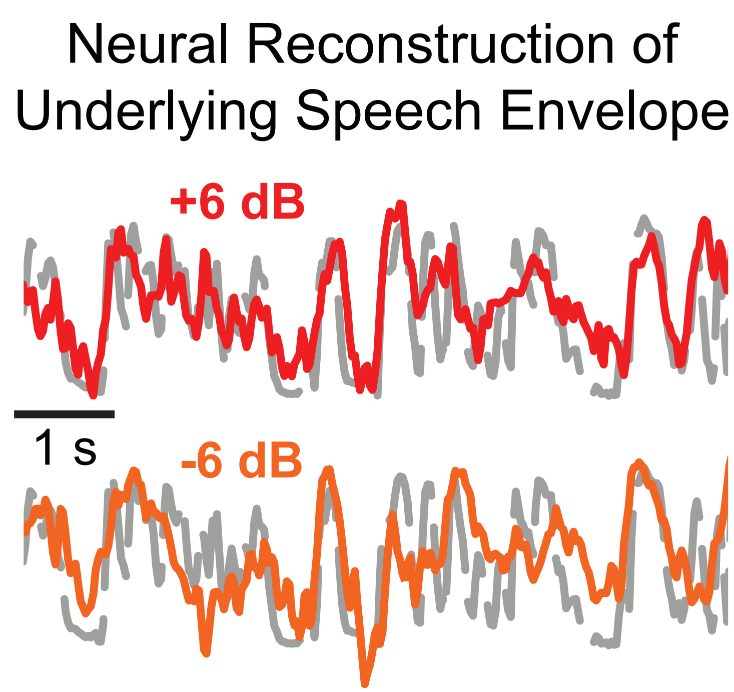


Ding & Simon, J Neuroscience (2013)

Speech in Noise: Results



Ding & Simon, J Neuroscience (2013)

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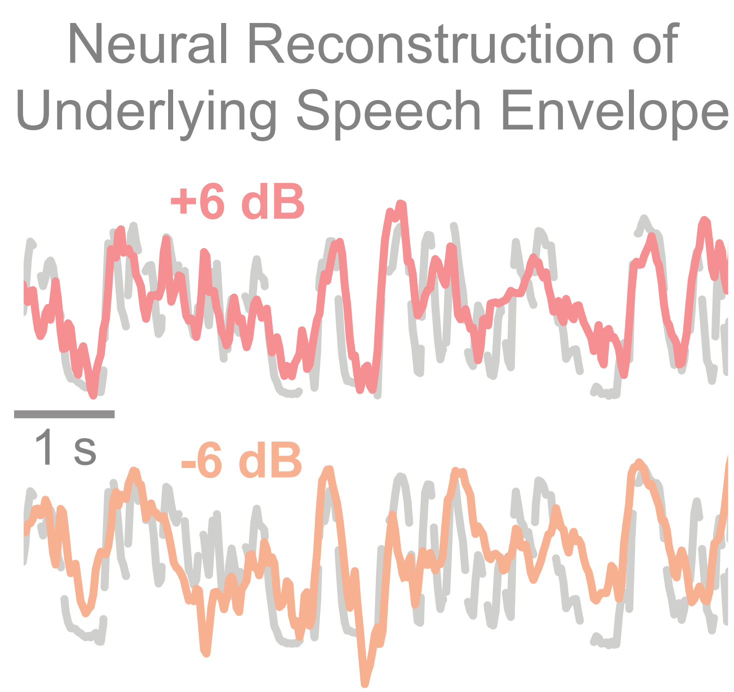

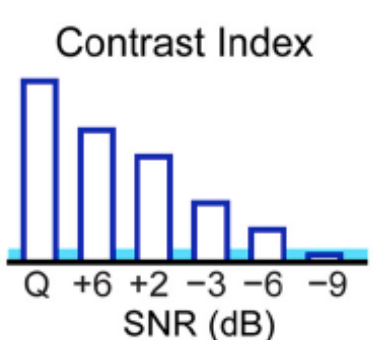

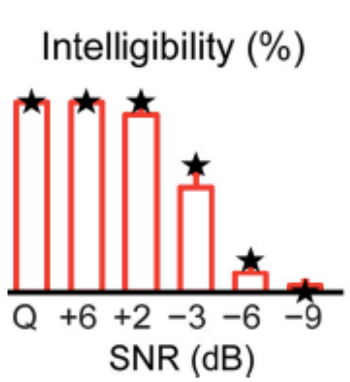

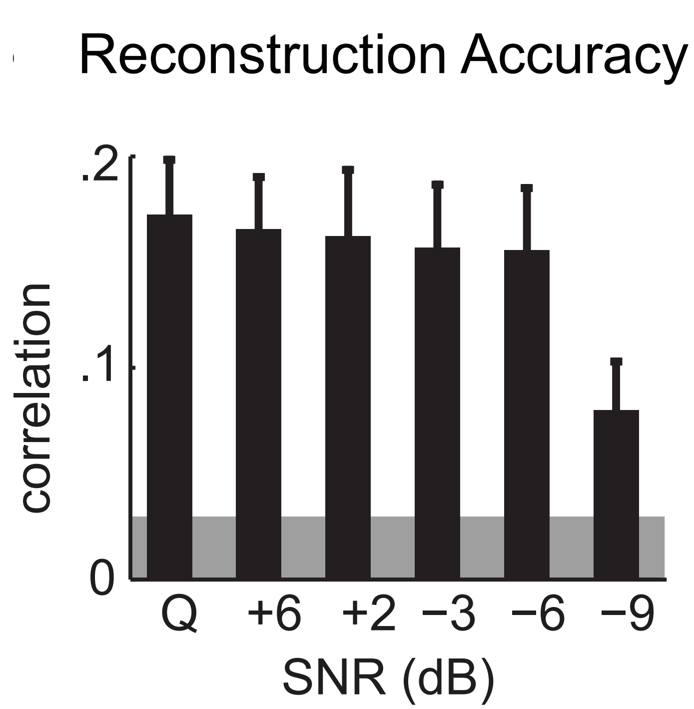

Ding & Simon, J Neuroscience (2013)

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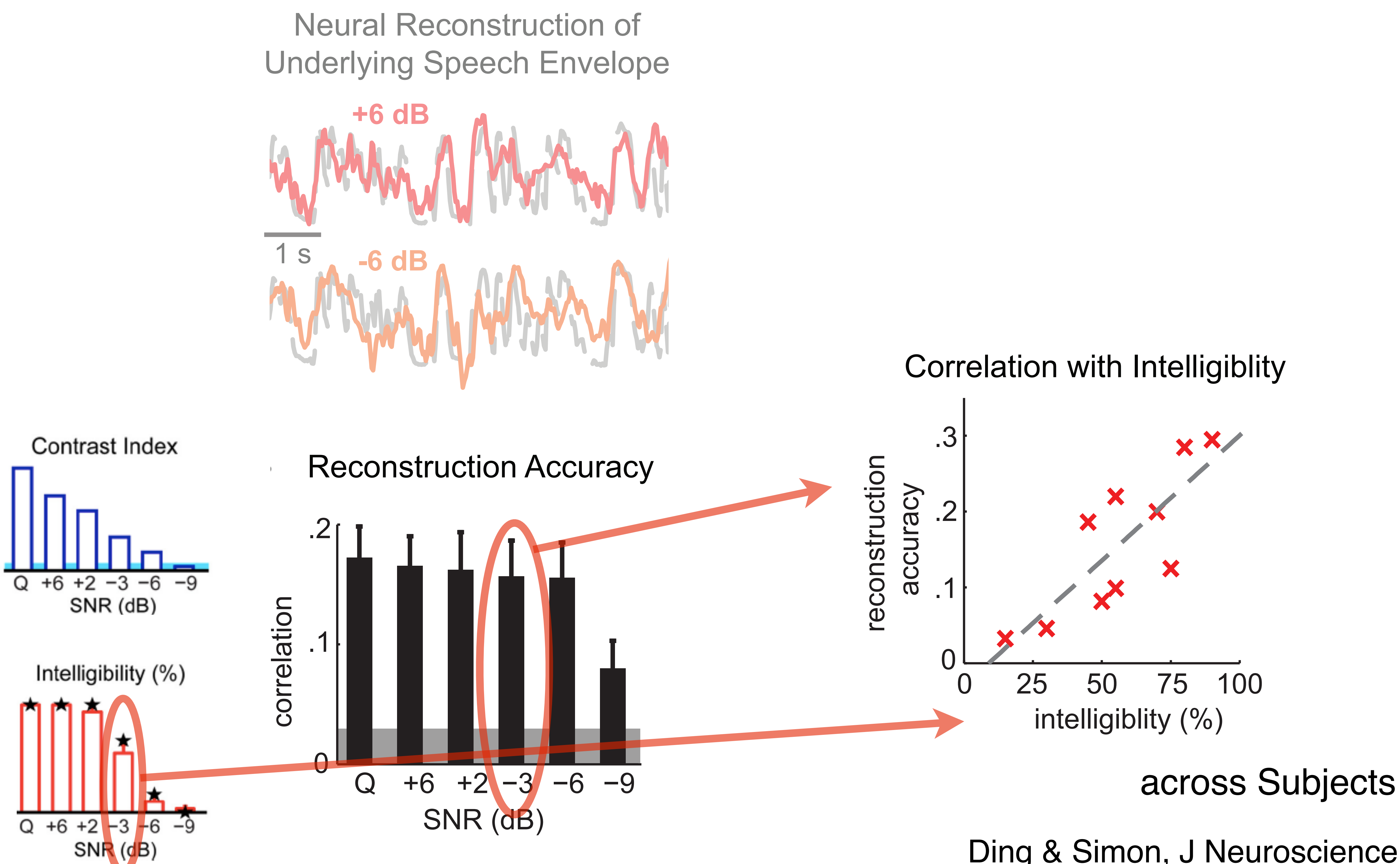
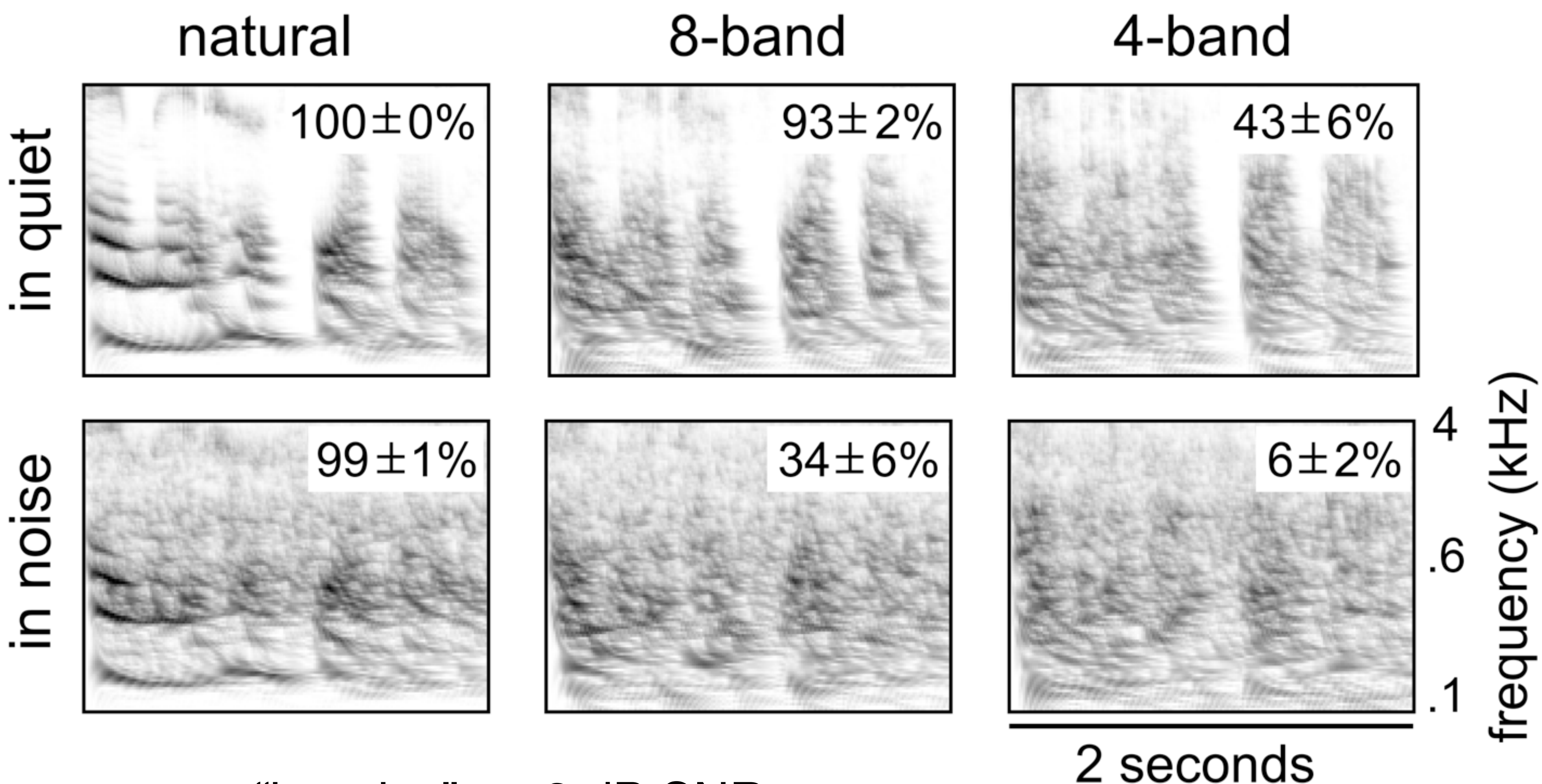


Ding & Simon, J Neuroscience (2013)

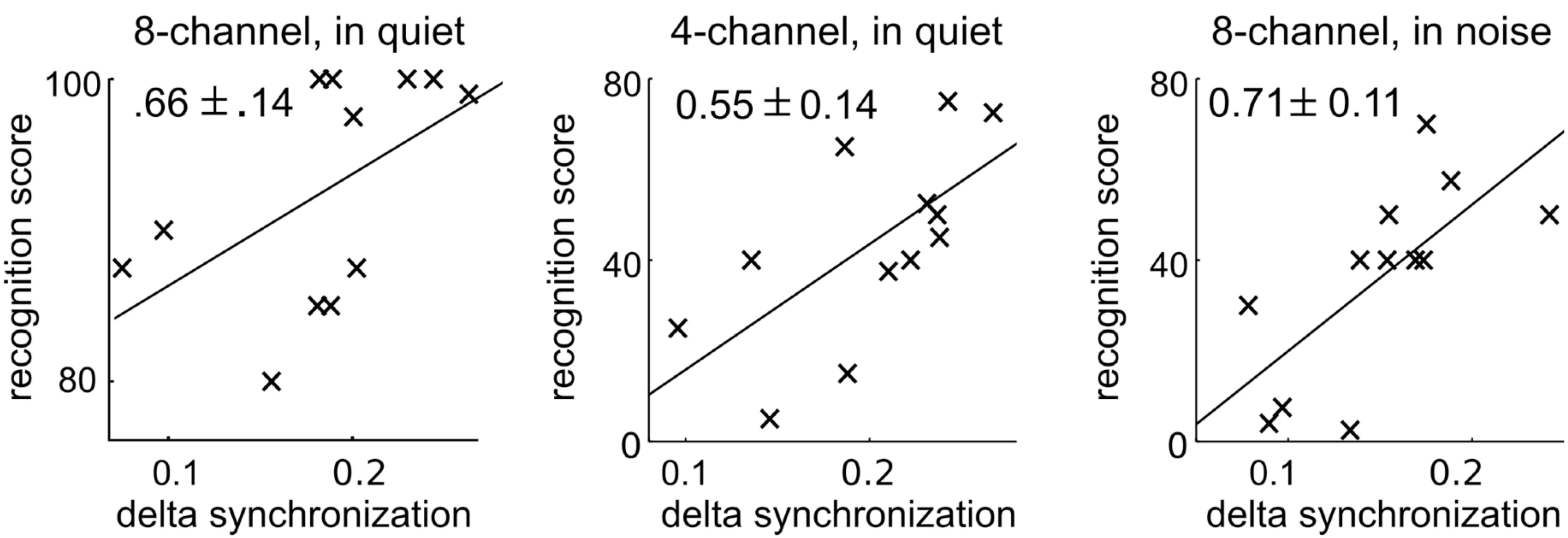
Noise-Vocoded Speech



“in noise” = +3 dB SNR

Ding, Chatterjee & Simon, NeuroImage (2014)

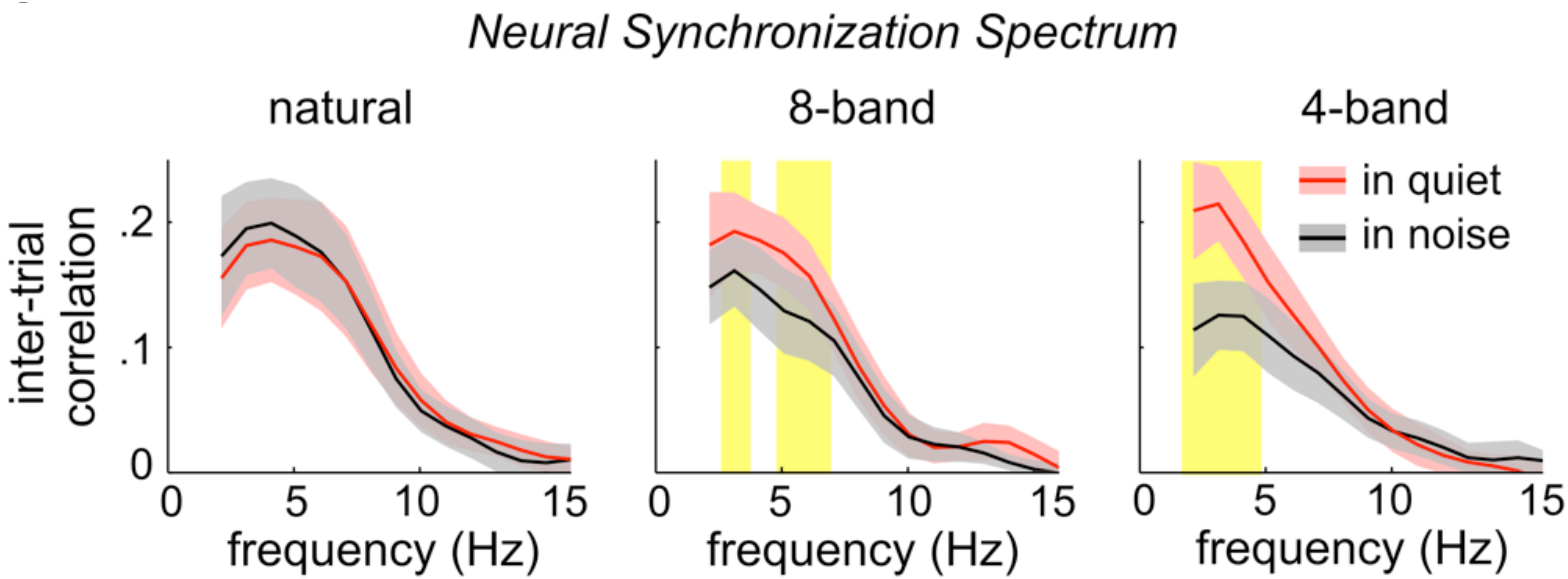
Noise-Vocoded Speech



Intelligibility Reflected only in Delta Band (1– 4 Hz)

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

Cortical Speech Representations

- Neural Representations: Encoding & Decoding
- Linear models: Useful & Robust
- Speech **Envelope** only (as seen in MEG)
- Envelope Rates: ~ 1 - 10 Hz
- Intelligibility linked to lower range of frequencies (Delta)

Multiple Cortical Speech Representations?

Di Liberto, et al. (2015) *Low-Frequency Cortical Entrainment to Speech Reflects Phoneme-Level Processing*

Kayser et al. (2015) *Irregular Speech Rate Dissociates Auditory Cortical Entrainment, Evoked Responses, and Frontal Alpha*

Ding et al. (2015) *Cortical tracking of hierarchical linguistic structures in connected speech*

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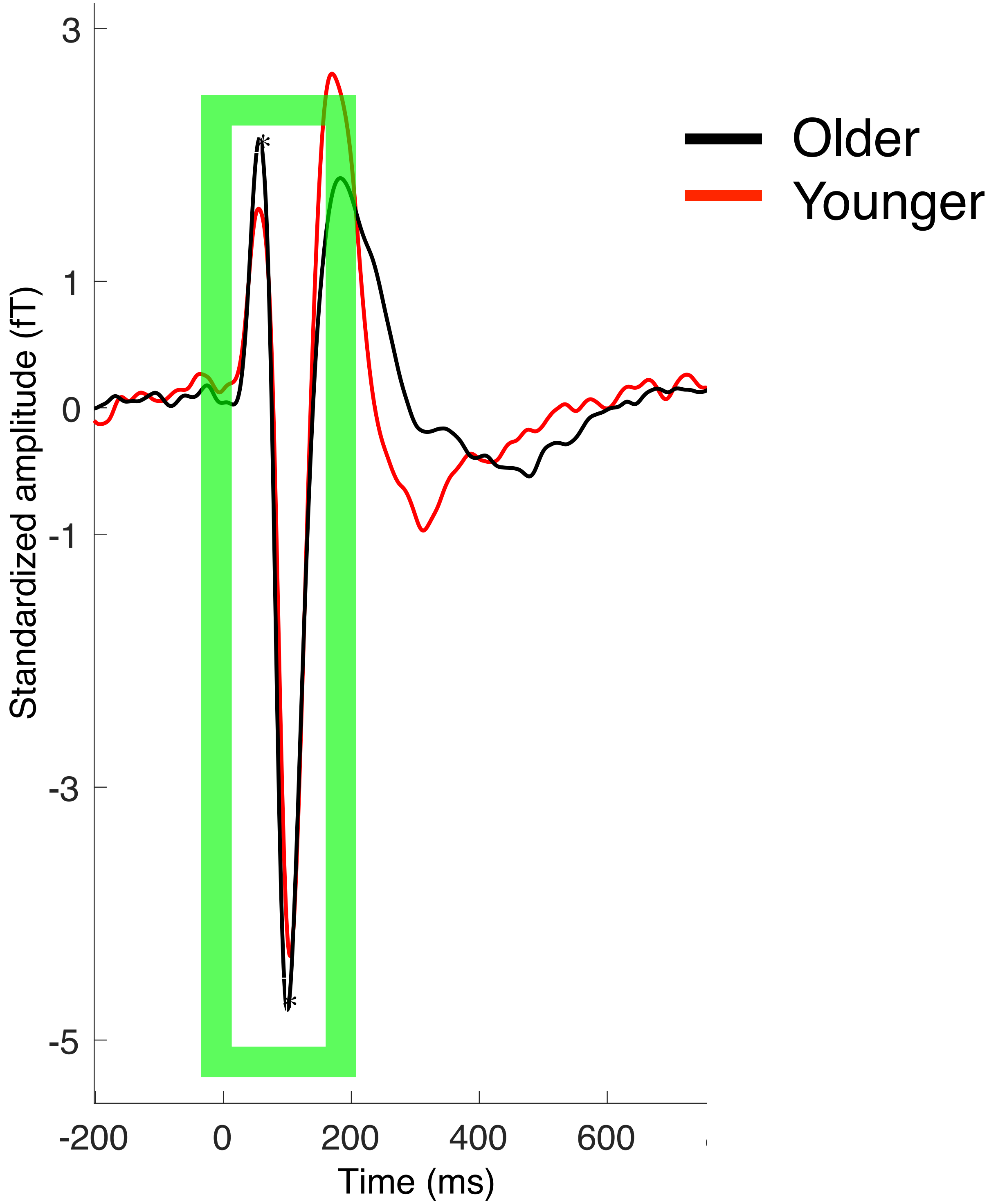
Aging & Auditory Cortex

Average Responses to Pure Tone

Aging & Auditory Cortex



Average Responses to Pure Tone

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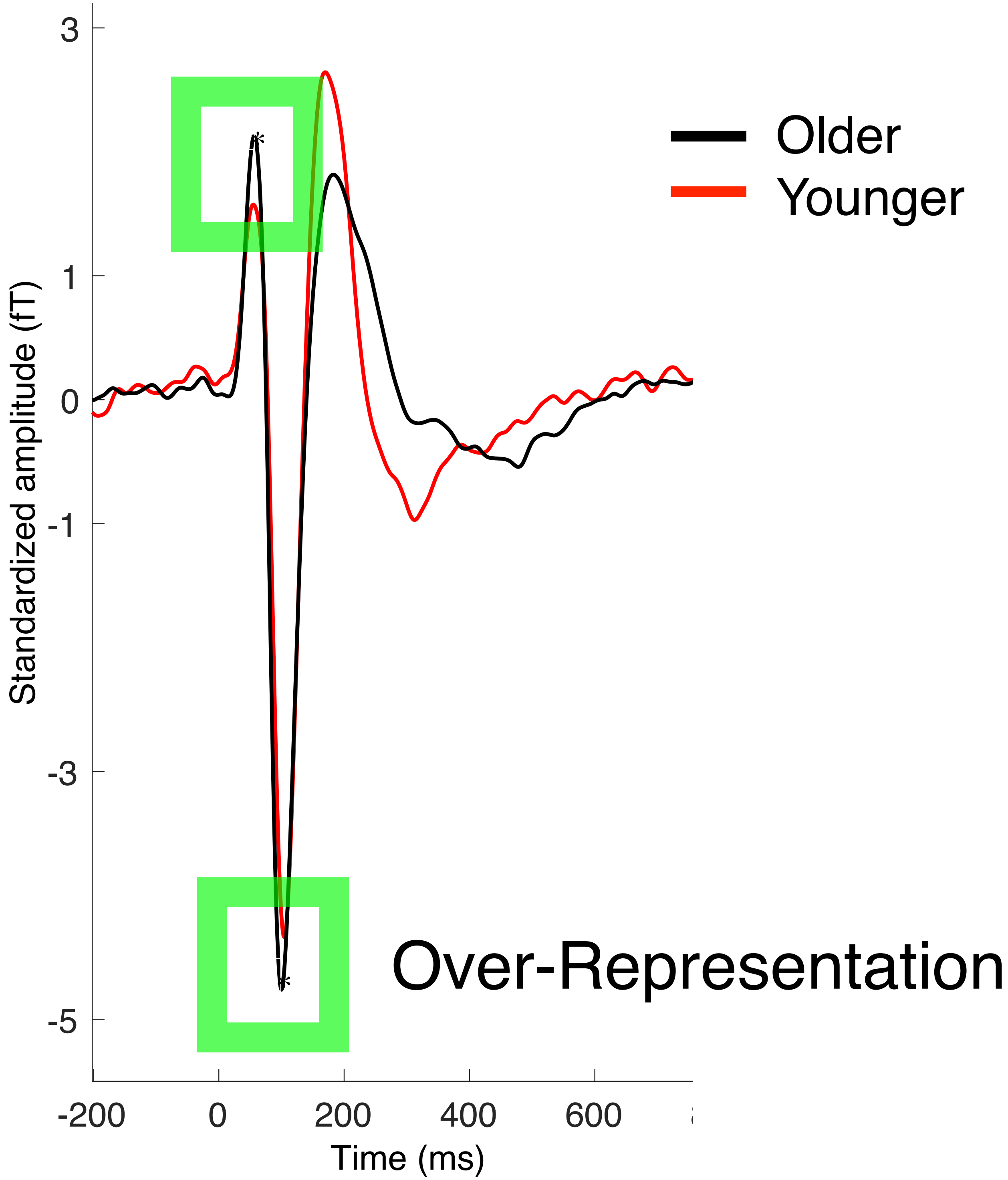

Average Responses to Pure Tone

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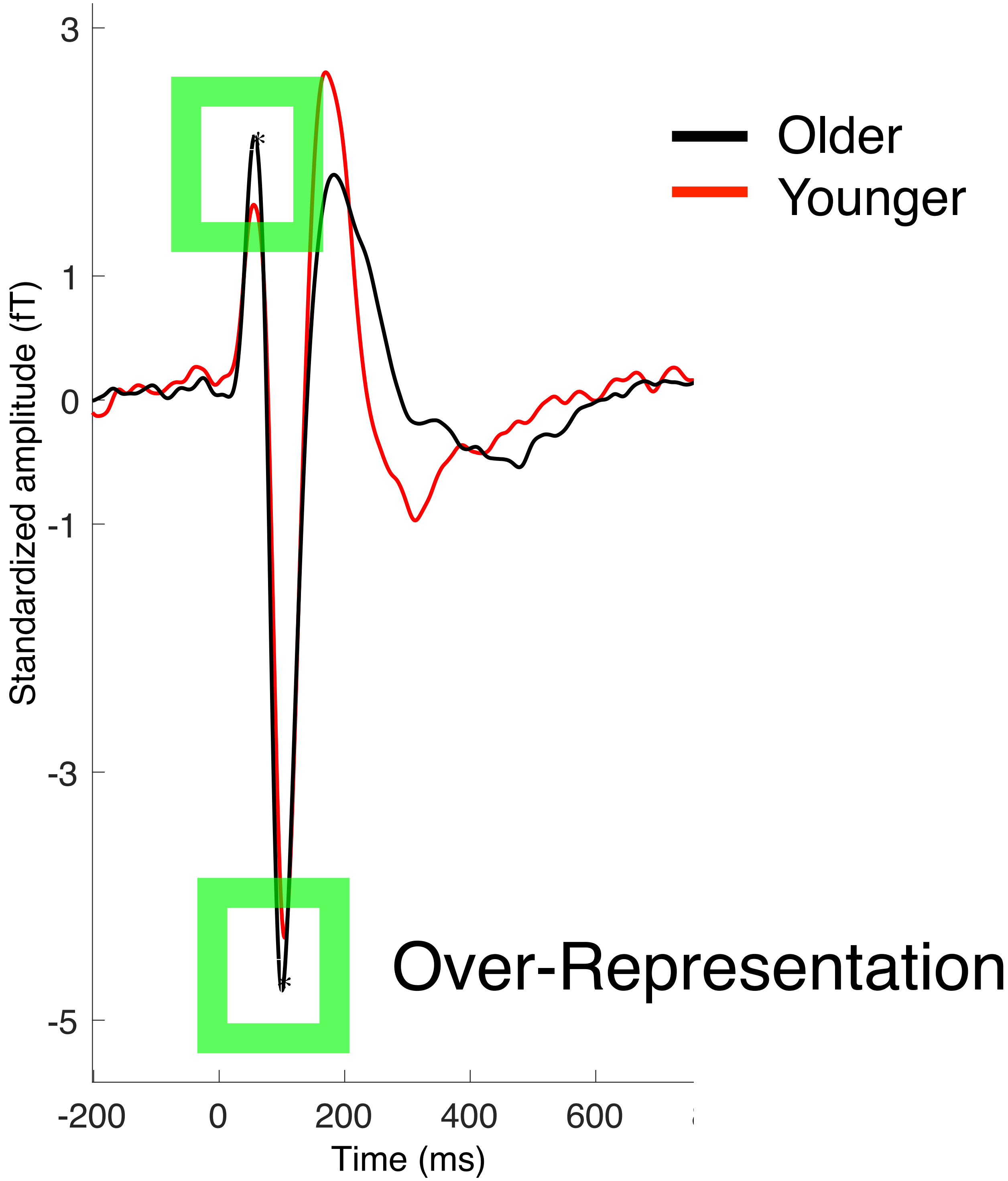

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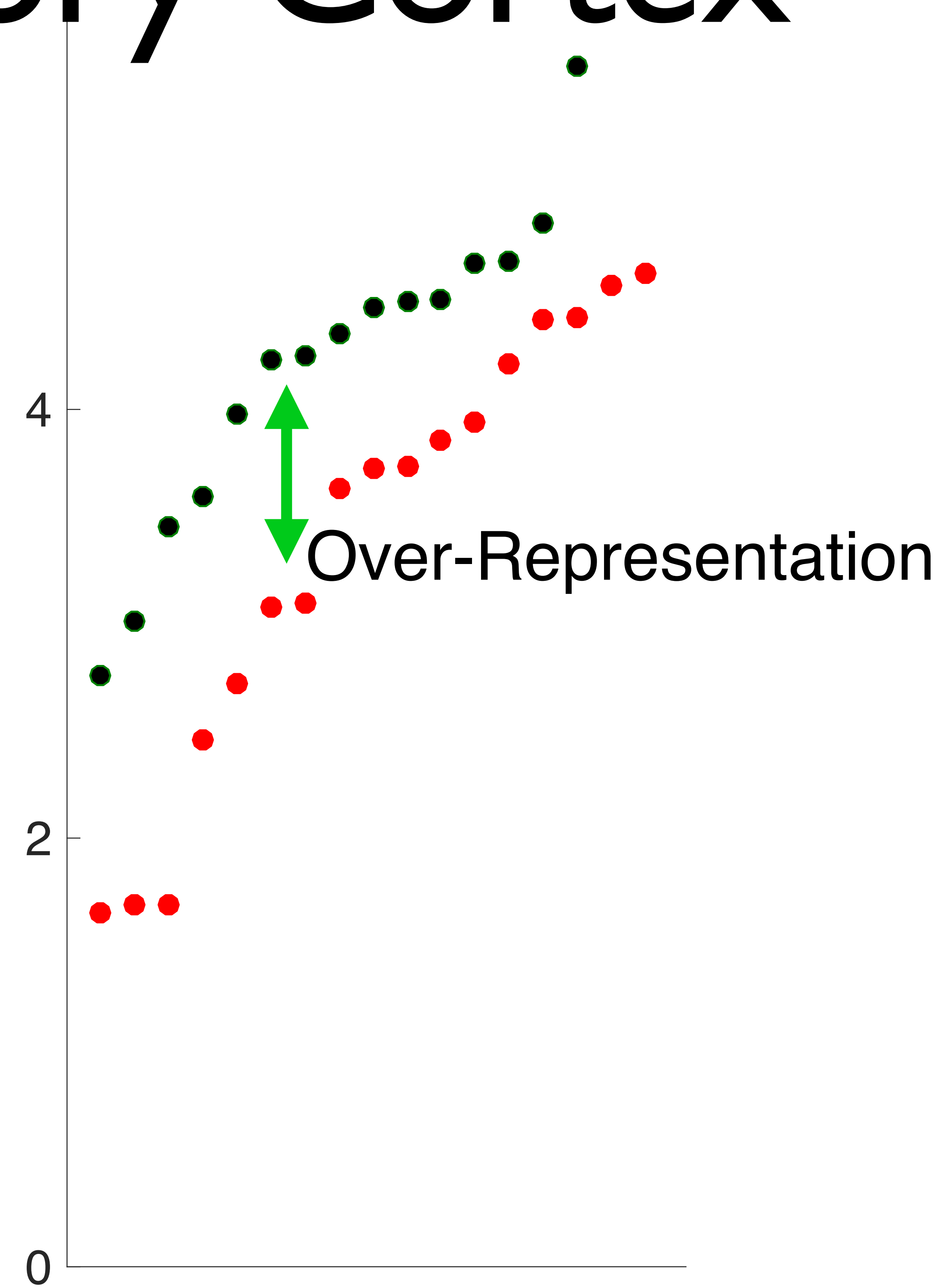
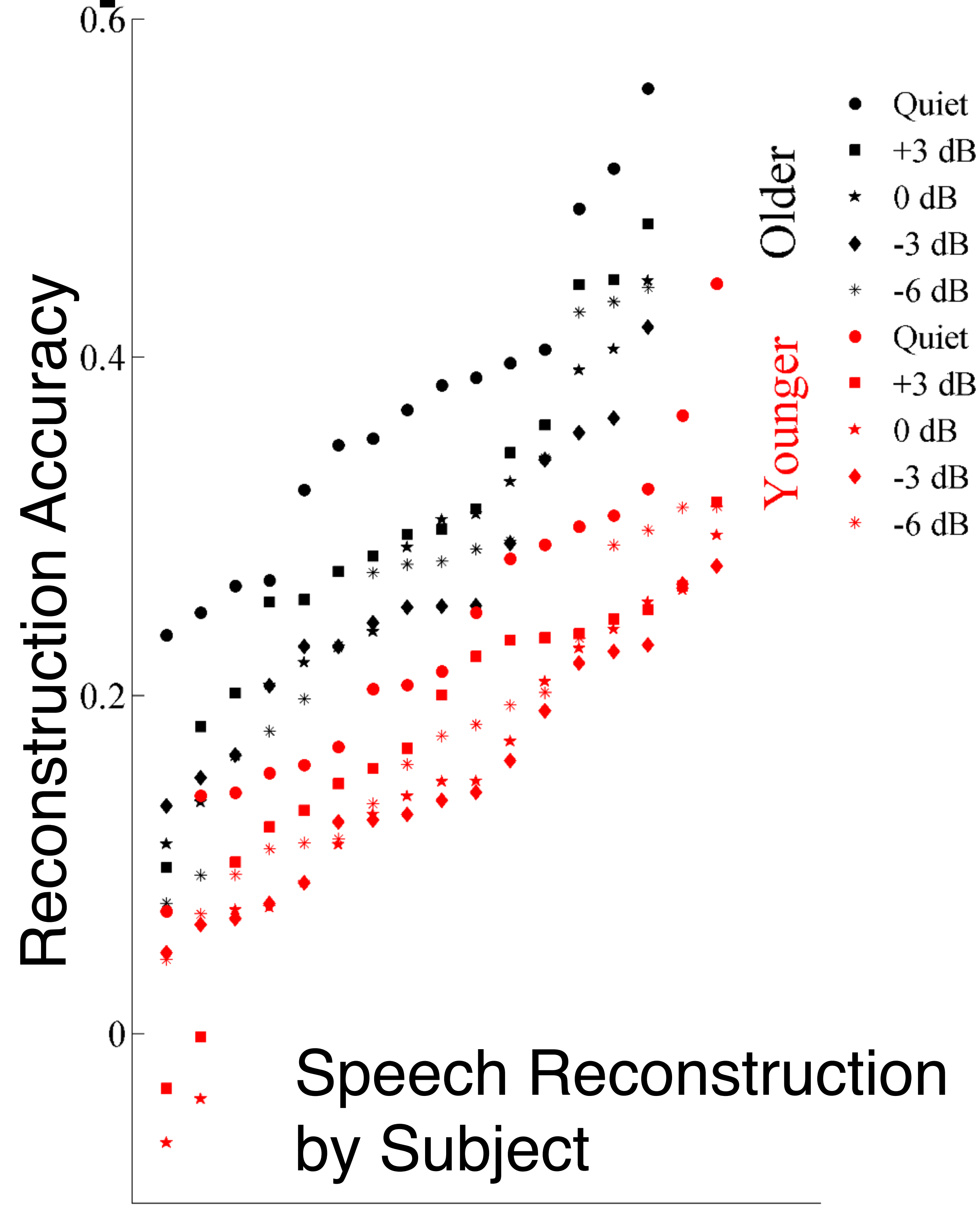


M100 Power by Subject

Speech Over-Representation



Presacco et al., J Neurophysiol (2016a)

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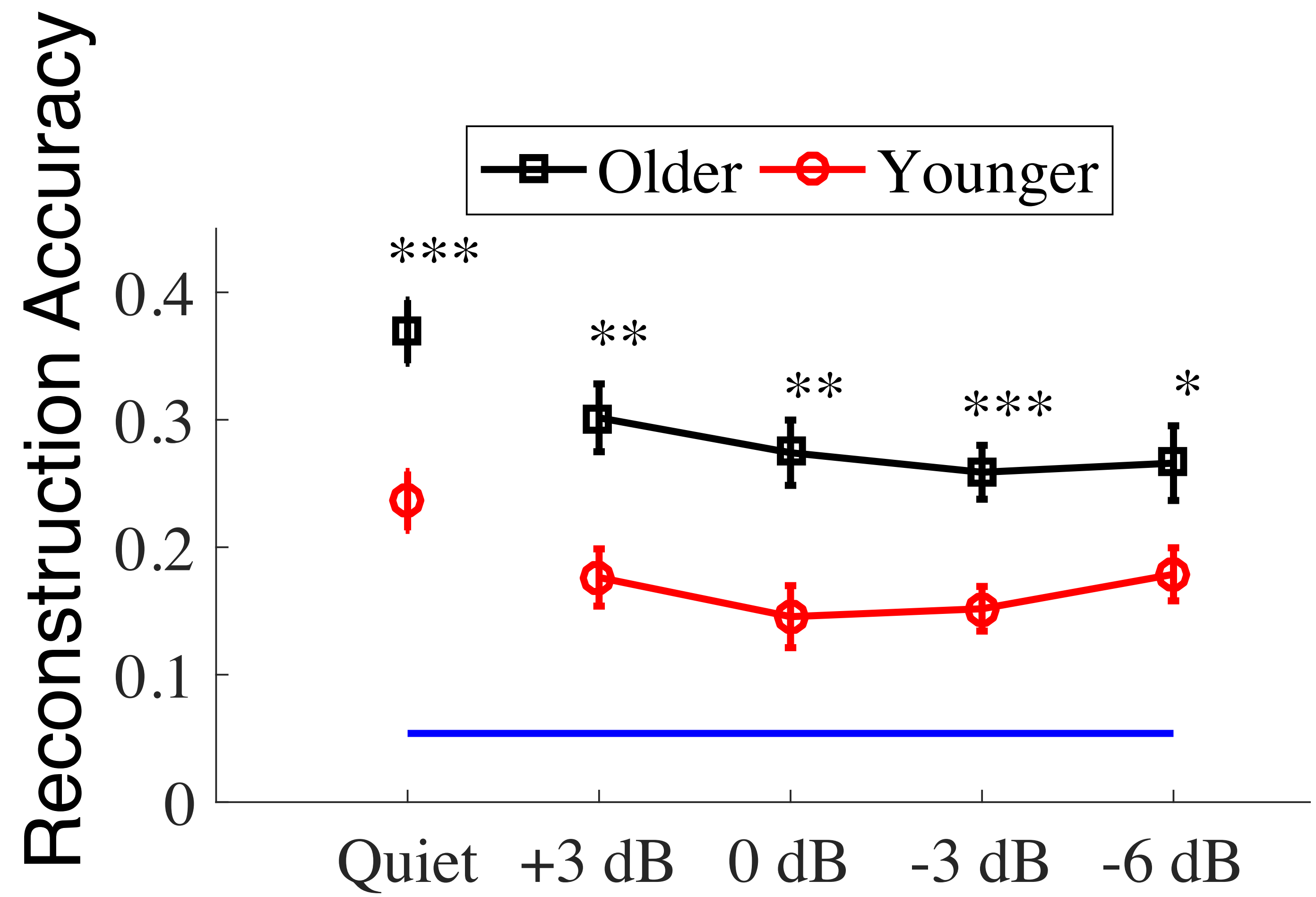
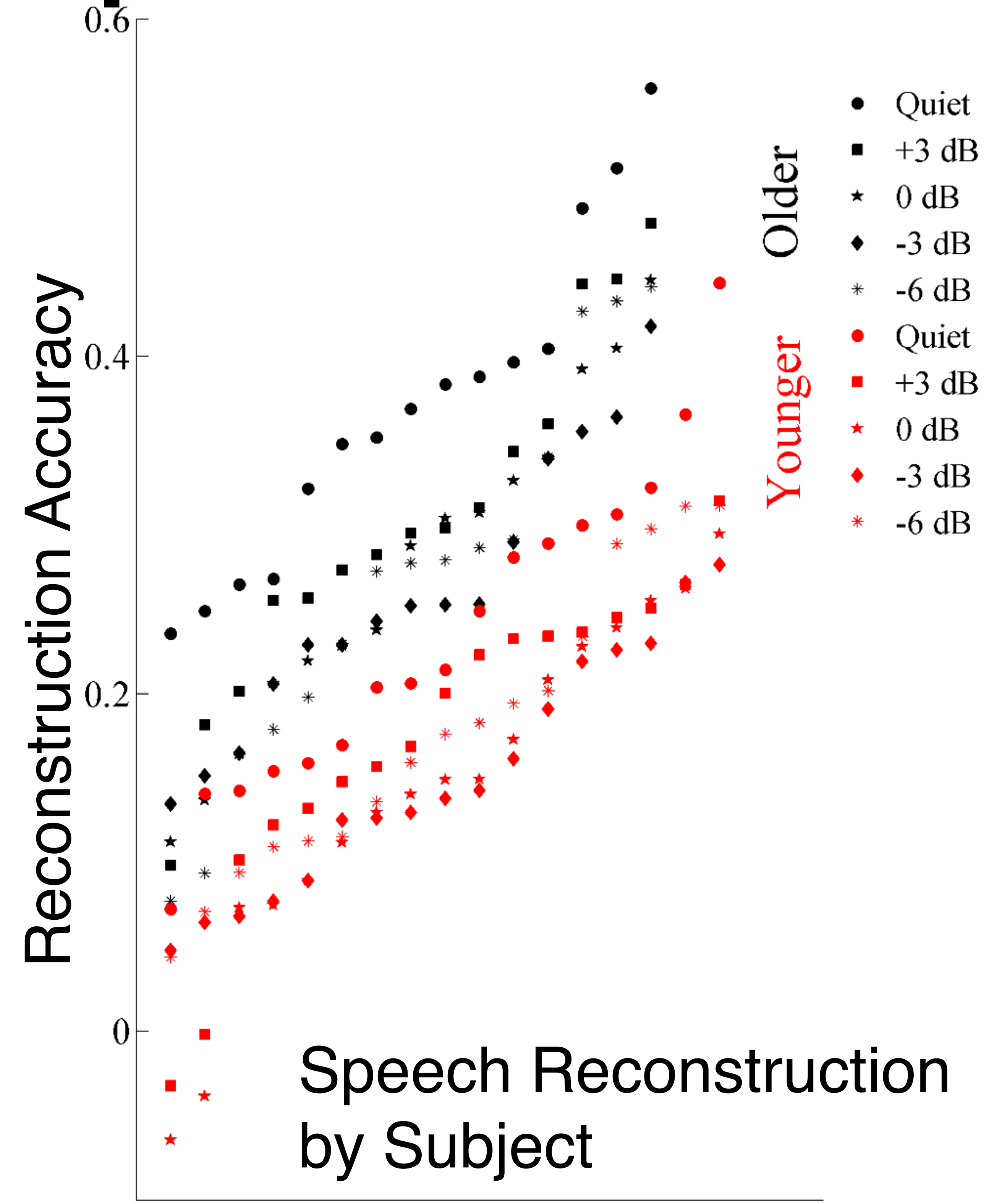


Speech Reconstruction by SNR



Speech Reconstruction by Subject

Presacco et al., J Neurophysiol (2016a)

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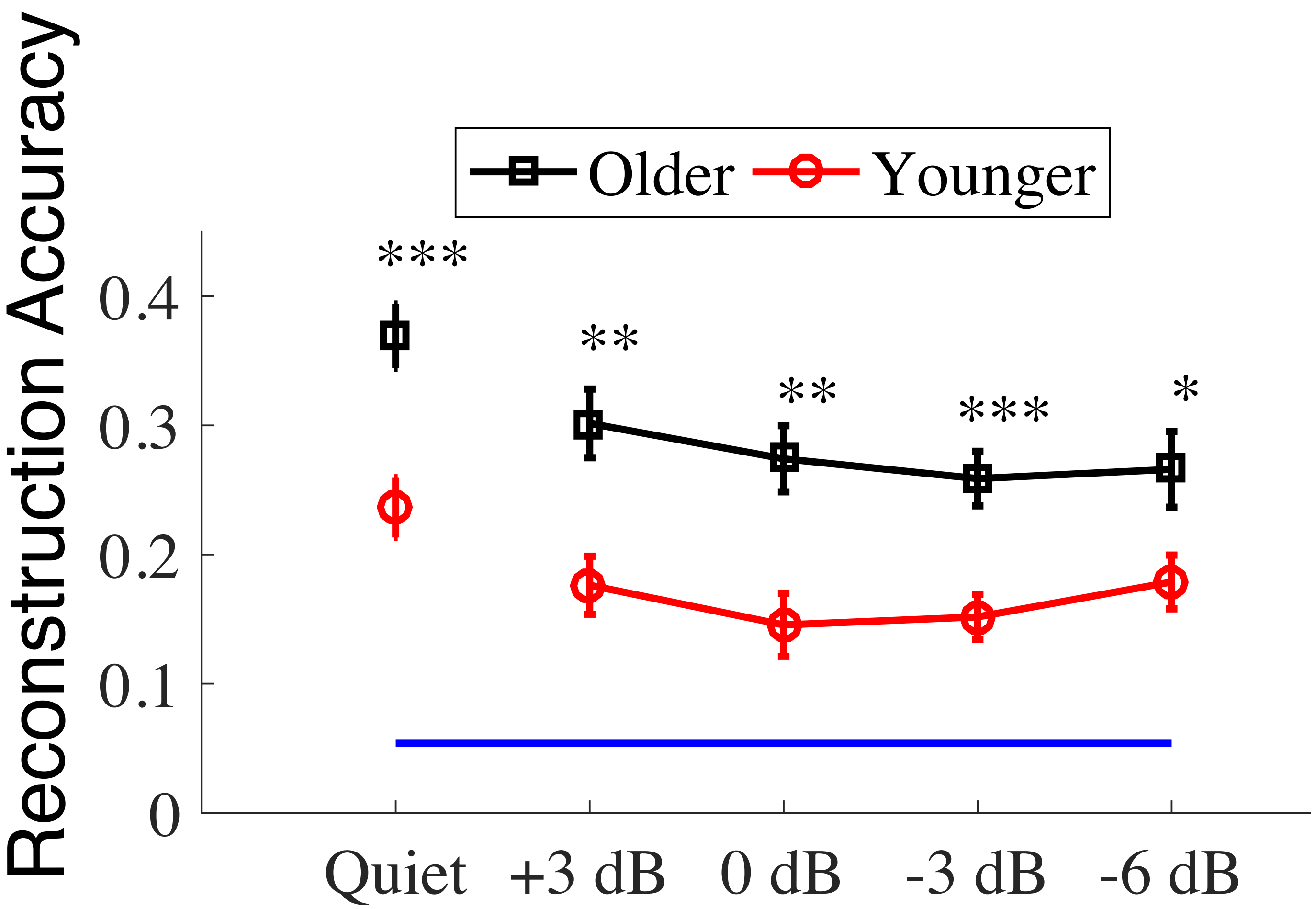
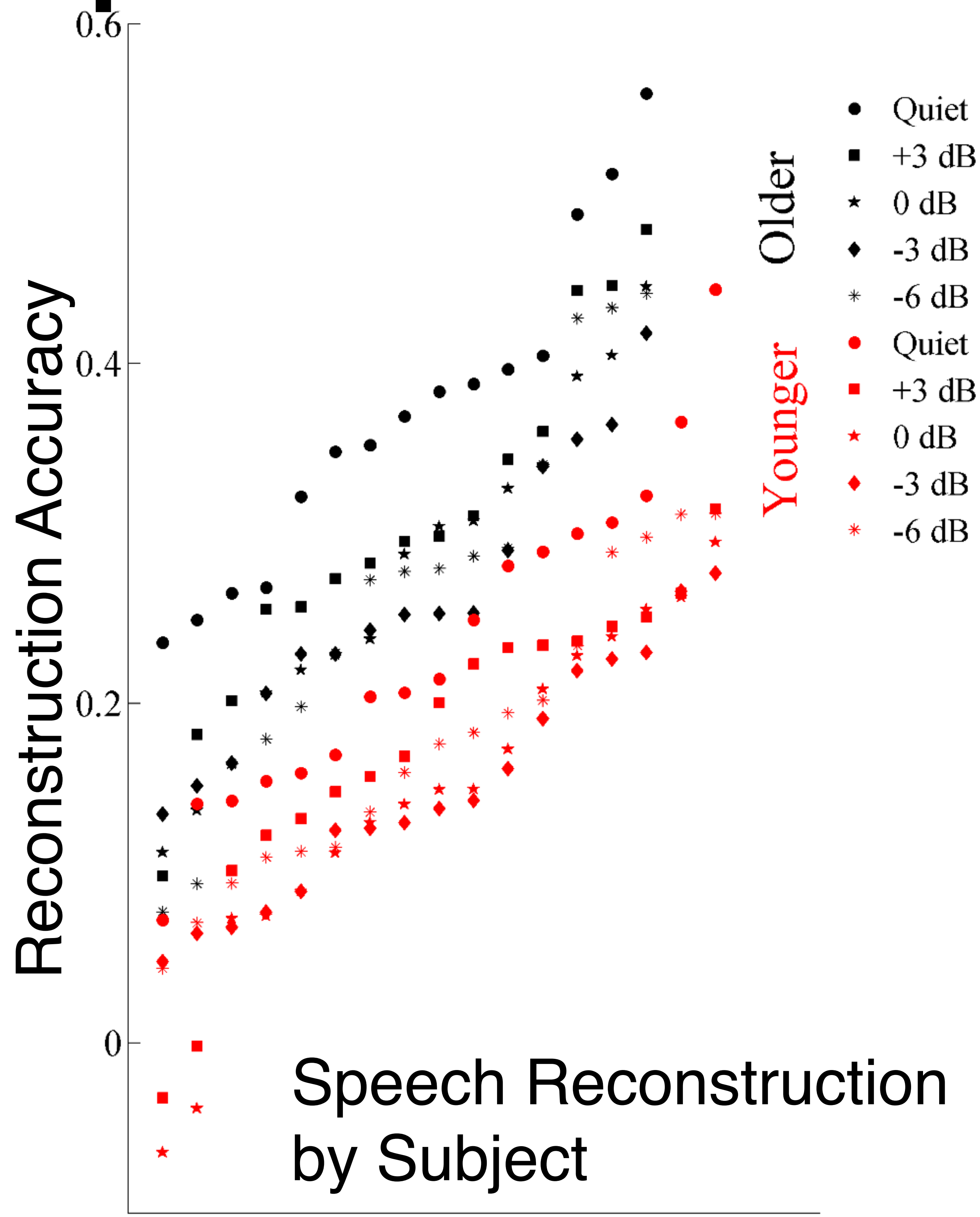


Speech Reconstruction by SNR

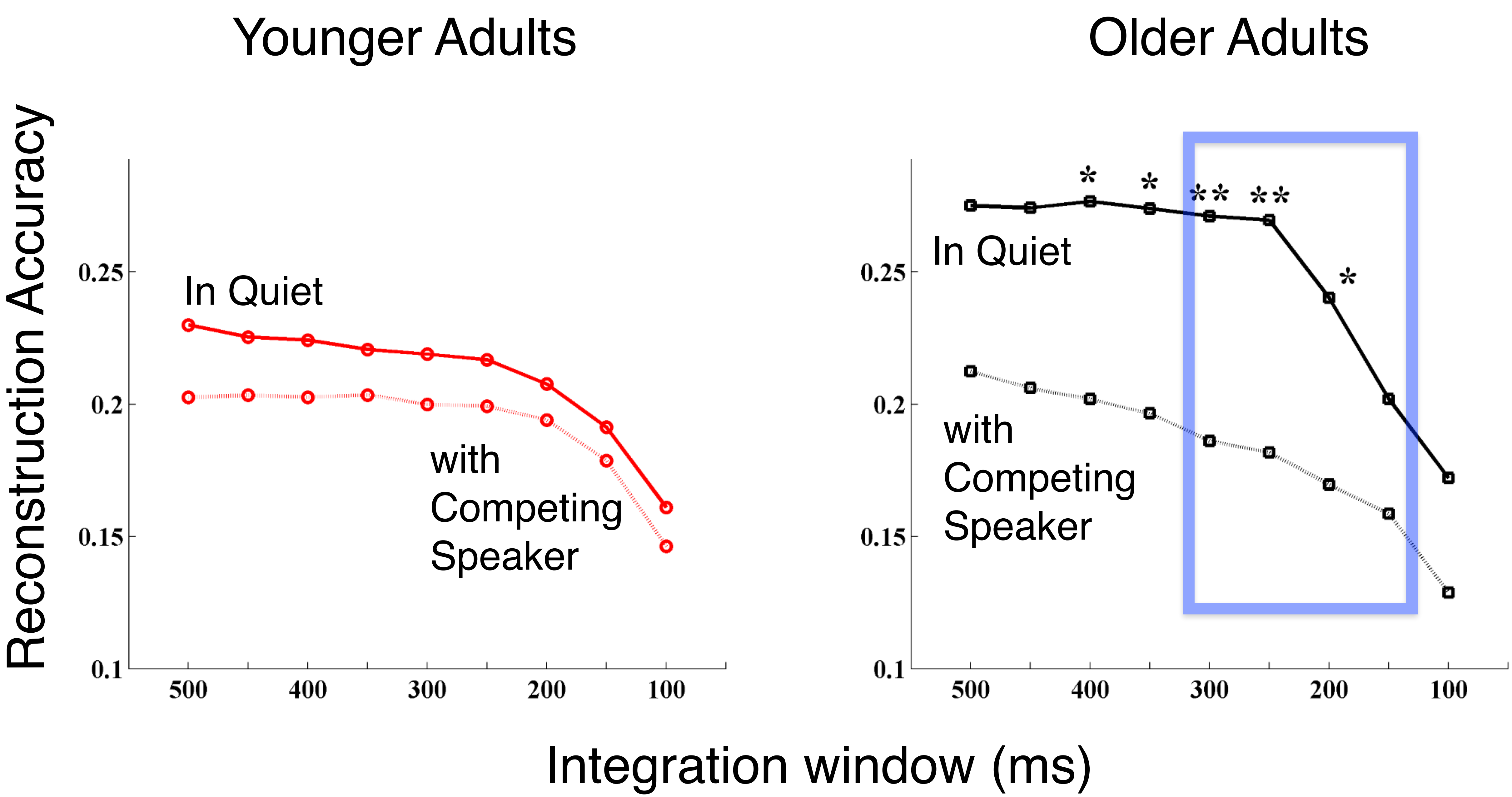


Speech Reconstruction by Subject

Older listeners show overrepresentation in reconstruction(!)

Presacco et al., J Neurophysiol (2016a)

Aging & Integration Time



Presacco et al., J Neurophysiol (2016a)

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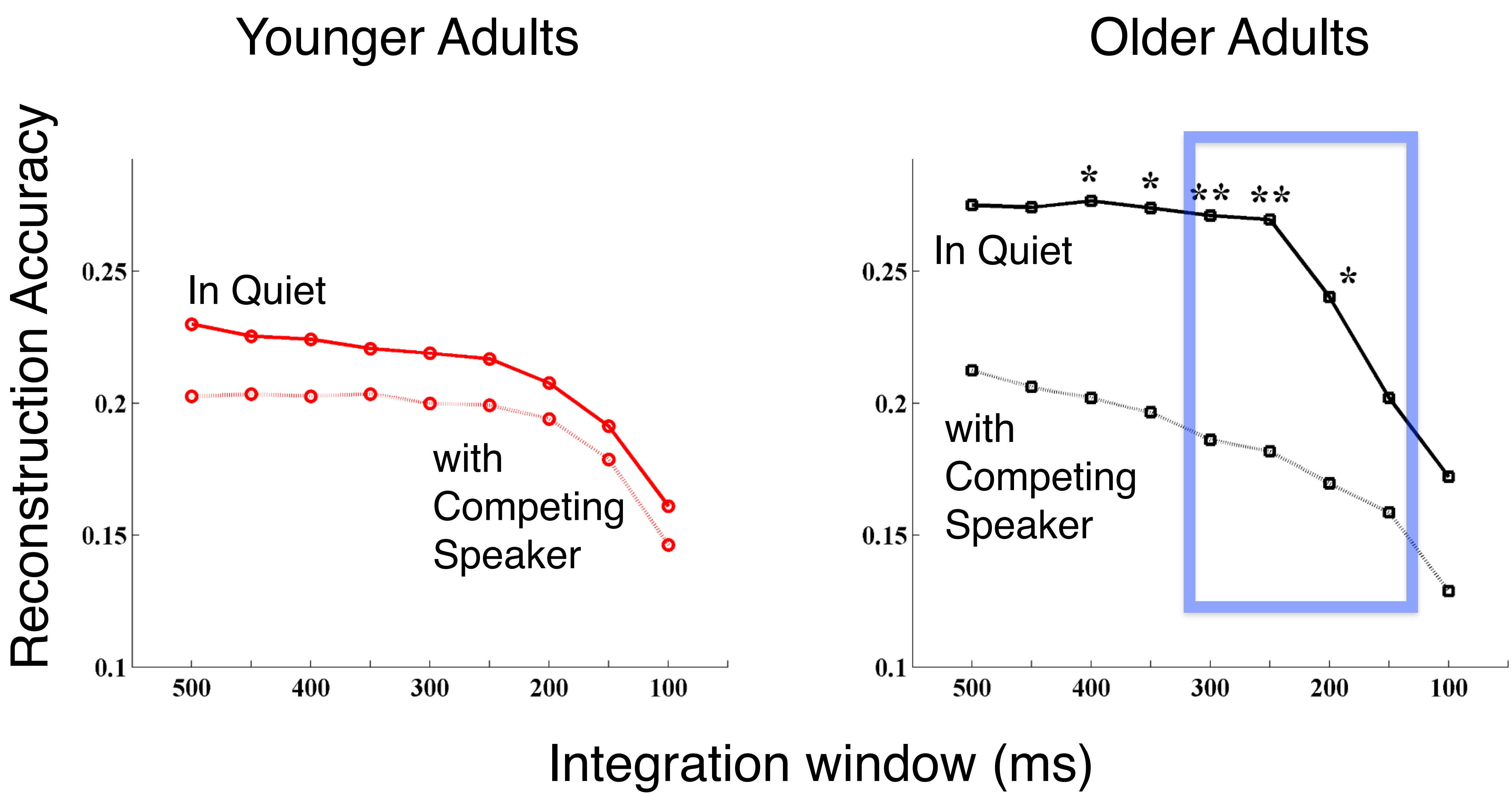
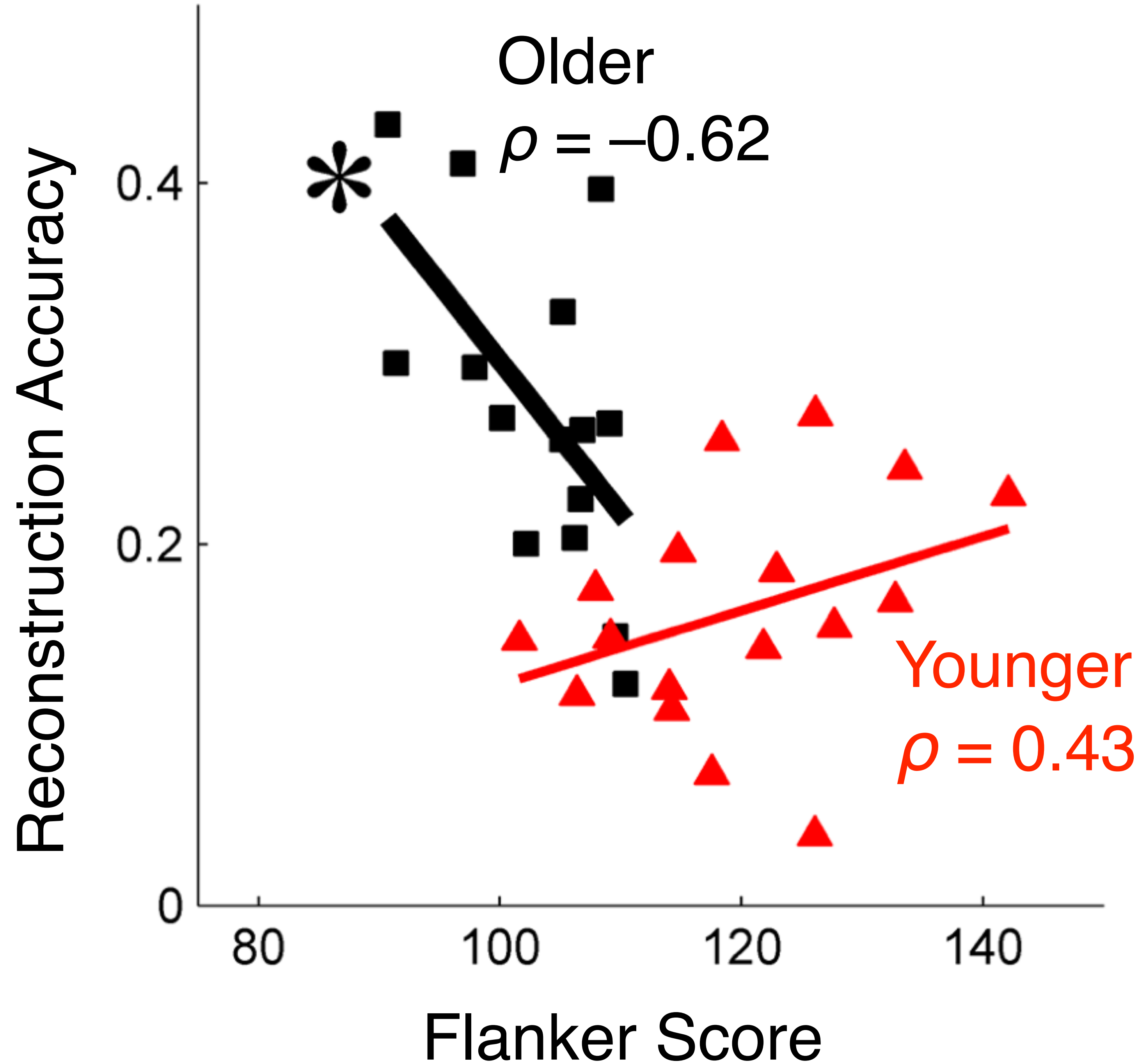


Older listeners require more time for stimulus reconstruction in noise

Presacco et al., J Neurophysiol (2016a)

Neural vs Inhibitory Control



Presacco et al., J Neurophysiol (2016b)

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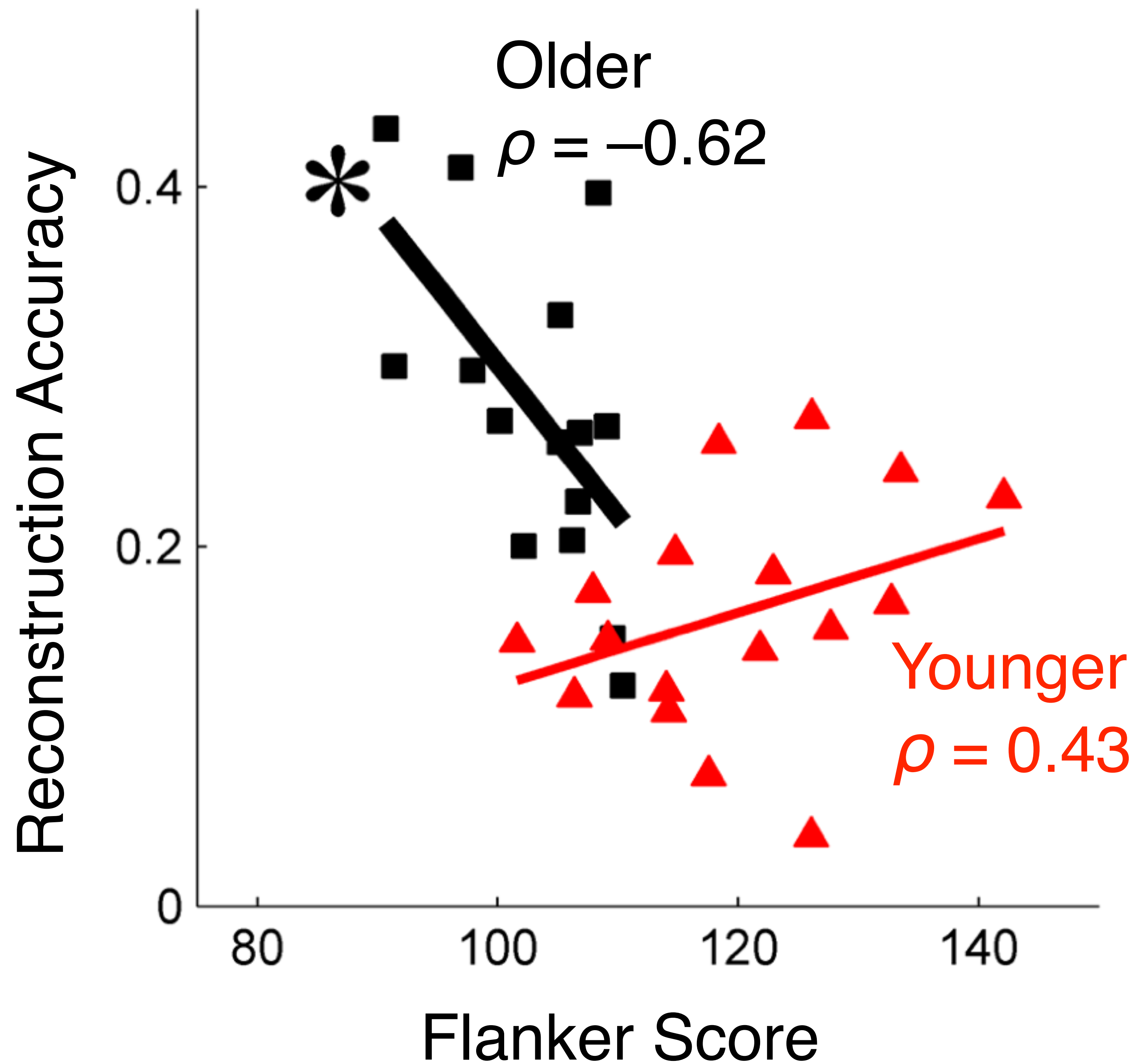
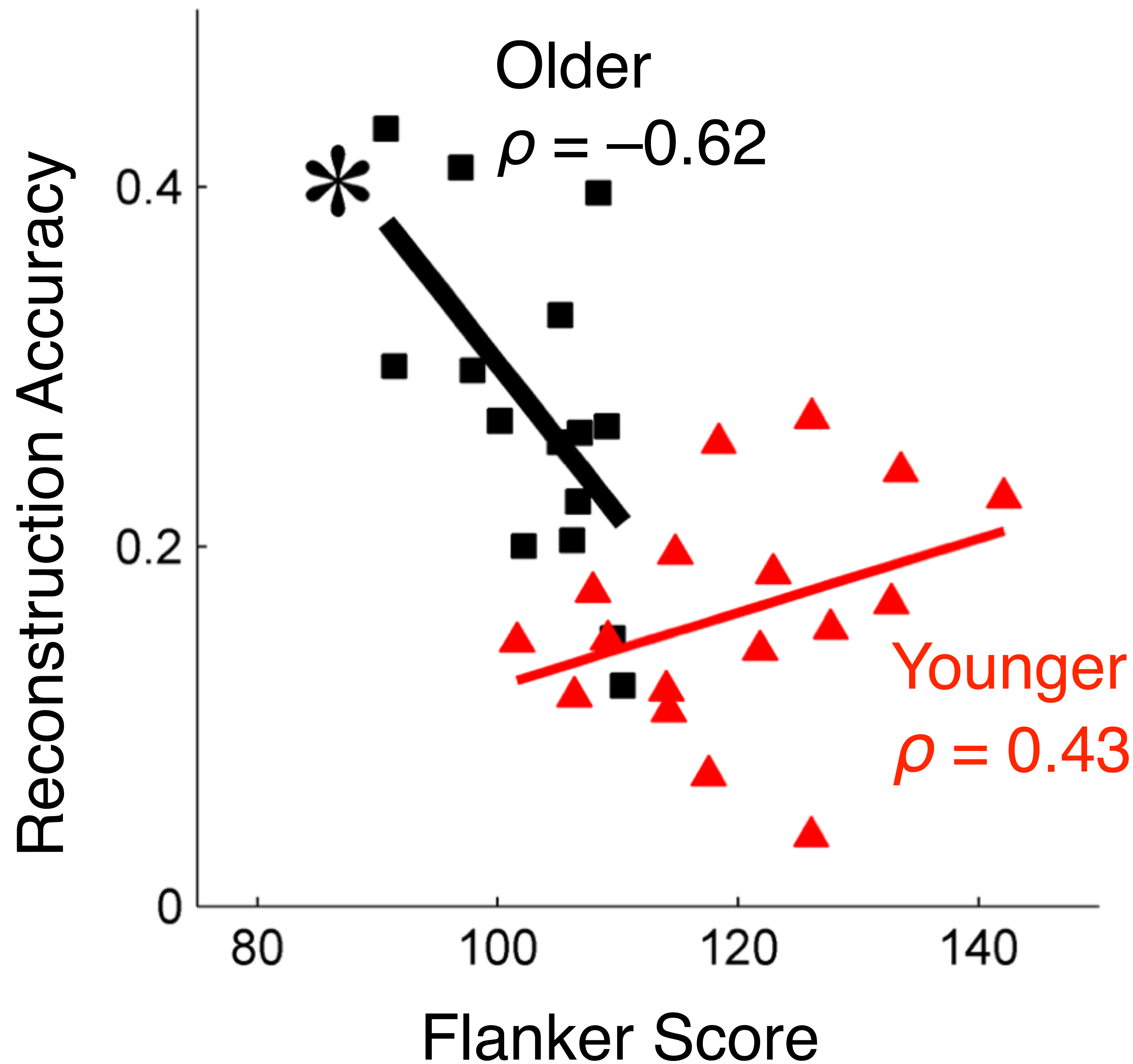


Older listeners are worse at suppressing interference

Presacco et al., J Neurophysiol (2016b)

Neural vs Inhibitory Control



Older listeners are worse at suppressing interference

Older over-representation in auditory cortex correlates with lack of interference suppression

Presacco et al., J Neurophysiol (2016b)

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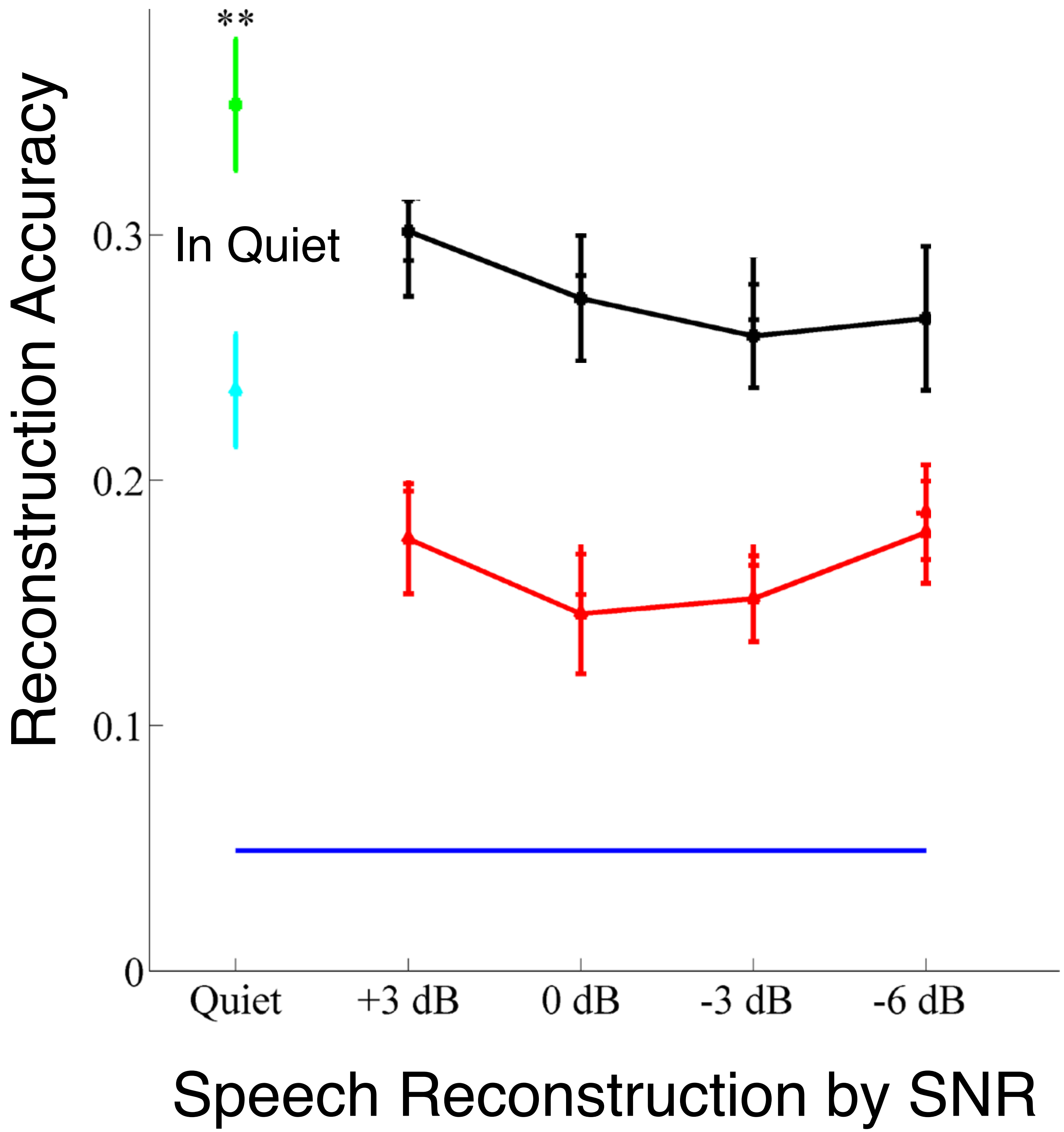
High Level Interference Effects



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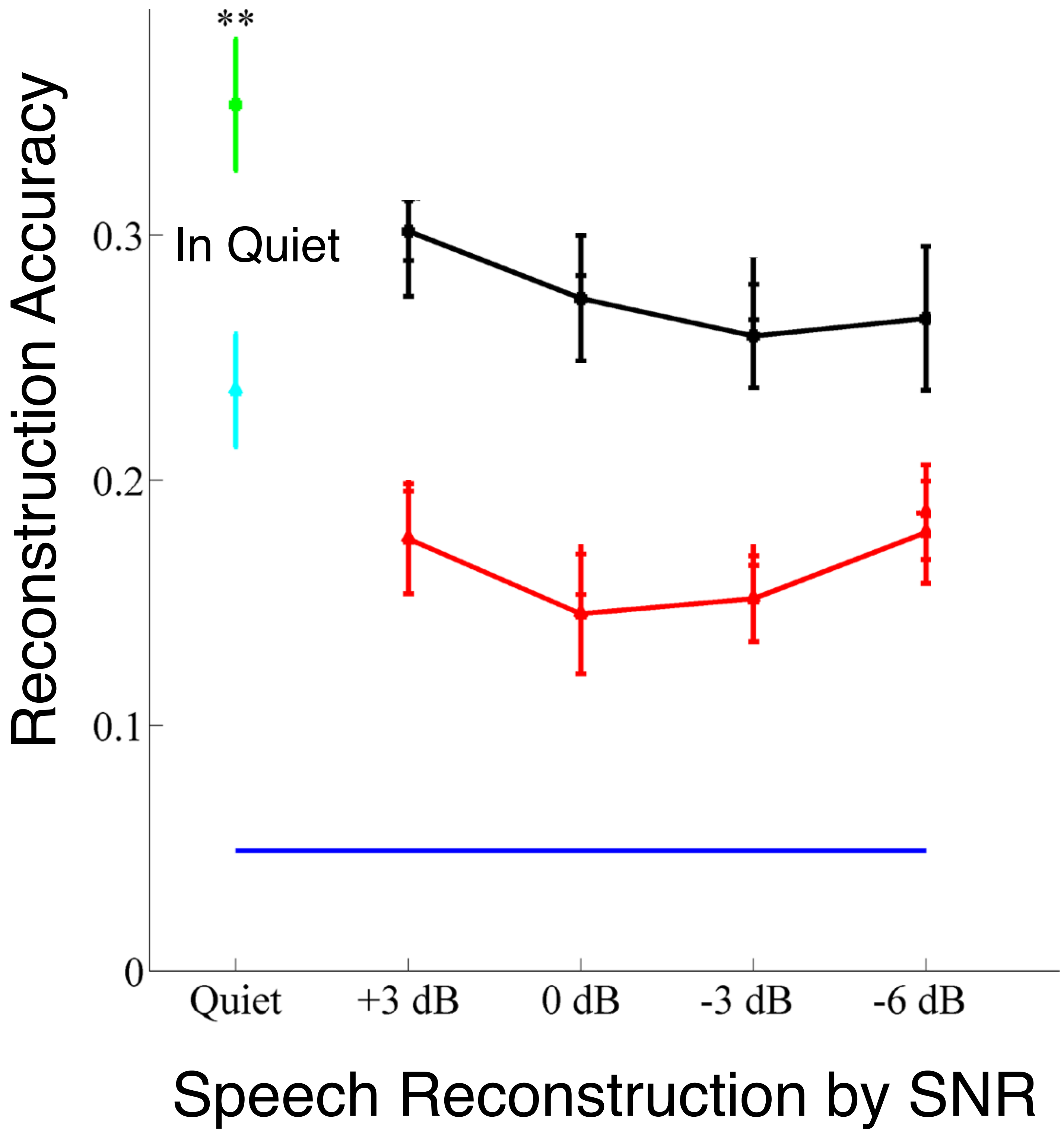

- **Unfamiliarity of Background**
  - Boosts Intelligibility of Attended Speech

Presacco et al., J Neurophysiol (2016b)

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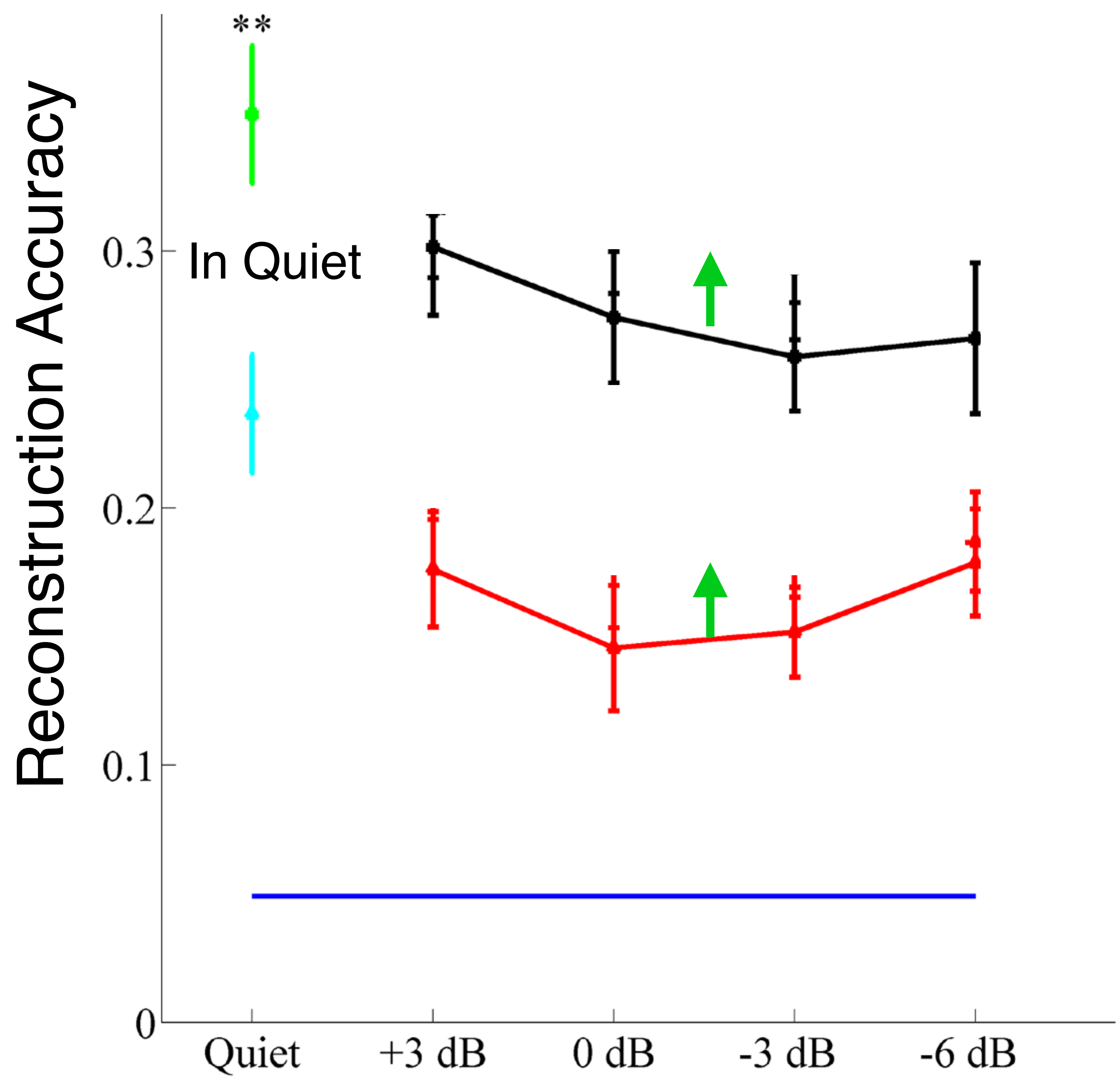

Speech Reconstruction by SNR

- **Unfamiliarity of Background**
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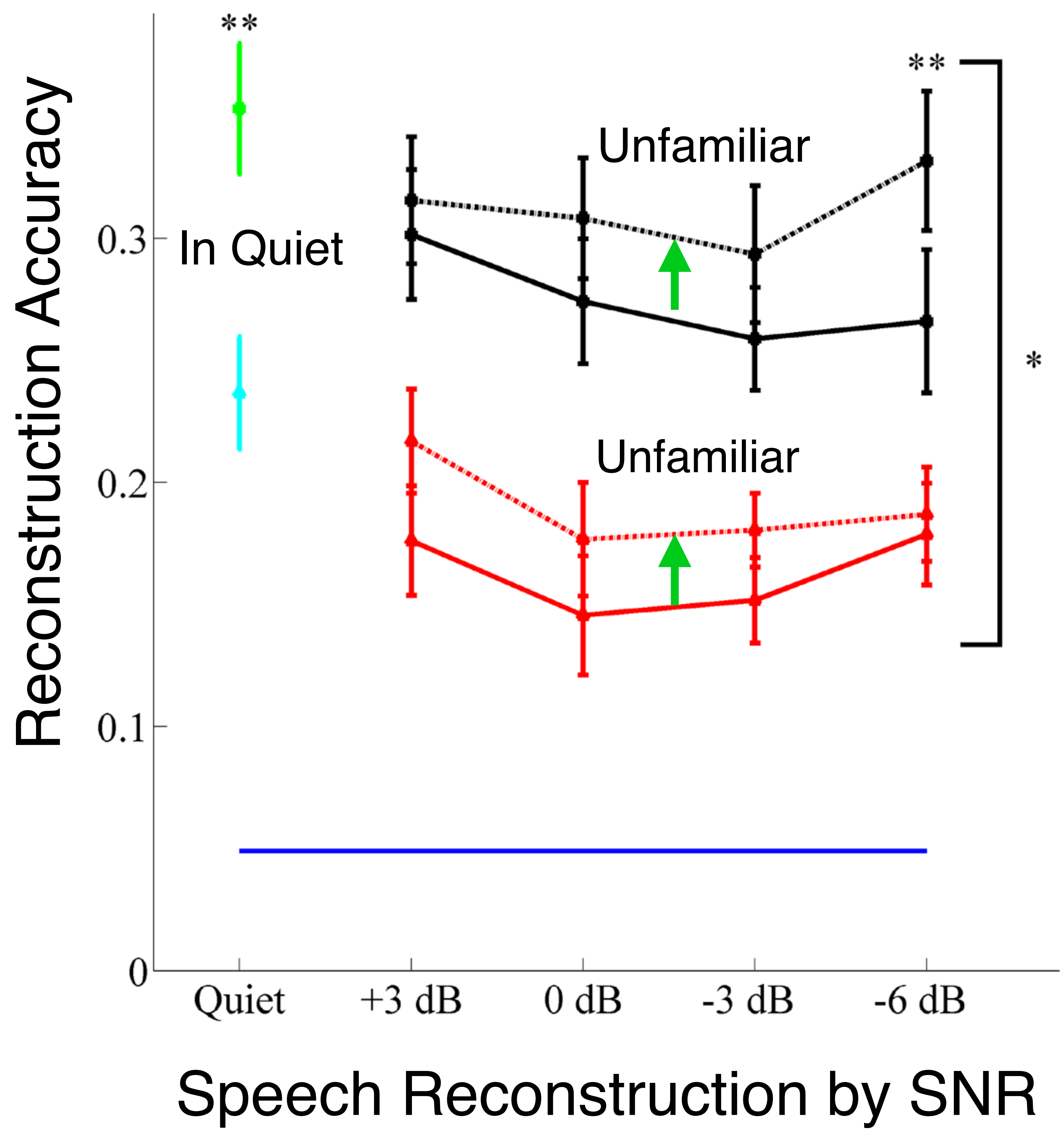
Presacco et al., J Neurophysiol (2016b)

High Level Interference Effects



- **Unfamiliarity of Background**
  - Boosts Intelligibility of Attended Speech
  - *Also Boosts Cortical Reconstruction of Attended Speech*

Presacco et al., J Neurophysiol (2016b)

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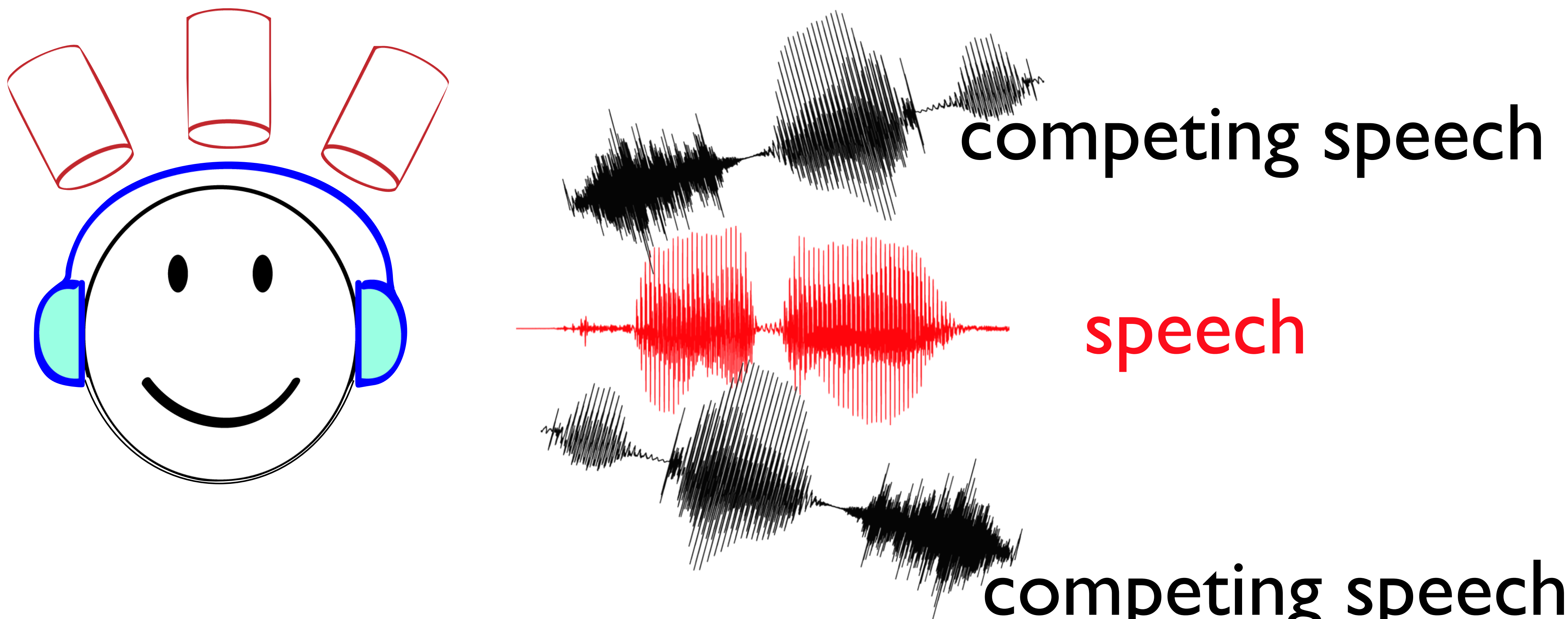
Three Competing Speakers



Puvvada & Simon, bioRχiv (2017)

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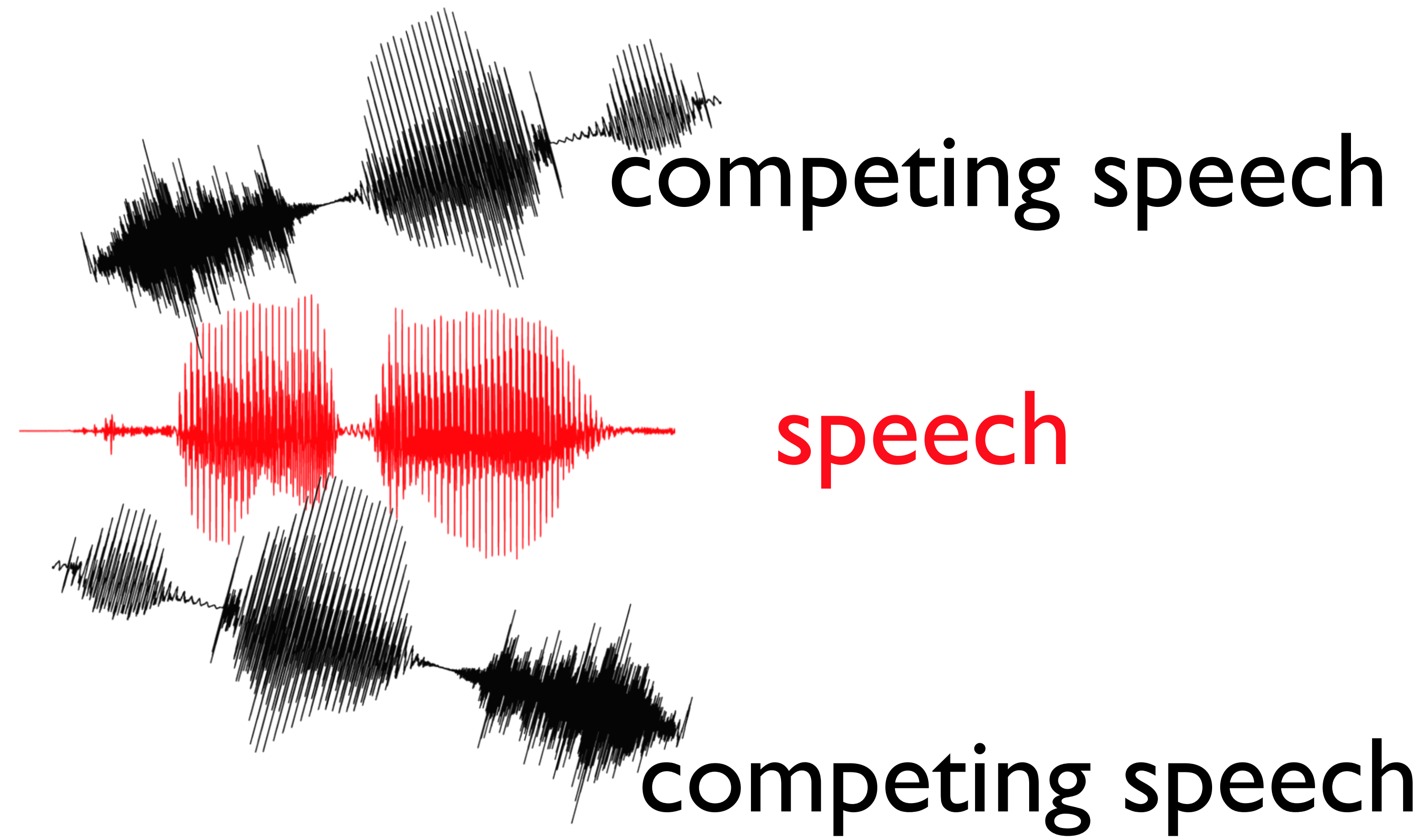

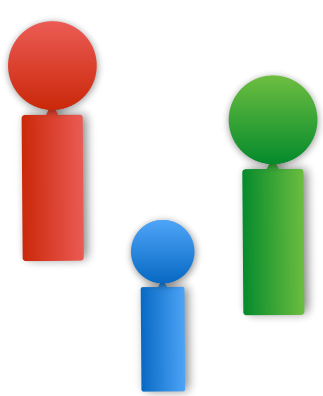

Puvvada & Simon, bioRχiv (2017)

Idea

- Latency as Proxy for Cortical Area(s)
  - Earlier Latency Responses from Heschl's Gyrus
  - Later Latency Responses from Planum Temporale (and beyond)
- Not just for Response but also Reconstruction
  - Earlier Integration Window Reconstructs from HG
  - Later Integration Window Reconstructs from PT (and beyond)

Idea

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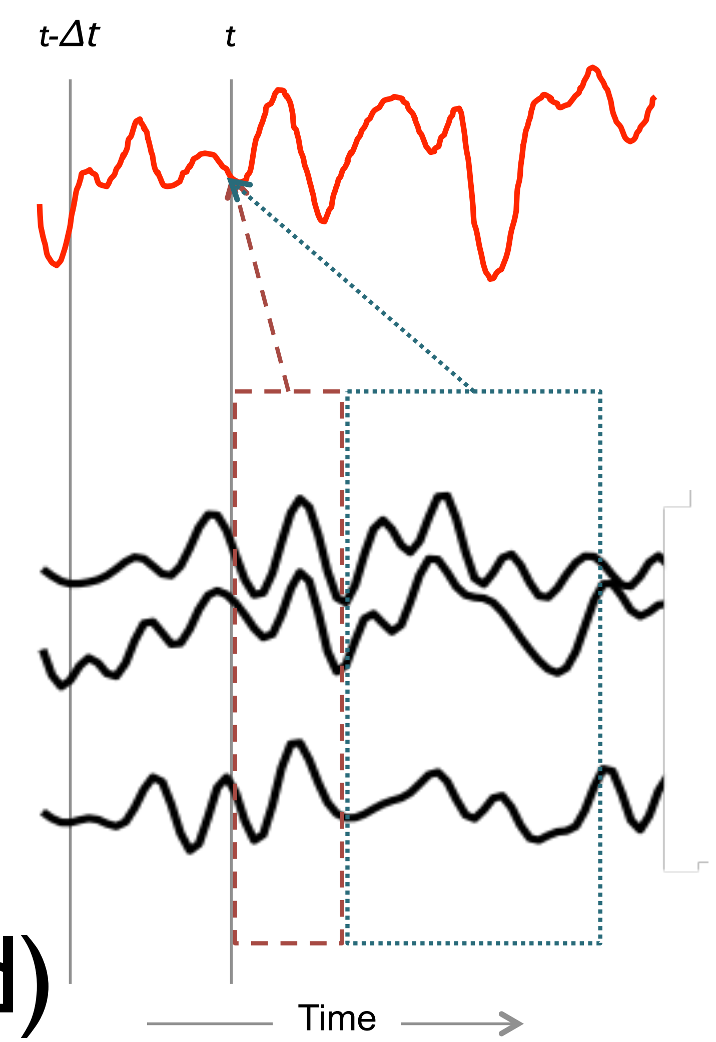
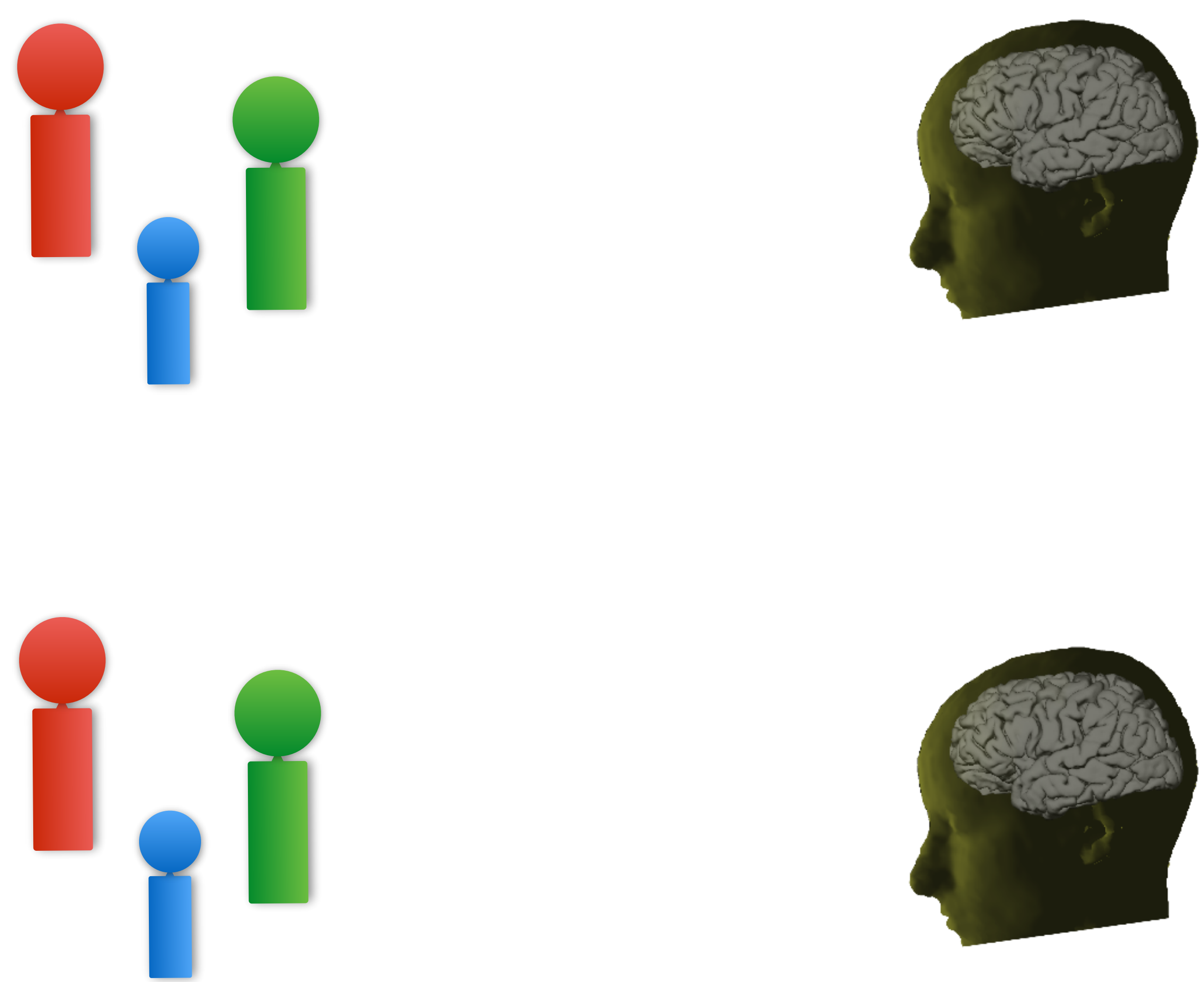
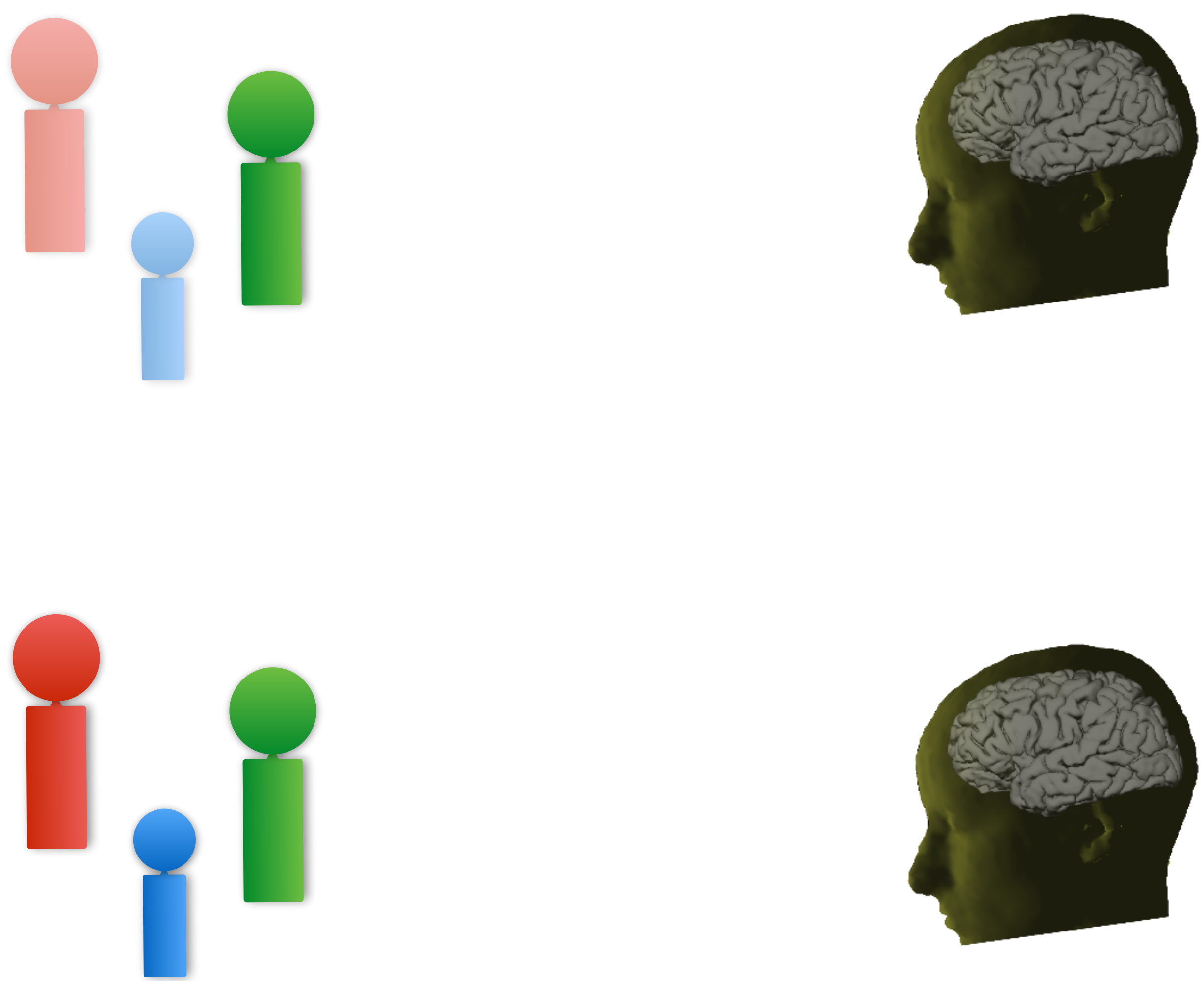


Where in Cortex is there a Segregated Foreground?



Puvvada & Simon, bioRχiv (2017)

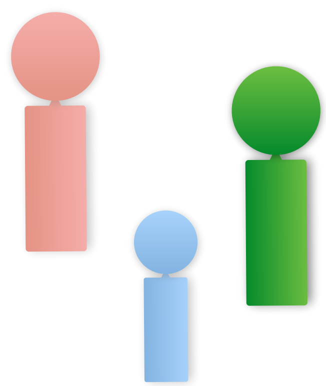
Where <u>in Cortex</u> is there a Segregated Foreground?

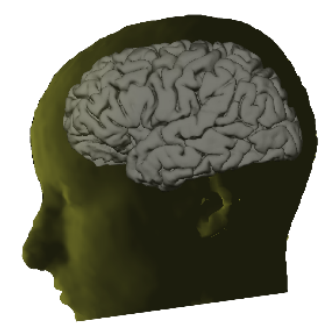


Puvvada & Simon, bioRχiv (2017)

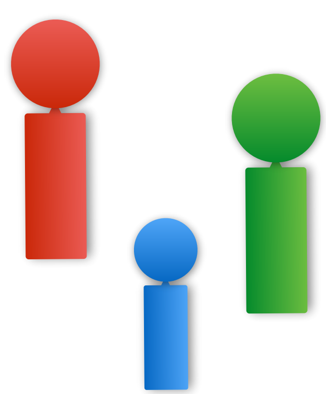
Where in Cortex is there a Segregated Foreground?

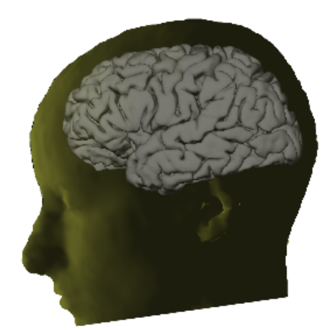
Late?





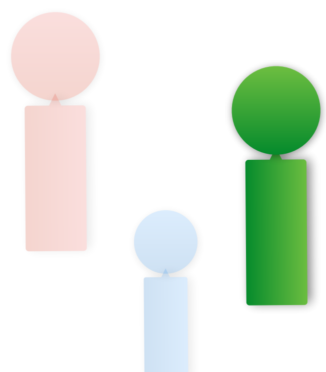
Early?



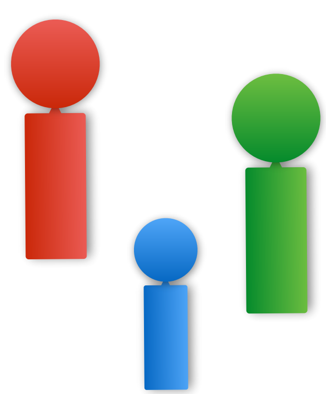


Puvvada & Simon, bioRχiv (2017)

Late Cortical Reconstruction



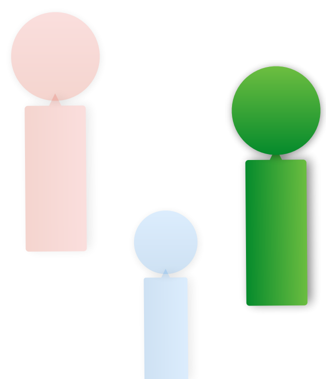
vs.



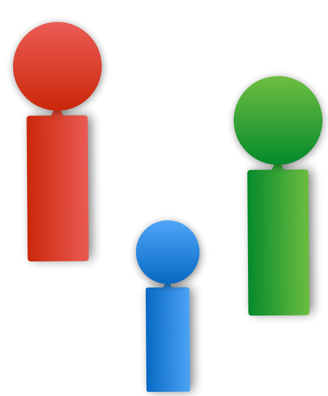
Puvvada & Simon, bioRχiv (2017)

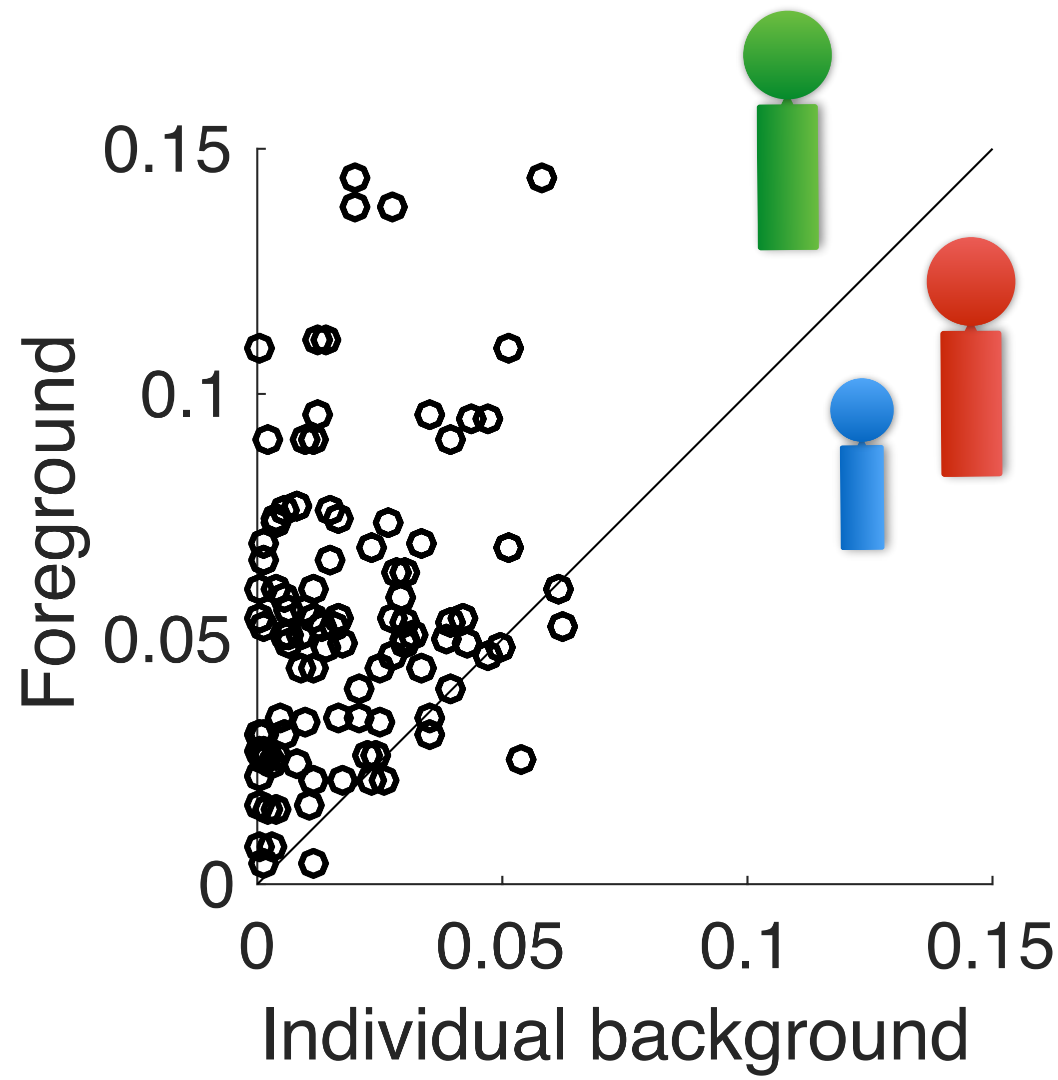
Integration Window over Late Times Only

Late Cortical Reconstruction



vs.



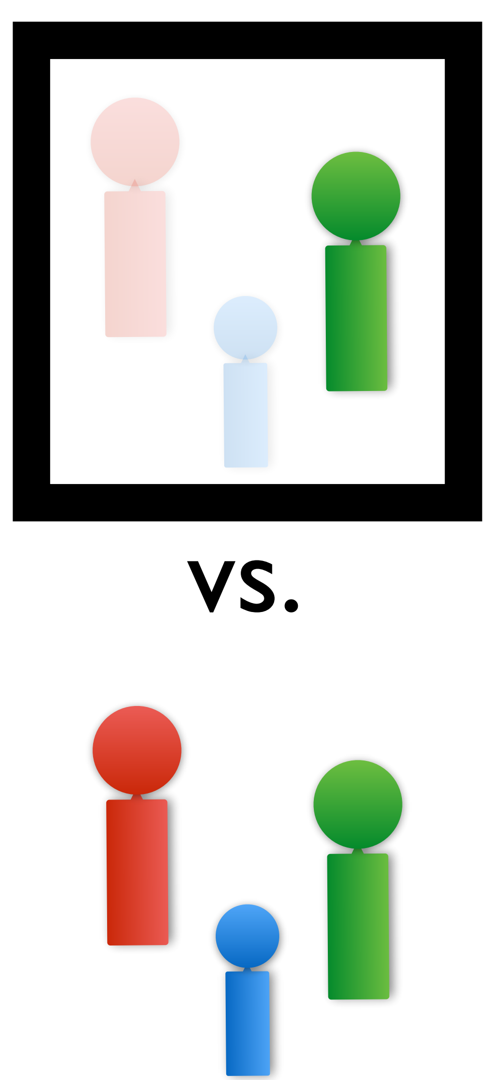


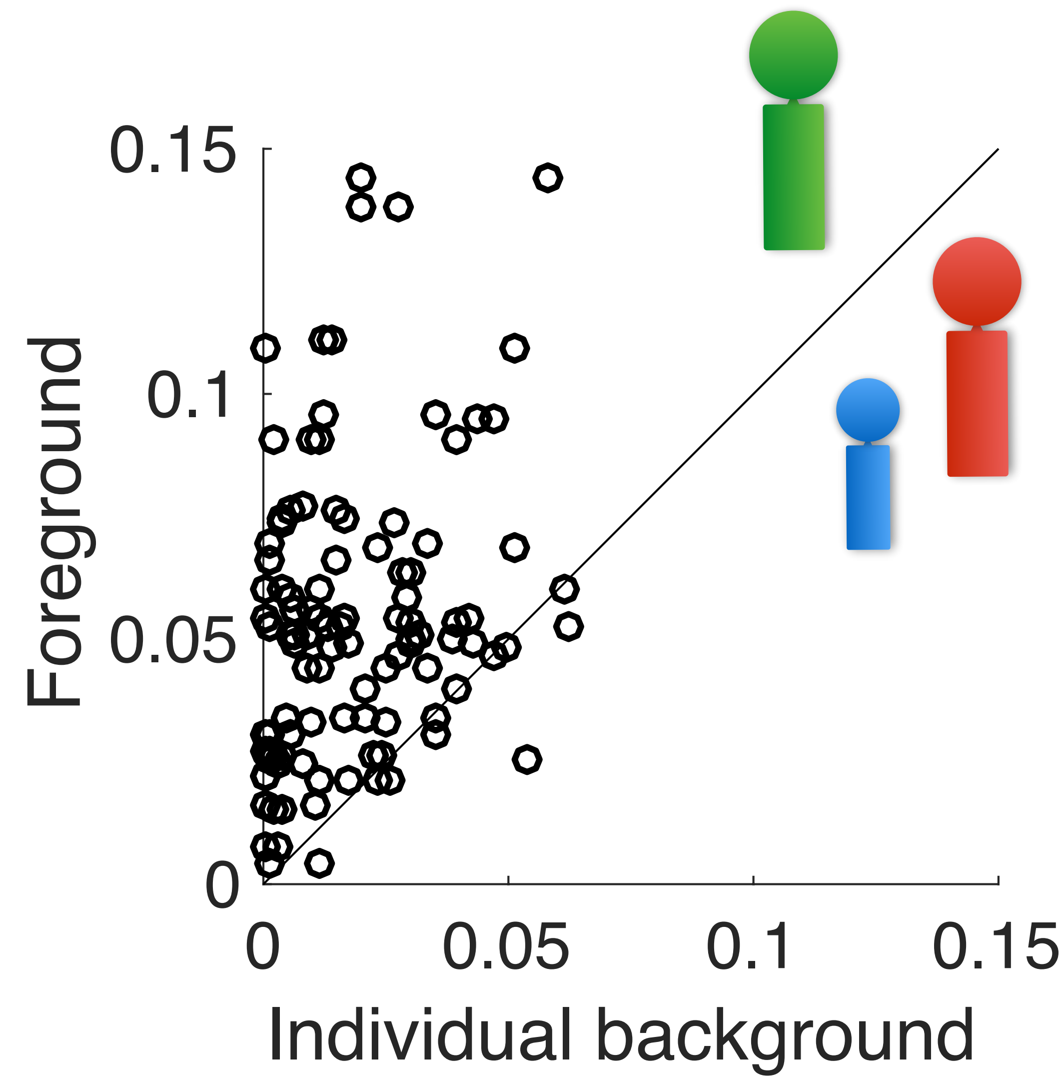
Note: r^2 Scatterplot (not r)

Puvvada & Simon, bioRχiv (2017)

Integration Window over Late Times Only

Late Cortical Reconstruction



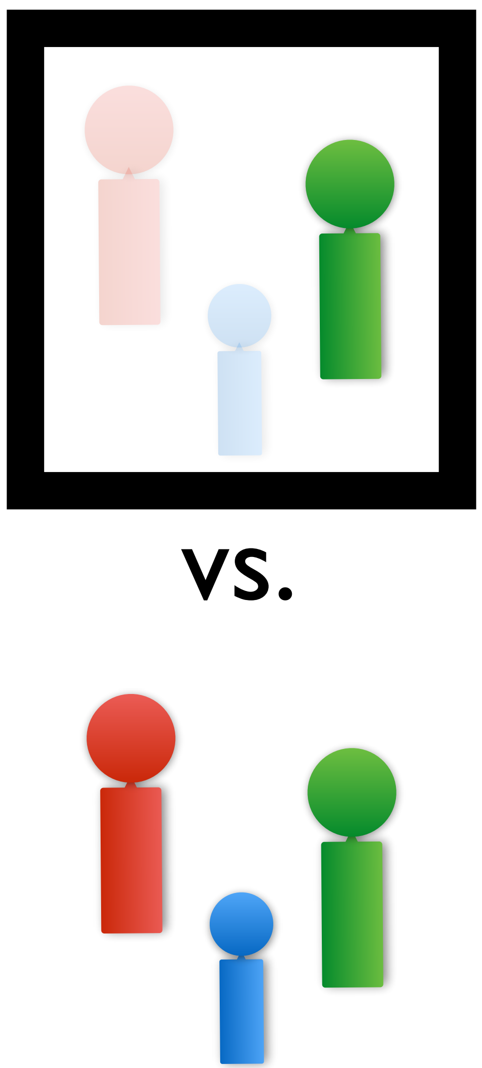


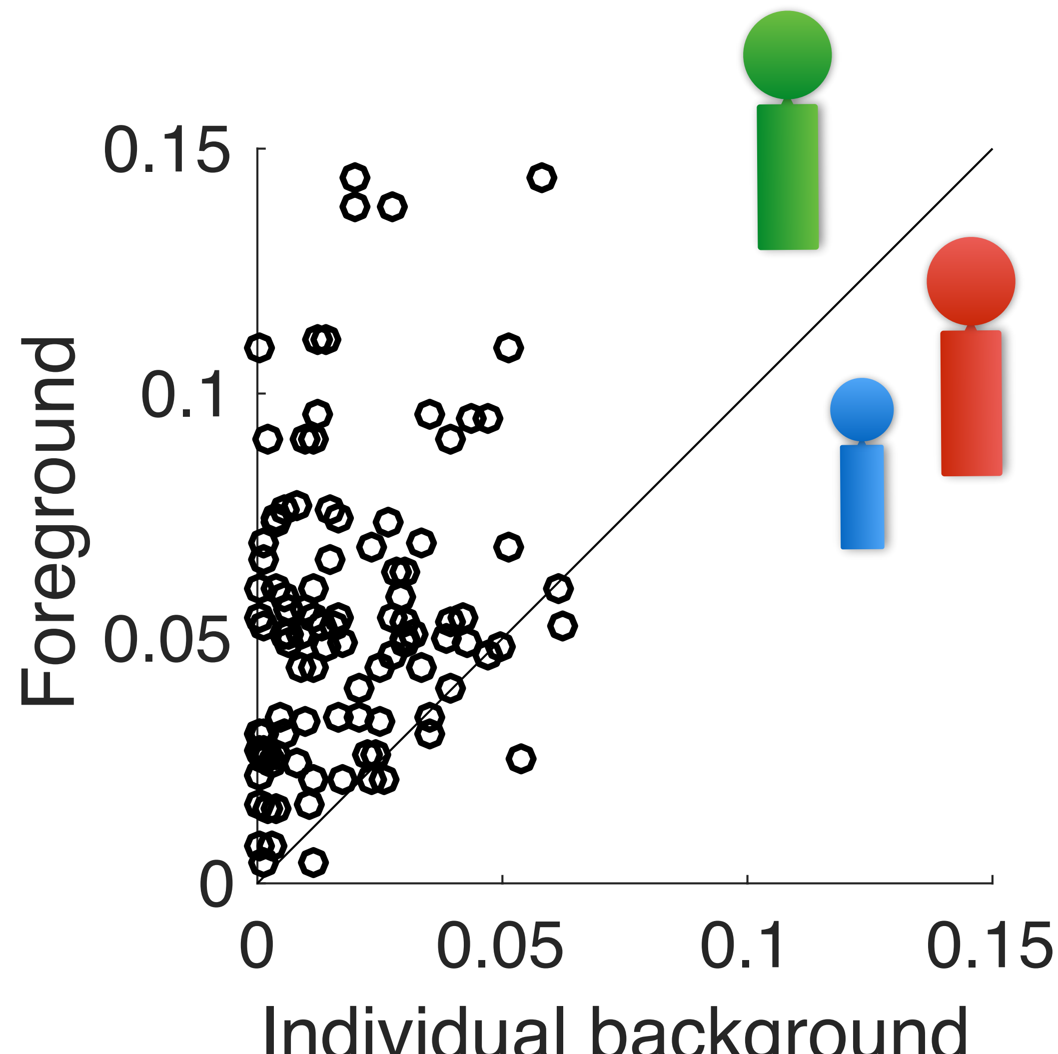
Note: r^2 Scatterplot (not r)

Puvvada & Simon, bioRχiv (2017)

Integration Window over Late Times Only

Late Cortical Reconstruction

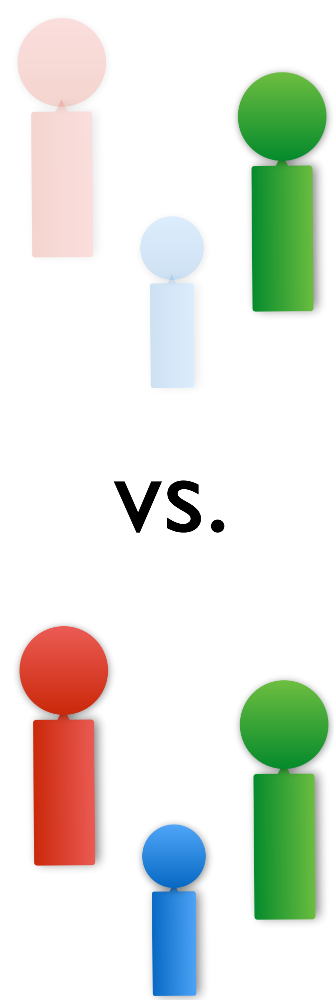




PT represents attended speech with much greater fidelity than unattended

Puvvada & Simon, bioRχiv (2017)

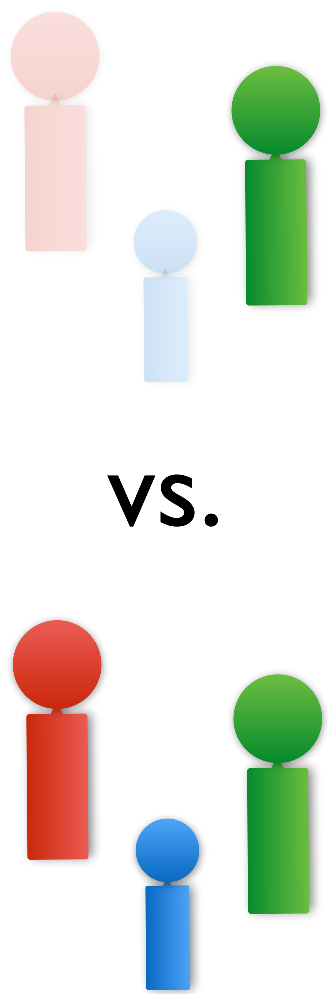
Early Cortical Reconstruction

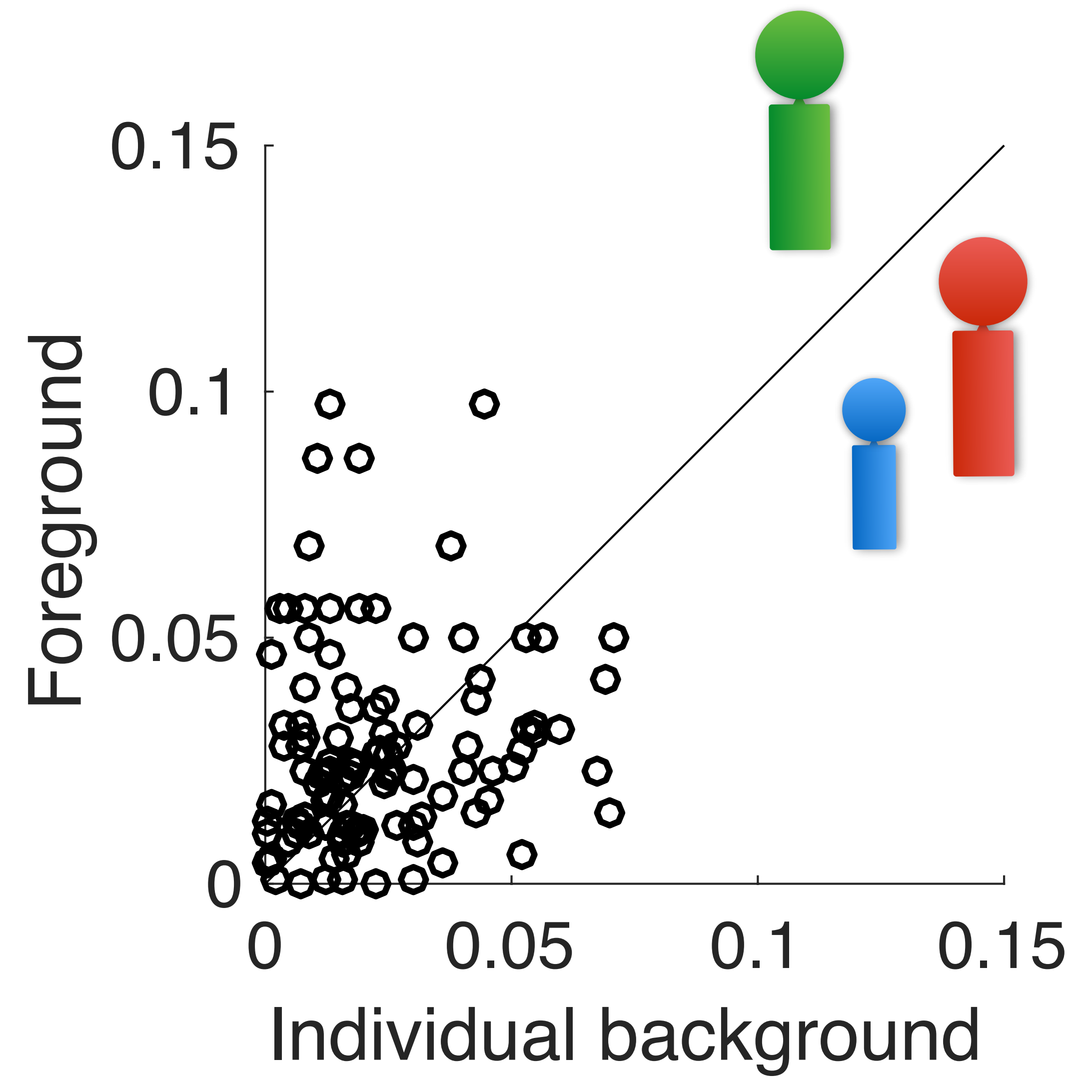


Puvvada & Simon, bioRχiv (2017)

Integration Window over Early Times Only

Early Cortical Reconstruction

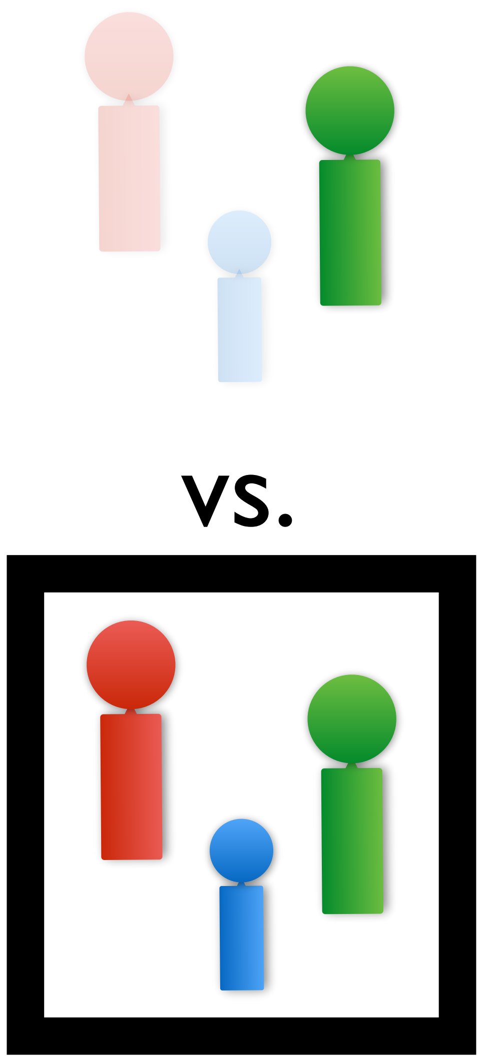


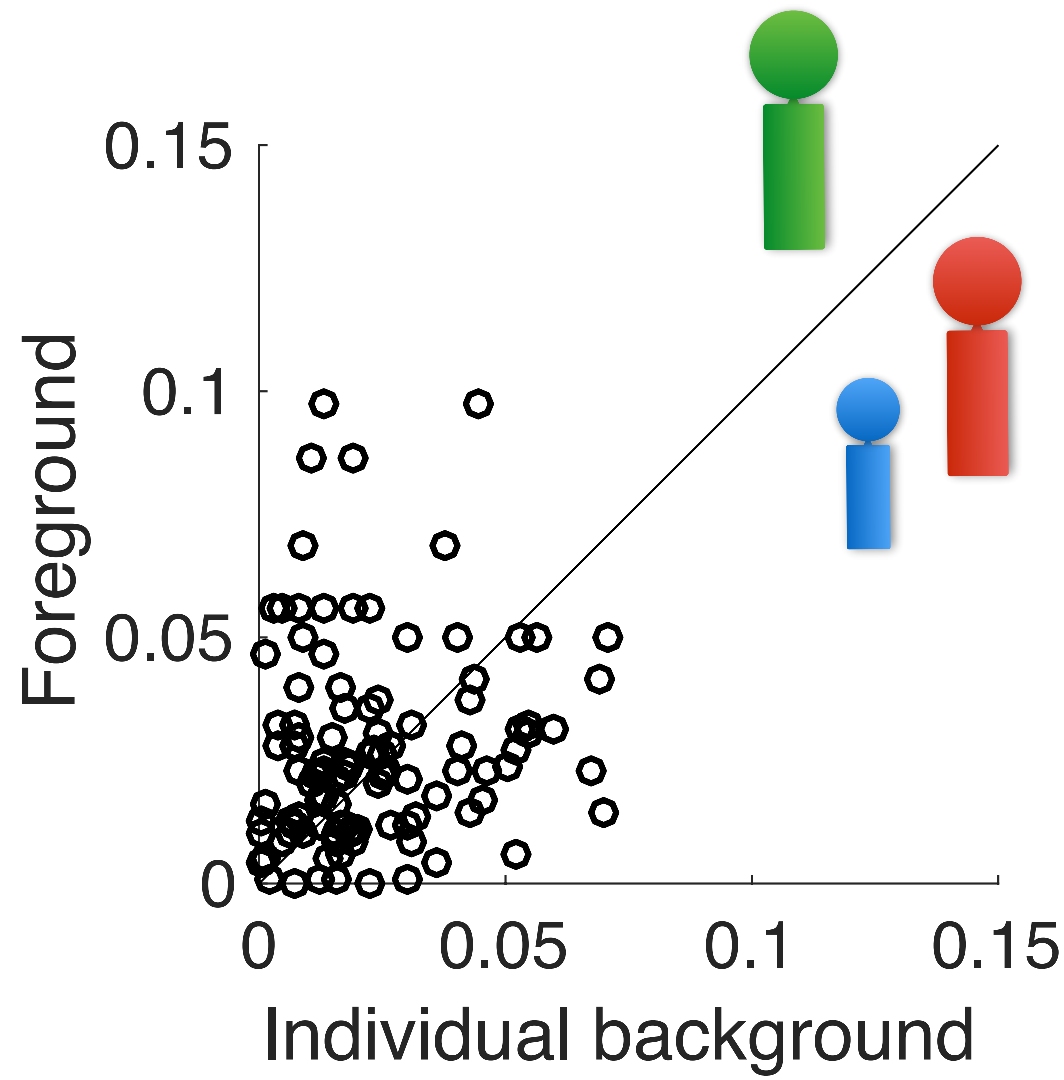


Puvvada & Simon, bioRχiv (2017)

Integration Window over Early Times Only

Early Cortical Reconstruction

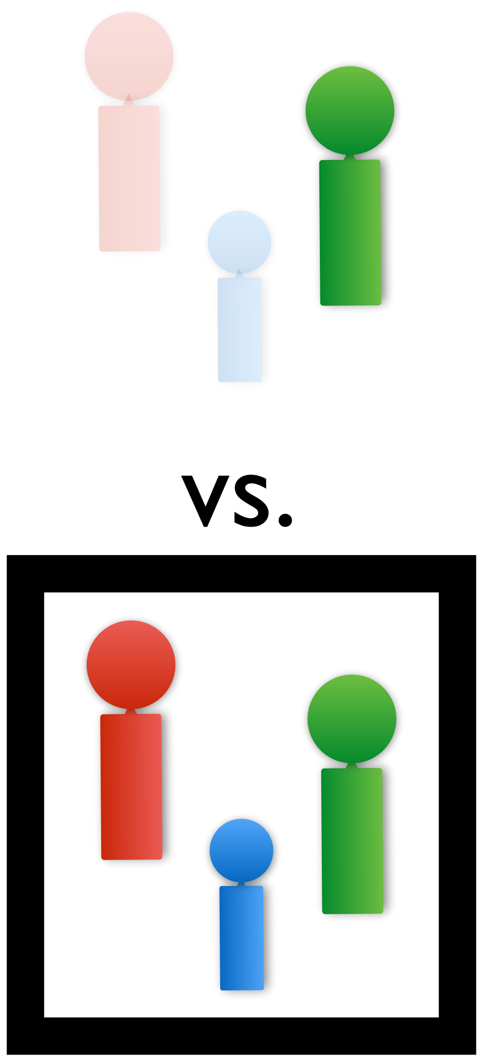


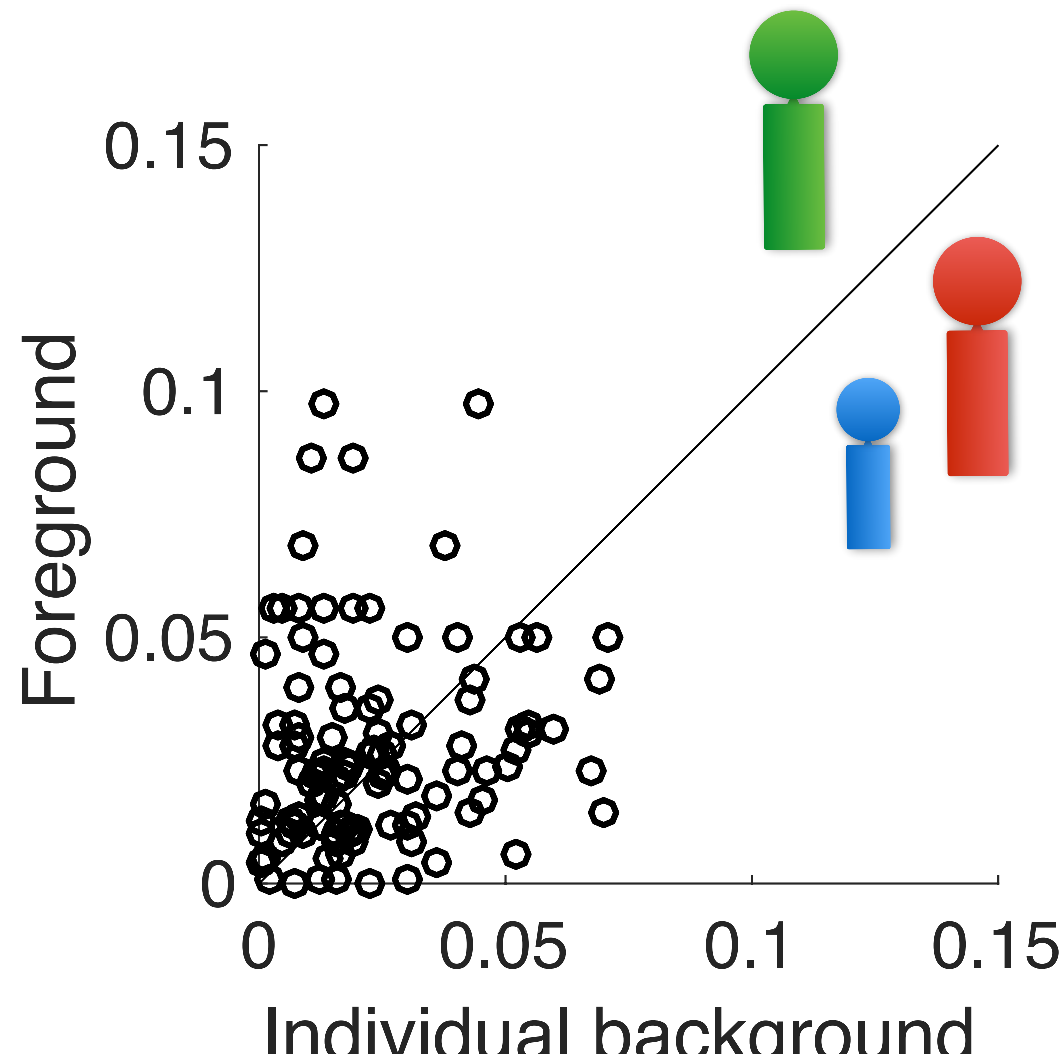


Puvvada & Simon, bioRχiv (2017)

Integration Window over Early Times Only

Early Cortical Reconstruction



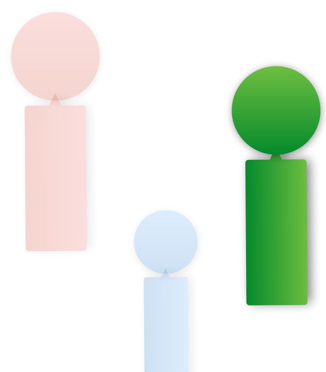


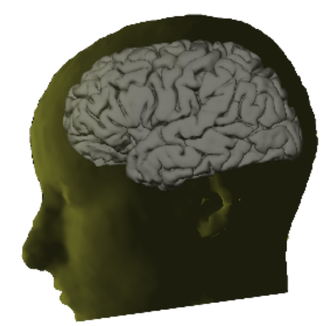
HG represents attended and unattended speech with almost equal fidelity

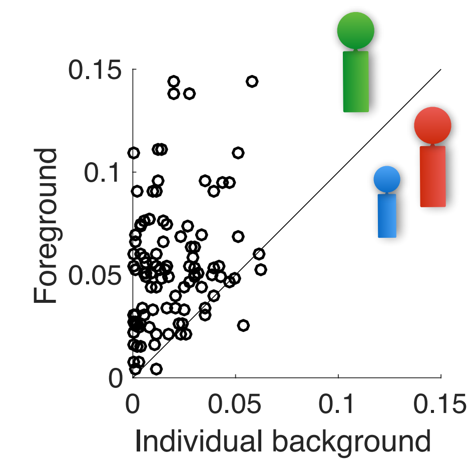
Puvvada & Simon, bioRχiv (2017)

Where in Cortex is there a Segregated Foreground?

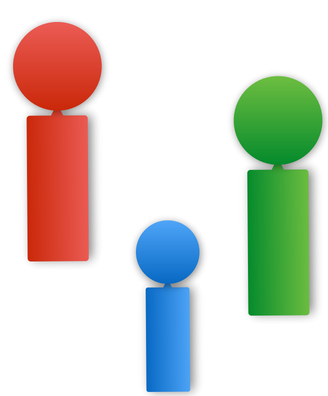
Planum Temporale

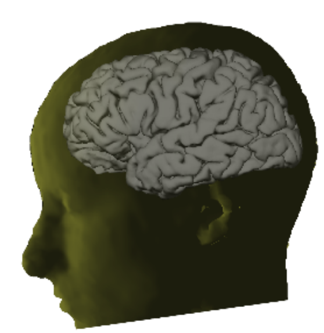


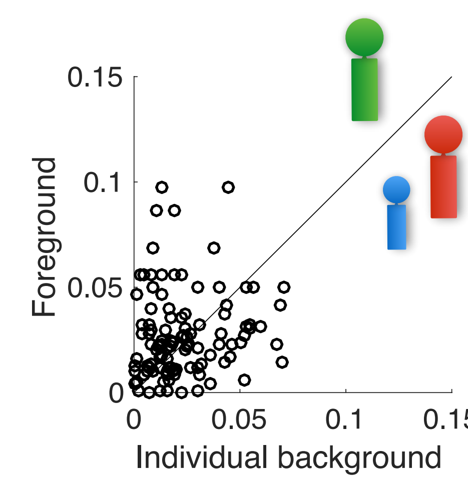




but not Heschl's Gyrus

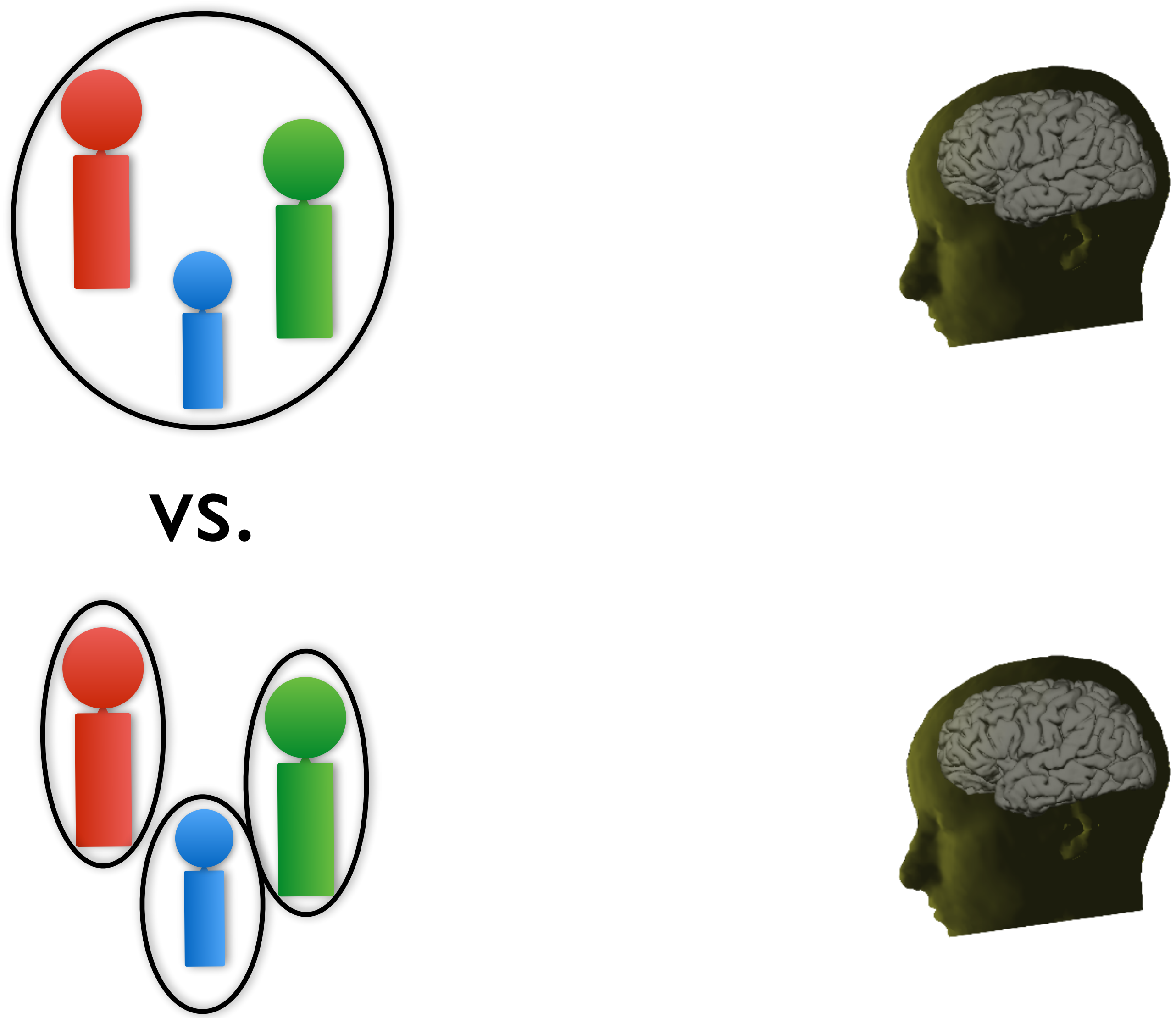






Puvvada & Simon, bioRχiv (2017)

Early Entire Acoustic Scene vs. Individual Streams

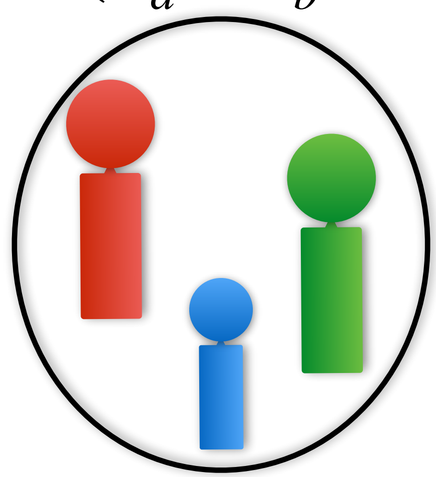


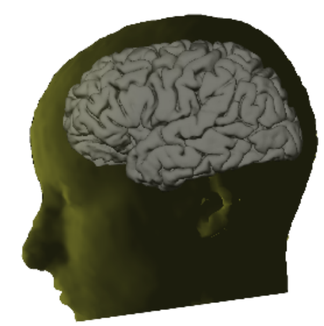
Puvvada & Simon, bioRχiv (2017)

Integration Window over Early Times Only

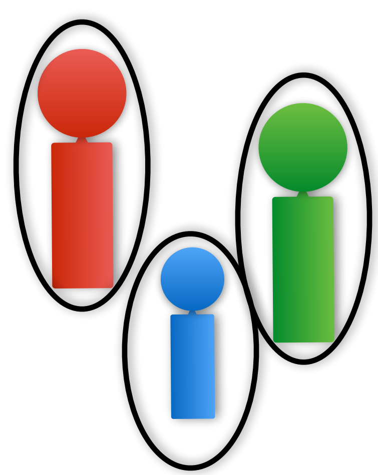
Early Entire Acoustic Scene vs. Individual Streams

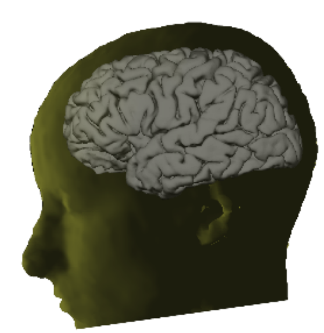
$$Env(S_a + S_b + S_c)$$





vs.



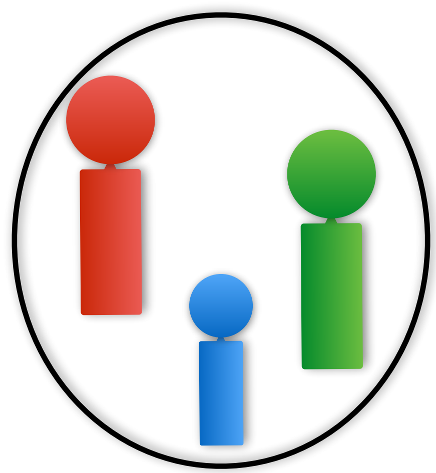


$$Env(S_a) + Env(S_b) + Env(S_c)$$

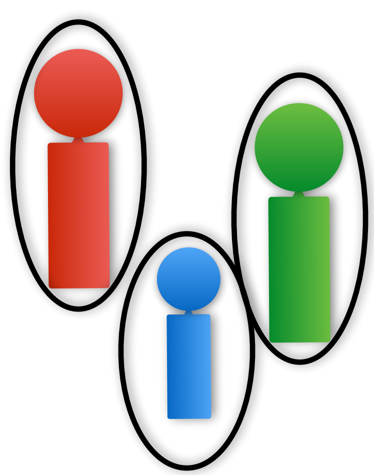
Puvvada & Simon, bioRχiv (2017)

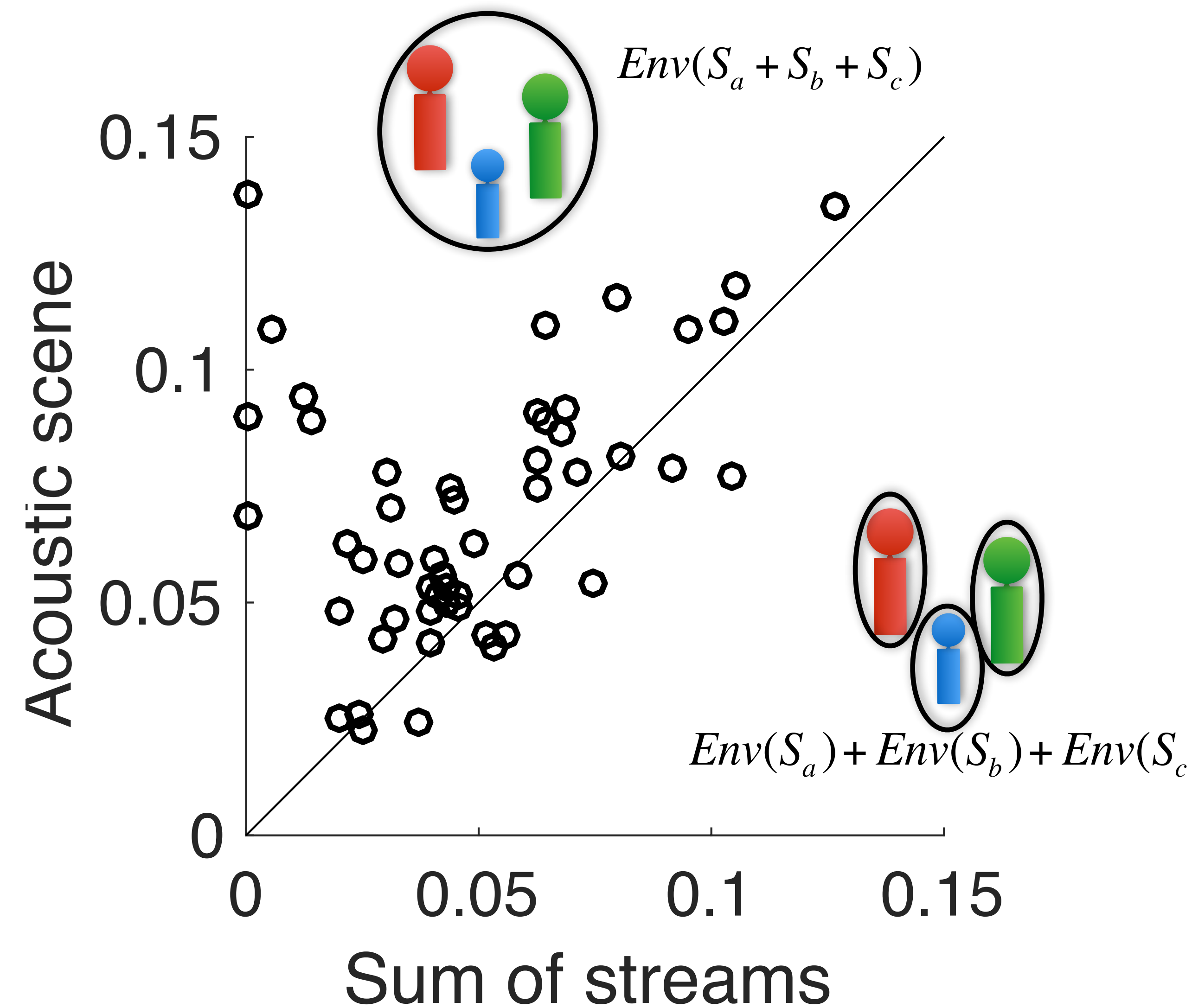
Integration Window over Early Times Only

Early Entire Acoustic Scene vs. Individual Streams



vs.

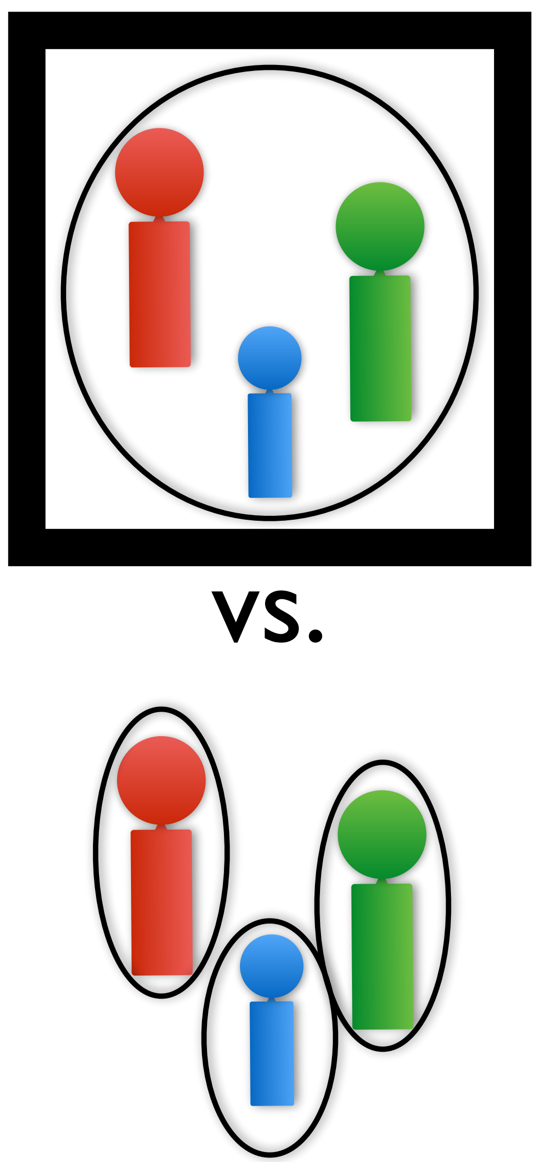


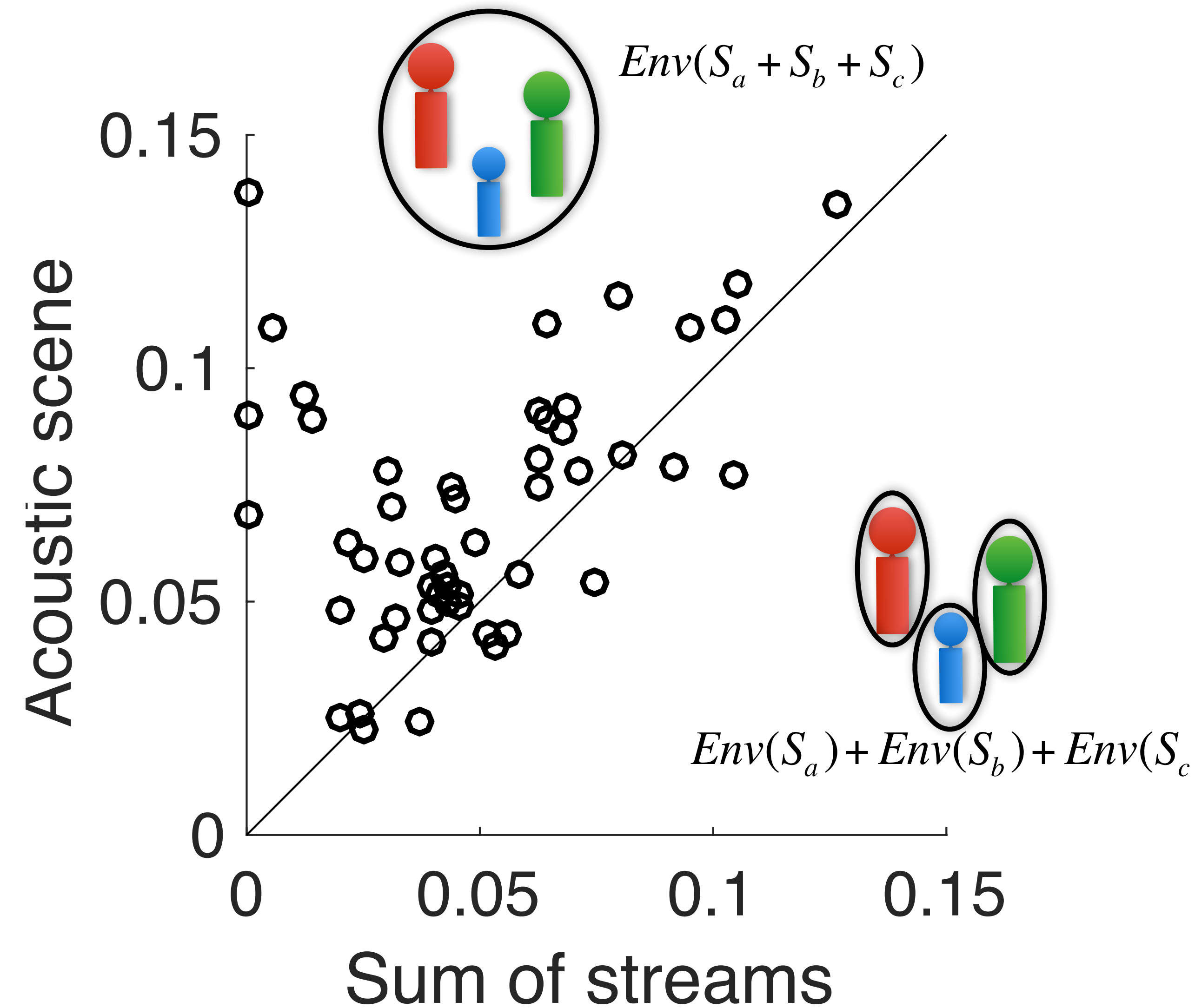


Puvvada & Simon, bioRχiv (2017)

Integration Window over Early Times Only

Early Entire Acoustic Scene vs. Individual Streams

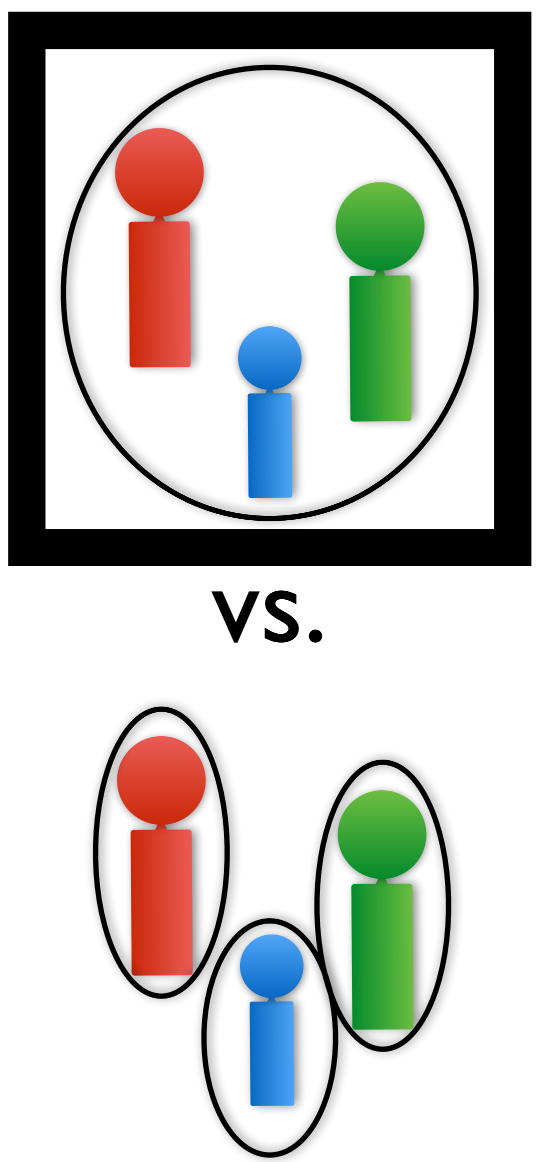


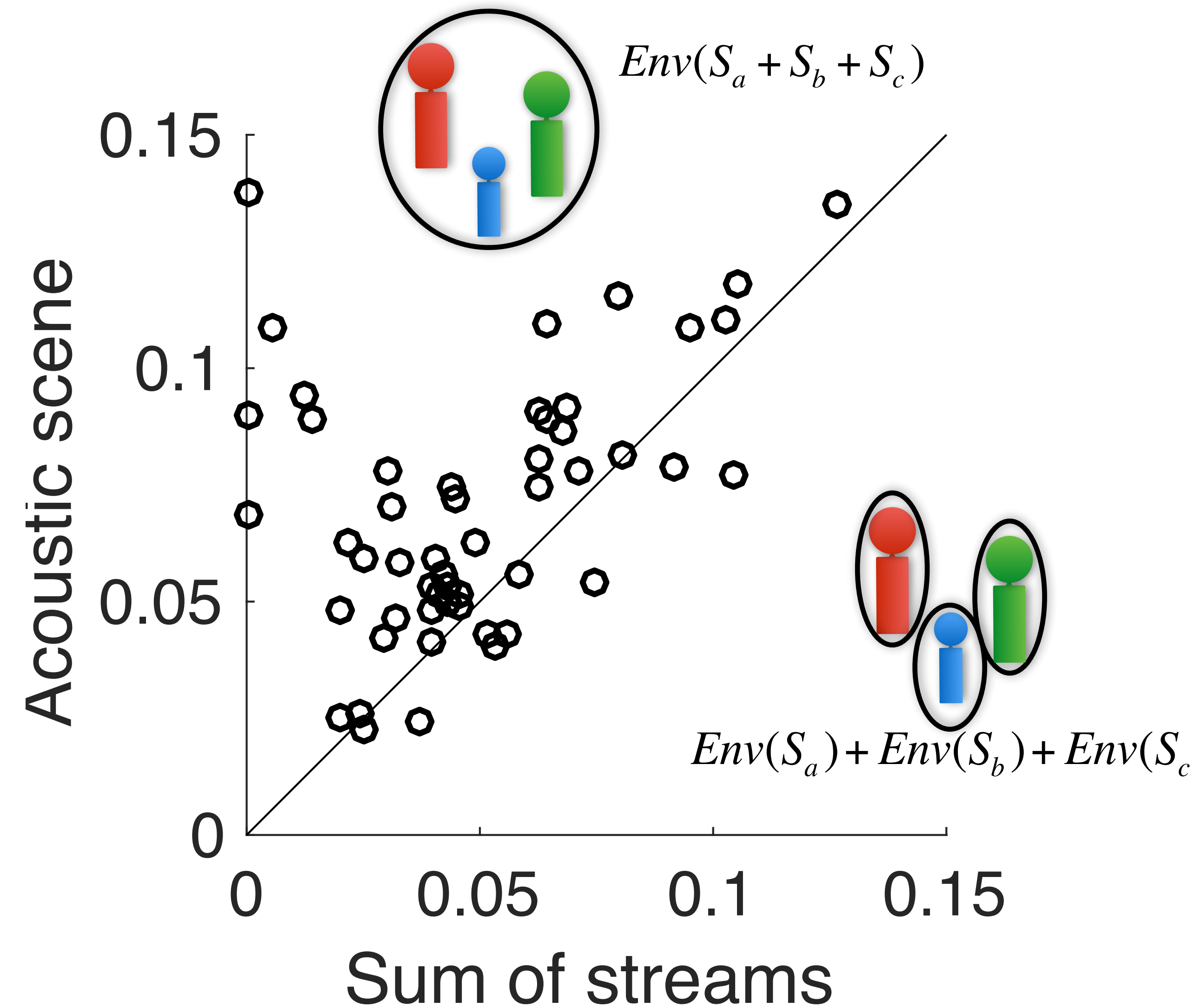


Puvvada & Simon, bioRχiv (2017)

Integration Window over Early Times Only

Early Entire Acoustic Scene vs. Individual Streams





HG Represents the (holistic) Acoustic Scene, not Individual Streams

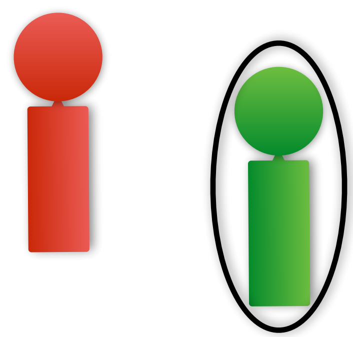
Puvvada & Simon, bioRχiv (2017)

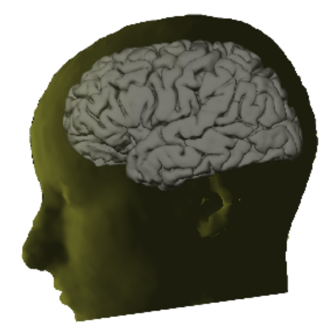
Foreground vs. Background

Puvvada & Simon, bioRχiv (2017)

Integration Window over Late Times Only

Foreground vs. Background





Puvvada & Simon, bioRχiv (2017)

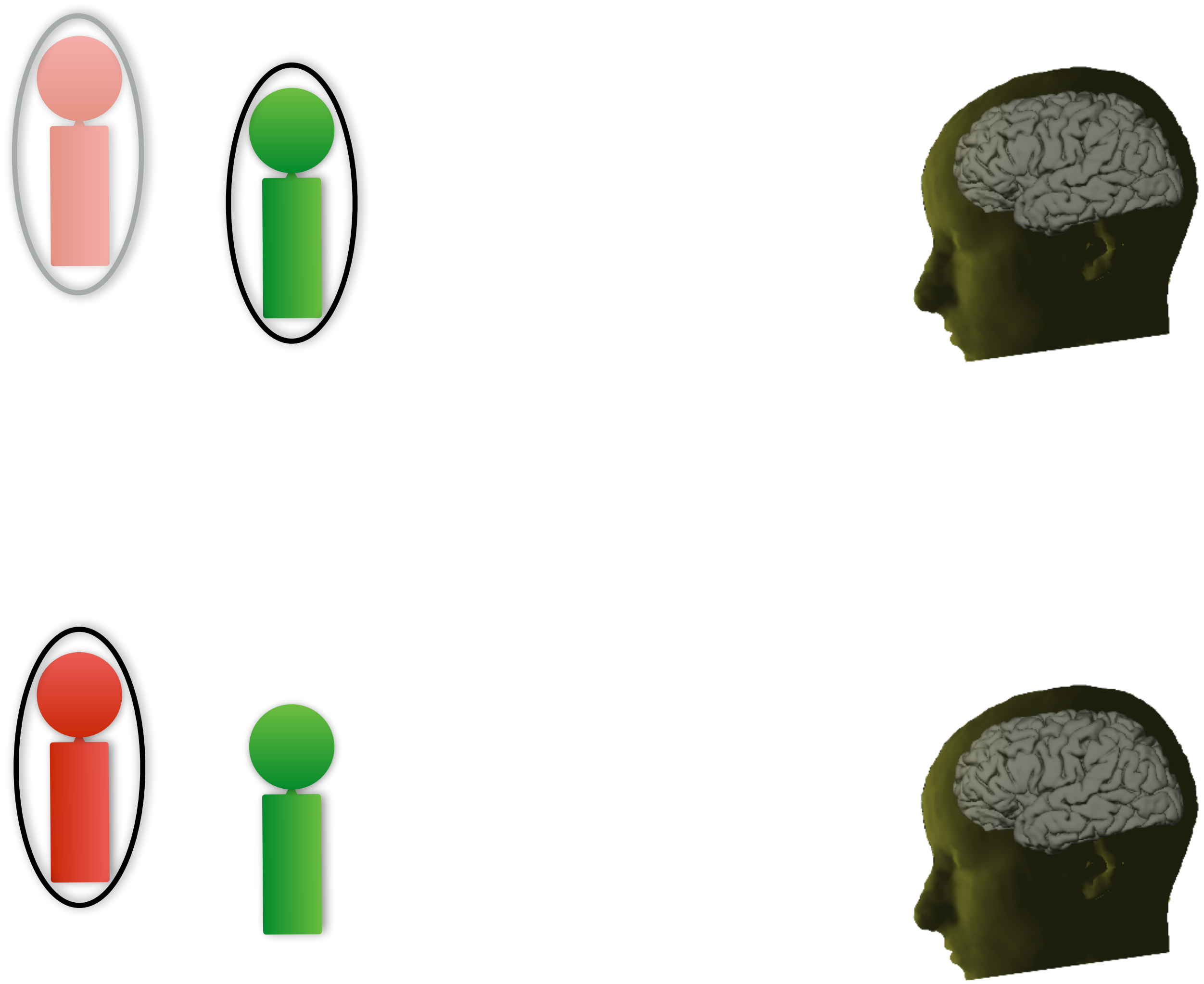
Integration Window over Late Times Only

Foreground vs. Background

Puvvada & Simon, bioRχiv (2017)

Integration Window over Late Times Only

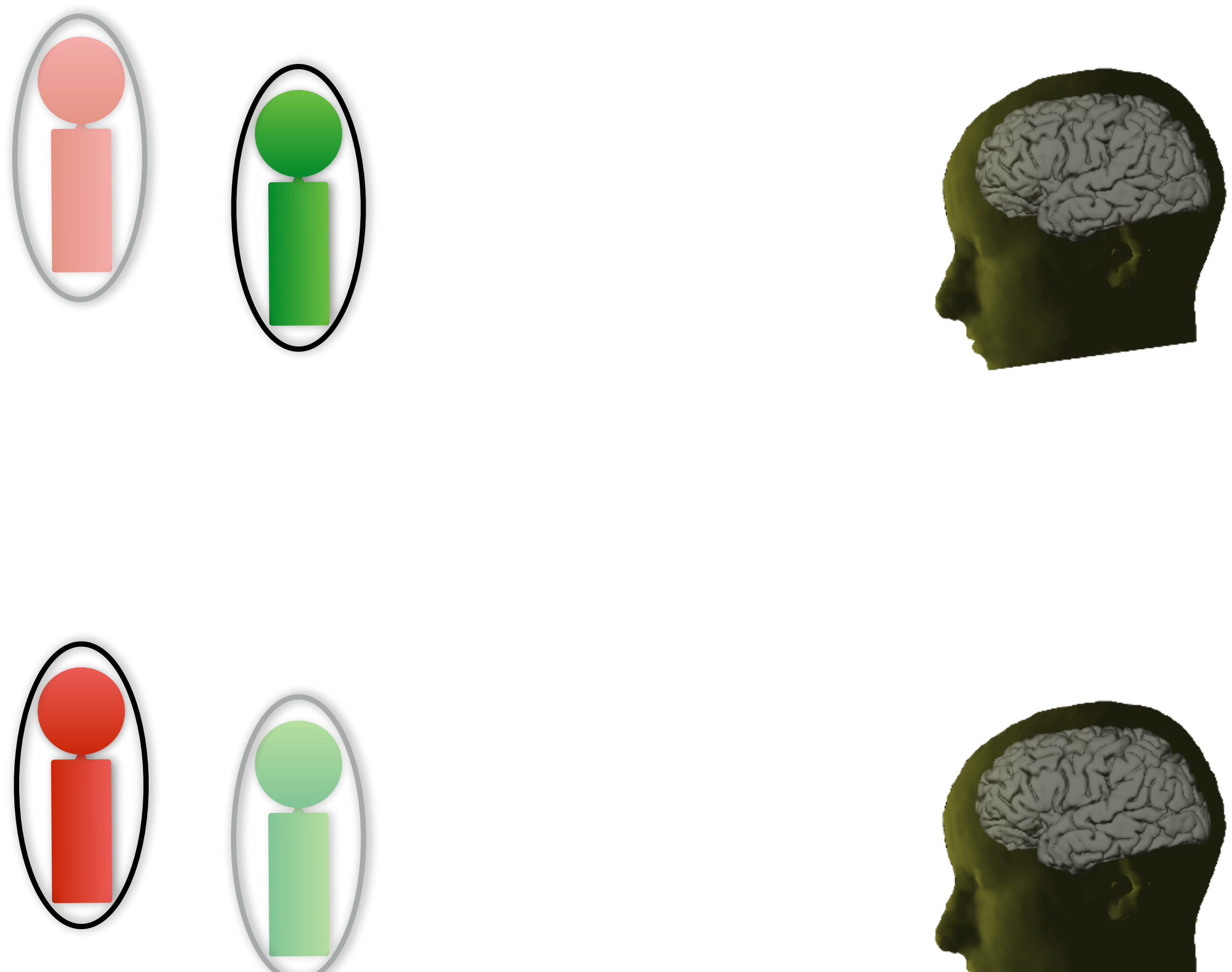
Foreground vs. Background



Puvvada & Simon, bioRχiv (2017)

Integration Window over Late Times Only

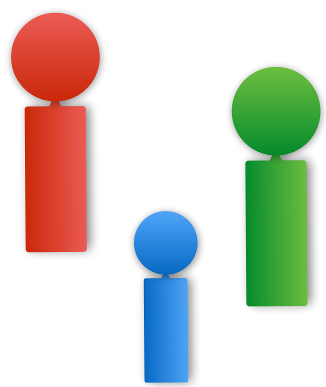
Foreground vs. Background

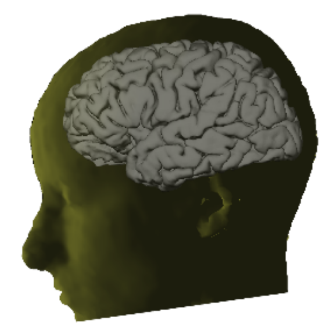


Puvvada & Simon, bioRχiv (2017)

Integration Window over Late Times Only

Foreground vs. Background

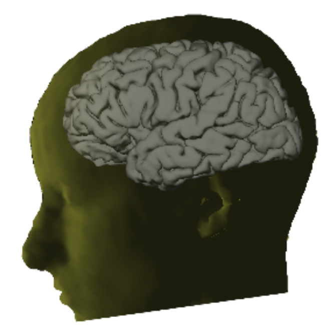




Puvvada & Simon, bioRχiv (2017)

Integration Window over Late Times Only

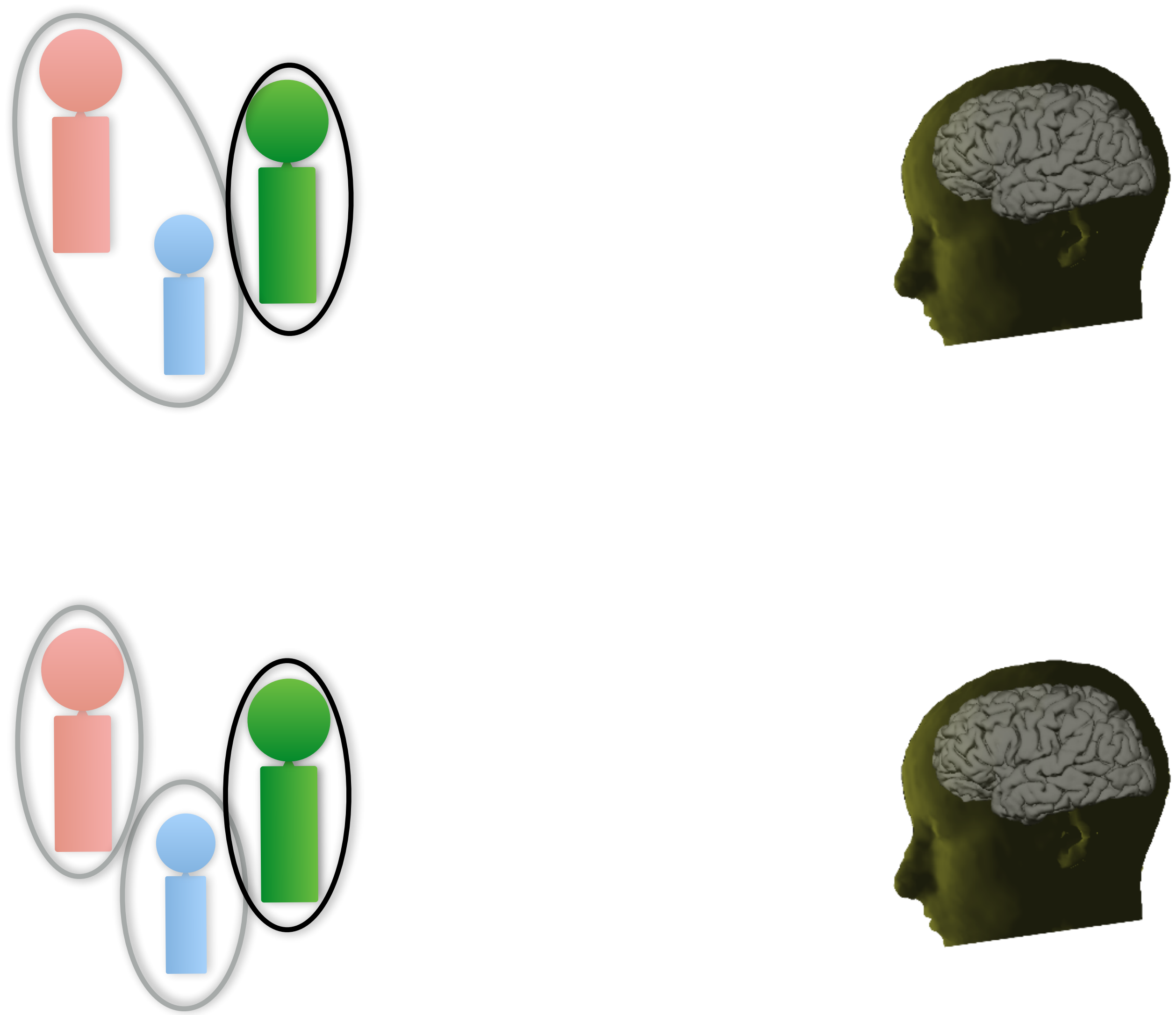
Foreground vs. Background



Puvvada & Simon, bioRχiv (2017)

Integration Window over Late Times Only

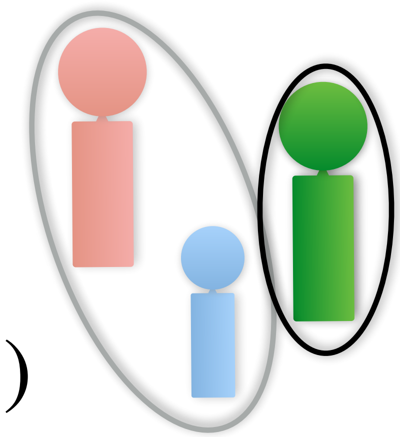
Foreground vs. Background



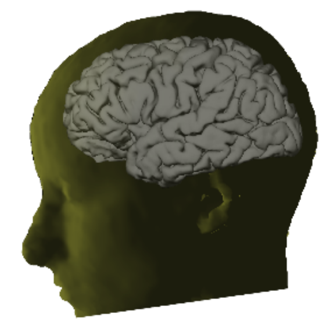
Puvvada & Simon, bioRχiv (2017)

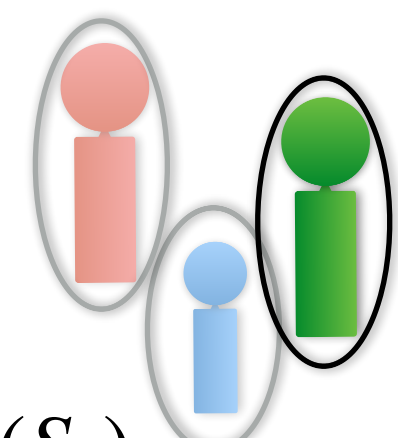
Integration Window over Late Times Only

Foreground vs. Background

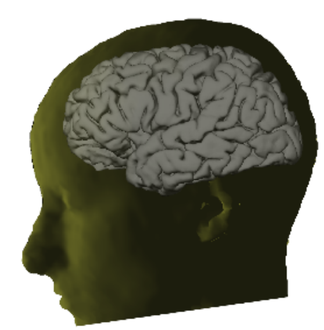


$$Env(S_b + S_c)$$





$$Env(S_b) + Env(S_c)$$



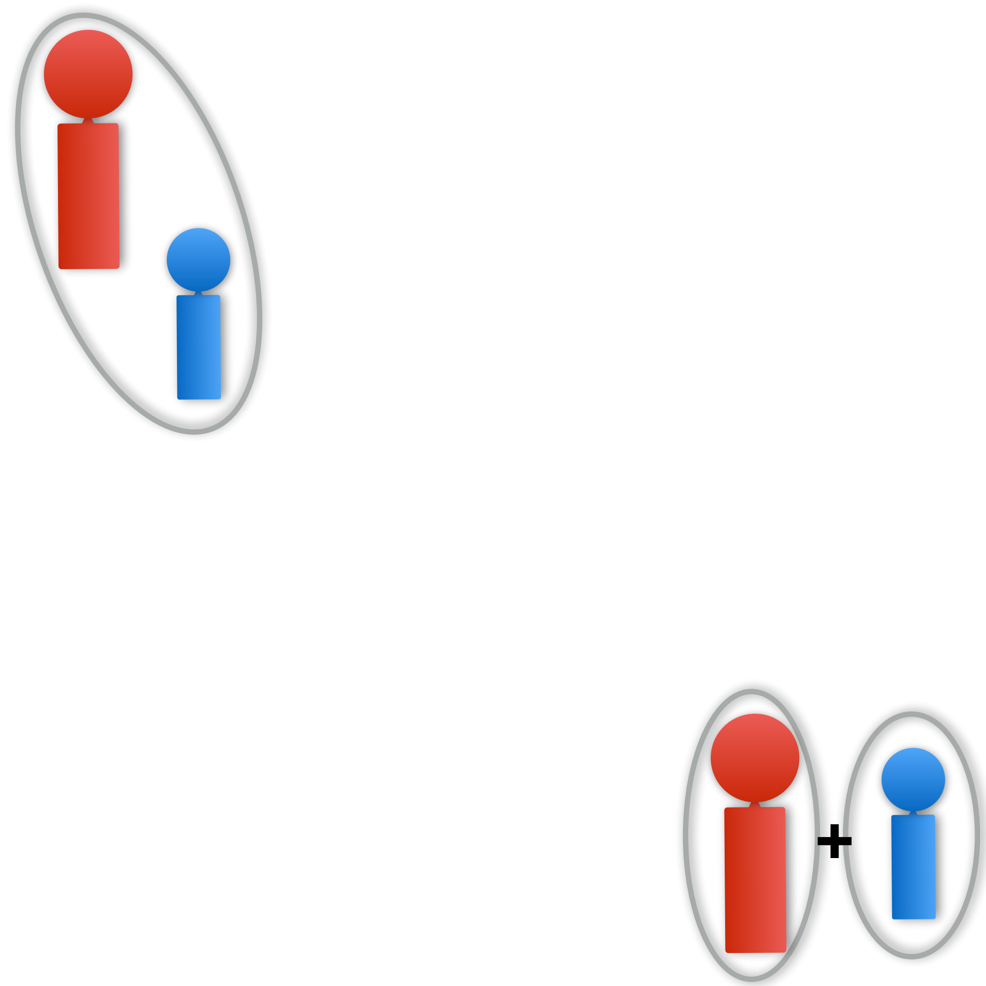
Puvvada & Simon, bioRχiv (2017)

Integration Window over Late Times Only

Background vs. Backgrounds

Fused Background

$Env(S_b + S_c)$



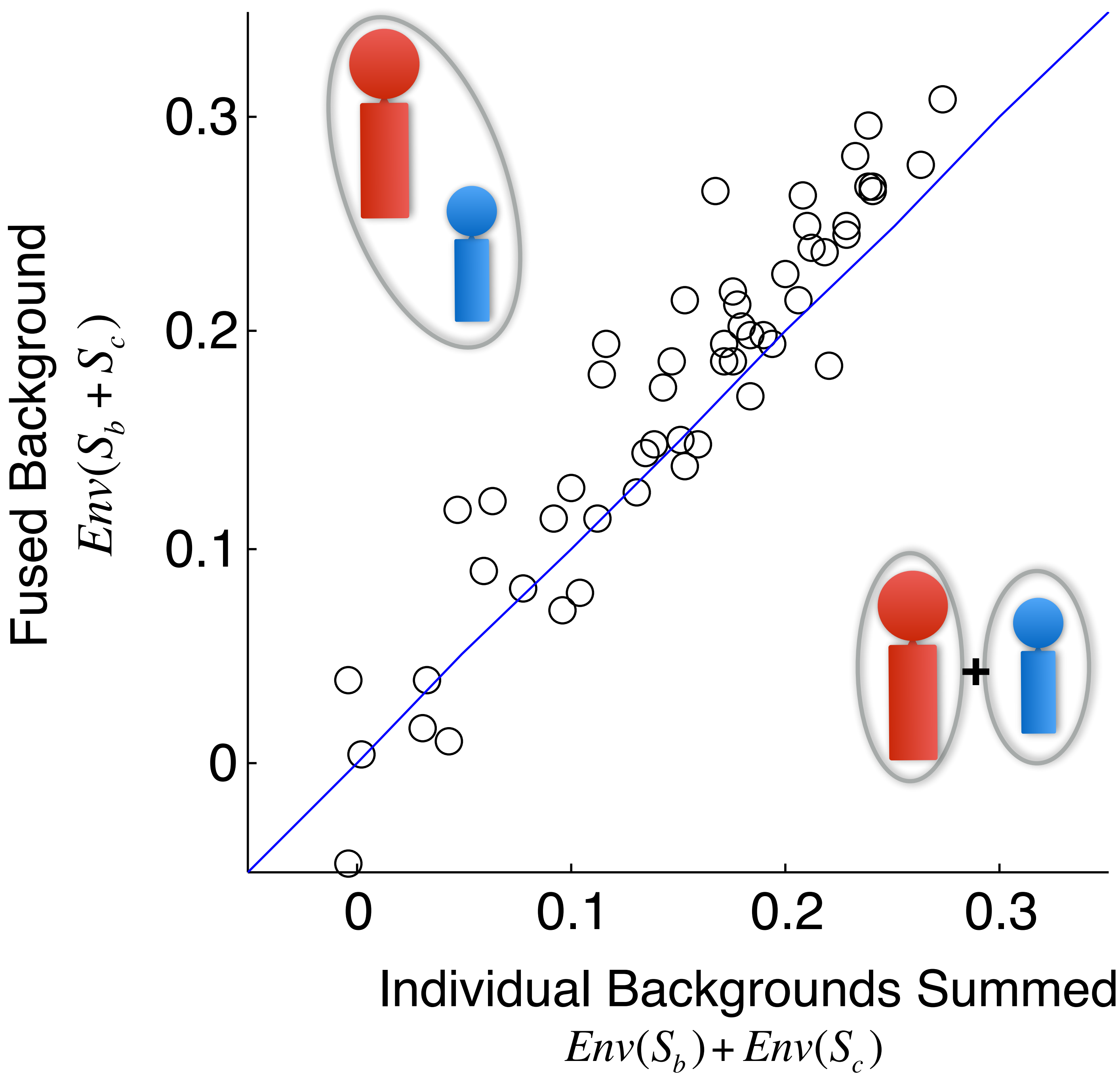
Individual Backgrounds Summed

$Env(S_b) + Env(S_c)$

Puvvada & Simon, bioRχiv (2017)

Integration Window over Late Times Only

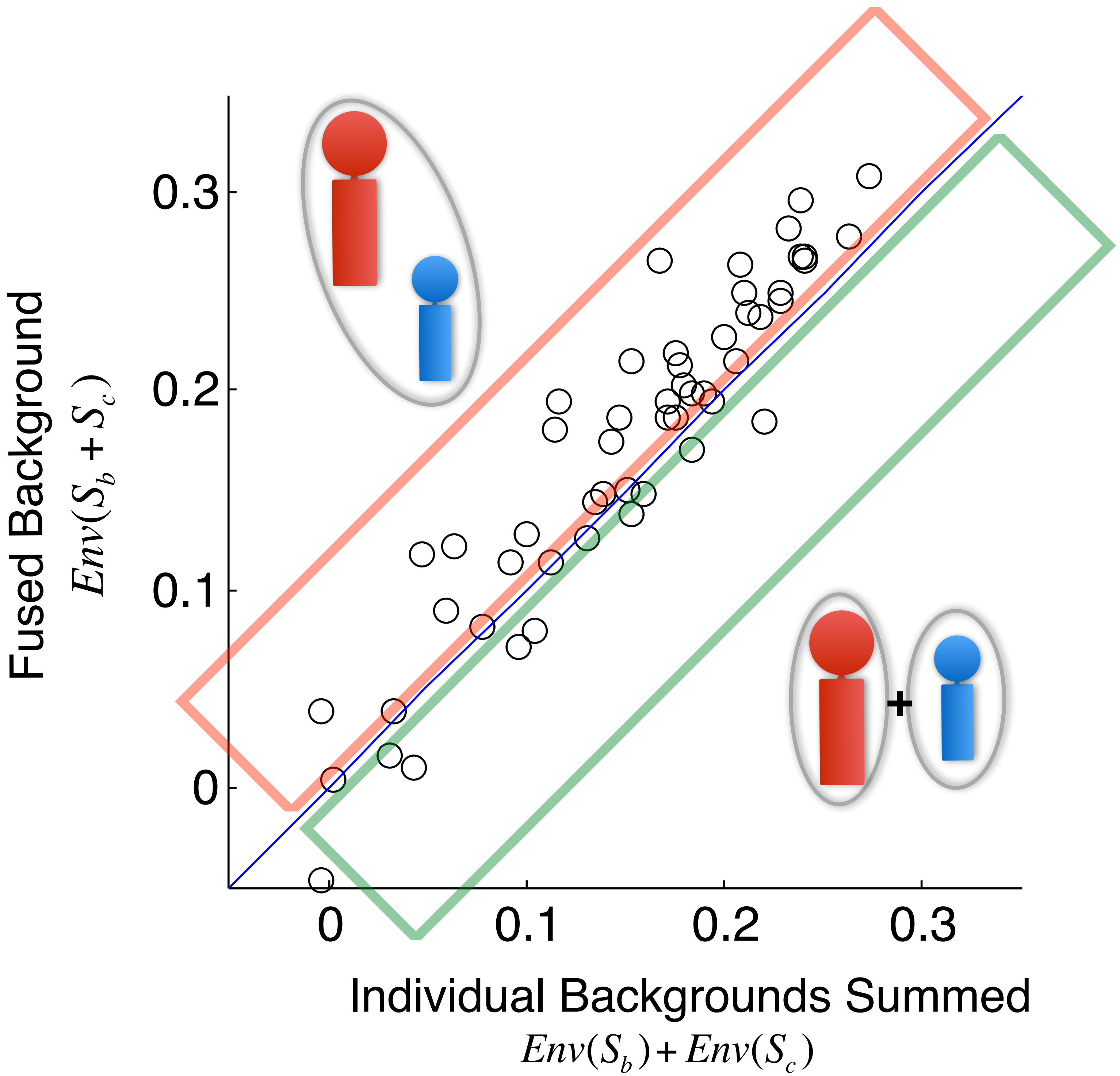
Background vs. Backgrounds



Puvvada & Simon, bioRχiv (2017)

Integration Window over Late Times Only

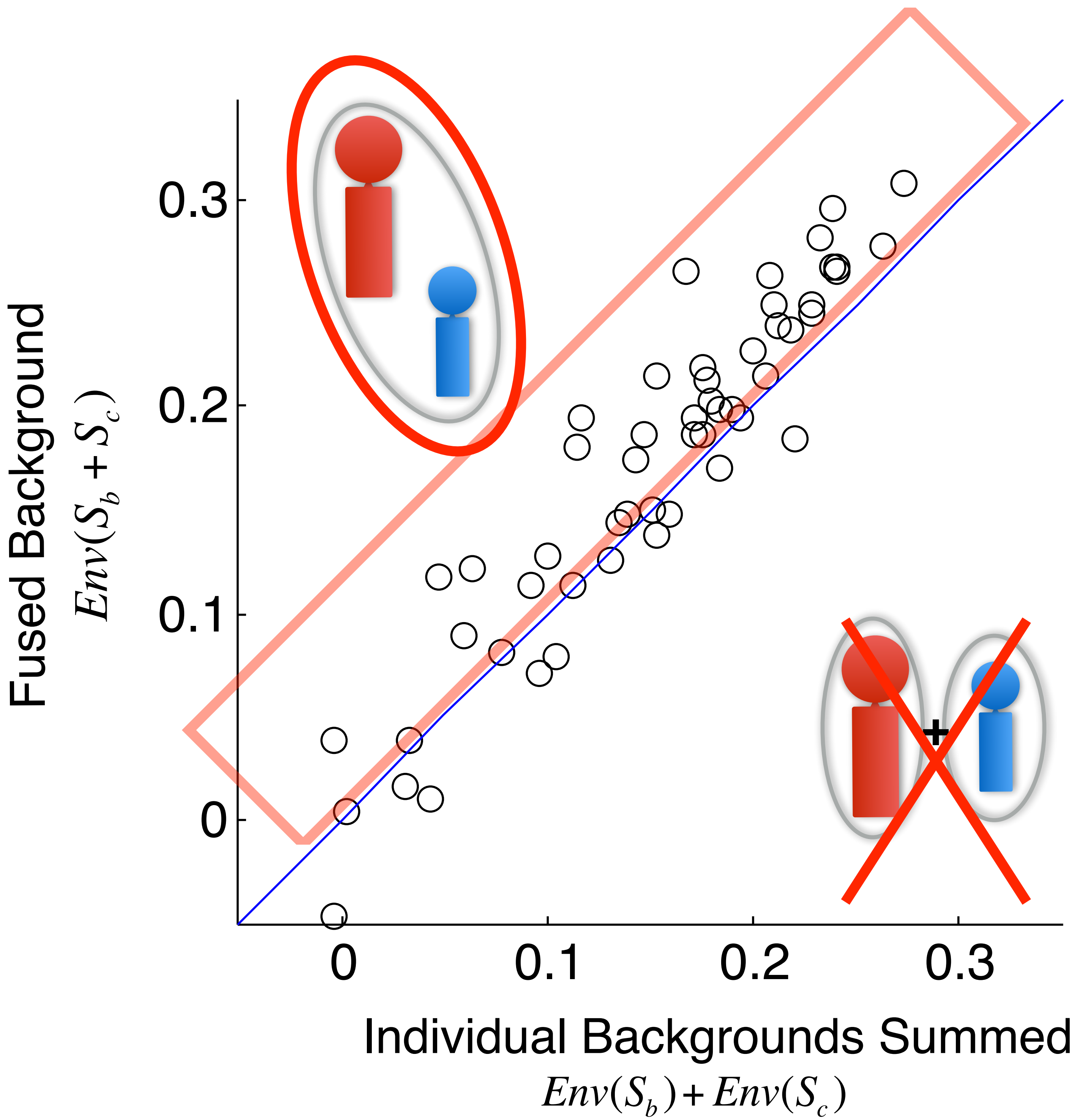
Background vs. Backgrounds



Puvvada & Simon, bioRχiv (2017)

Integration Window over Late Times Only

Background vs. Backgrounds



PT represents a fused background with much better fidelity than individual backgrounds

Puvvada & Simon, bioRχiv (2017)

Forward Model?

Current Competing Speaker TRF model:

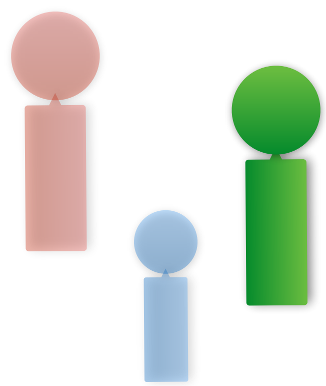
$$r(t) = \sum_{\tau} TRF_a(t-\tau)S_a(\tau) + \sum_{\tau} TRF_b(t-\tau)S_b(\tau) + \sum_{\tau} TRF_c(t-\tau)S_c(\tau) + \varepsilon(t)$$

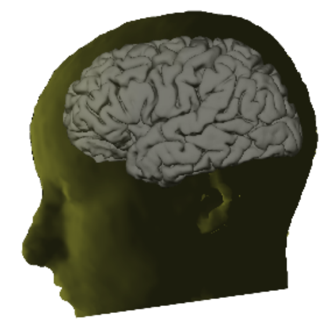
Puvvada & Simon, bioRχiv (2017)

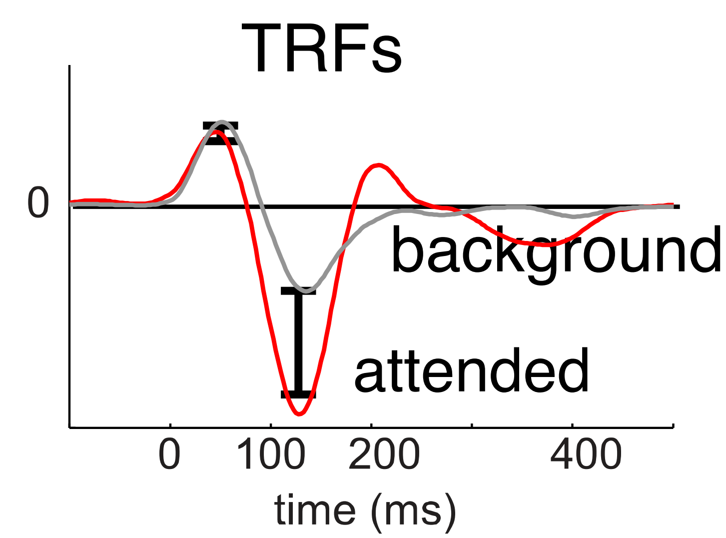
Forward Model?

Current Competing Speaker TRF model:

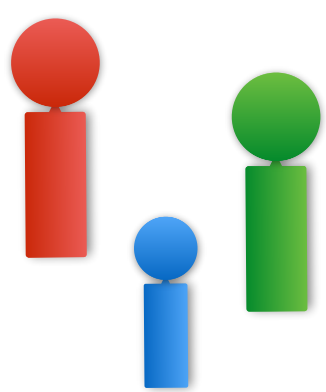
$$r(t) = \sum_{\tau} TRF_a(t-\tau)S_a(\tau) + \sum_{\tau} TRF_b(t-\tau)S_b(\tau) + \sum_{\tau} TRF_c(t-\tau)S_c(\tau) + \varepsilon(t)$$

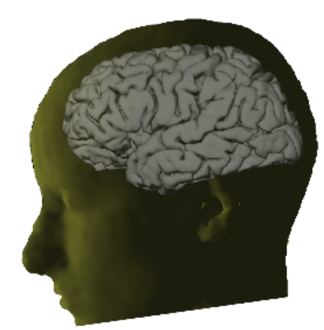






or





or…

Puvvada & Simon, bioRχiv (2017)

Better Forward Model?

$$r(t) = \sum_{\tau=0}^{\tau=\tau_1} TRF_{Scene}(t-\tau) S_{Scene}(\tau) +$$

$$+ \sum_{\tau=\tau_1}^{\tau=\tau_2} TRF_{Foregound}(t-\tau) S_{Foregound}(\tau)$$

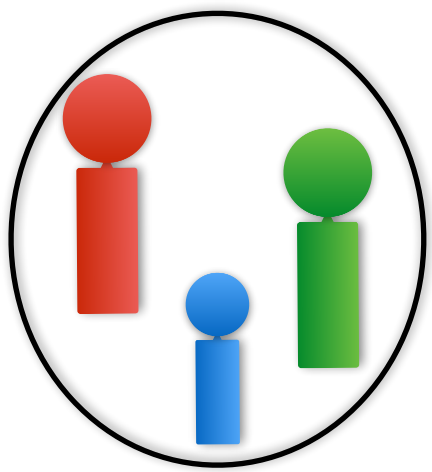
$$+ \sum_{\tau=\tau_1}^{\tau=\tau_2} TRF_{Background}(t-\tau) S_{Background}(\tau)$$

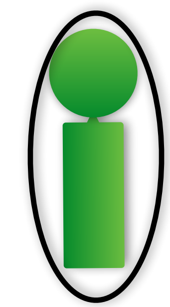
$$+ \varepsilon(t)$$

Puvvada & Simon, bioRχiv (2017)

Better Forward Model?

$$r(t) = \sum_{\tau=0}^{\tau=\tau_1} TRF_{Scene}(t-\tau)S_{Scene}(\tau) +$$

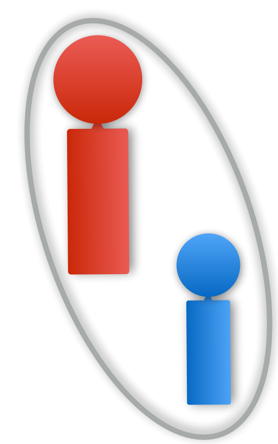




$$+\sum_{\tau=\tau_1}^{\tau=\tau_2} TRF_{Foregound}(t-\tau)S_{Foregound}(\tau)$$

$$+\sum_{\tau=\tau_1}^{\tau=\tau_2} TRF_{Background}(t-\tau)S_{Background}(\tau)$$

$$+\varepsilon(t)$$



Puvvada & Simon, bioRχiv (2017)

Forward Models Compared

$$r(t)=\sum_{\tau=0}^{\tau=\tau_1} TRF_{Scene}(t-\tau)S_{Scene}(\tau)+$$
$$+\sum_{\tau=\tau_1}^{\tau=\tau_2} TRF_{Foregound}(t-\tau)S_{Foregound}(\tau)$$
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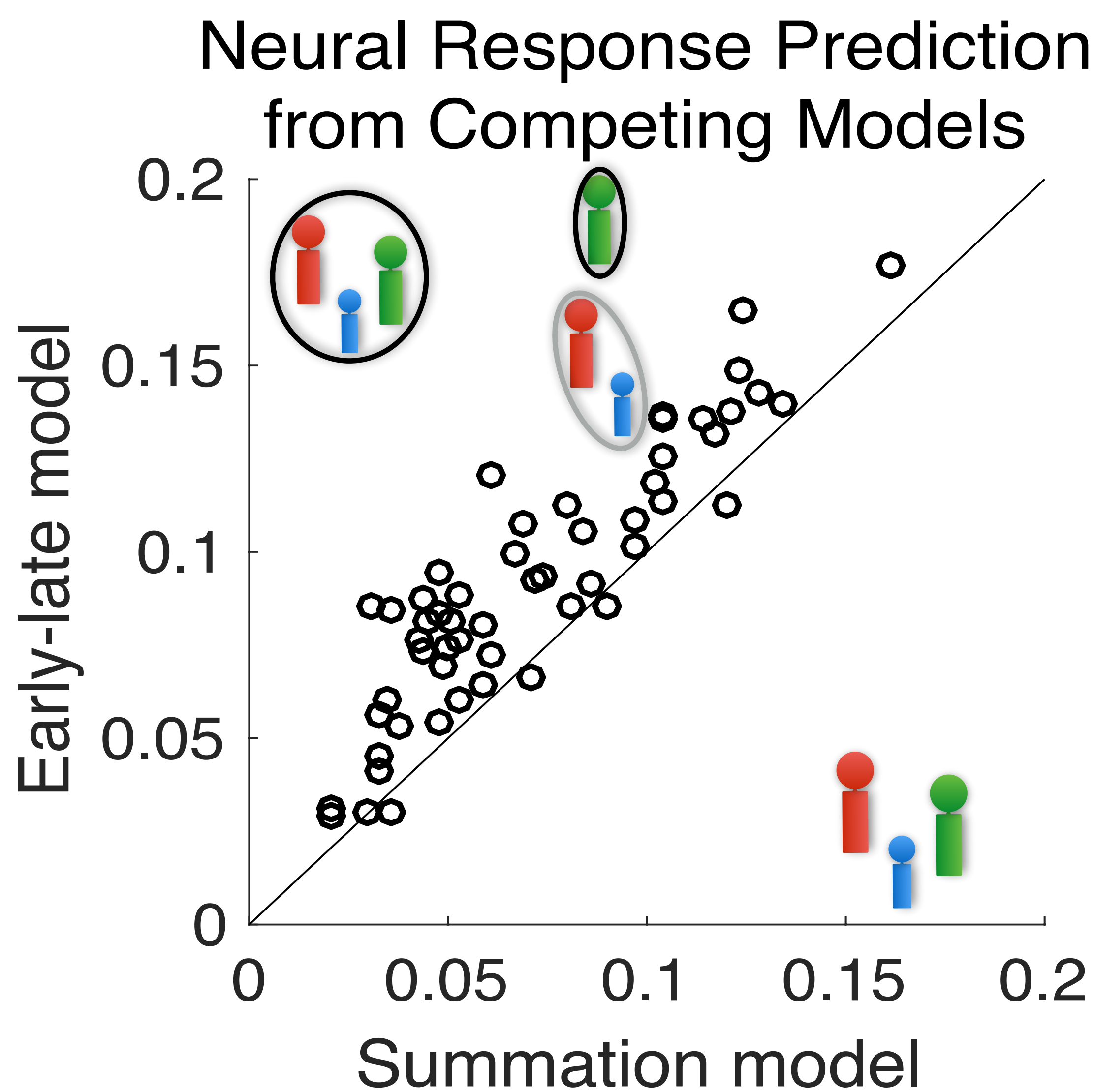
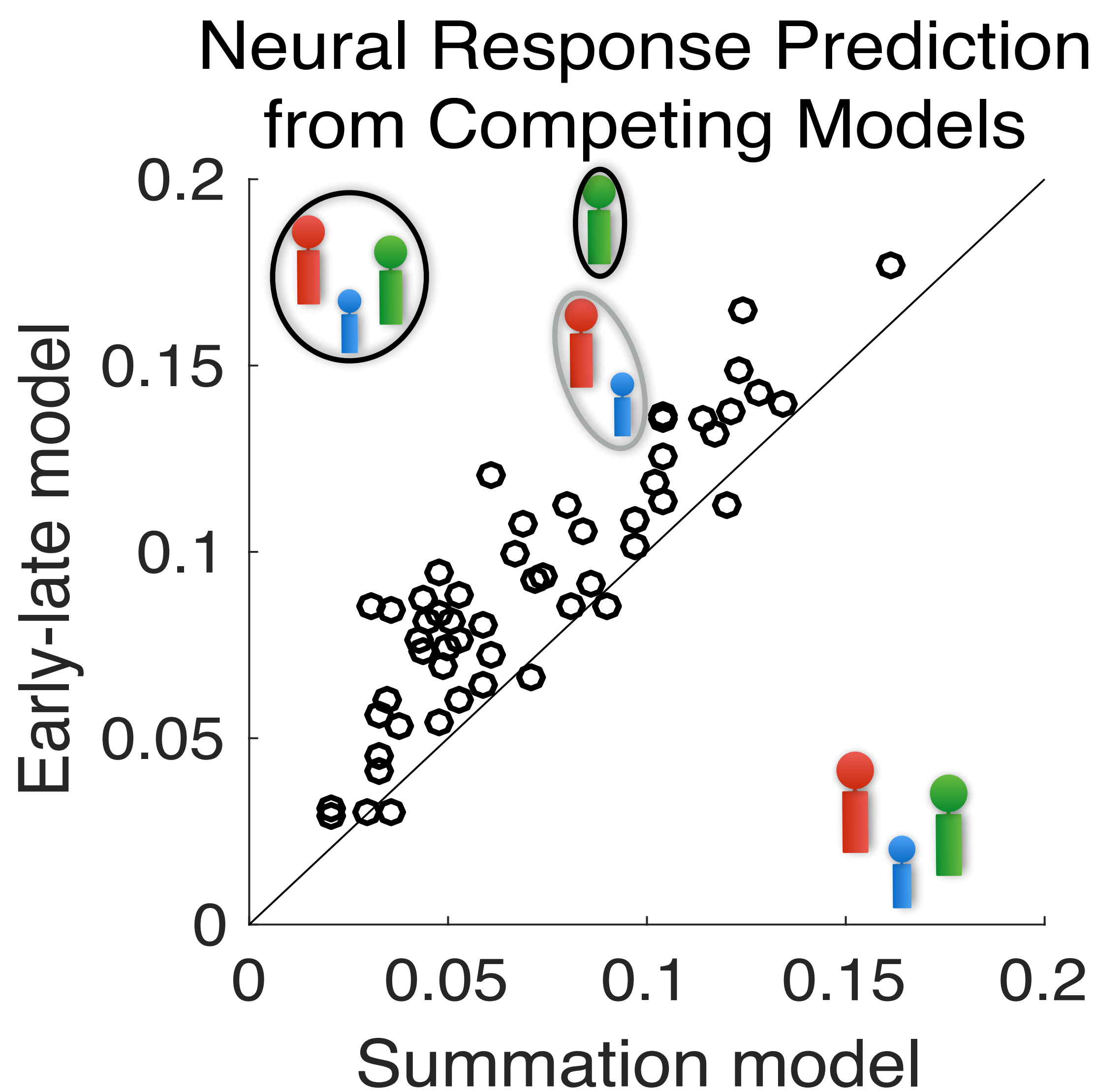


$$r(t)=\sum_{\tau} TRF_a(t-\tau)S_a(\tau)+\sum_{\tau} TRF_b(t-\tau)S_b(\tau)+\sum_{\tau} TRF_c(t-\tau)S_c(\tau)+\varepsilon(t)$$

Puvvada & Simon, bioRχiv (2017)

Forward Models Compared

$$r(t)=\sum_{\tau=0}^{\tau=\tau_1} TRF_{Scene}(t-\tau)S_{Scene}(\tau)+\sum_{\tau=\tau_1}^{\tau=\tau_2} TRF_{Foregound}(t-\tau)S_{Foregound}(\tau)+\sum_{\tau=\tau_1}^{\tau=\tau_2} TRF_{Background}(t-\tau)S_{Background}(\tau)+\varepsilon(t)$$



$$r(t)=\sum_{\tau} TRF_{a}(t-\tau)S_{a}(\tau)+\sum_{\tau} TRF_{b}(t-\tau)S_{b}(\tau)+\sum_{\tau} TRF_{c}(t-\tau)S_{c}(\tau)+\varepsilon(t)$$

Early-late model outperforms naive model

Puvvada & Simon, bioRχiv (2017)

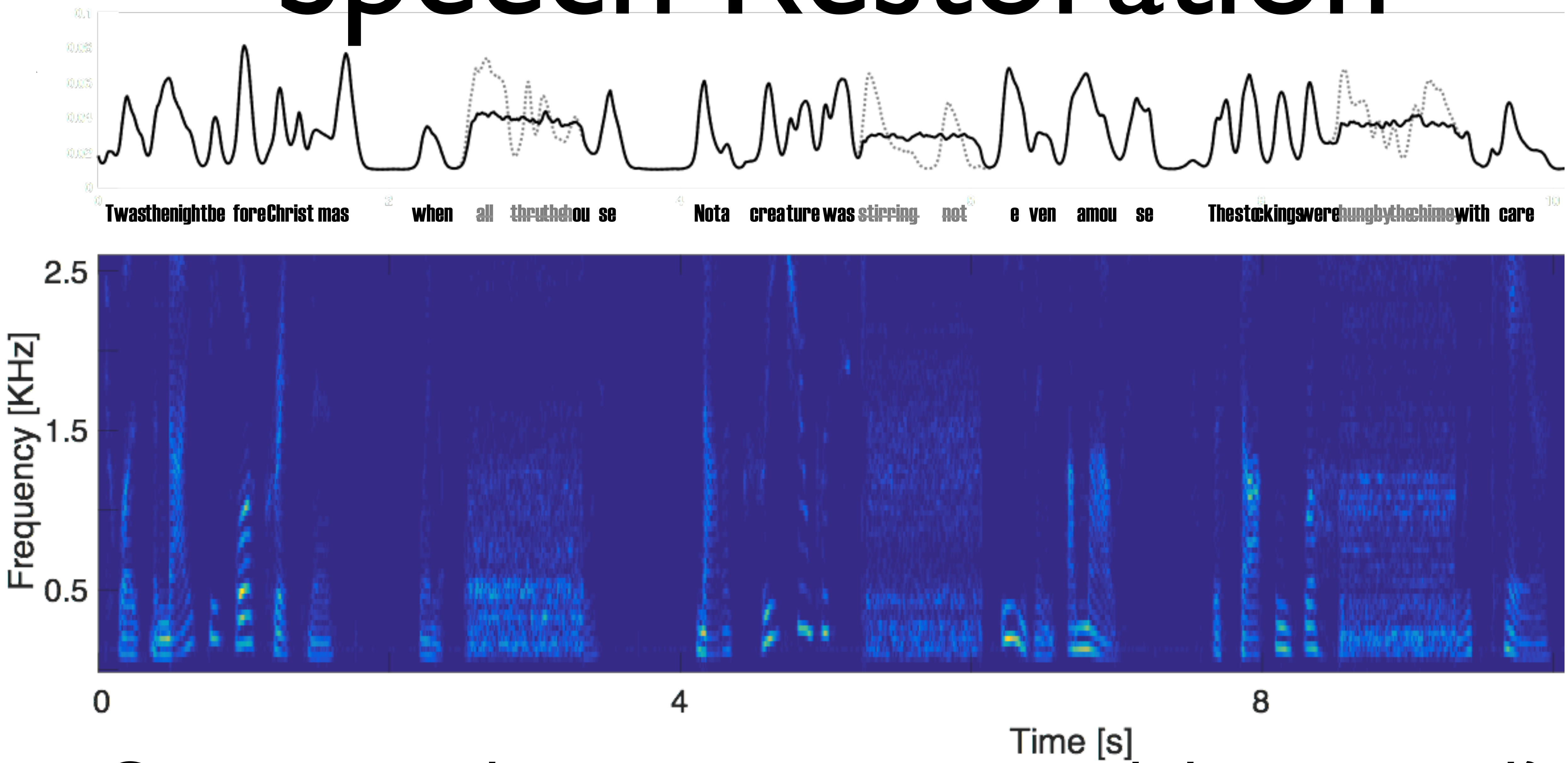
Latencies as Proxy for Cortical Areas

- Using biologically defined integration windows to reconstruct stimulus can distinguish between different representations
  - Early areas (HG) are best at reconstructing the entire acoustic sound scene
  - Later areas (PT) are best at reconstructing the foreground stream, with an integrated background
- Modified TRF model performs better than naive

Outline

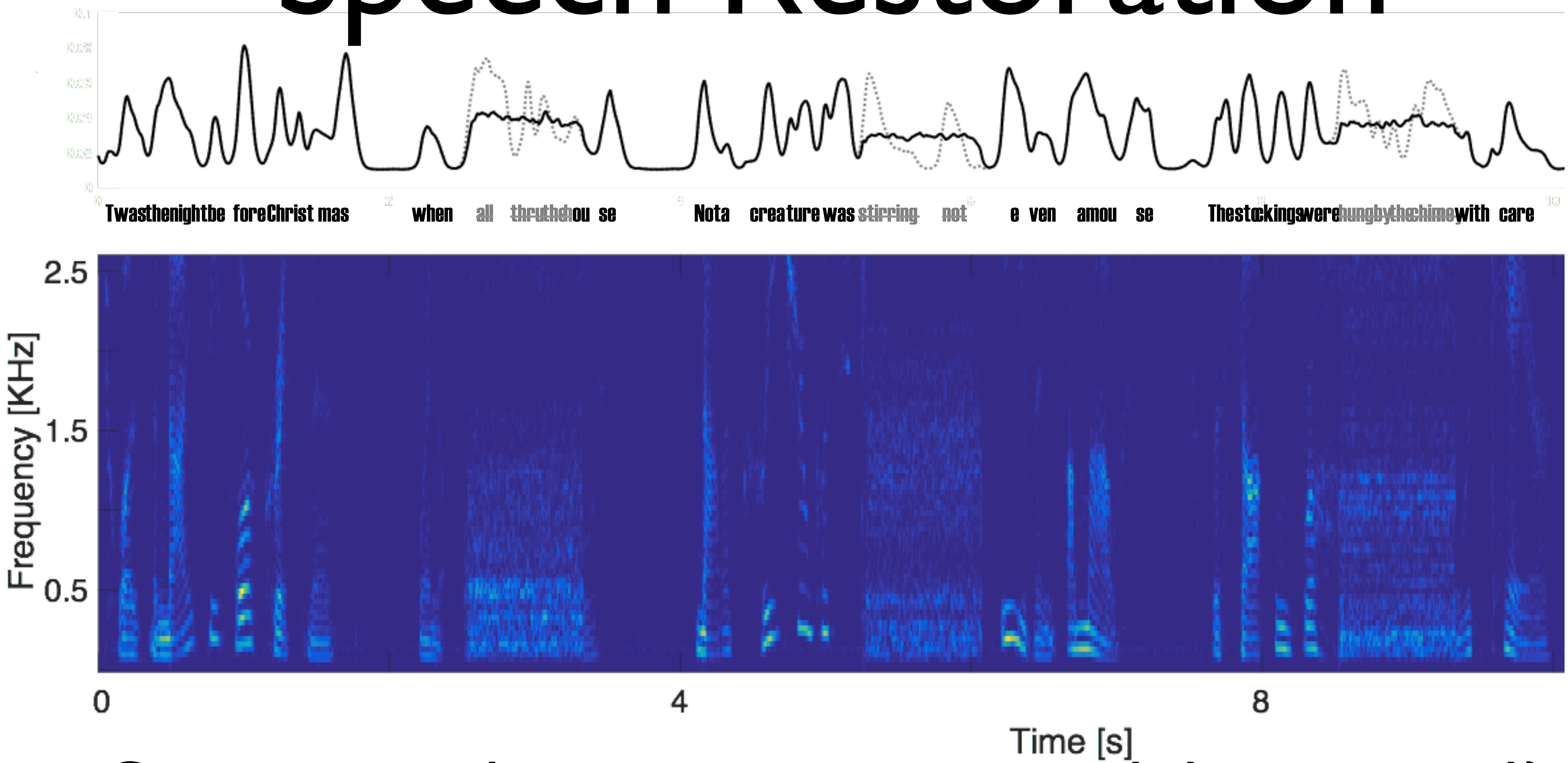
- Cortical Representations of Speech (via MEG)
  - Encoding vs. Decoding
- Cortical Representations Speech in Noise
- Recent Results
  - Aging & Cortical Representations of Speech
  - Higher Level Interference & Noise
  - Foreground and Background Representations
  - Speech Restoration

Speech Restoration



- Can sustained, non-stationary, speech be restored?
  - Might be aided by contextual knowledge/familiarity
  - Might be aided by strong rhythmicity

Speech Restoration



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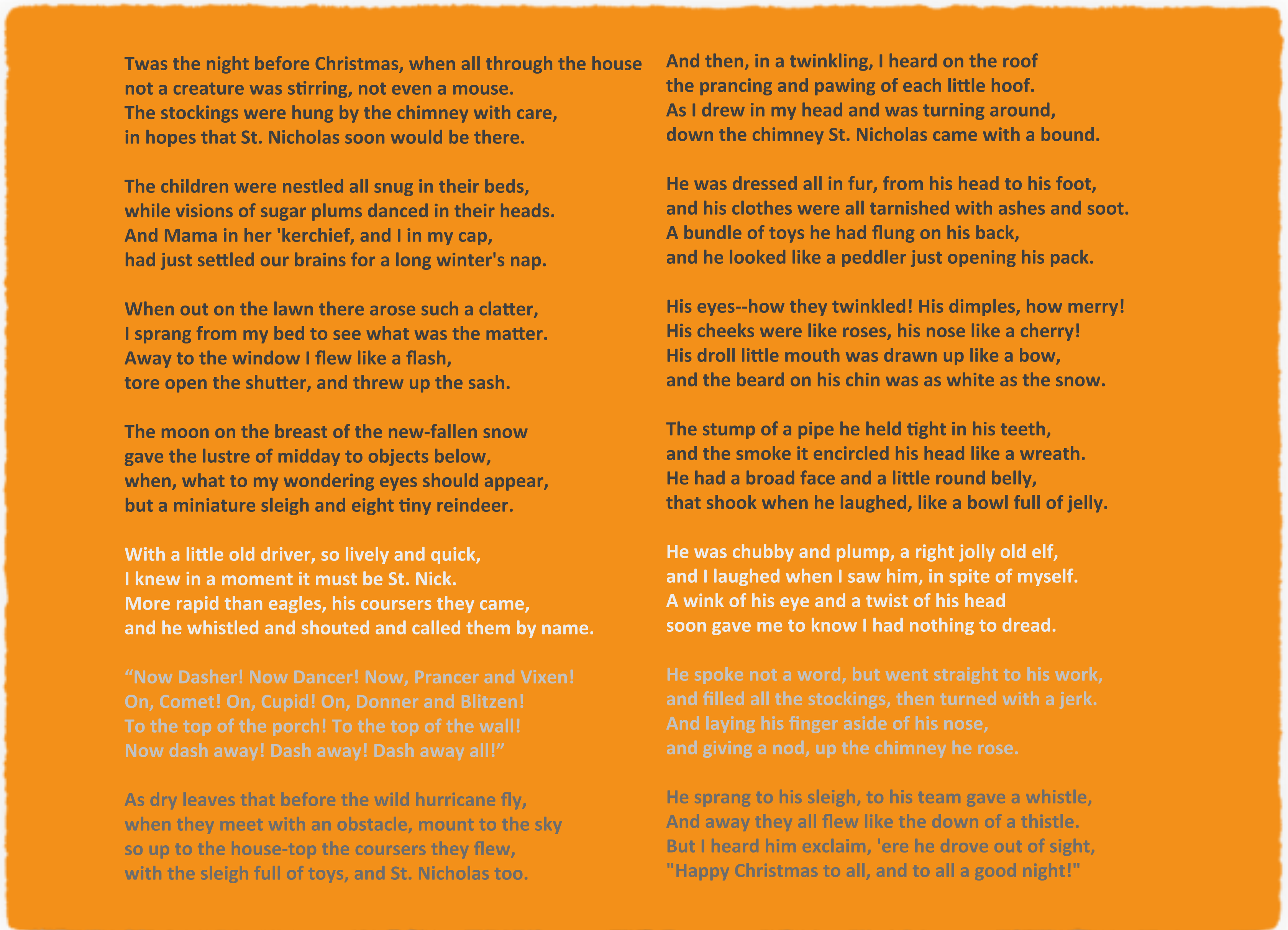
Speech Restoration



Twas the night before Christmas, when all through the house
not a creature was stirring, not even a mouse.
The stockings were hung by the chimney with care,
in hopes that St. Nicholas soon would be there.

The children were nestled all snug in their beds,
while visions of sugar plums danced in their heads.
And Mama in her 'kerchief, and I in my cap,
had just settled our brains for a long winter's nap.

When out on the lawn there arose such a clatter,
I sprang from my bed to see what was the matter.
Away to the window I flew like a flash,
tore open the shutter, and threw up the sash.

The moon on the breast of the new-fallen snow
gave the lustre of midday to objects below,
when, what to my wondering eyes should appear,
but a miniature sleigh and eight tiny reindeer.

With a little old driver, so lively and quick,
I knew in a moment it must be St. Nick.
More rapid than eagles, his coursers they came,
and he whistled and shouted and called them by name.

"Now Dasher! Now Dancer! Now, Prancer and Vixen!
On, Comet! On, Cupid! On, Donner and Blitzen!
To the top of the porch! To the top of the wall!
Now dash away! Dash away! Dash away all!"

As dry leaves that before the wild hurricane fly,
when they meet with an obstacle, mount to the sky
so up to the house-top the coursers they flew,
with the sleigh full of toys, and St. Nicholas too.

And then, in a twinkling, I heard on the roof
the prancing and pawing of each little hoof.
As I drew in my head and was turning around,
down the chimney St. Nicholas came with a bound.

He was dressed all in fur, from his head to his foot,
and his clothes were all tarnished with ashes and soot.
A bundle of toys he had flung on his back,
and he looked like a peddler just opening his pack.

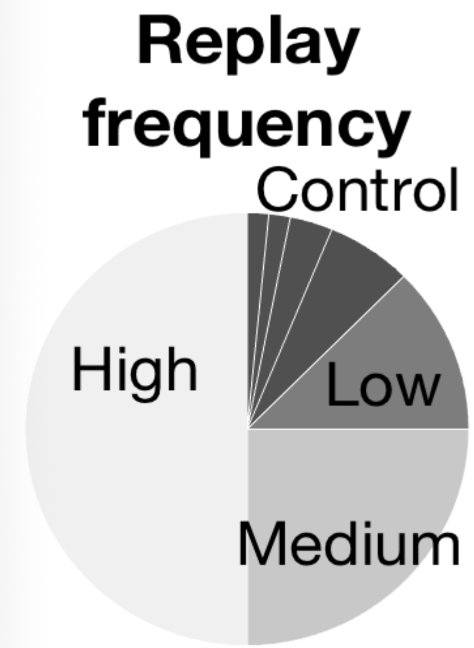
His eyes--how they twinkled! His dimples, how merry!
His cheeks were like roses, his nose like a cherry!
His droll little mouth was drawn up like a bow,
and the beard on his chin was as white as the snow.

The stump of a pipe he held tight in his teeth,
and the smoke it encircled his head like a wreath.
He had a broad face and a little round belly,
that shook when he laughed, like a bowl full of jelly.

He was chubby and plump, a right jolly old elf,
and I laughed when I saw him, in spite of myself.
A wink of his eye and a twist of his head
soon gave me to know I had nothing to dread.

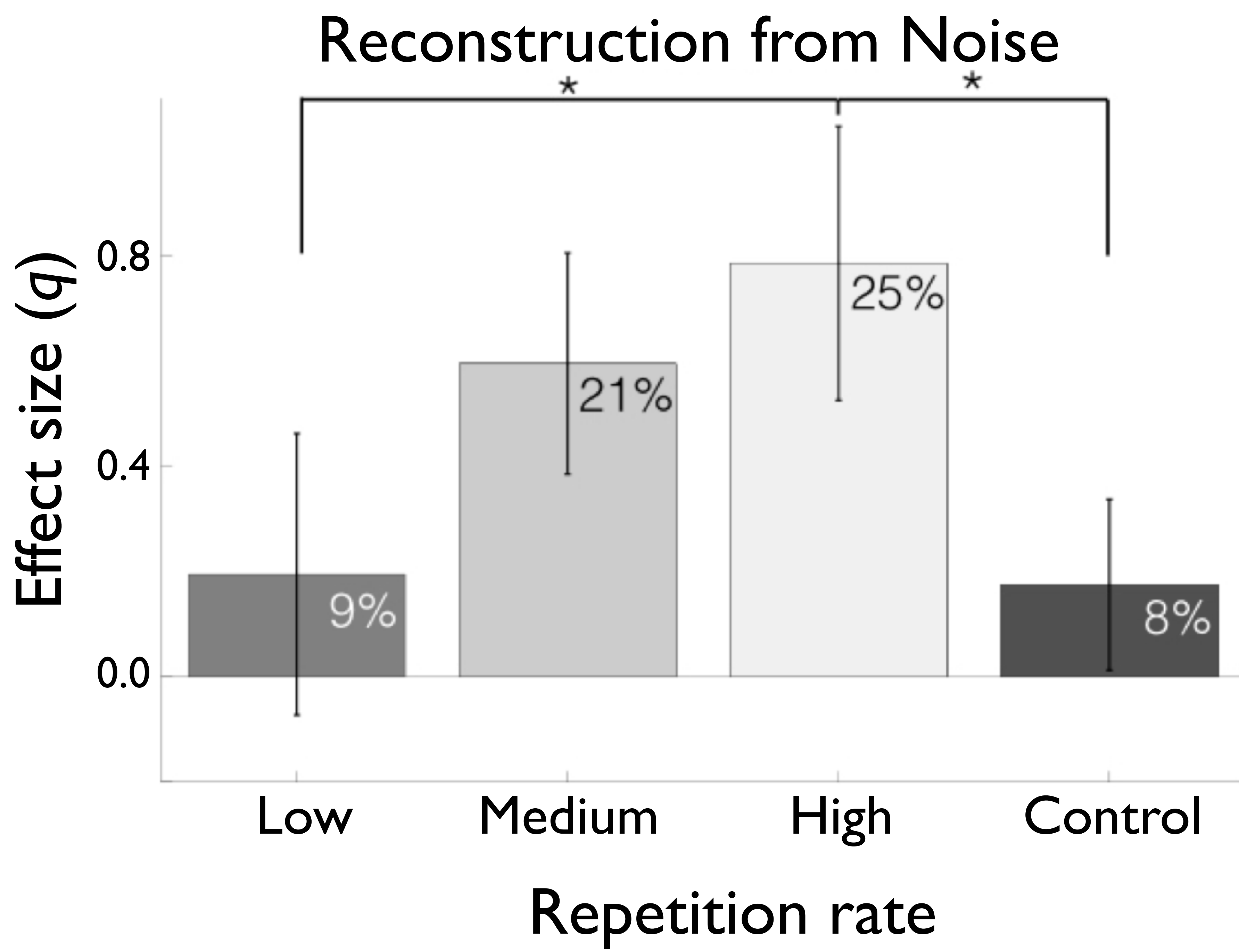
He spoke not a word, but went straight to his work,
and filled all the stockings, then turned with a jerk.
And laying his finger aside of his nose,
and giving a nod, up the chimney he rose.

He sprang to his sleigh, to his team gave a whistle,
And away they all flew like the down of a thistle.
But I heard him exclaim, 'ere he drove out of sight,
"Happy Christmas to all, and to all a good night!"

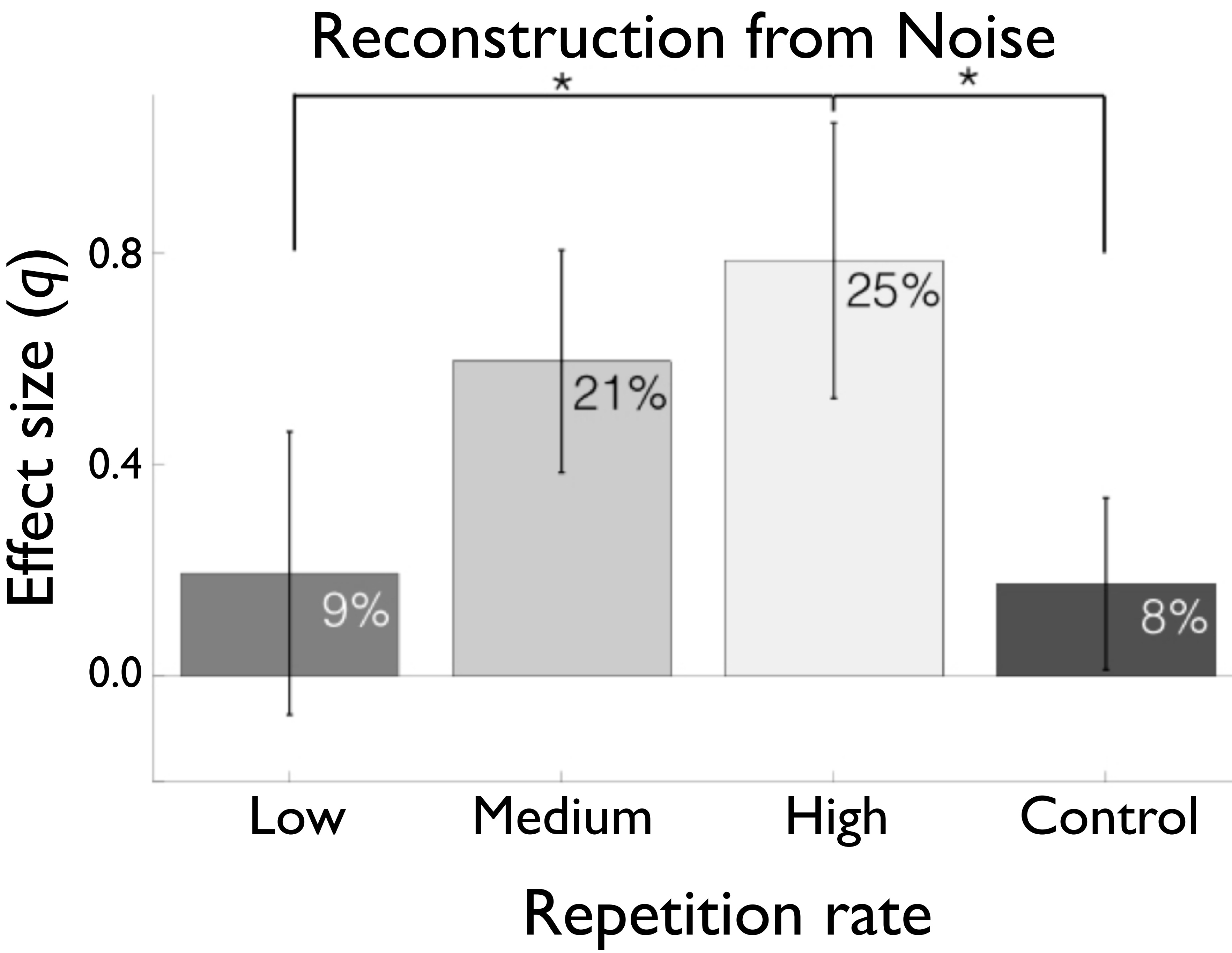


- Hypothesis: contextual knowledge of missing speech can be controlled by exposure to the speech

Speech Restoration

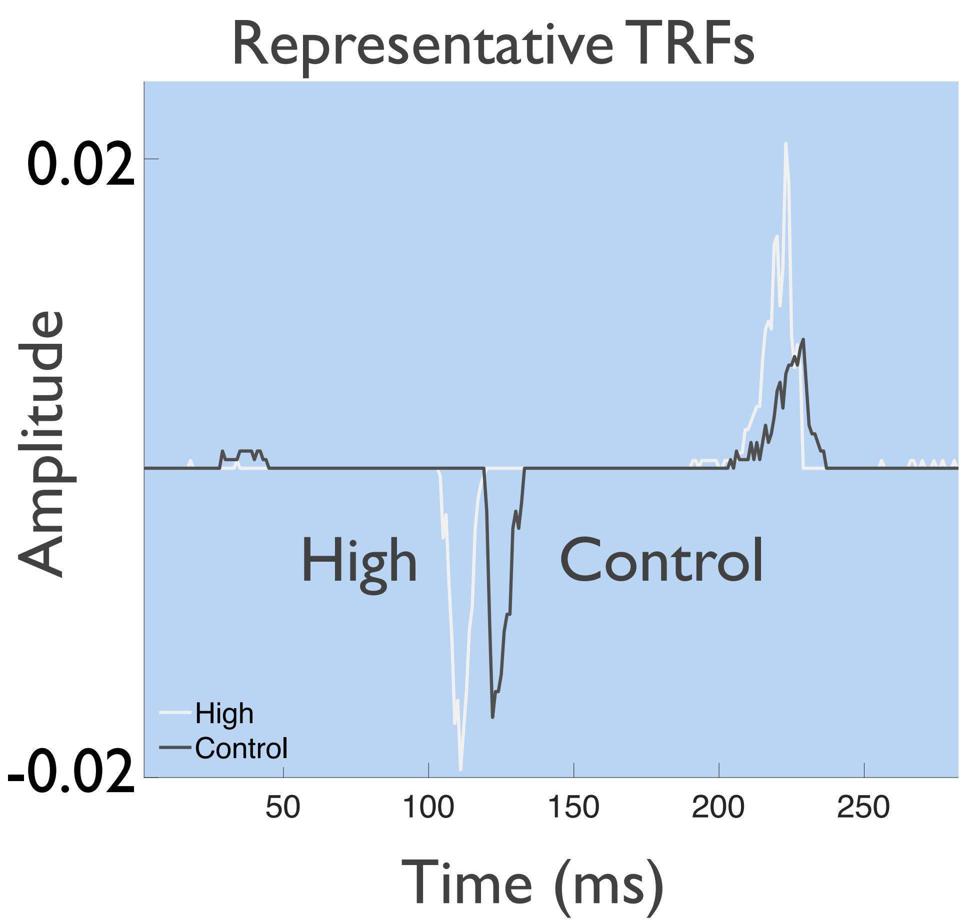


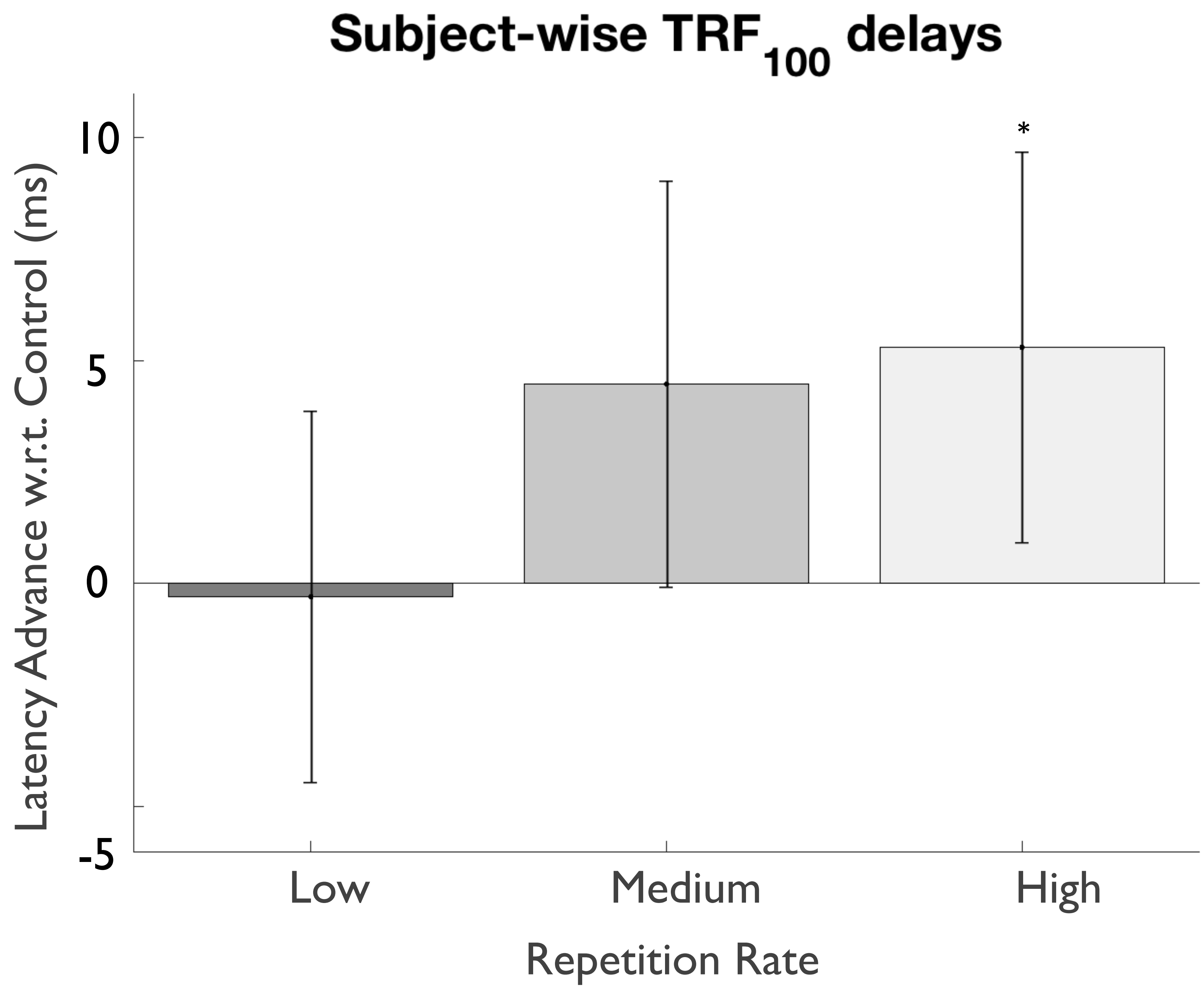
Speech Restoration



- Decoding of the ***missing*** speech token improves with prior experience
- Performance is a considerable fraction of that for clean speech

Speech Anticipation





- Prior experience speeds subsequent responses

Summary

- Cortical representations of speech in MEG
  - Representation of envelope (up to ~10 Hz)
  - Information transfer: a few bits/s
  - Robust against a variety of noise types
  - Neural representation of perceptual object
- Over-Representation with Aging
  - Reconstruction depends on integration time
  - Over-Representation tracks cognitive behavior
- Interfering speech familiarity: neural tracks behavior
- PT (late): Foreground + undifferentiated Background
- HG (early): undifferentiated entire acoustic scene

Thank You