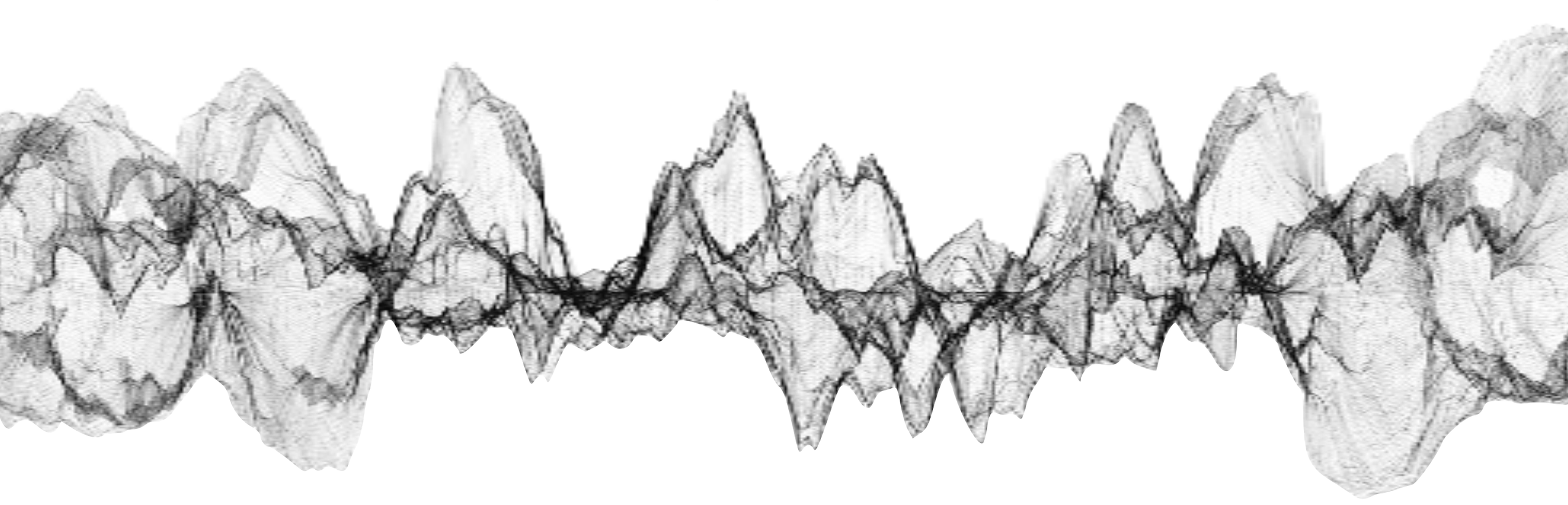
NEW YORK UNIVERSITY

# In spoken word recognition, the future predicts the past

**Laura Gwilliams**

*5th June 2017*



# Road Map

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## Completed Research:

- Sensitivity to **phonological ambiguity** is reflected in the very initial stages (~50 ms) of processing a speech sound

- Sub-phonemic information is **maintained** for long periods of time, and is **re-evoked** at subsequent phoneme positions in the spoken word

- The system **commits to phonological interpretations** on a shorter time-scale in parallel to phonetic maintenance

## Future Directions:

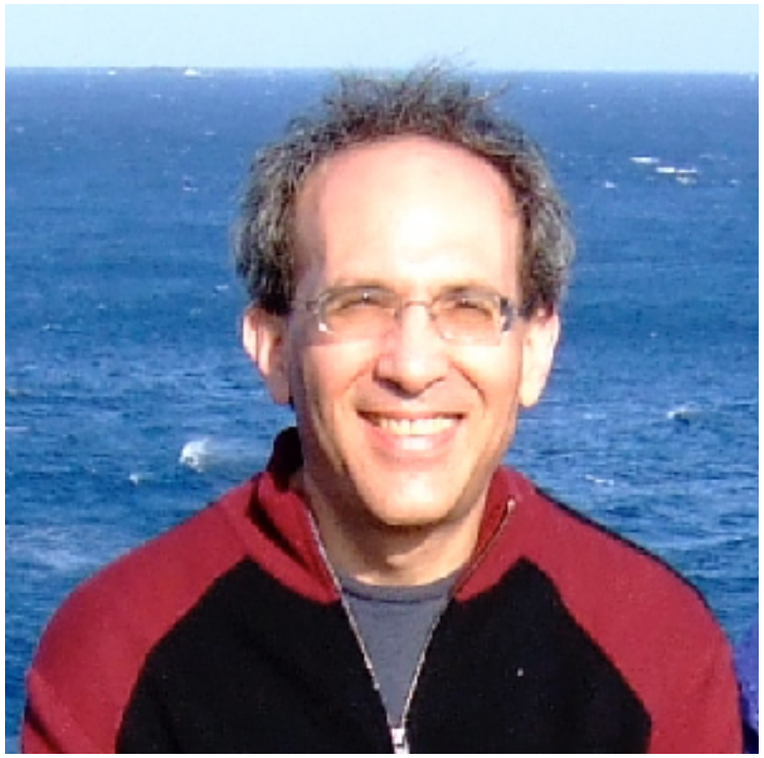
- Can we apply **machine-learning** analysis techniques to MEG data to unveil the dynamics with which sub-phonemic information is processed?

# Recognition & Resolution of Phoneme Ambiguity in Spoken Words

# Collaborators

Tal Linzen

David Poeppel



Alec Marantz

# Future Influences on Perception

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- To fluently derive meaning, listeners must **integrate top-down** contextual information to guide their interpretation

- Top-down input occurring *after* an acoustic signal can be integrated to **affect the perception of earlier sounds**
  (Bicknell et al., submitted; Connine et al., 1991; Samuel, 1981; Szostak & Pitt, 2013; Warren & Sherman, 1974)

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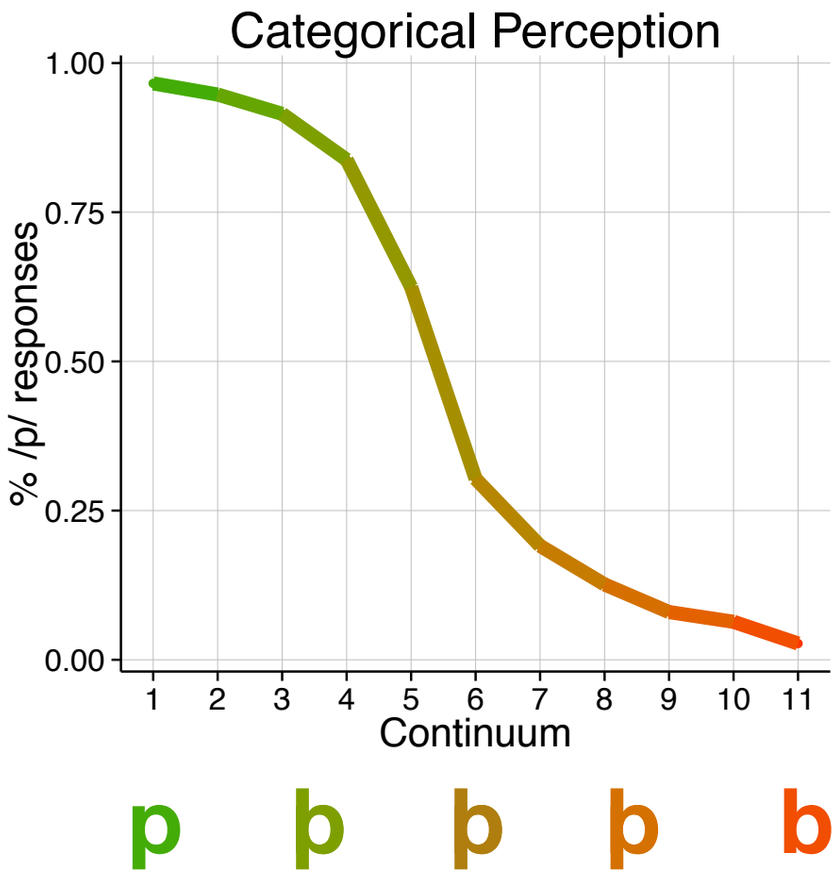

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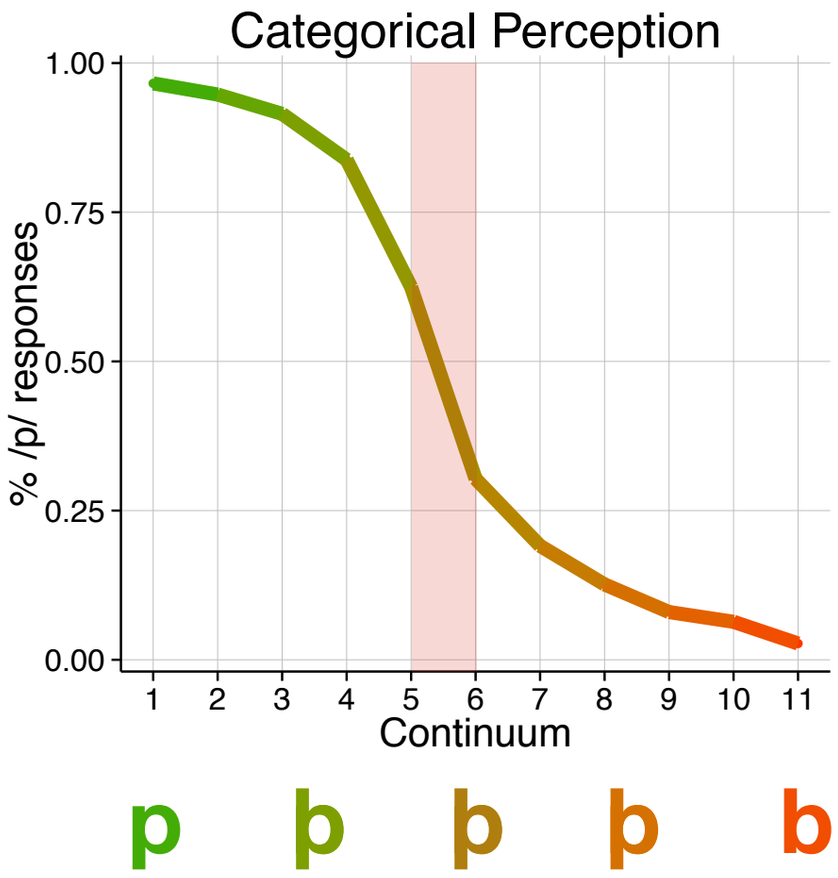

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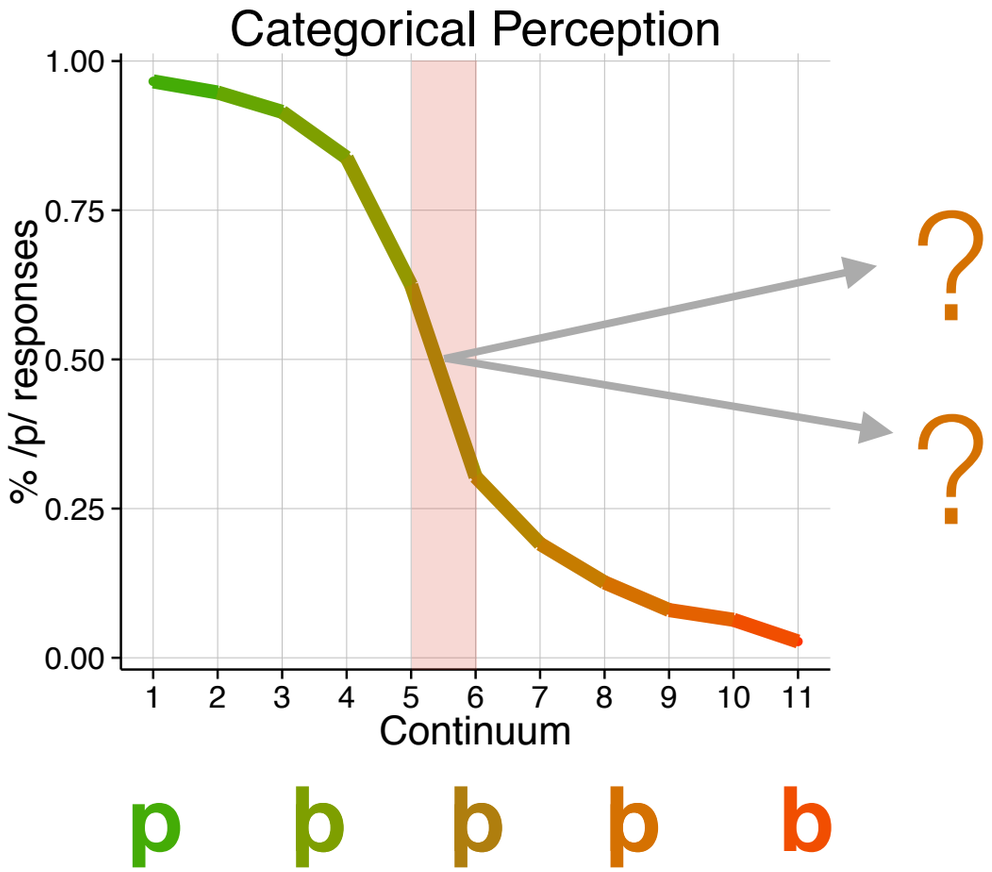

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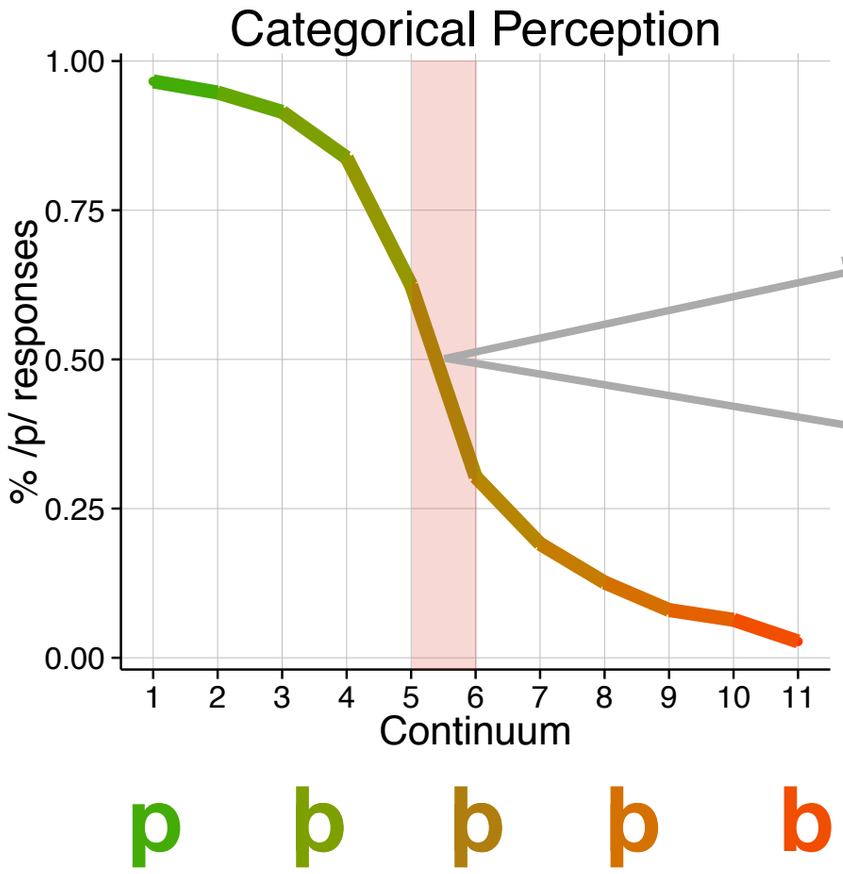


p p p p b

? a

? a

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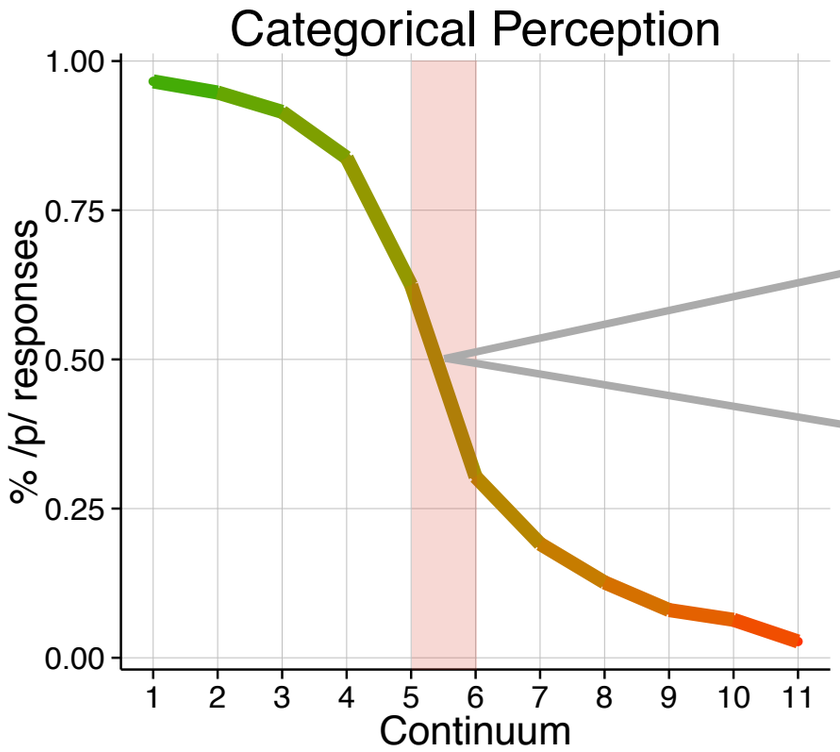


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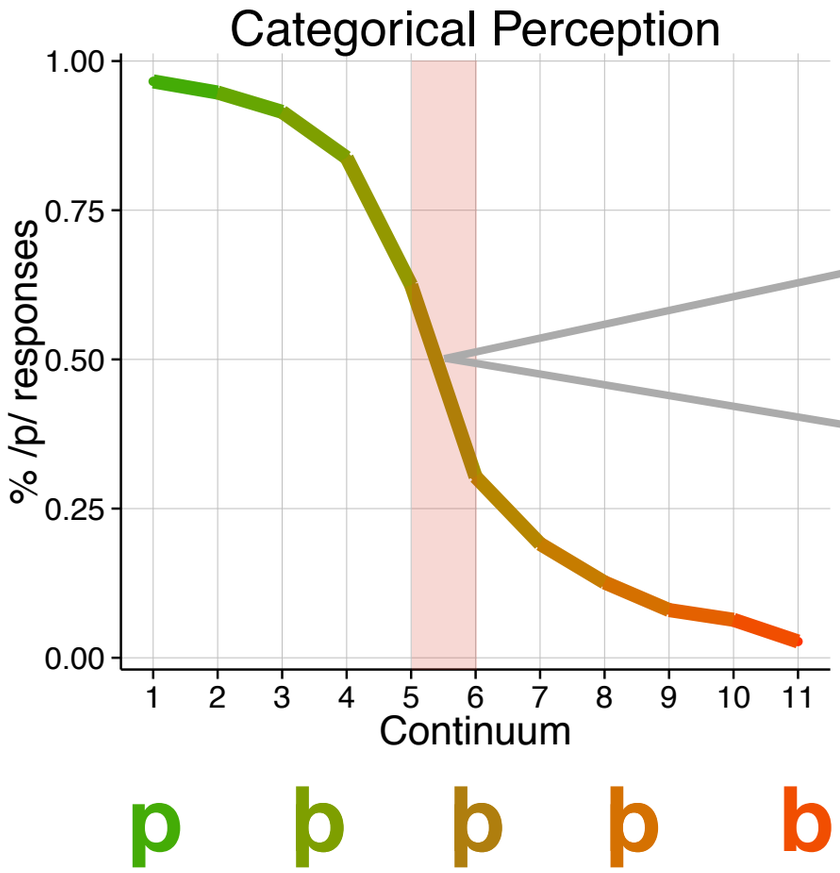


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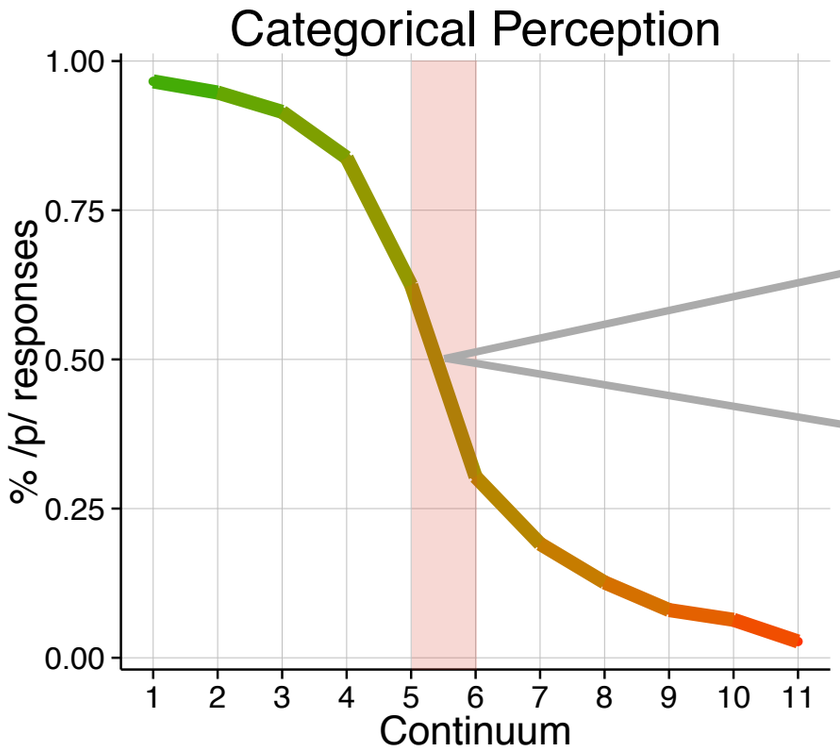


p p p p b

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? a r a k

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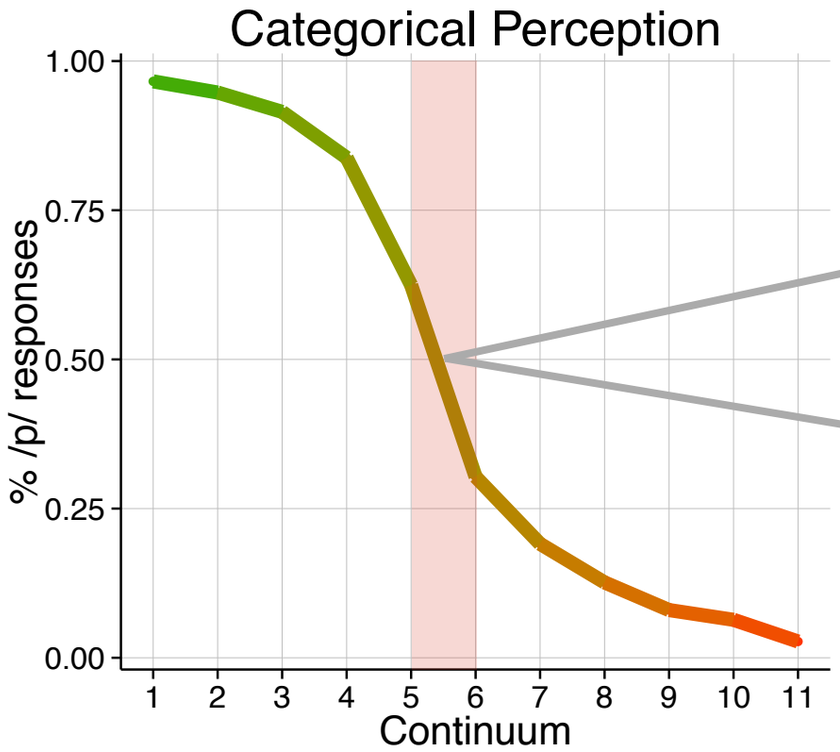


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"**P**oint **o**f **D**isambiguation" (POD)

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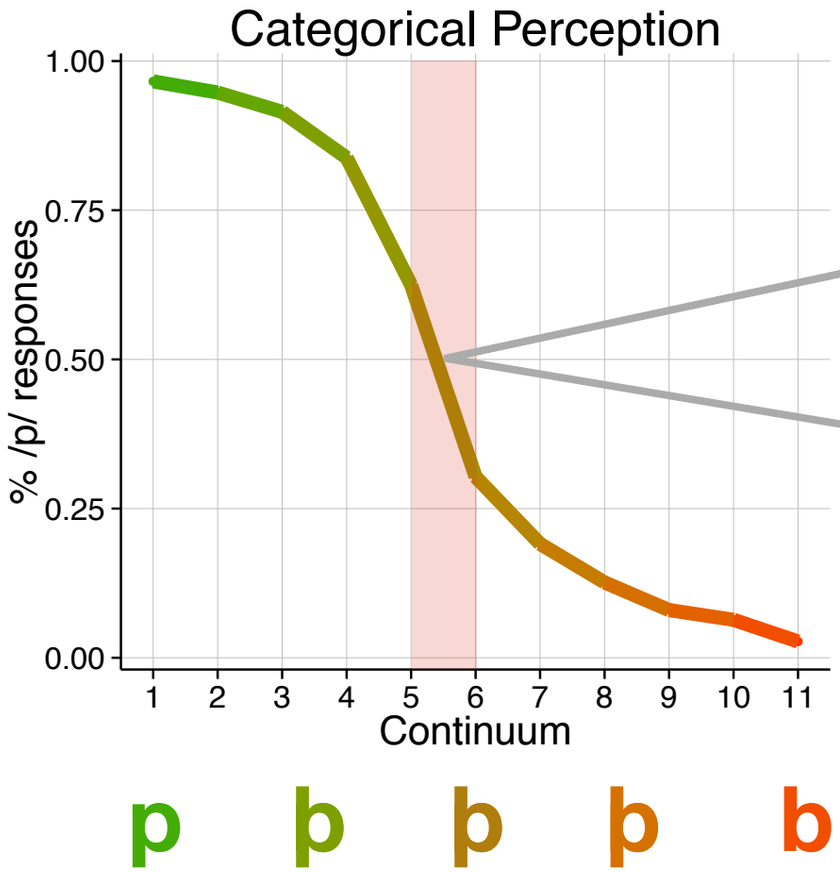


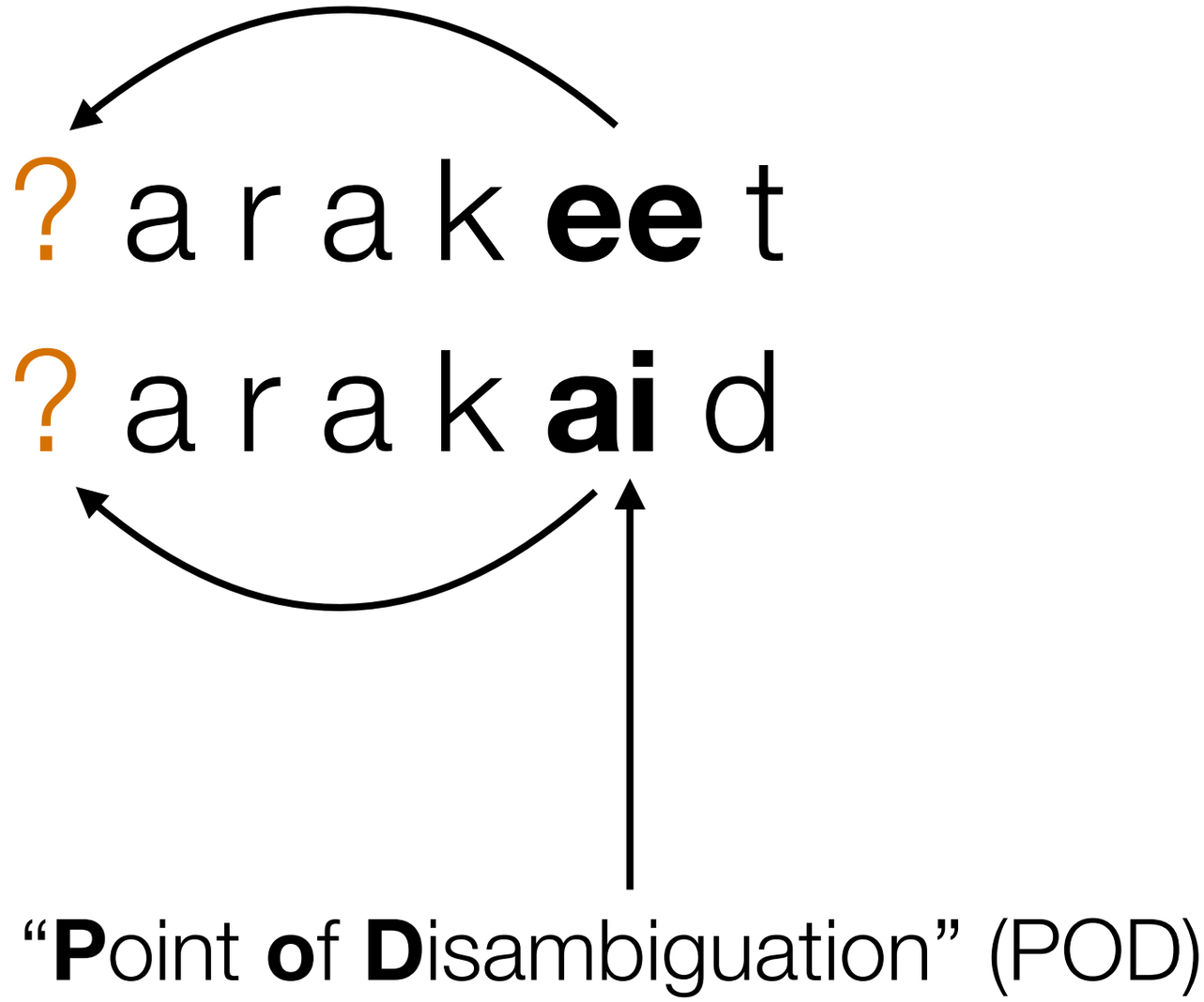

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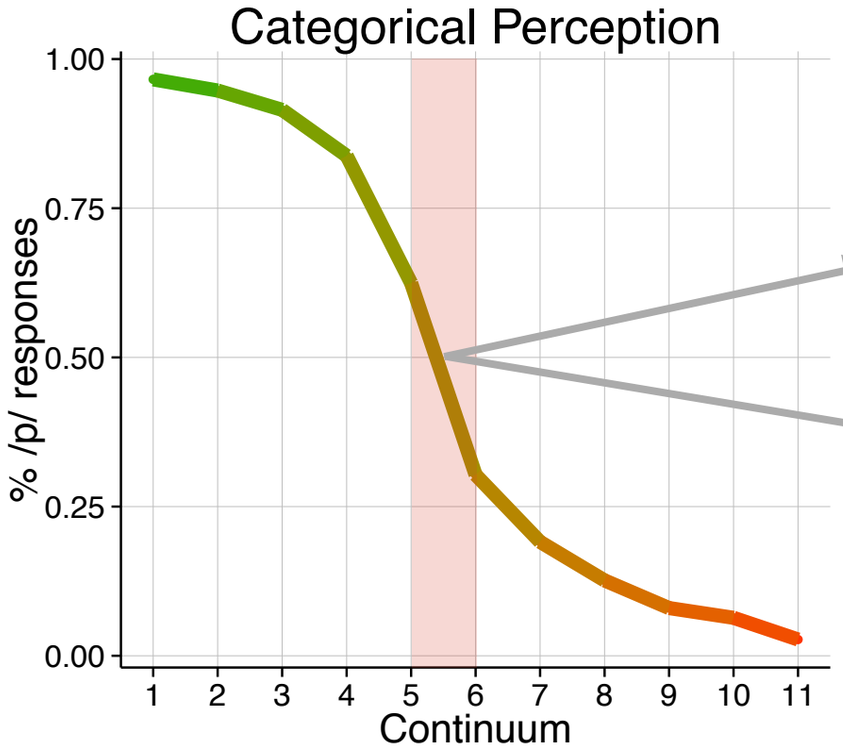


p a r a k **ee** t

b a r a k **ai** d

**(this is a parakeet)**

**(this is a barricade)**

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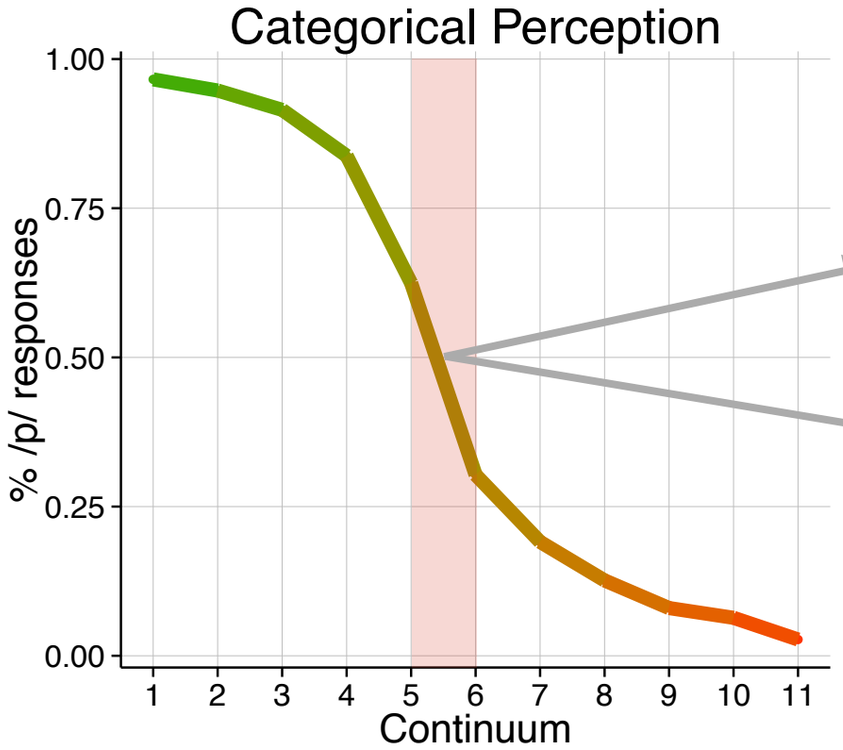


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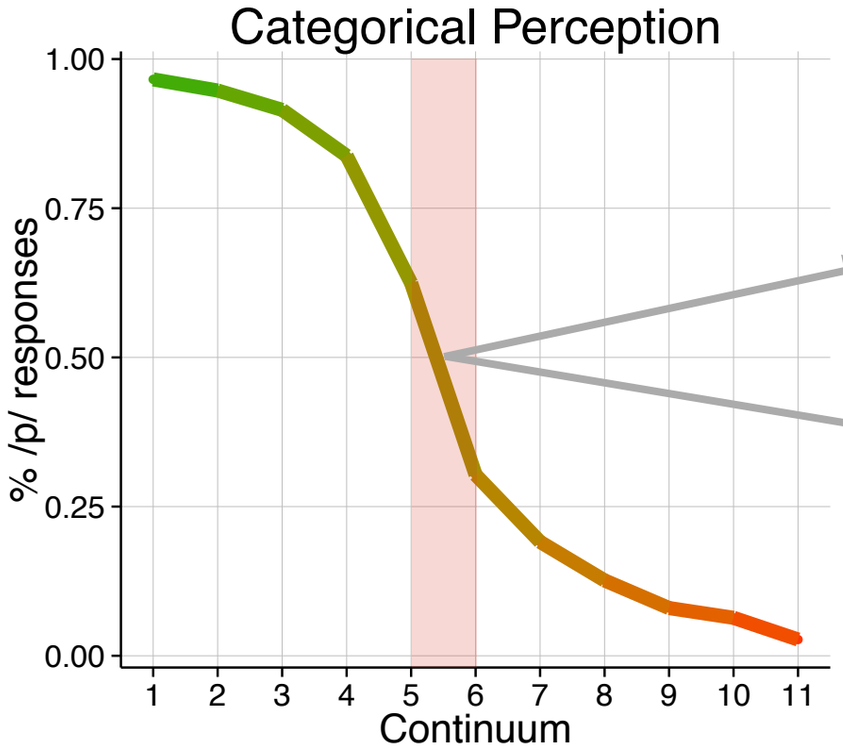


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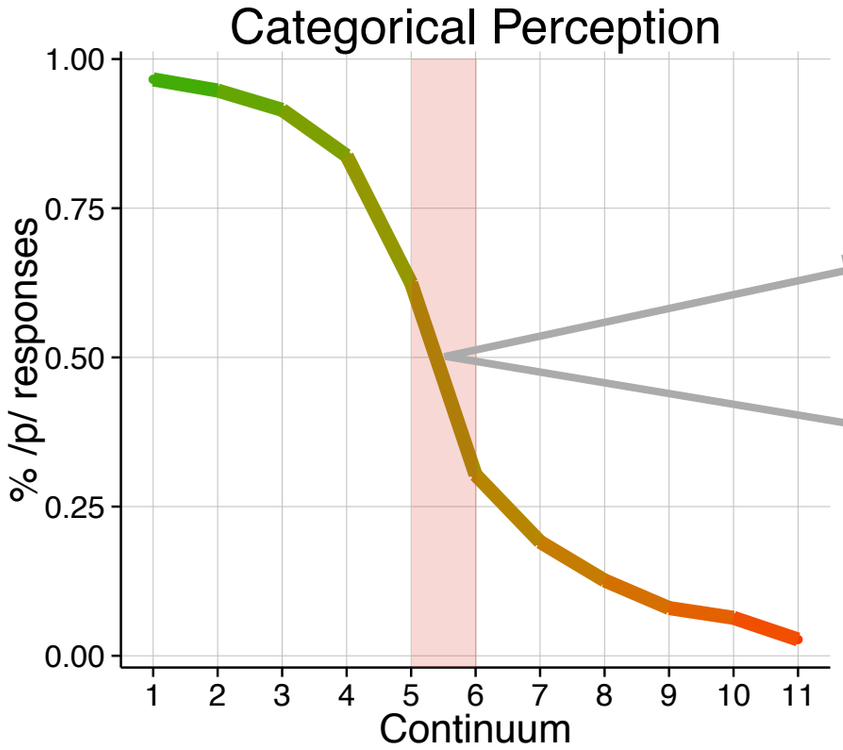


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# Today's Questions

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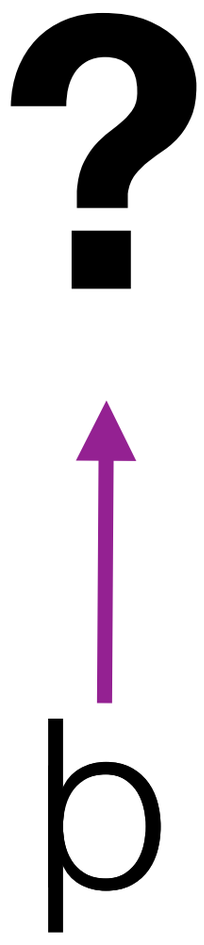
How does the auditory cortex **respond** to phonological ambiguity?



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How does the auditory cortex **respond** to phonological ambiguity?

What are the neural signatures of ambiguity **resolution**?

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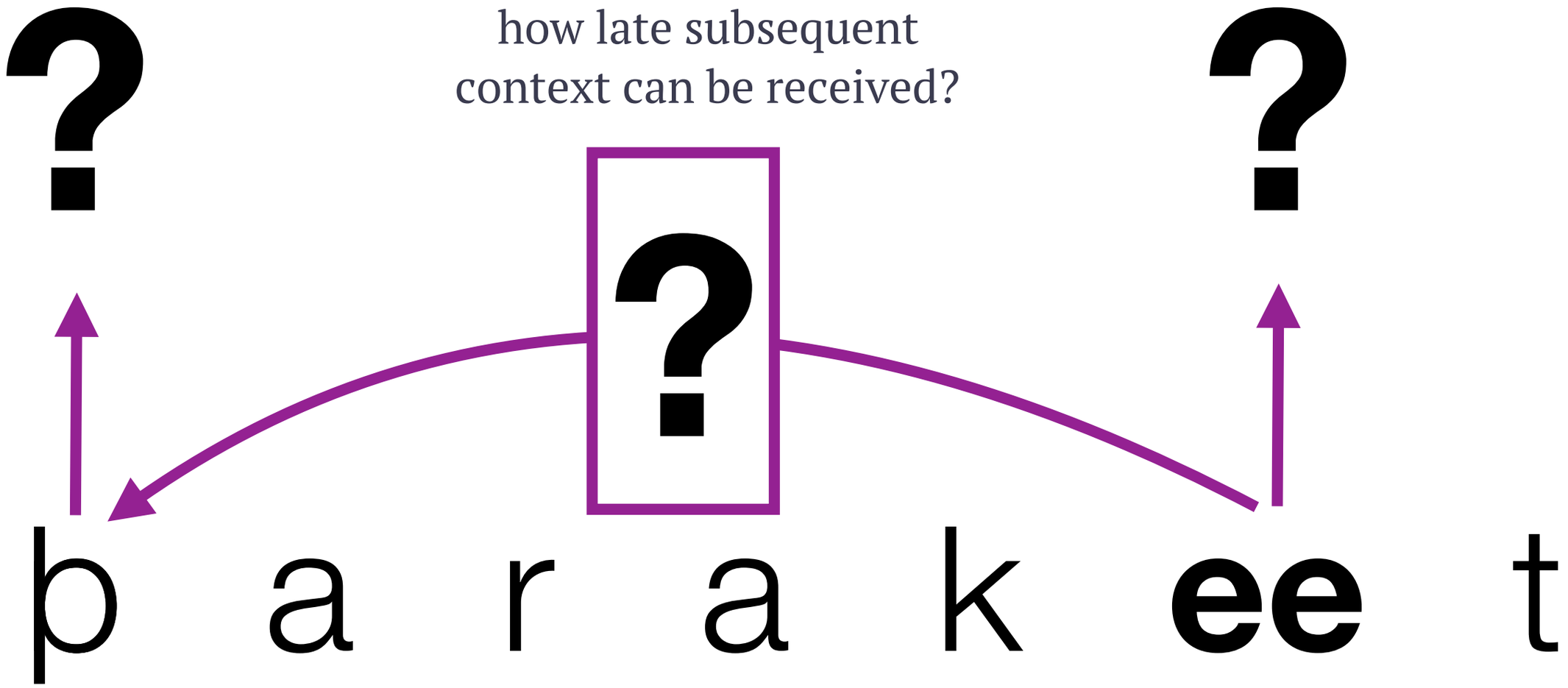
How does the auditory cortex **respond** to phonological ambiguity?

What is the **time-limit** on how late subsequent context can be received?

What are the neural signatures of ambiguity **resolution**?



# Design & Materials

53 x ?

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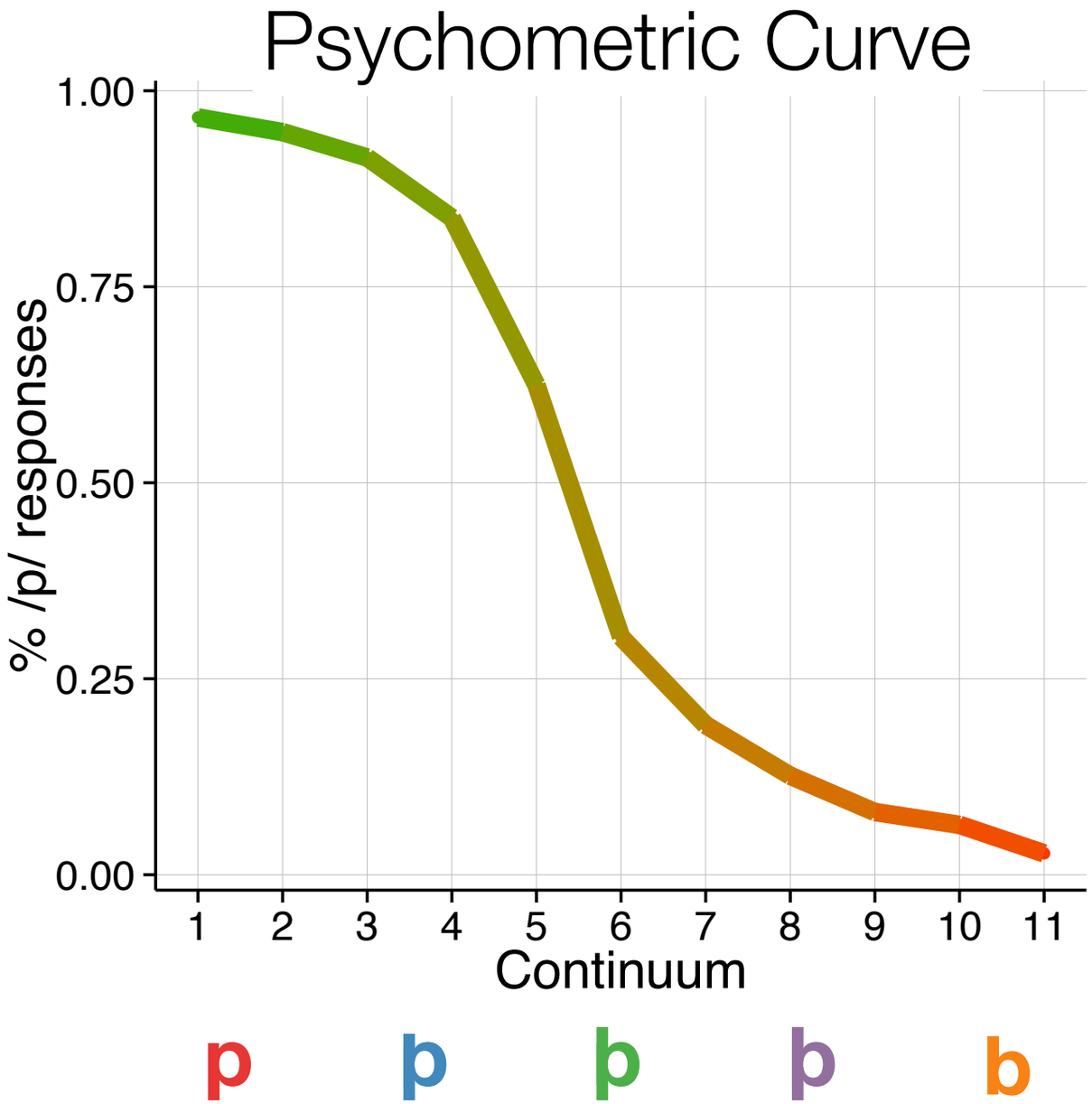
(see also McMurray et al., 2009)

# Design & Materials





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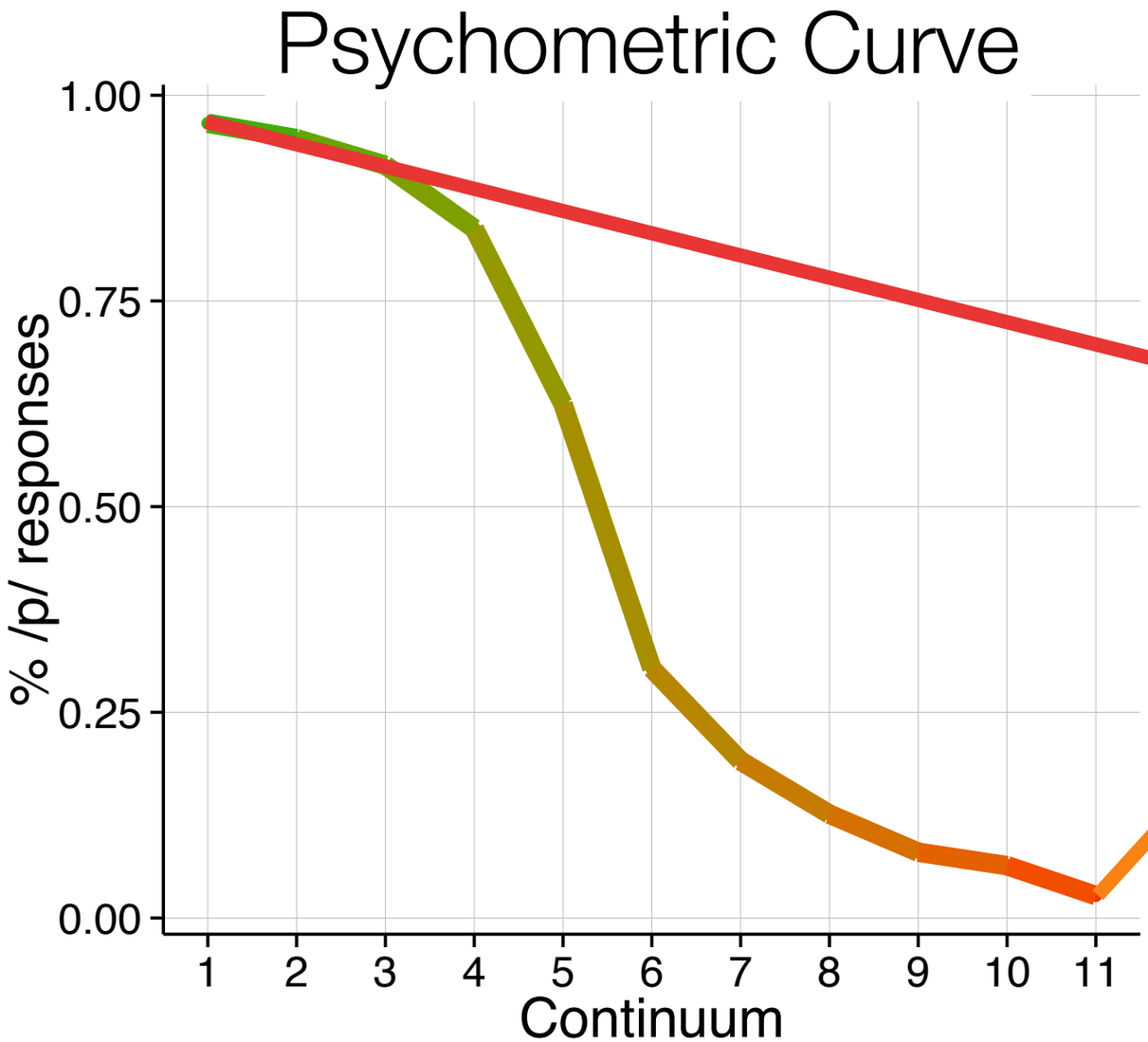


p p p p b

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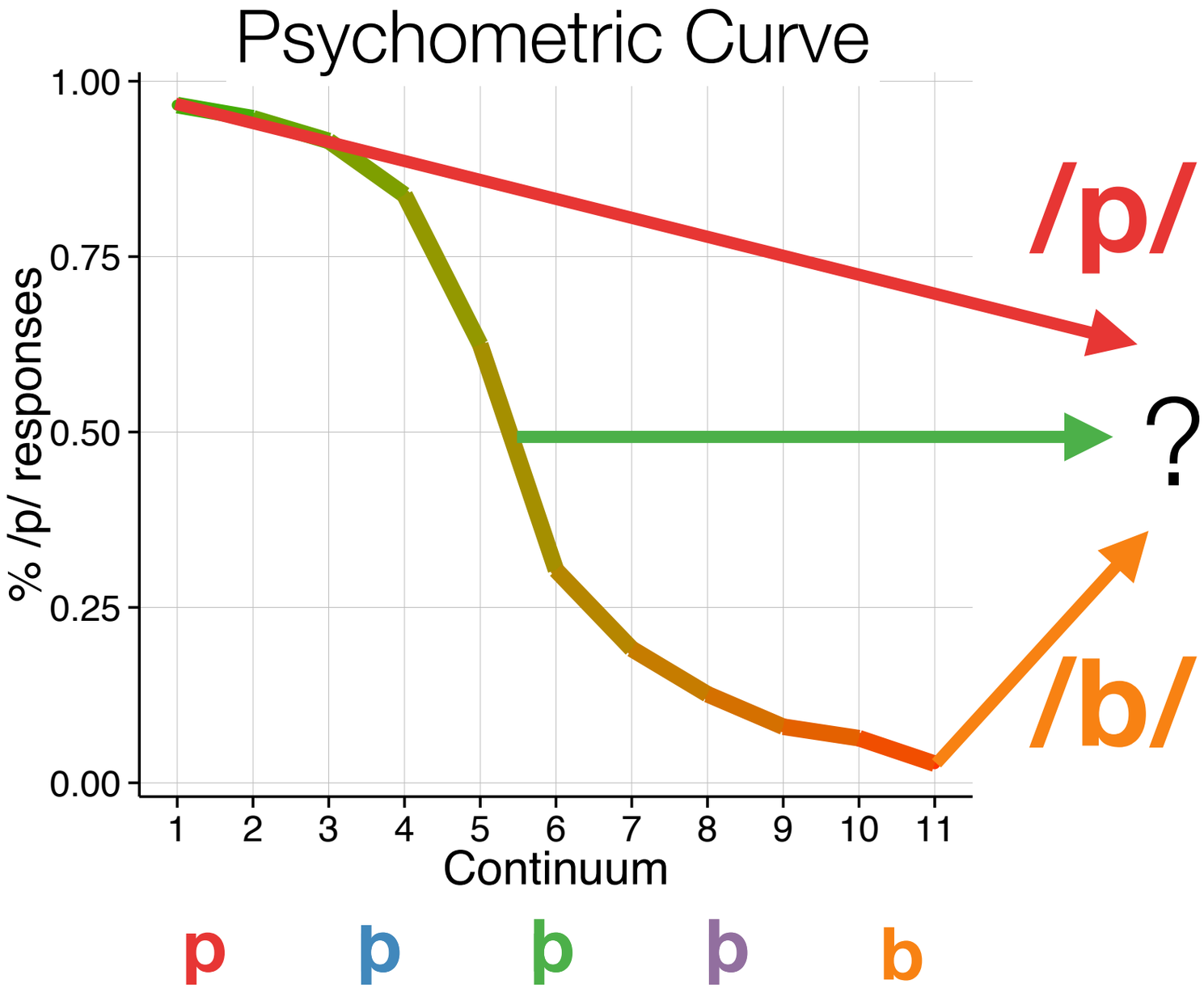


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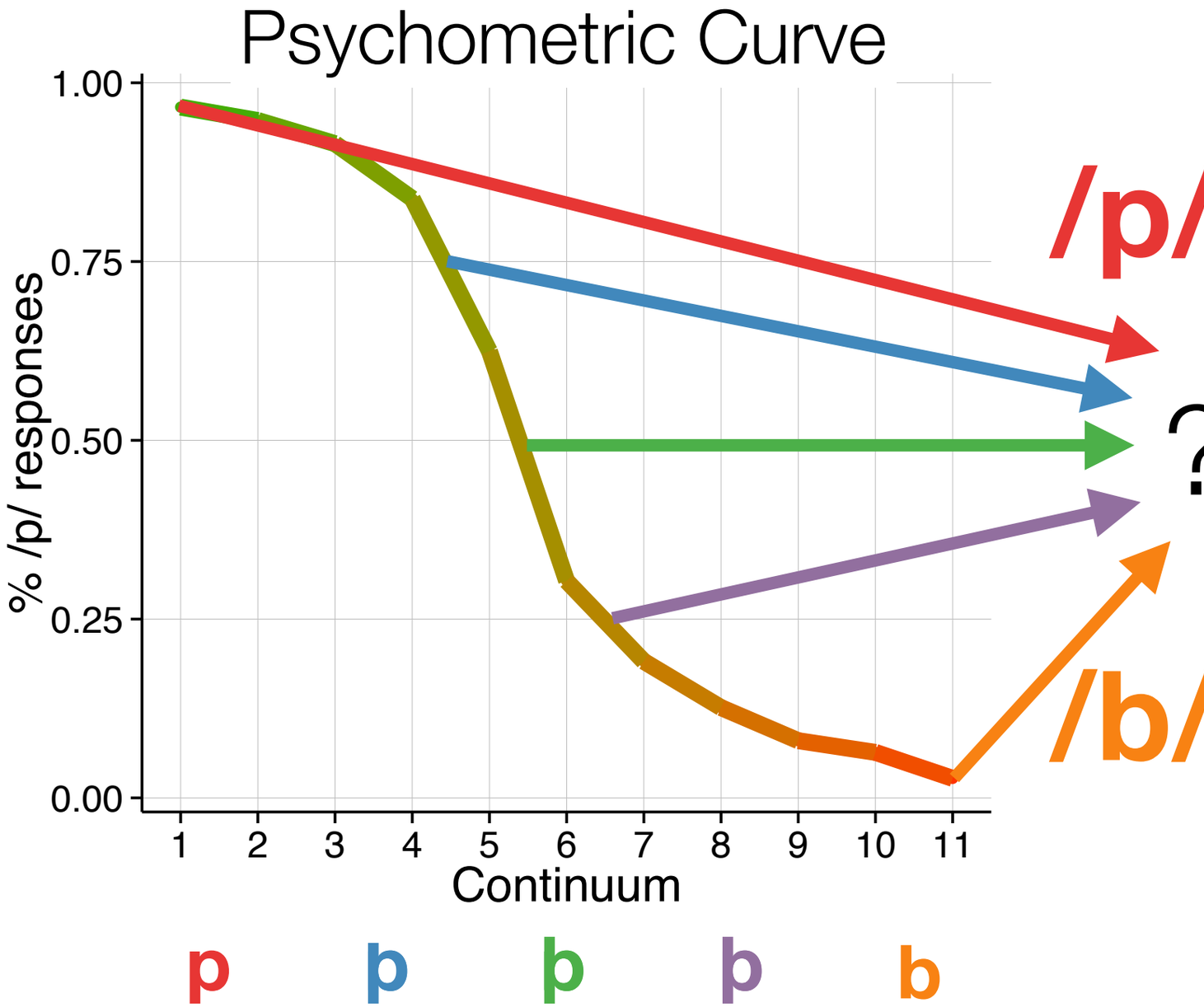


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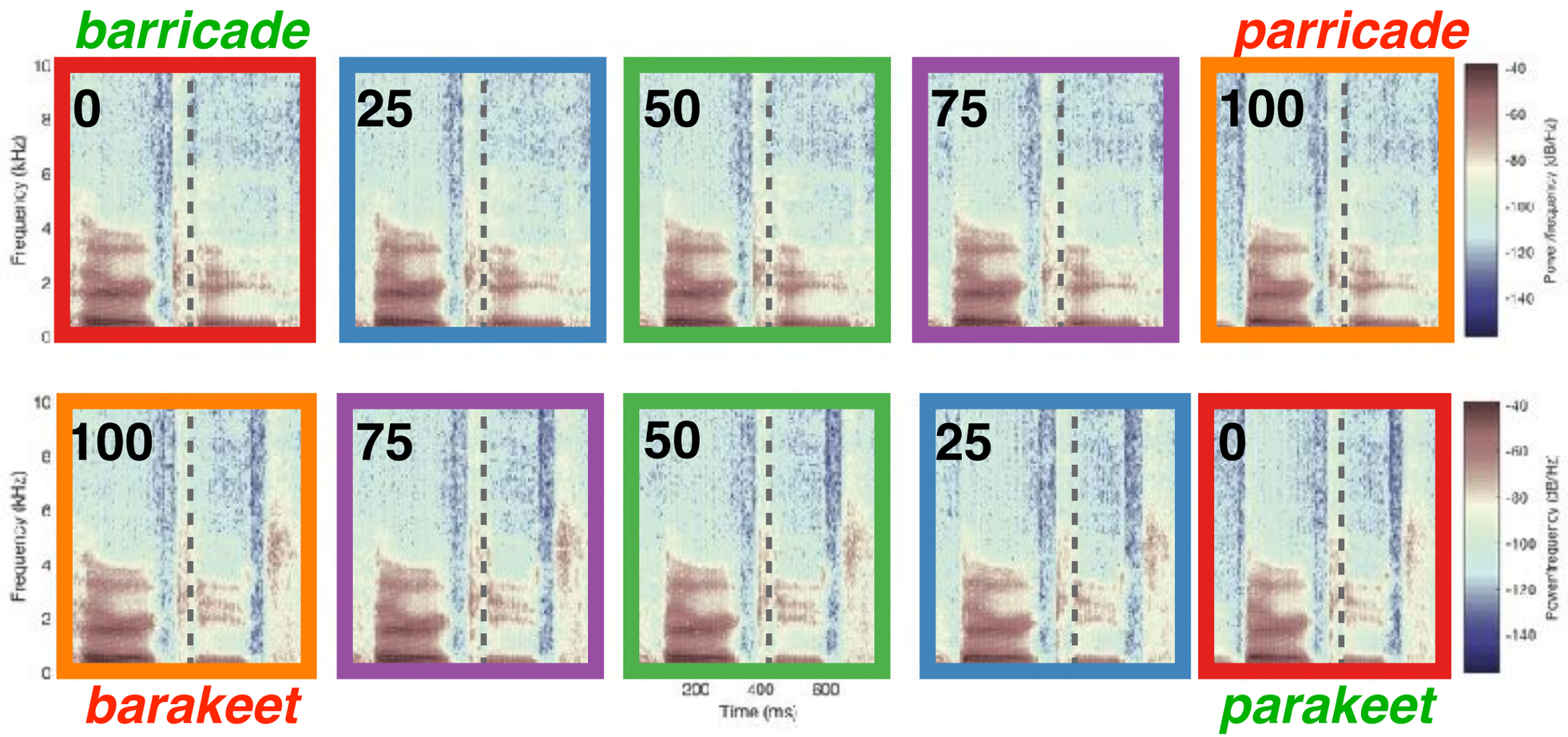

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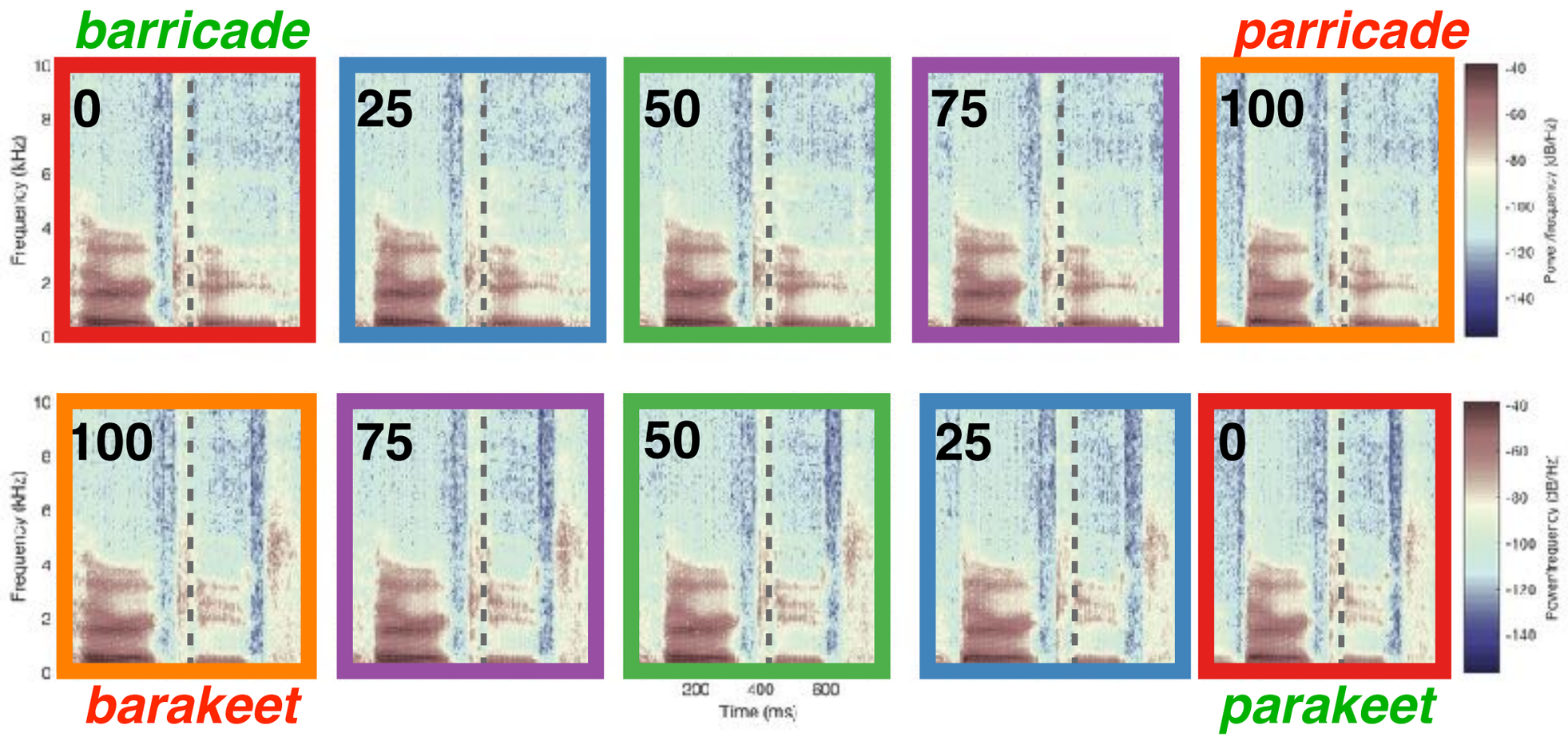


- Point of Disambiguation (POD) ranged 3-8 phonemes / 150-750 ms

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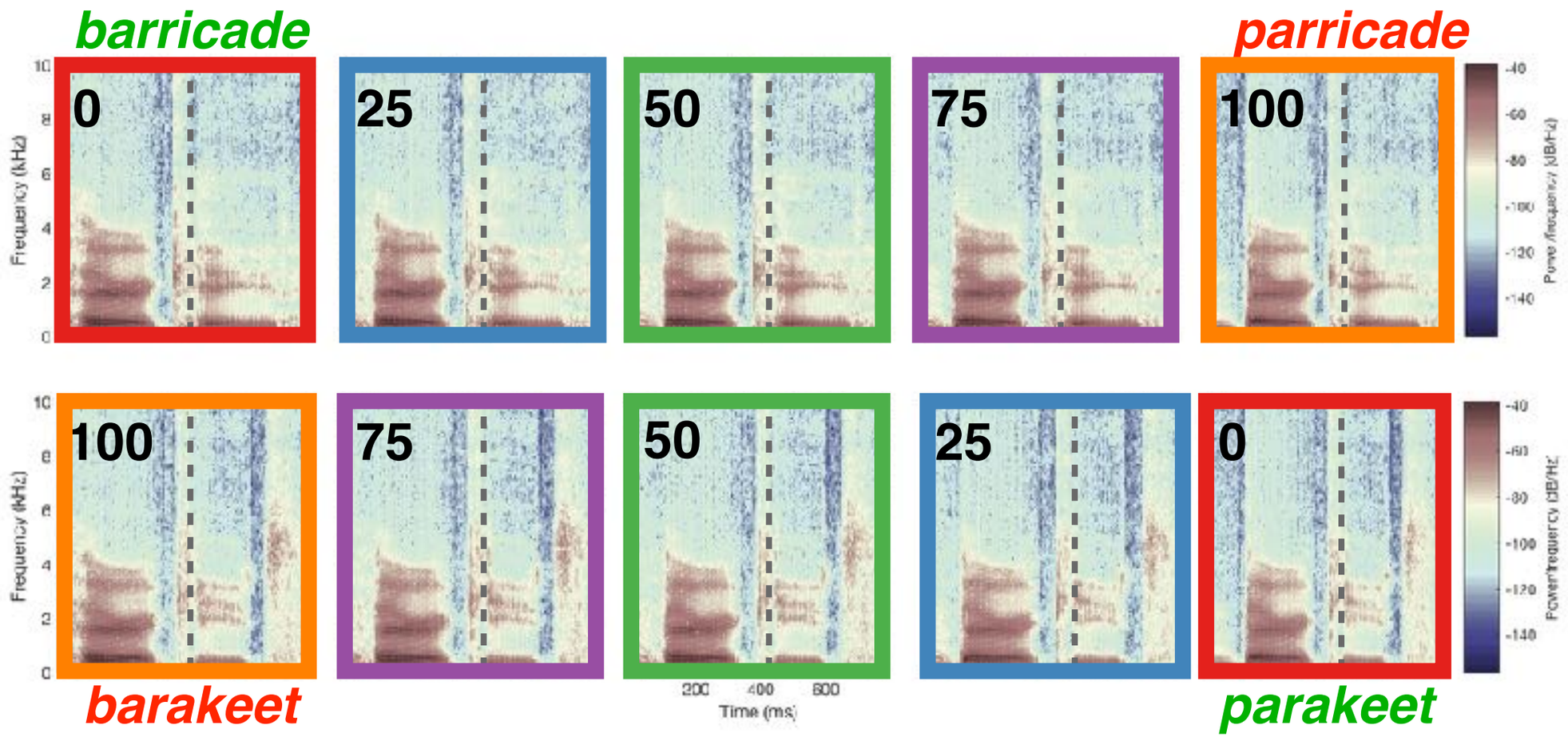


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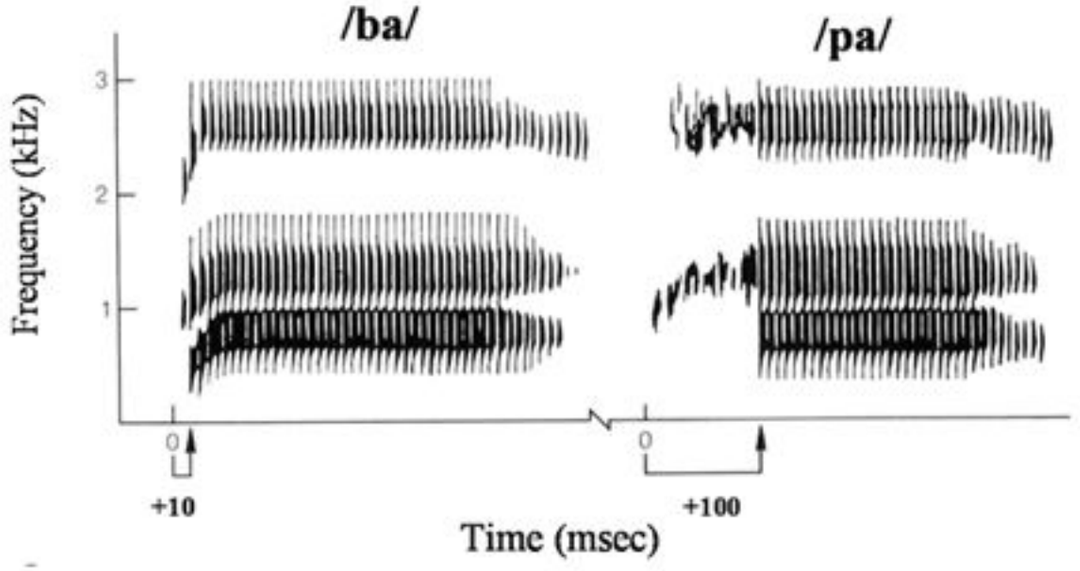
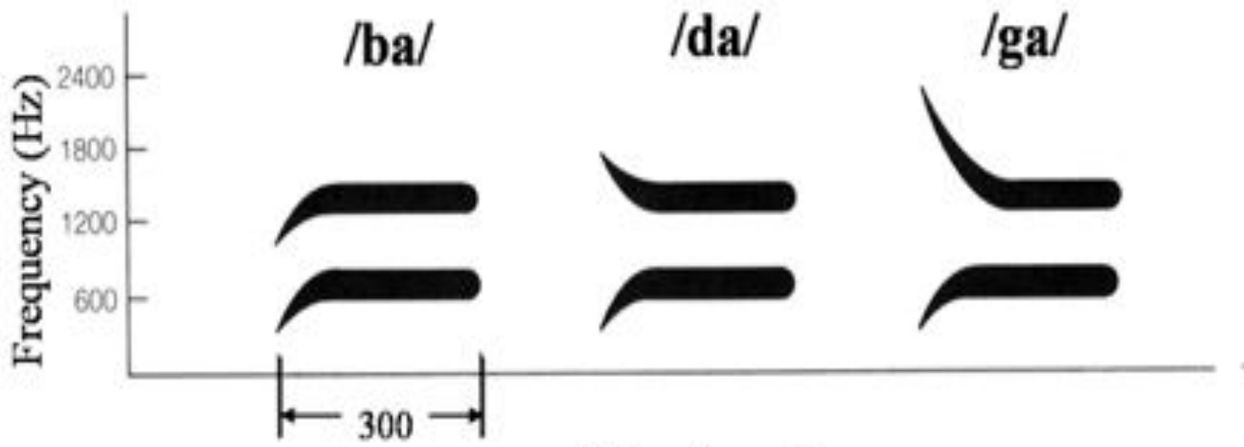
- VOT (31 pairs) {p-b, t-d, k-g} and POA (22 pairs) {t-k, p-t}

# Design & Materials

**Contrast: Voice Onset Time (VOT)**




**Contrast: Place of Articulation (POA)**

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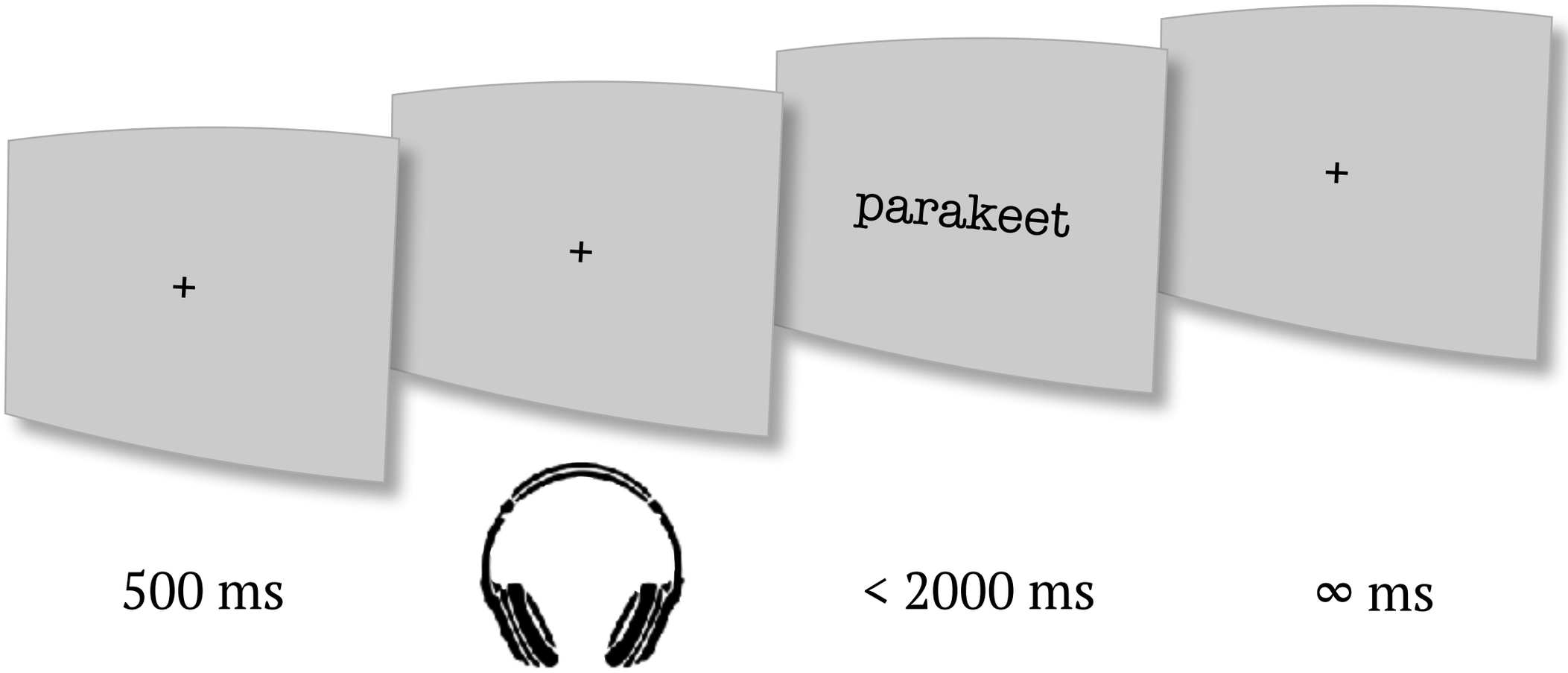

# Procedure & Analysis

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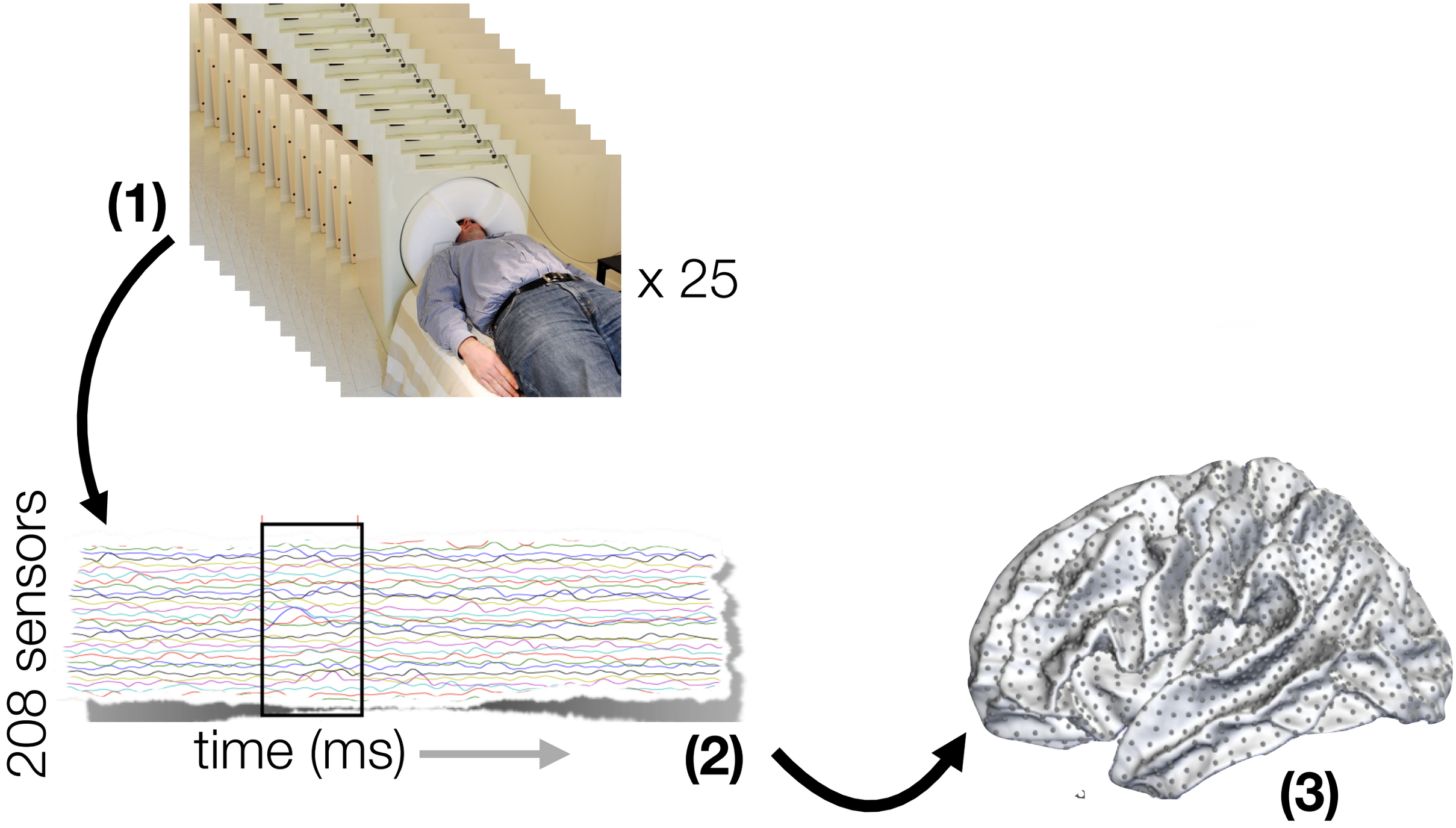
x 25

# Procedure & Analysis

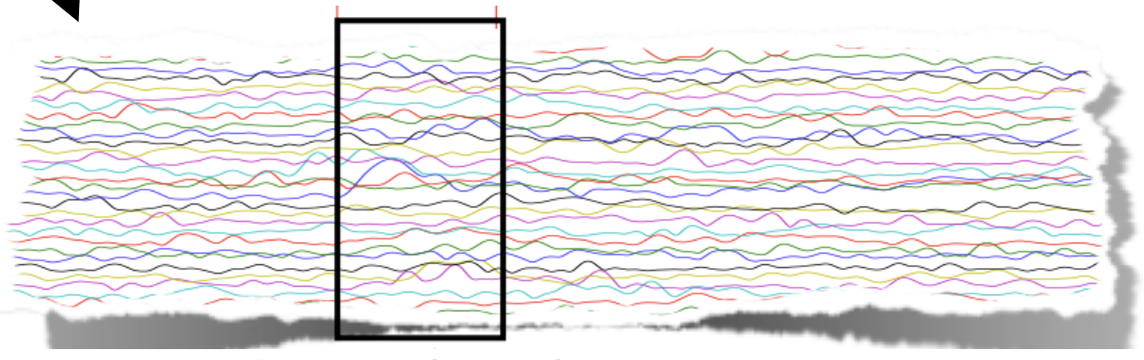


# Procedure & Analysis

(1)

x 25

208 sensors



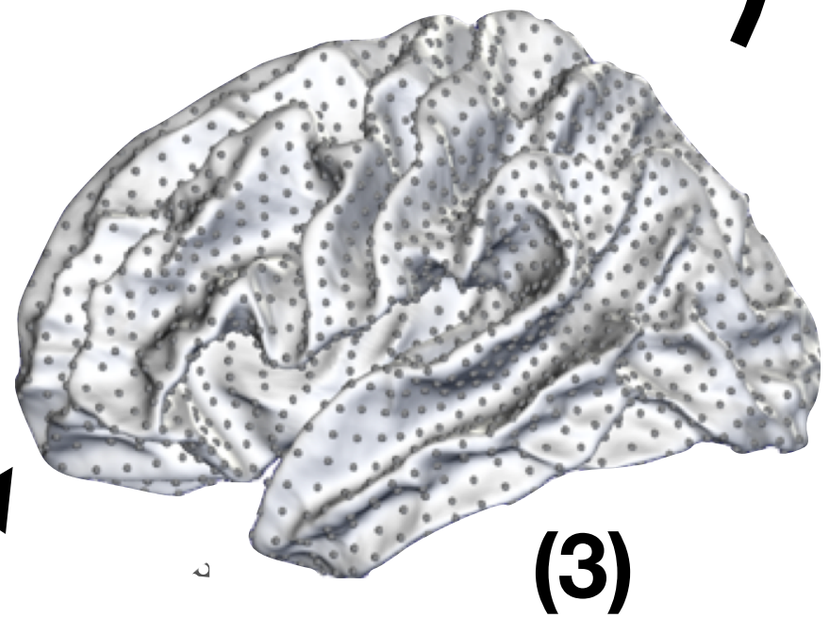
time (ms)

(2)

100 ms

(see Gwilliams, Lewis & Marantz, 2016 for more information about the analysis technique)

(3)



(4)

# Three Experimental Variables

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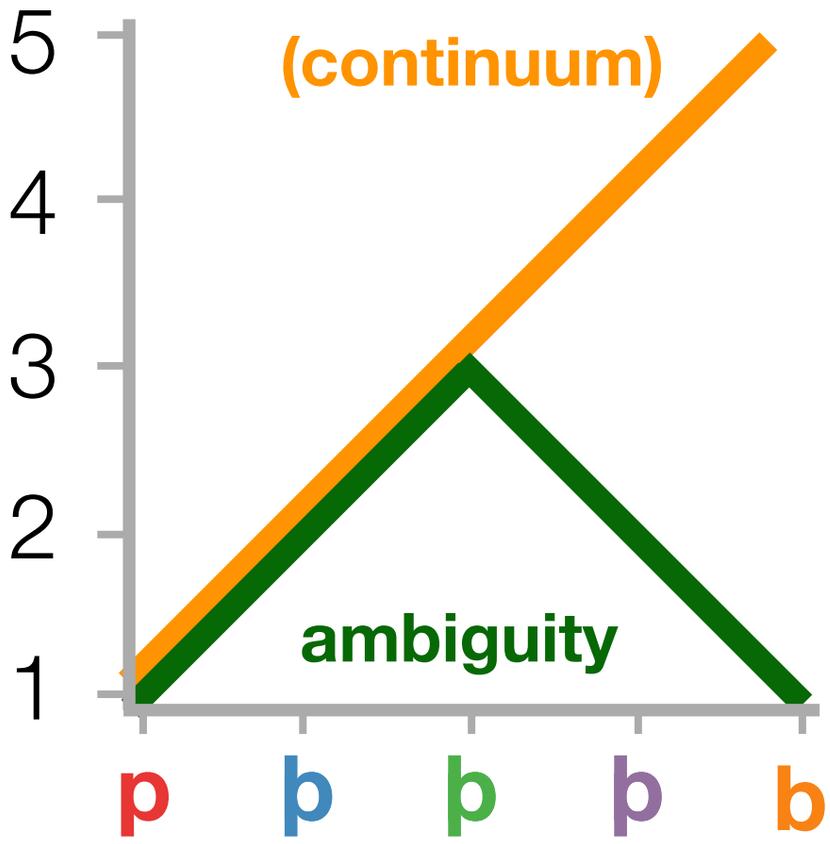

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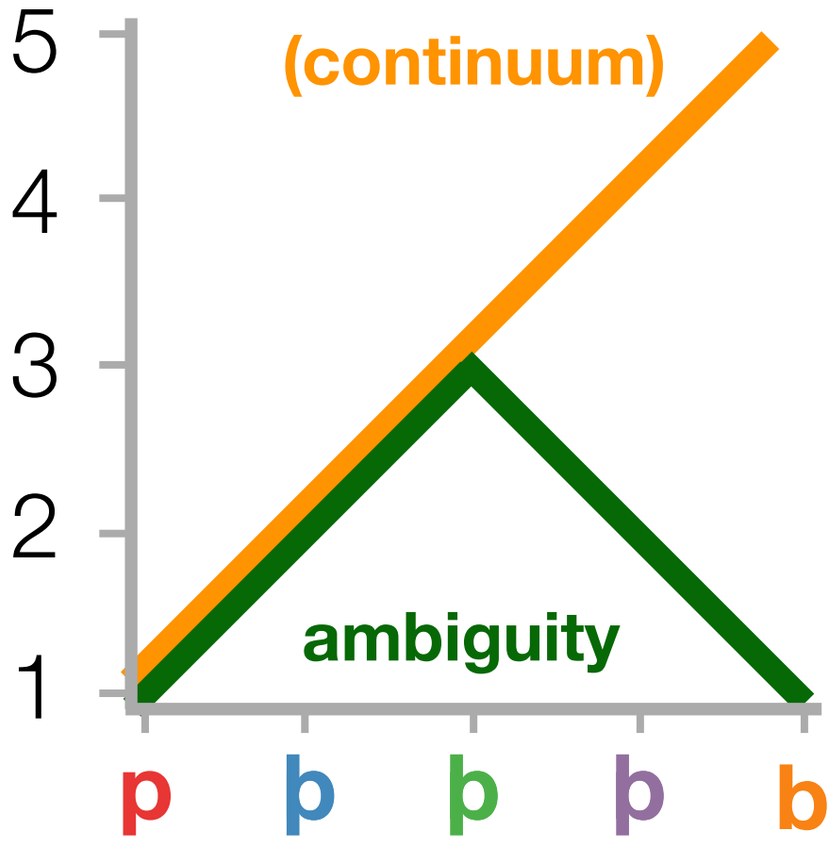


| voiceless | voiced | |
|---|---|---|
| p p | b b | bilabial |
| t t | d d | labio-dental |
| k k | g g | velar |

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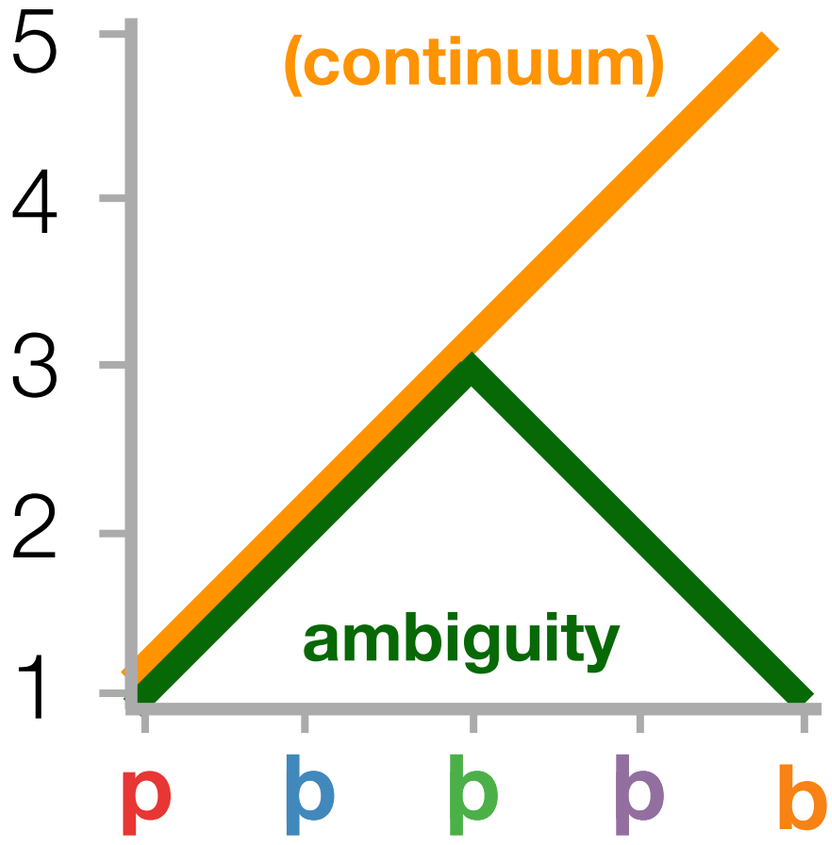


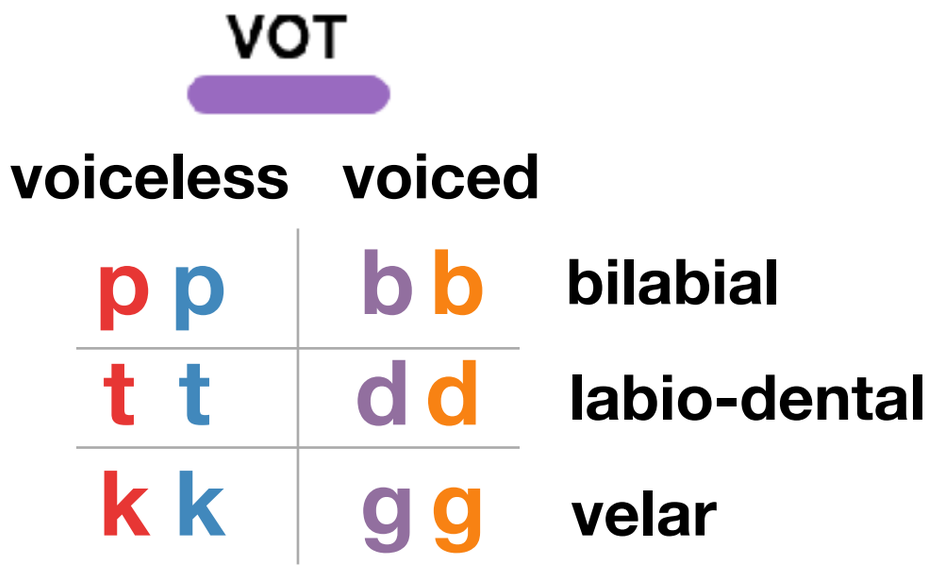

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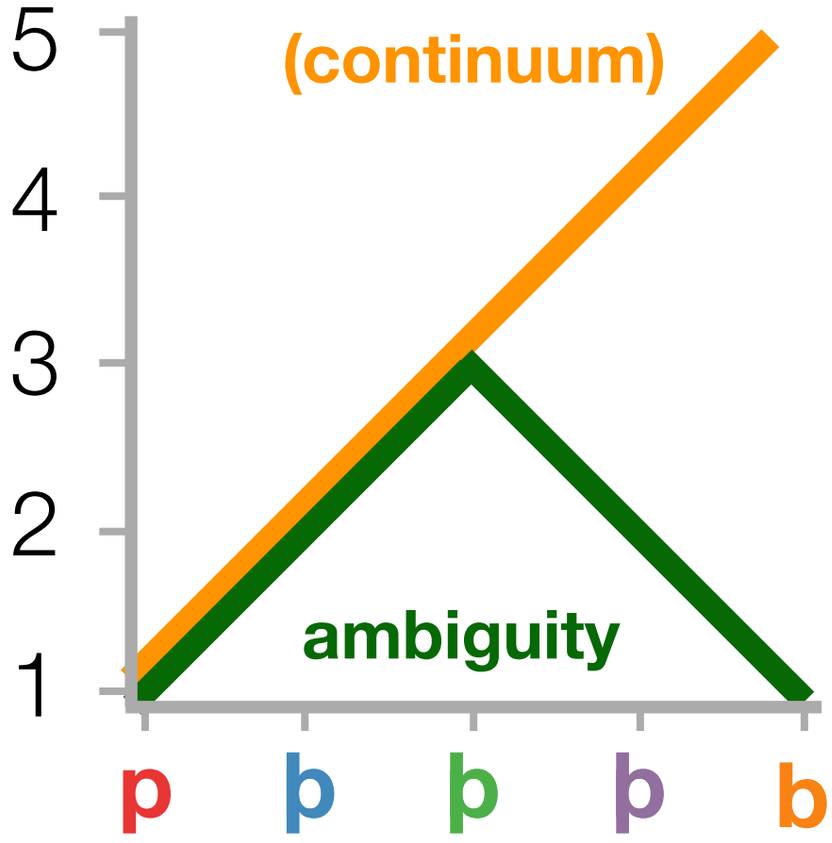
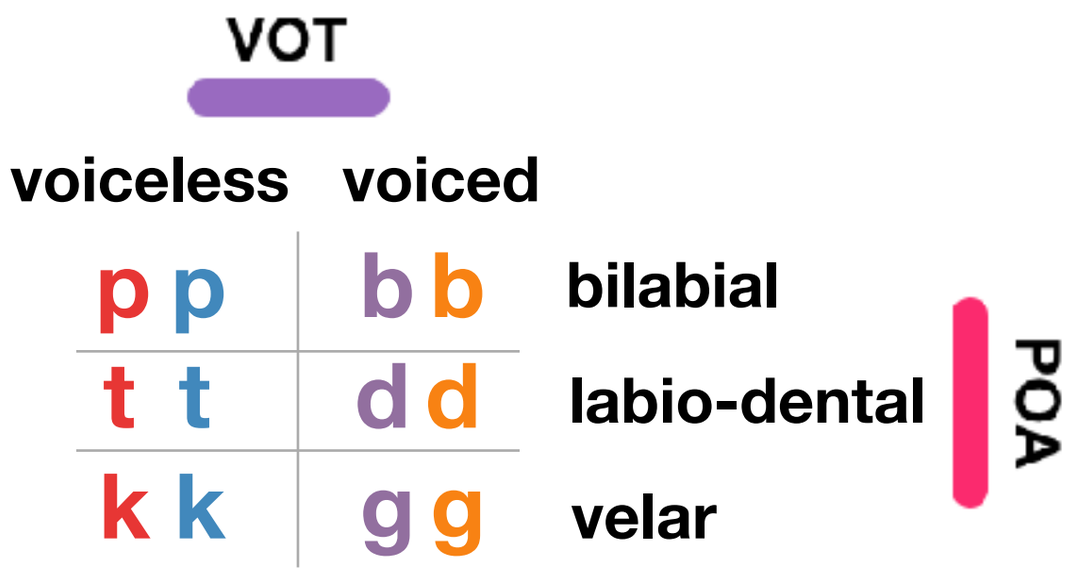


# Today's Questions

How does the auditory cortex **respond** to phonological ambiguity?

# Today's Questions

## How does the auditory cortex **respond** to phonological ambiguity?

**Sensitivity to phonetic features ~100 ms after onset in superior temporal gyrus:**

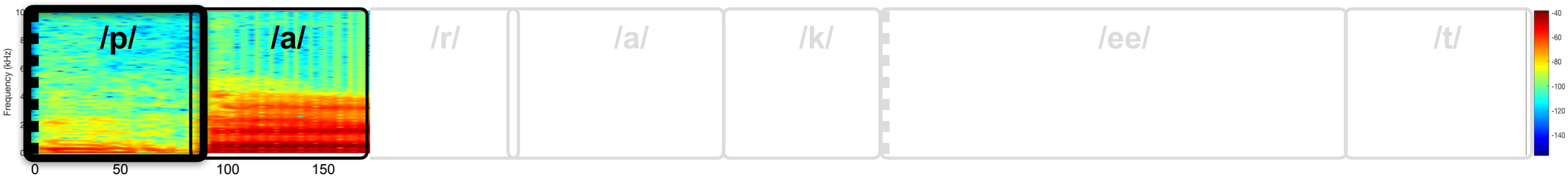
Simos et al. 1998, Ackermann et al. 1999, Obleser et al. 2003, Papanicolaou et al. 2003, Obleser et al. 2004 Mesgarani et al. 2014, Di Liberto et al. 2015

p p b b b

# Ambiguity at Onset

p p b b b

# Ambiguity at Onset



p p b b b

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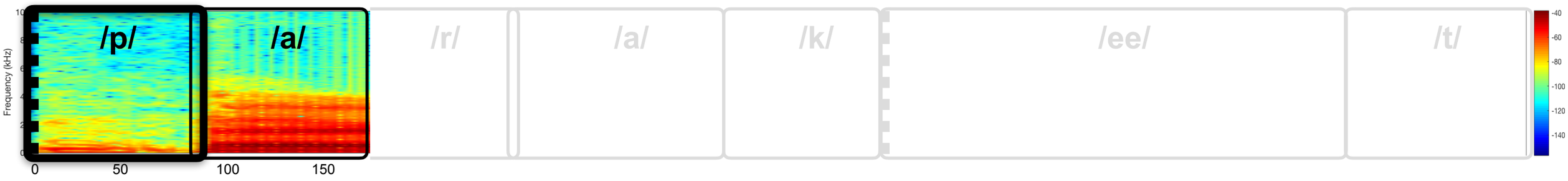

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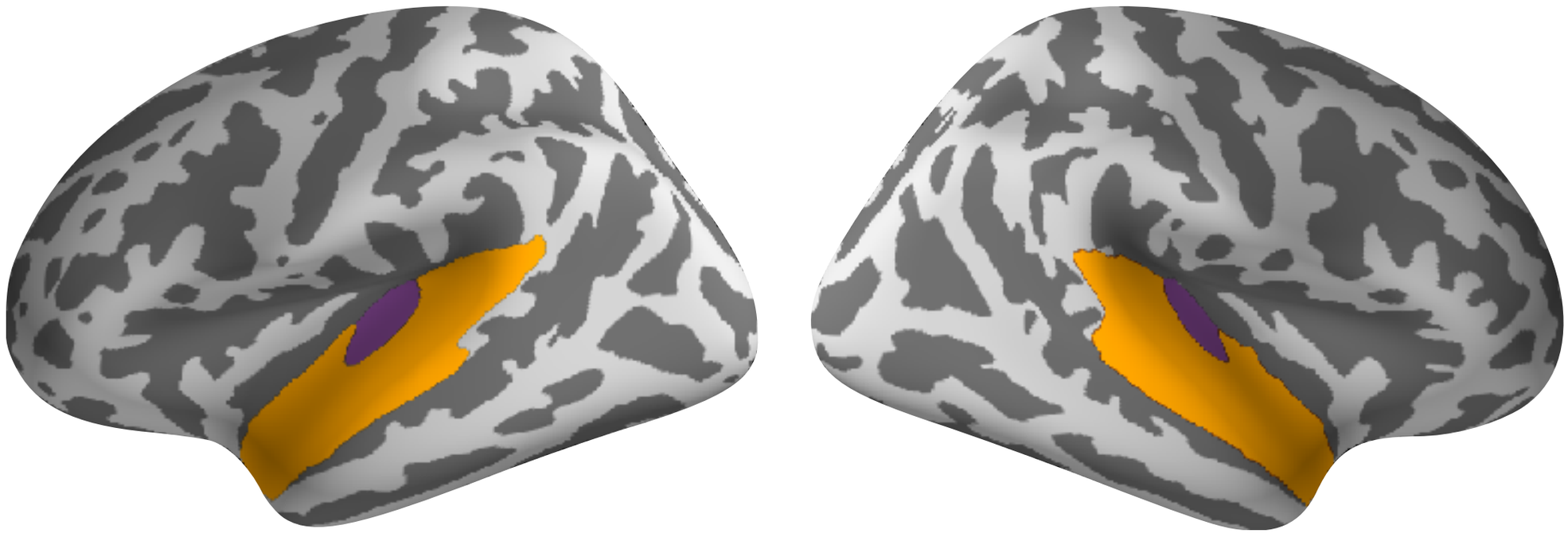
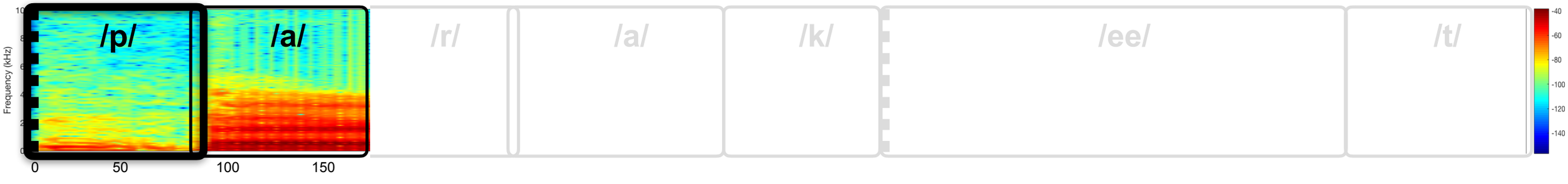


- Time-window: 0-200 ms after word onset
- Region: **Heschl's gyrus** & **superior temporal gyrus** bilaterally



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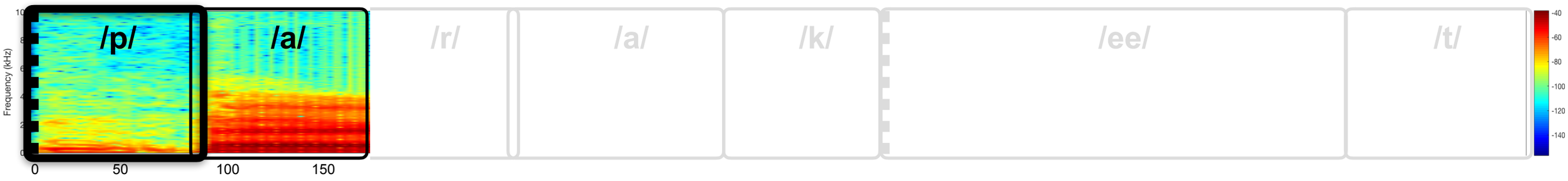

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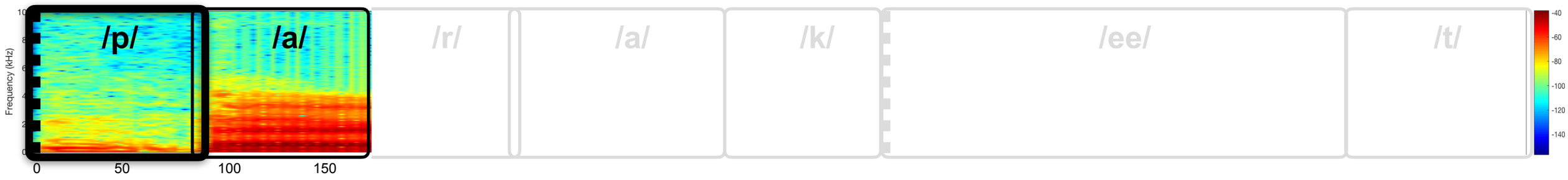
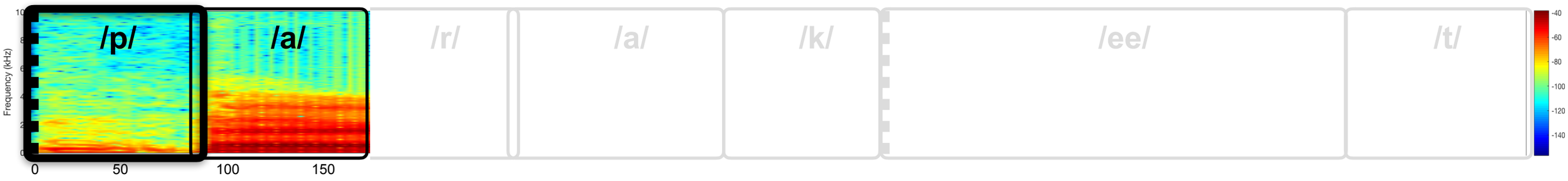


p p b b b

# Ambiguity at Onset

**Ambiguity**



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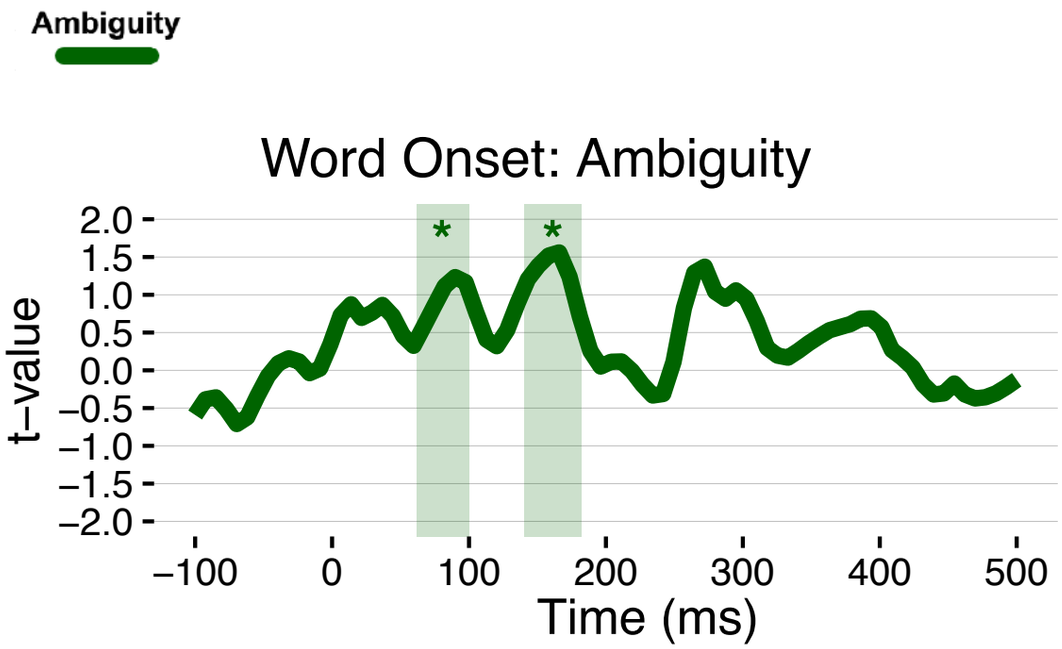


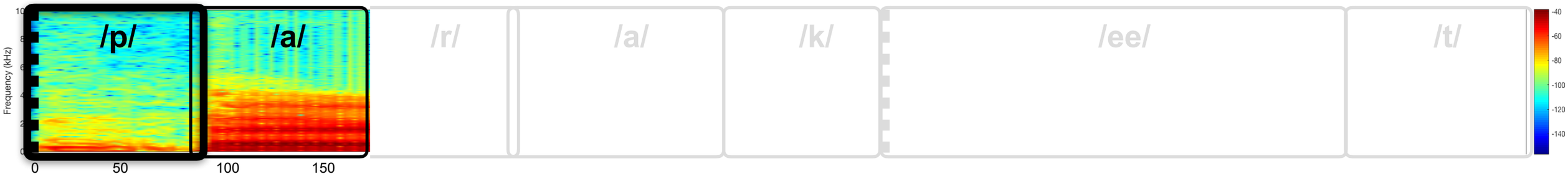

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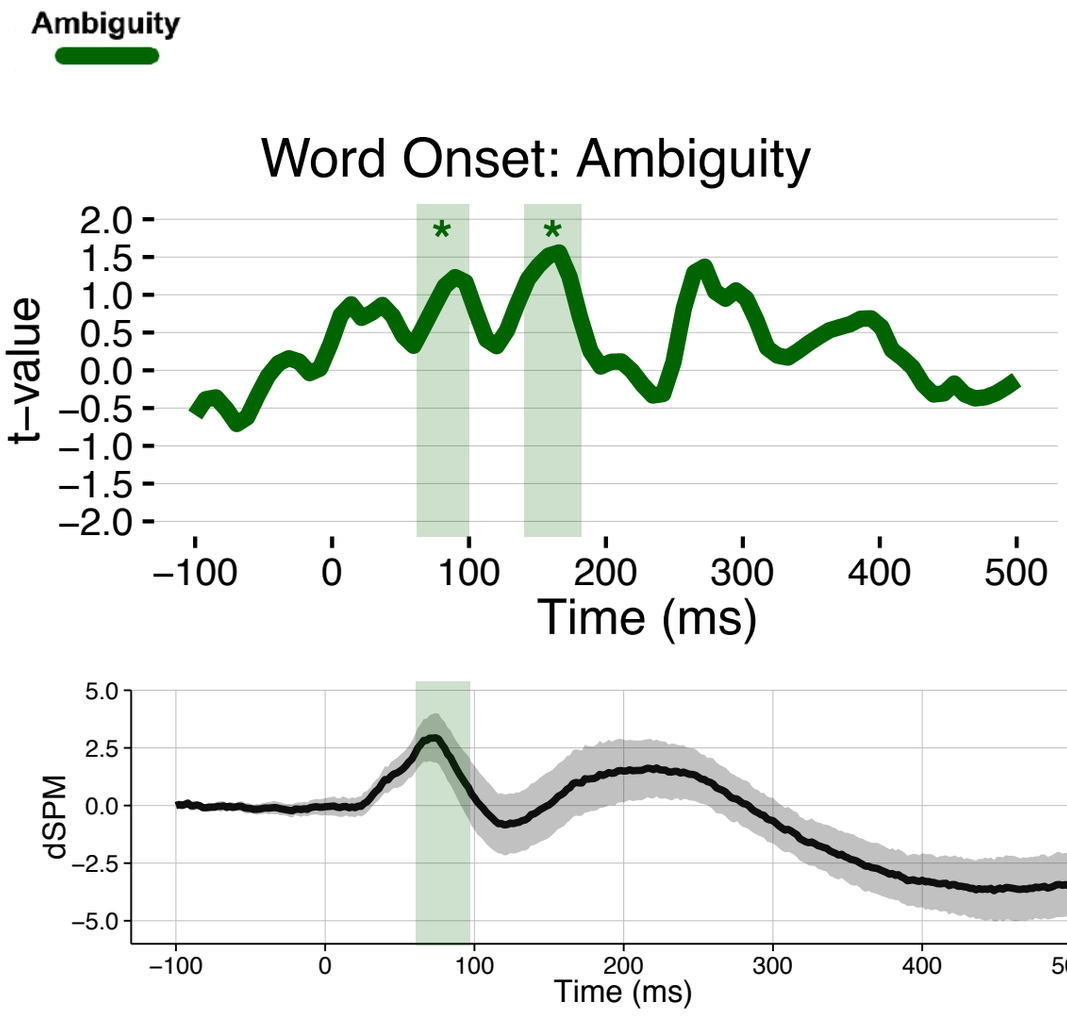


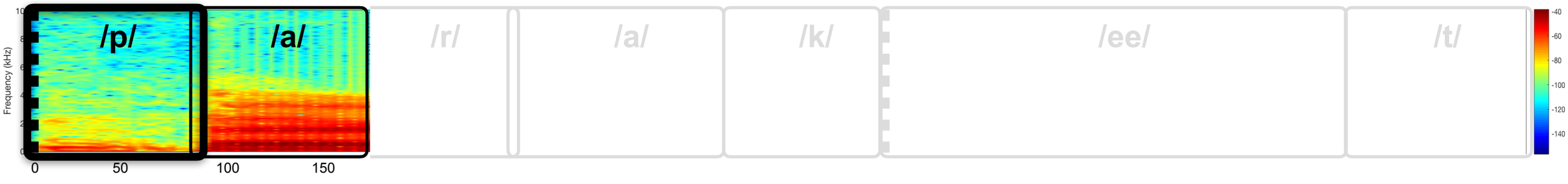

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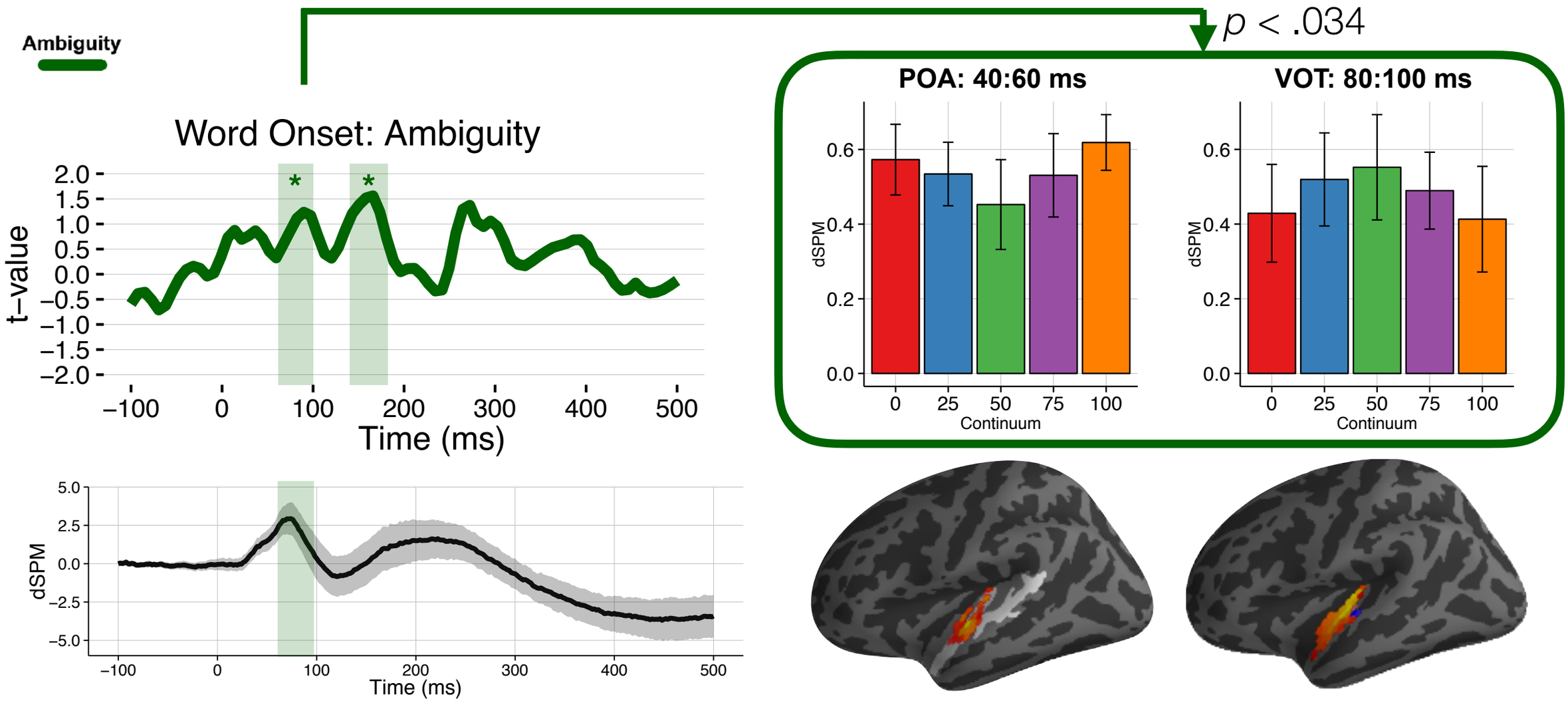
# Ambiguity at Onset



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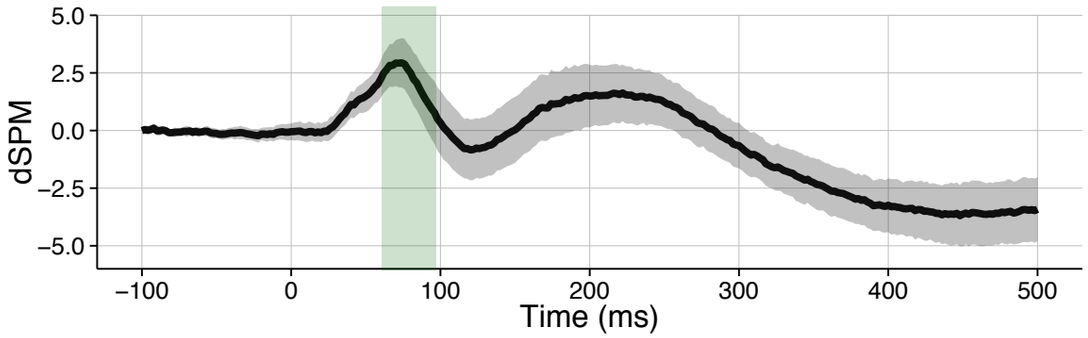


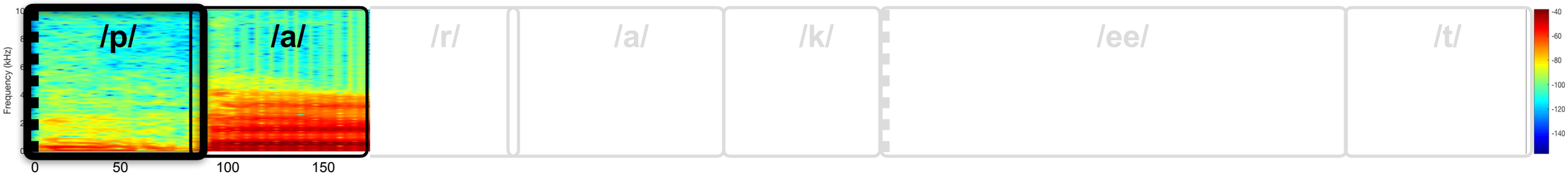

# Ambiguity at Onset

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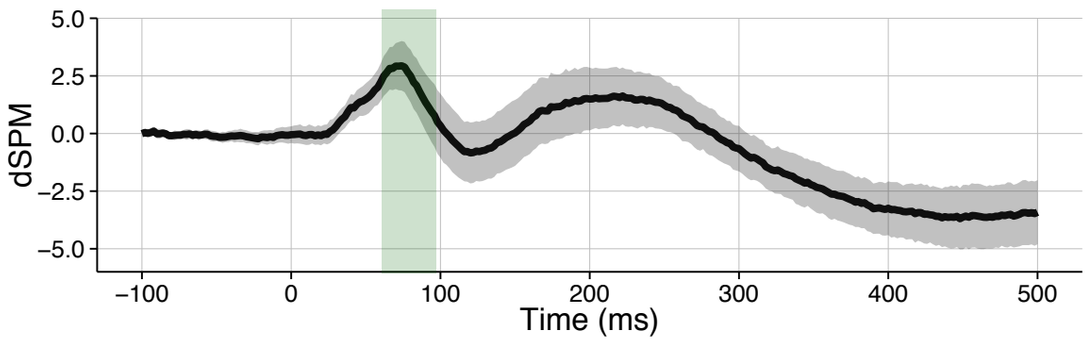


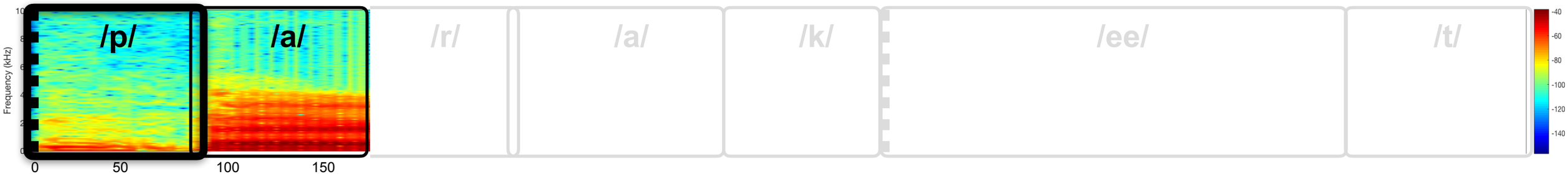

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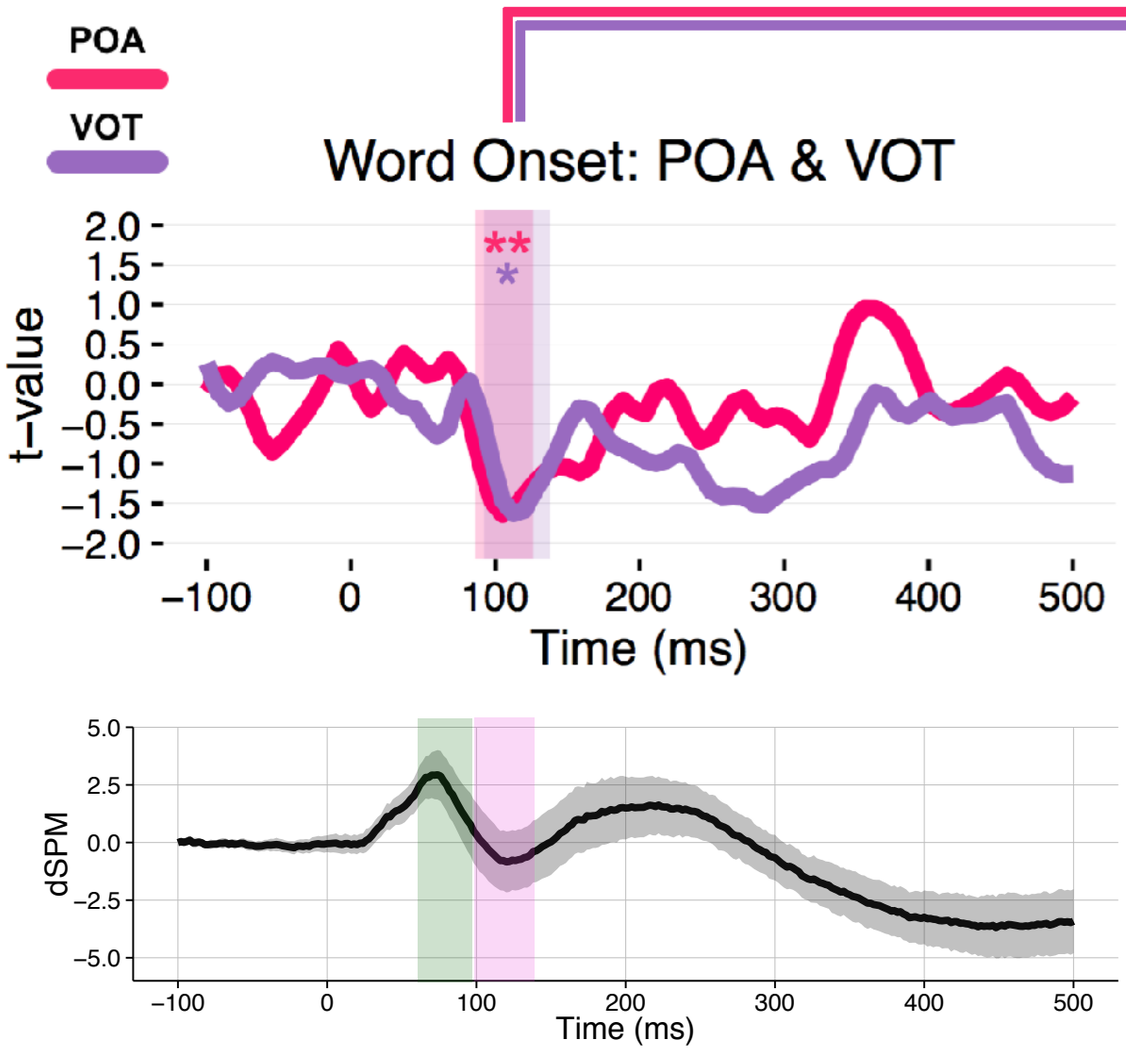


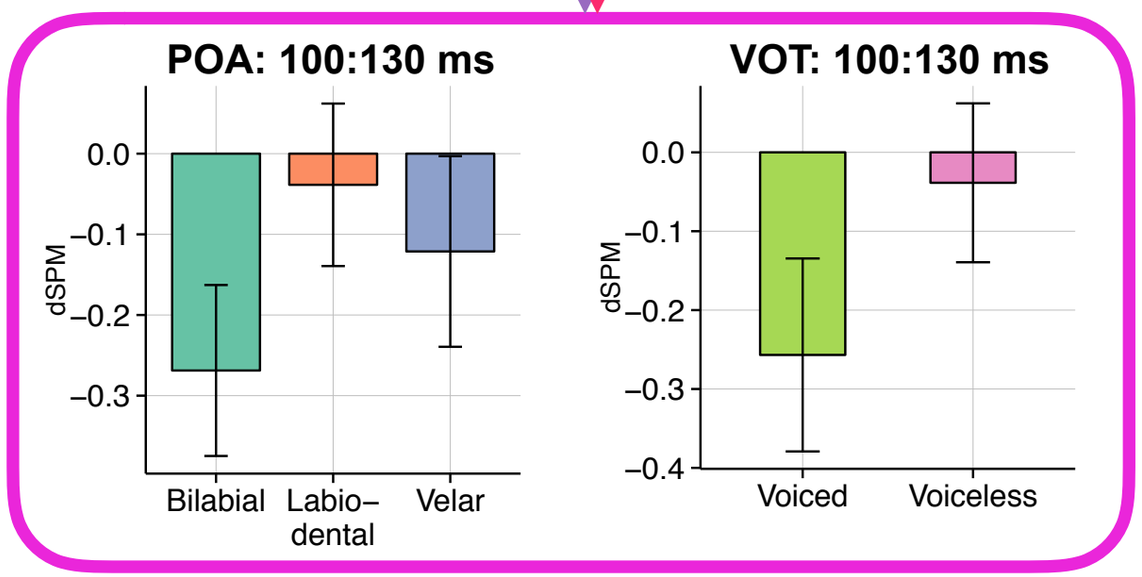


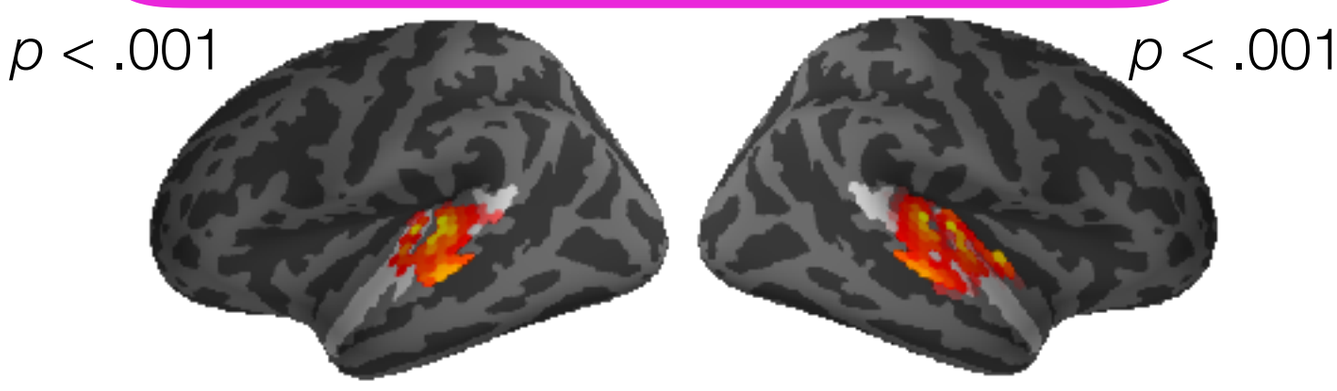


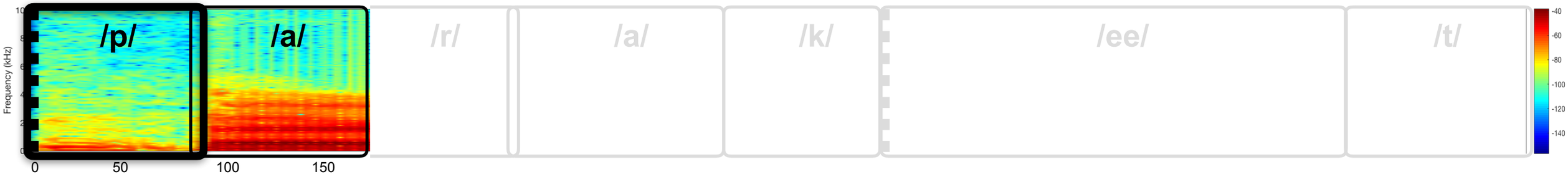

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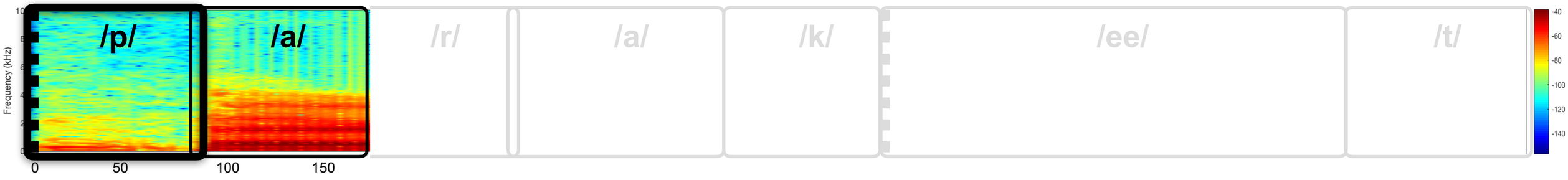

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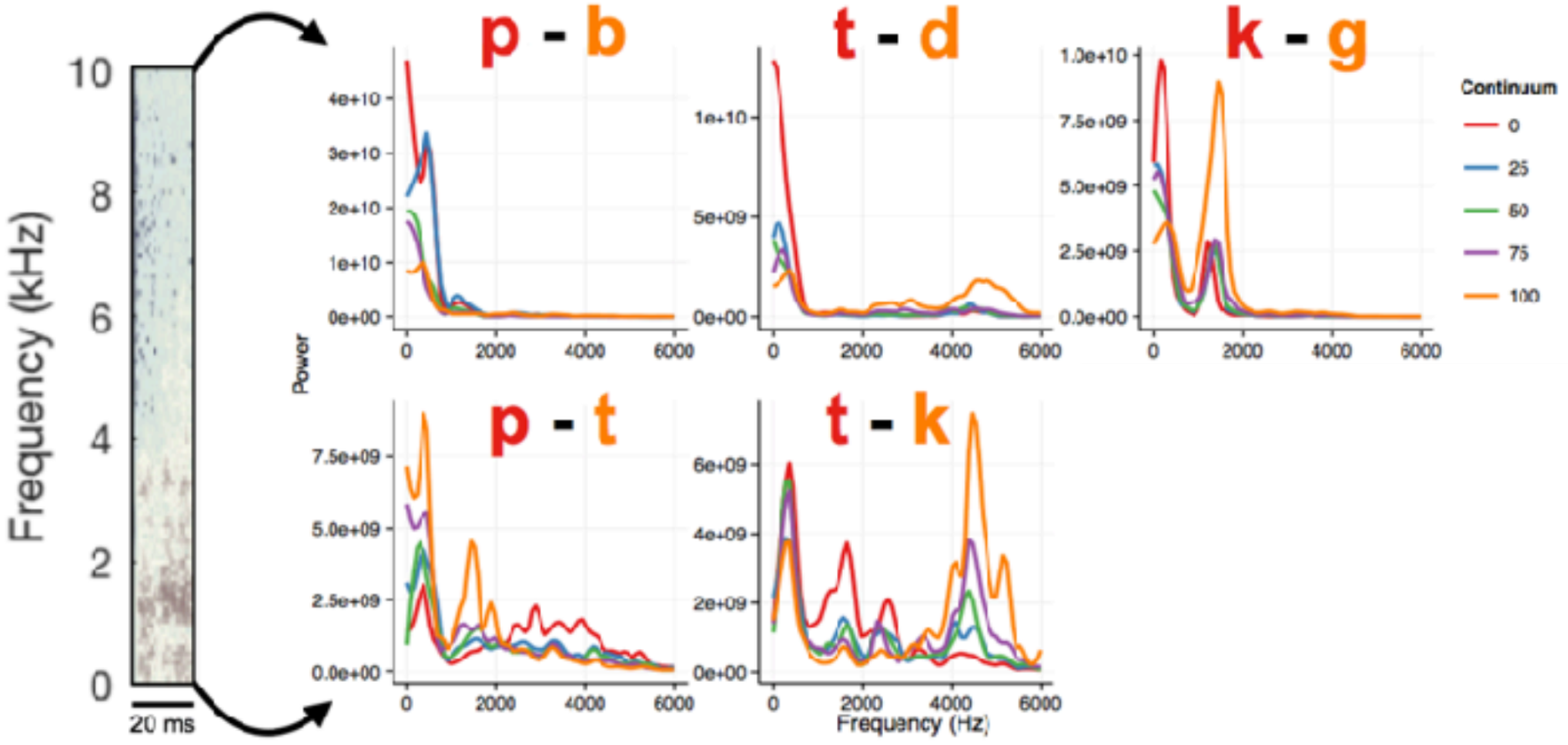


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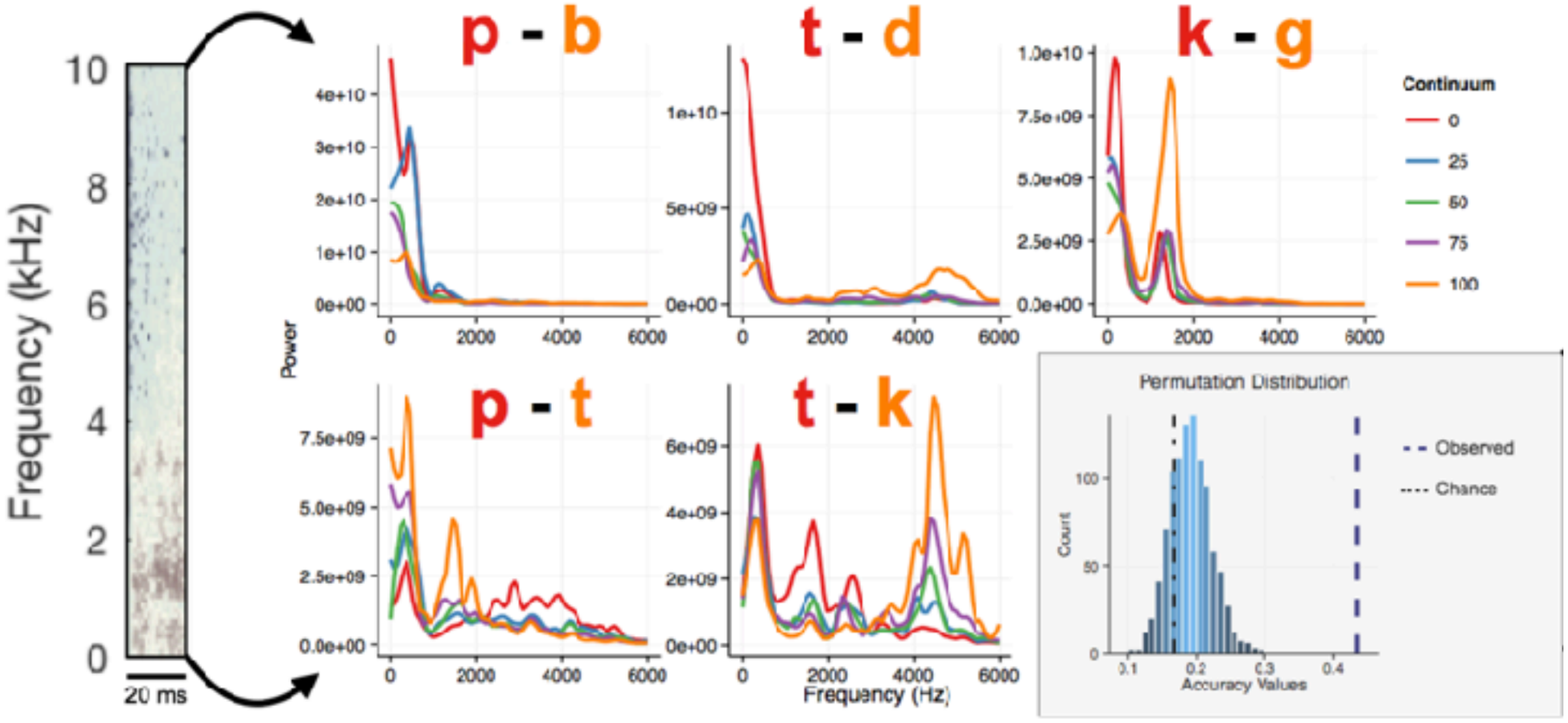


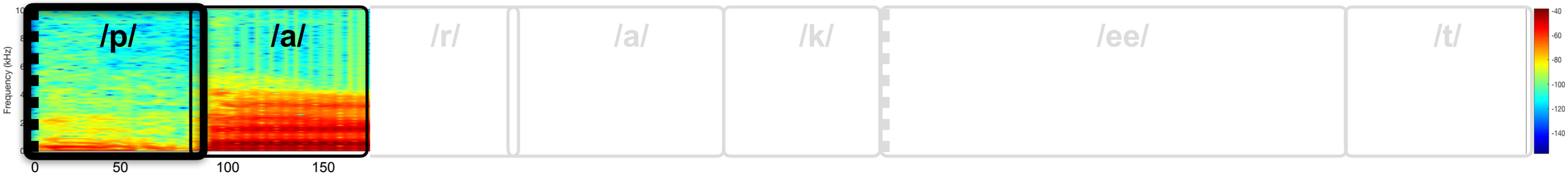

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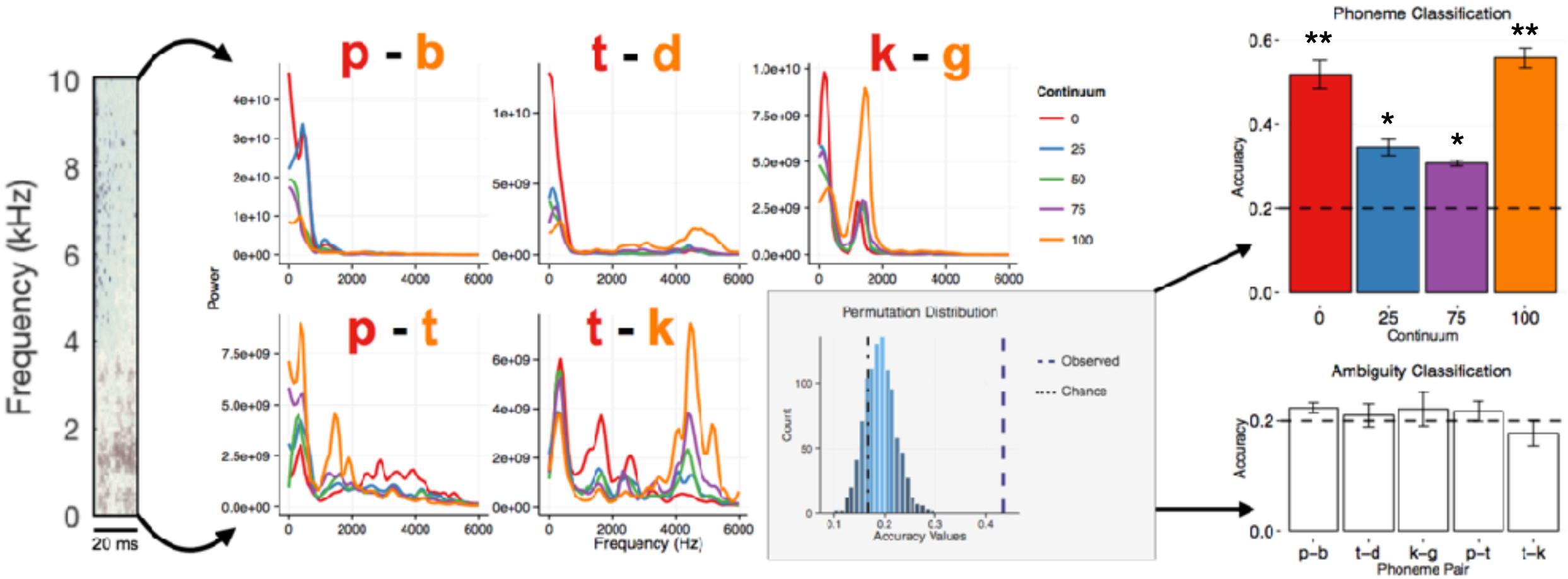


# Interim Conclusion

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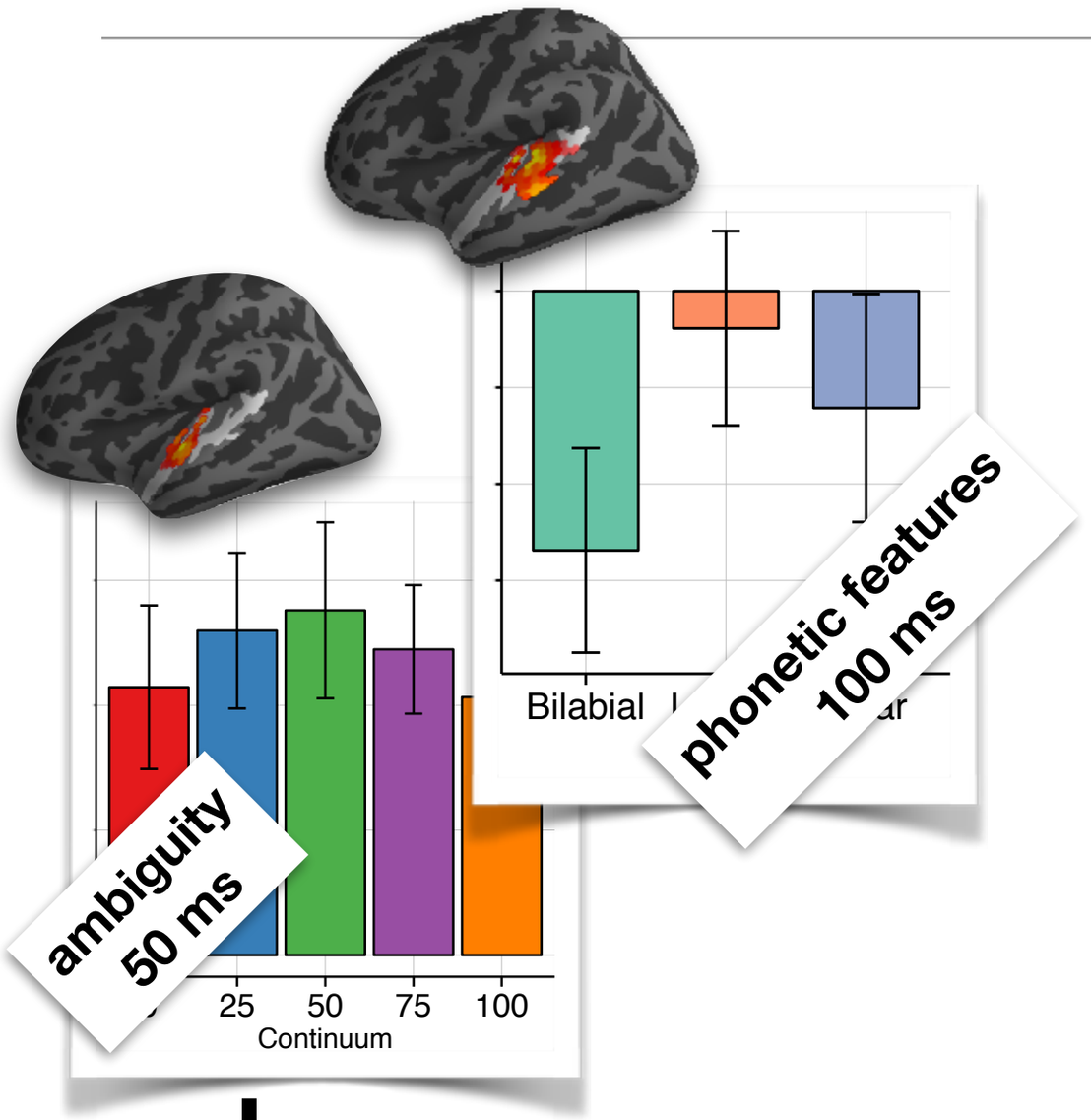


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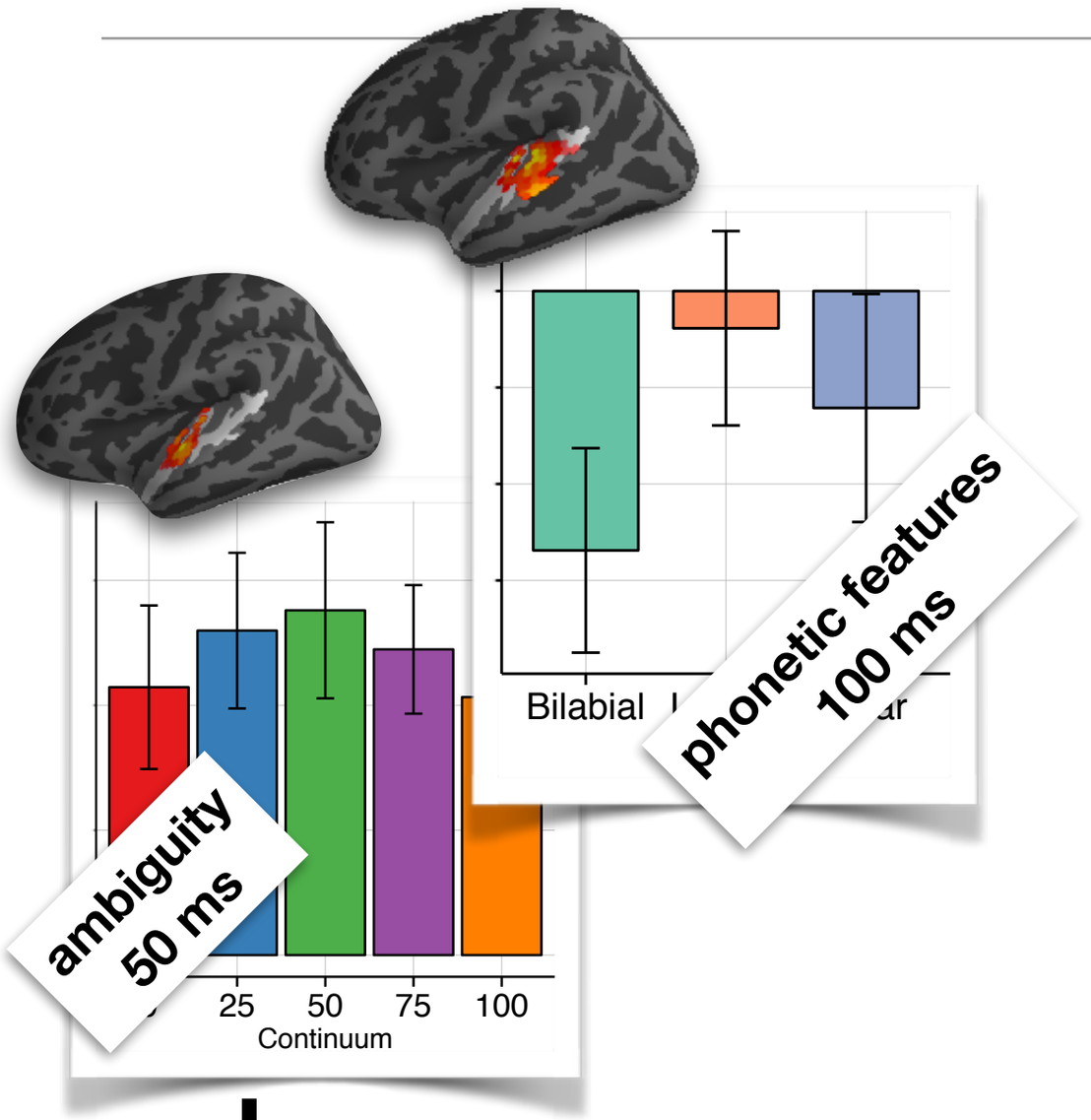


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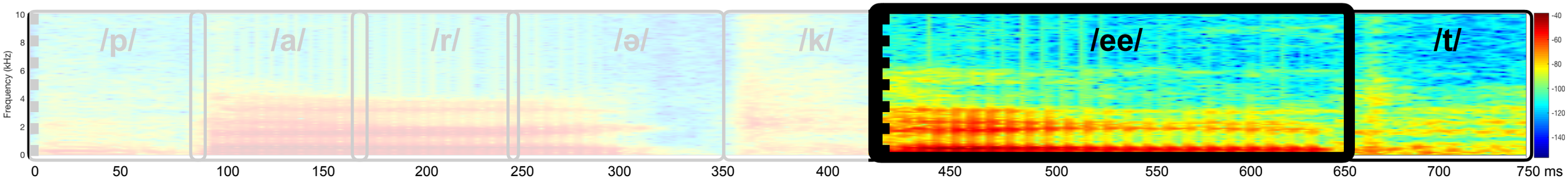
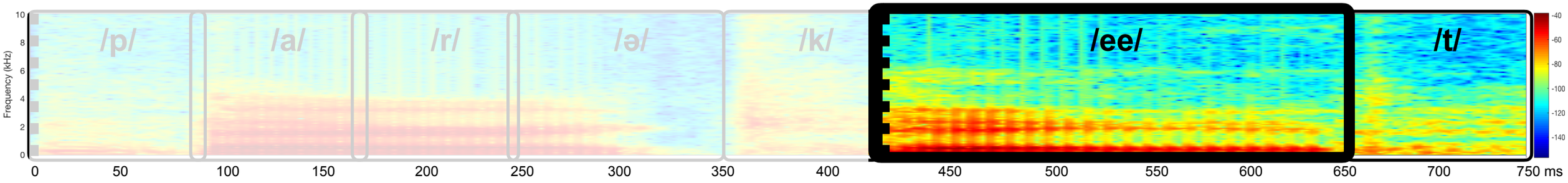
# Today's Questions

What are the neural signatures of ambiguity **resolution**?

# Ambiguity at POD

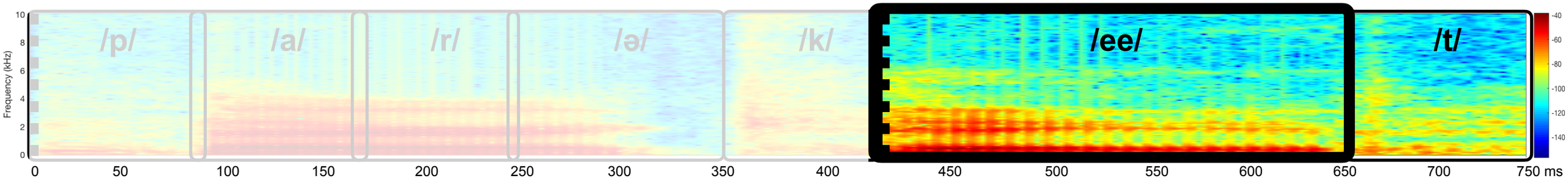


# Ambiguity at POD



# Ambiguity at POD

- Time-window: 0-200 ms after POD onset
- Region: **Heschl's gyrus** & **superior temporal gyrus** bilaterally



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**Ambiguity**

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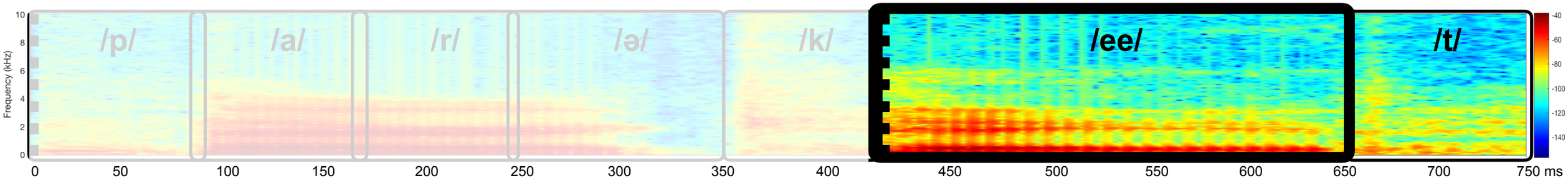
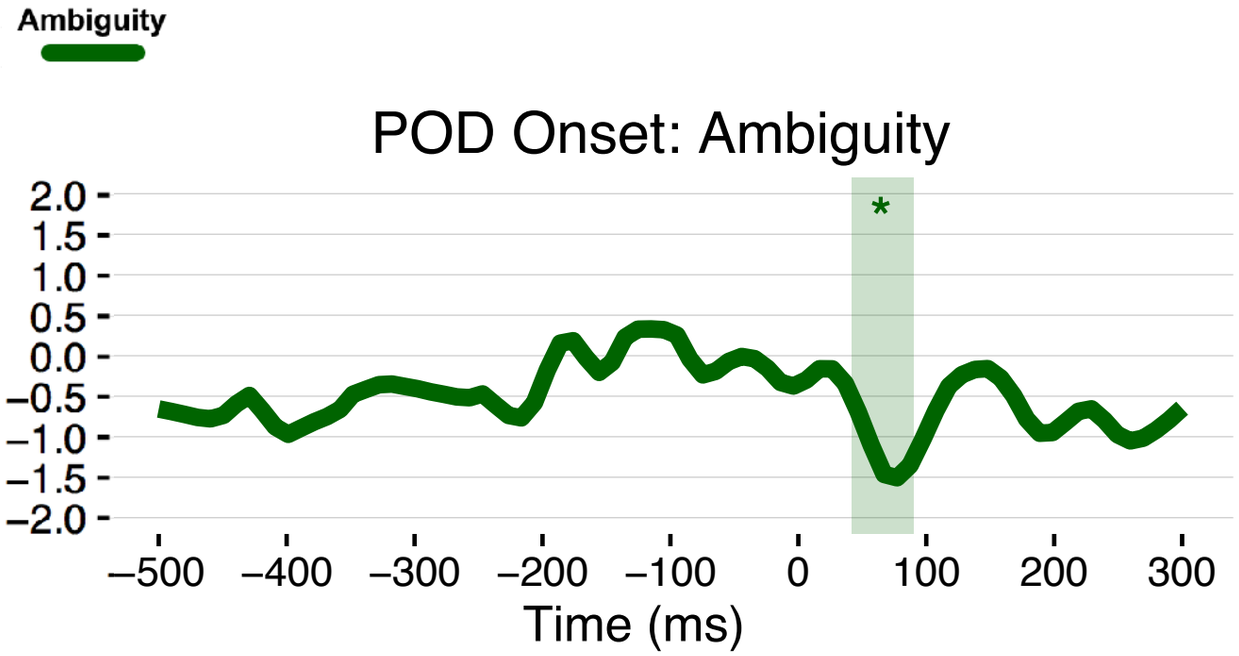


# Ambiguity at POD

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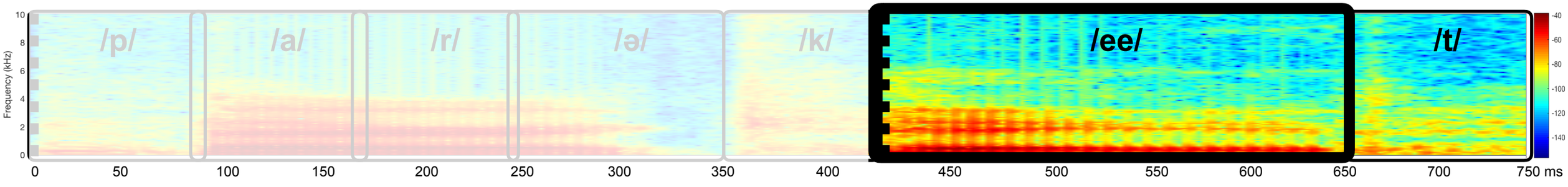

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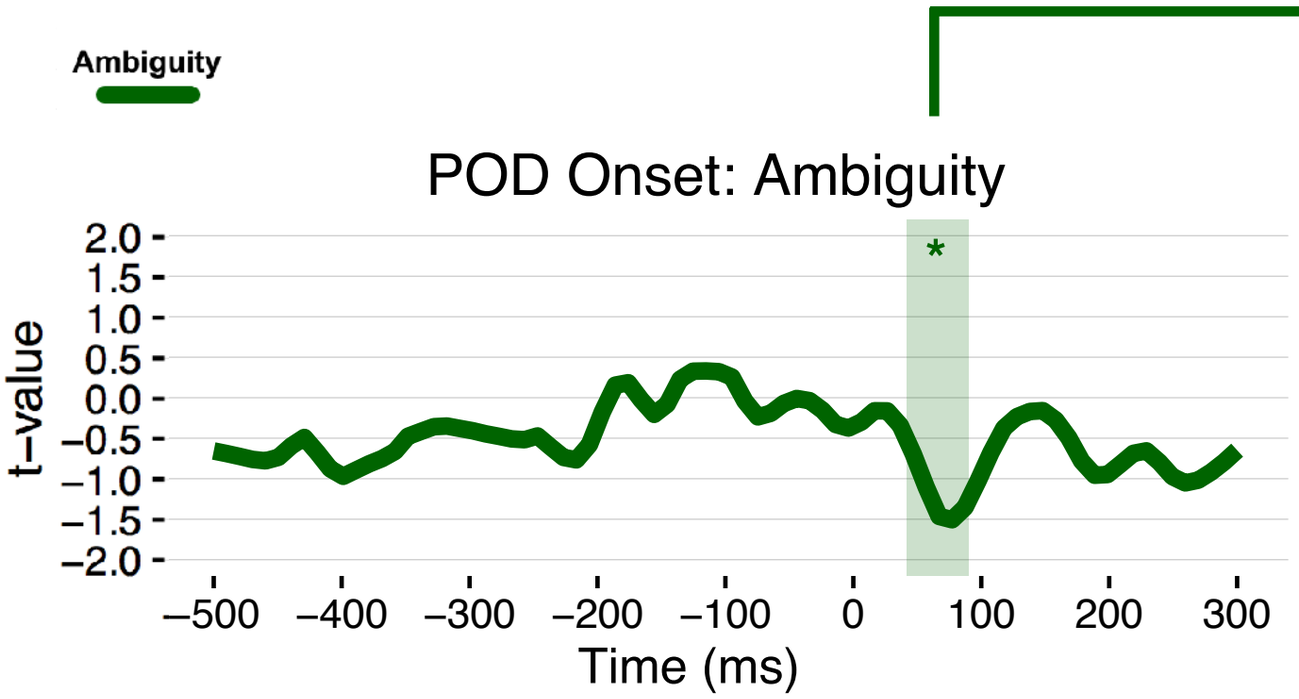


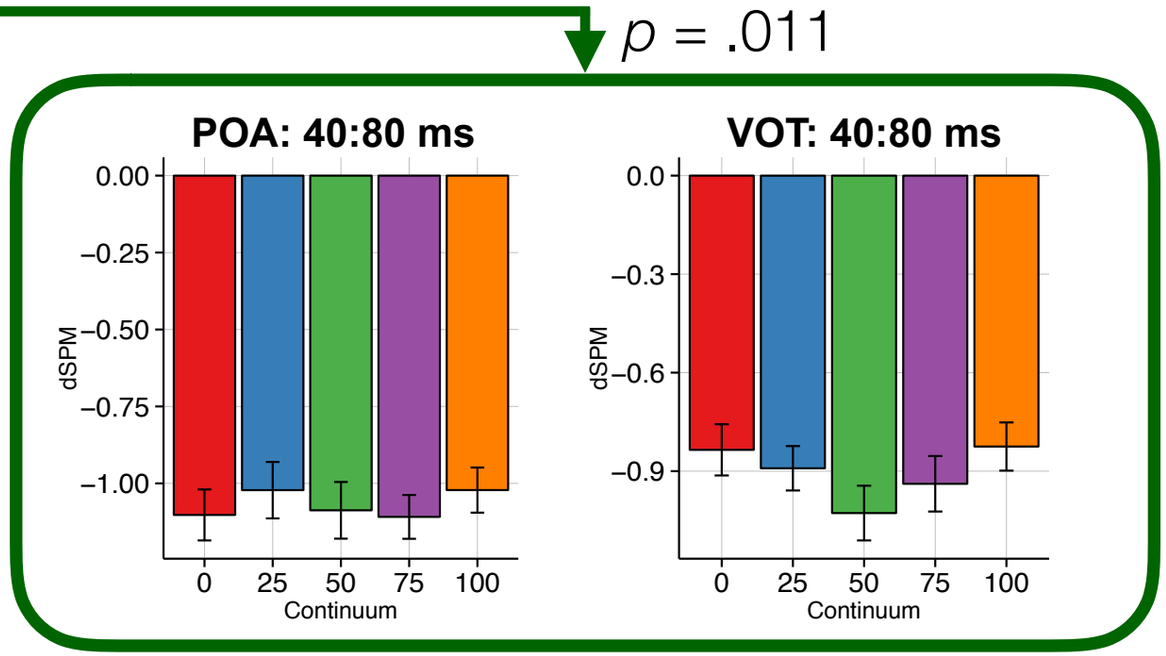


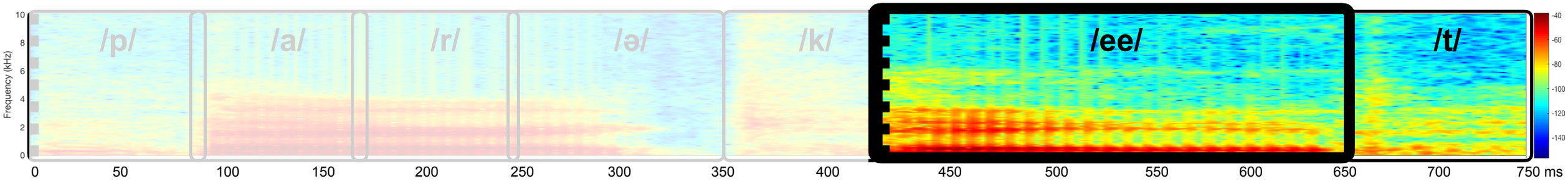

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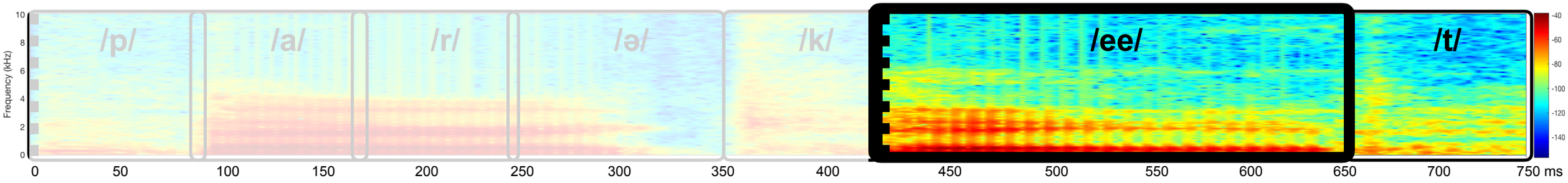

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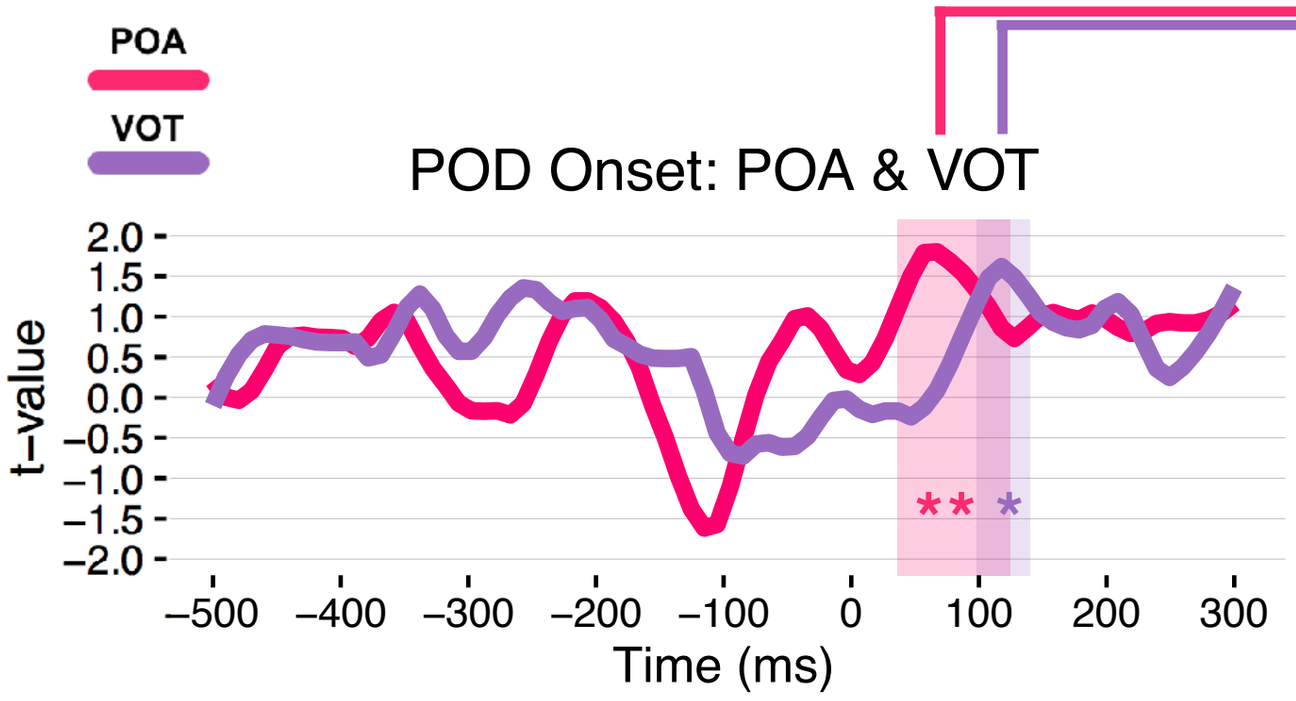
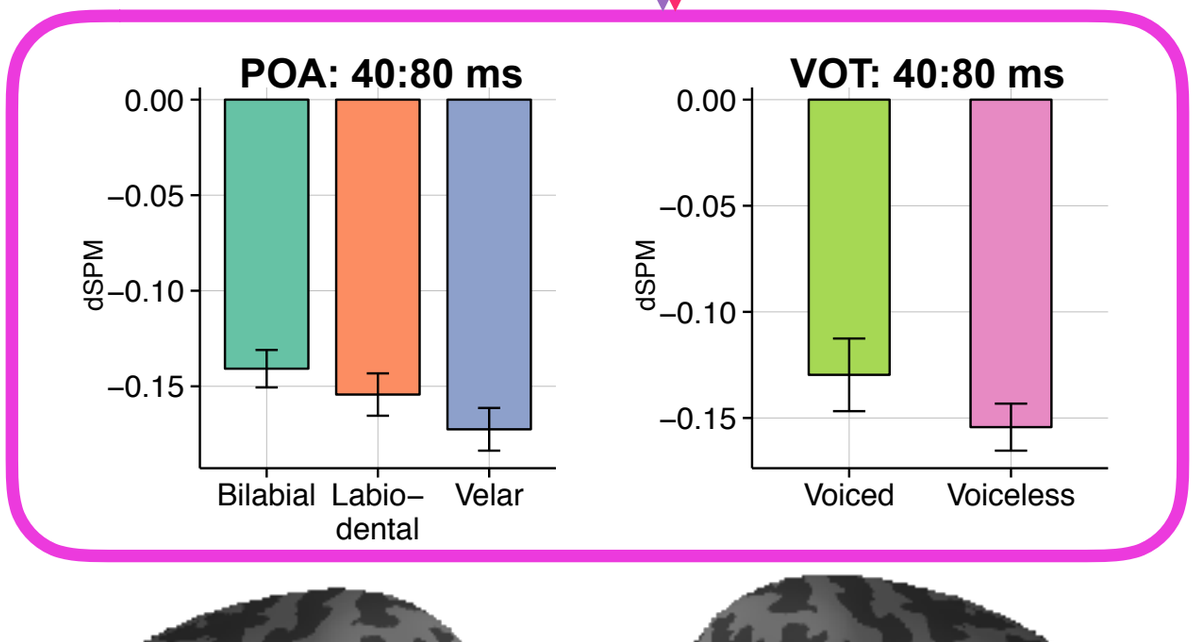
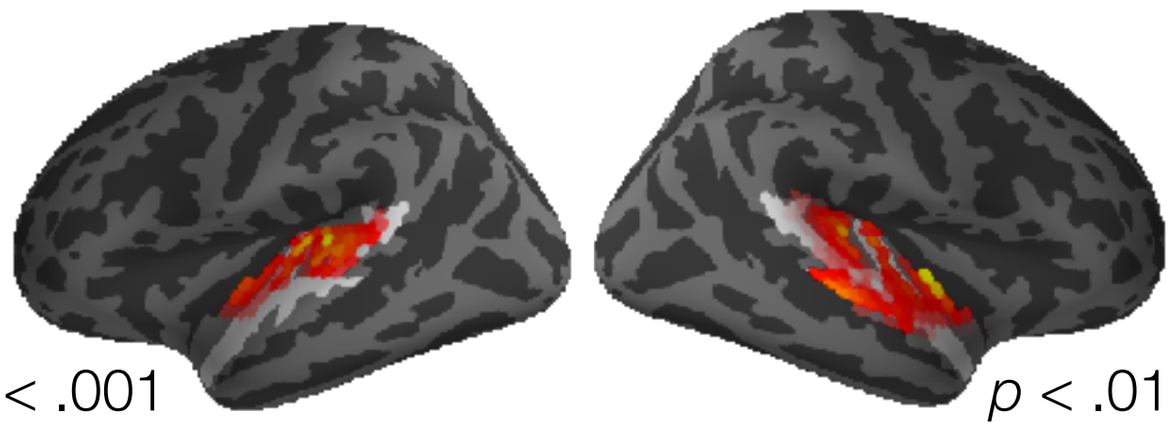
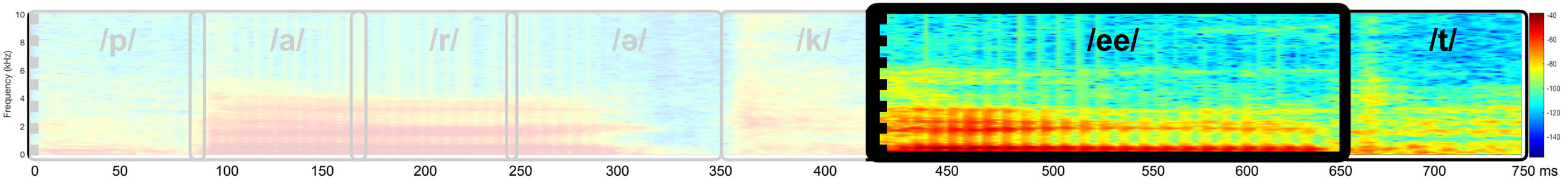
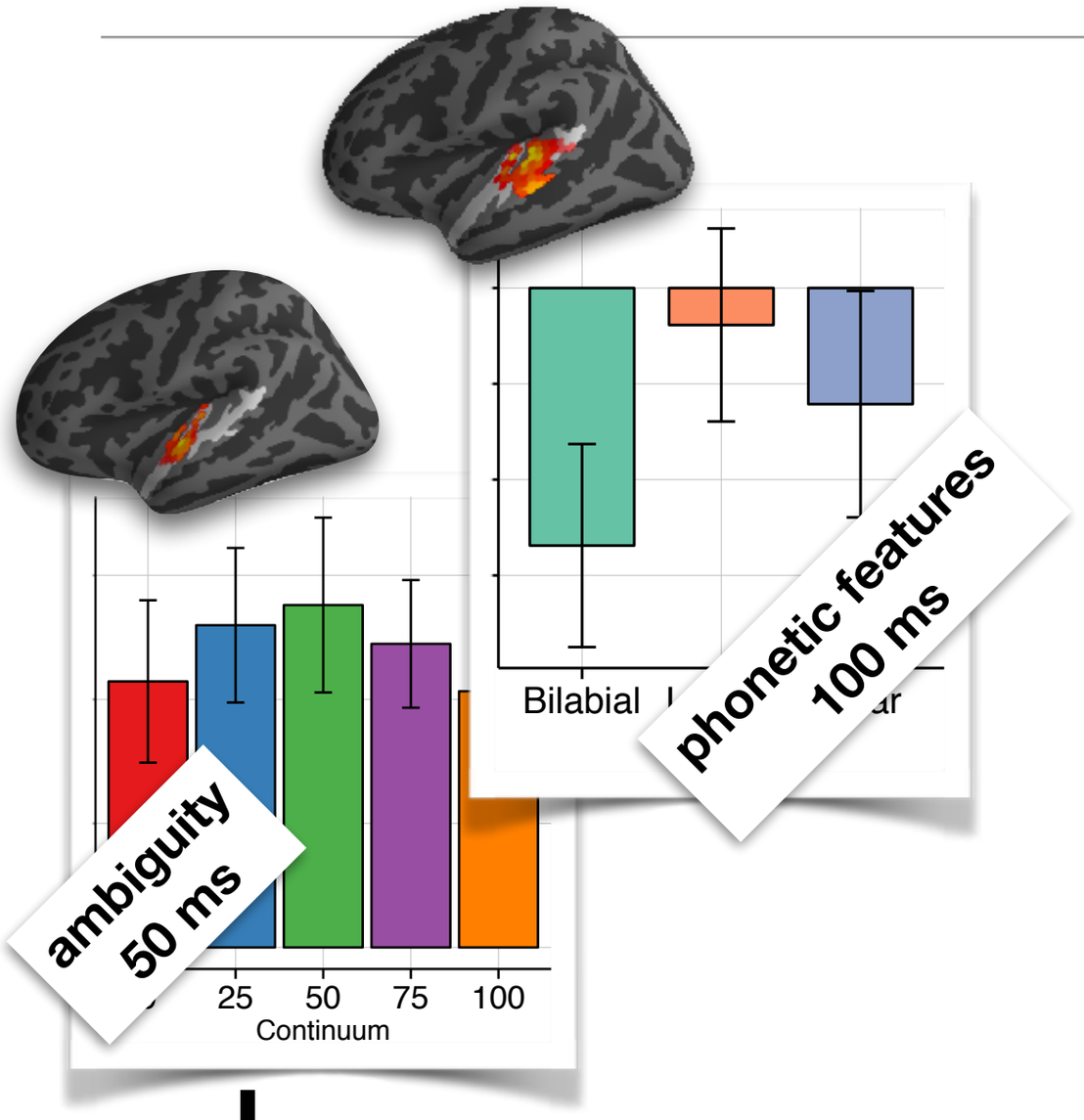


# Interim Conclusion

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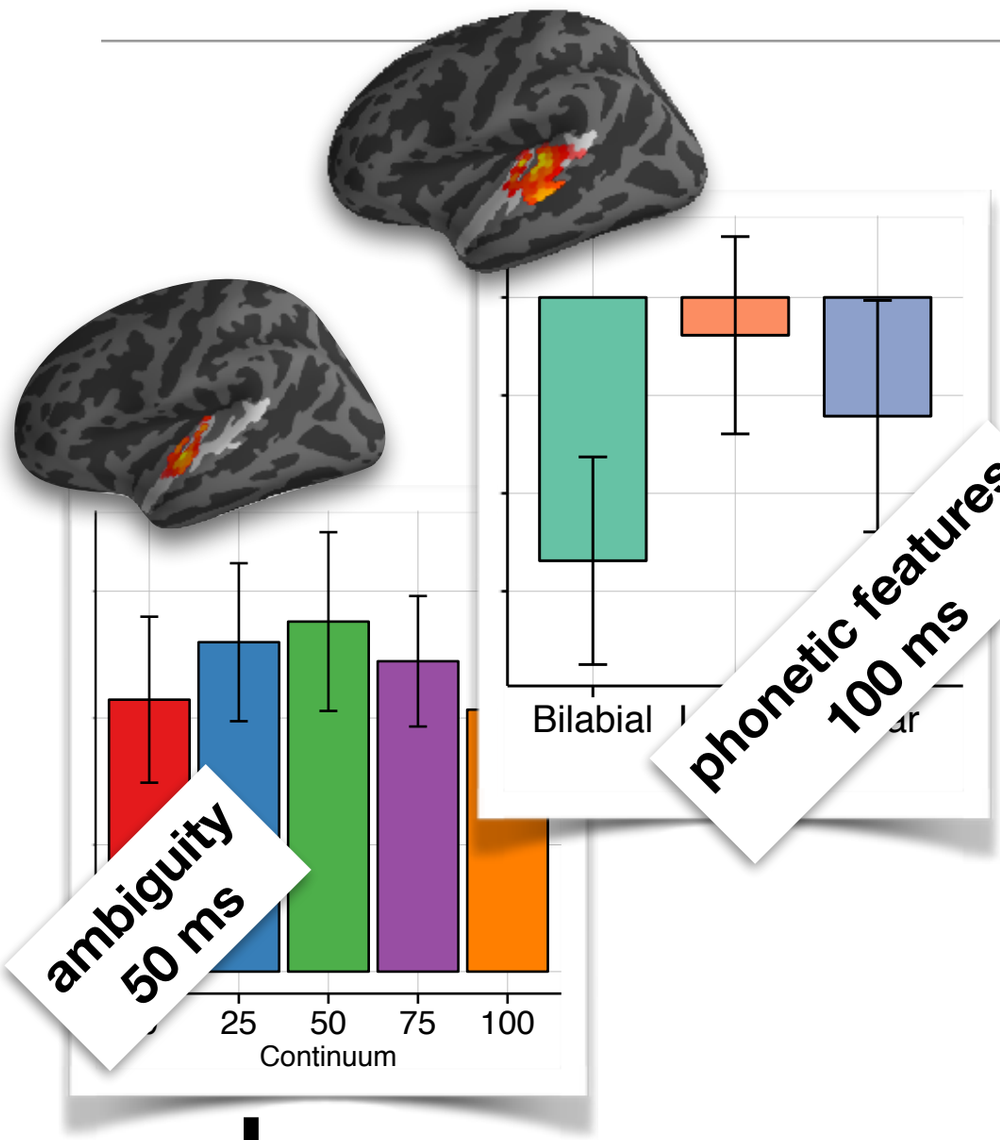


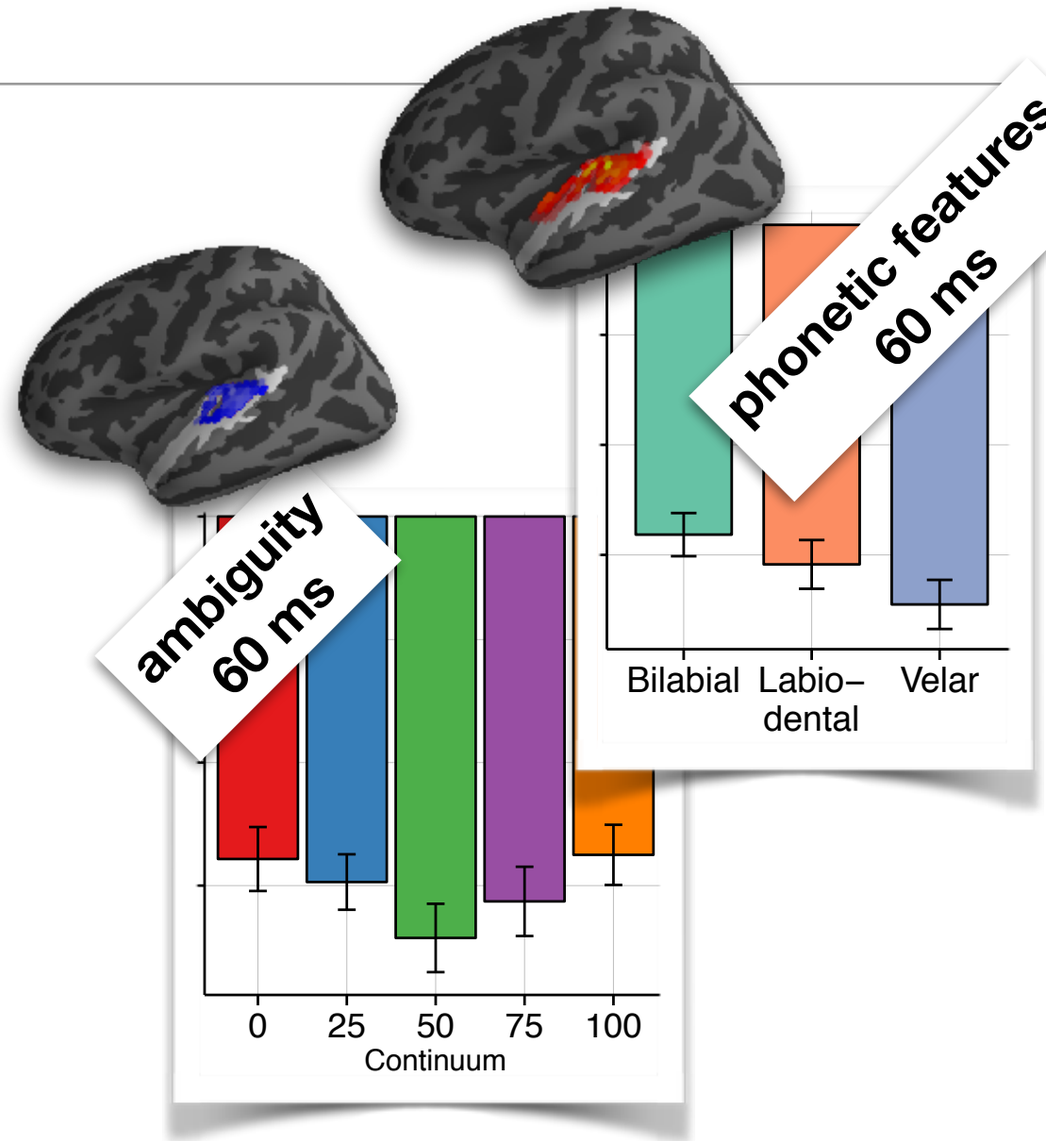


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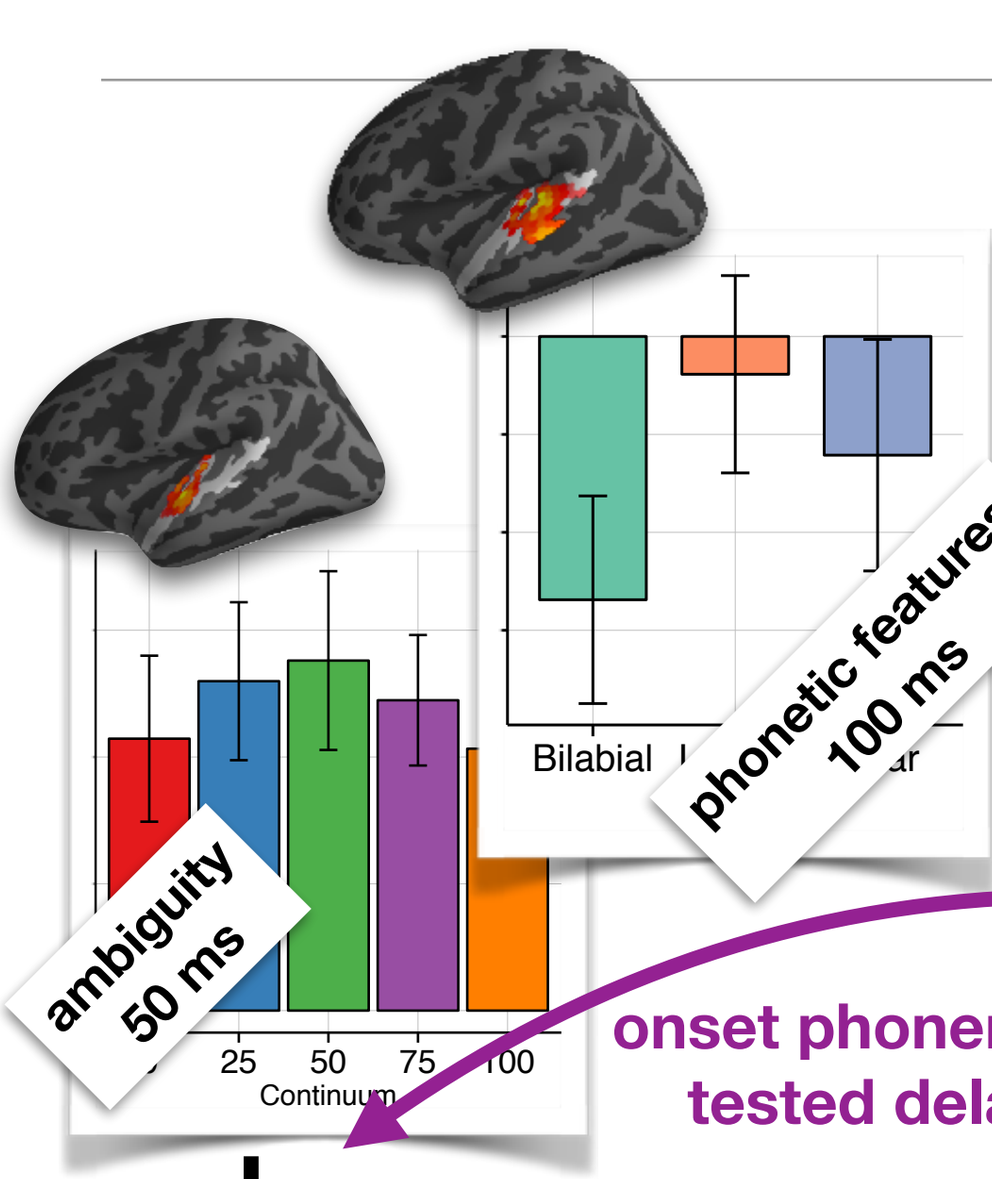
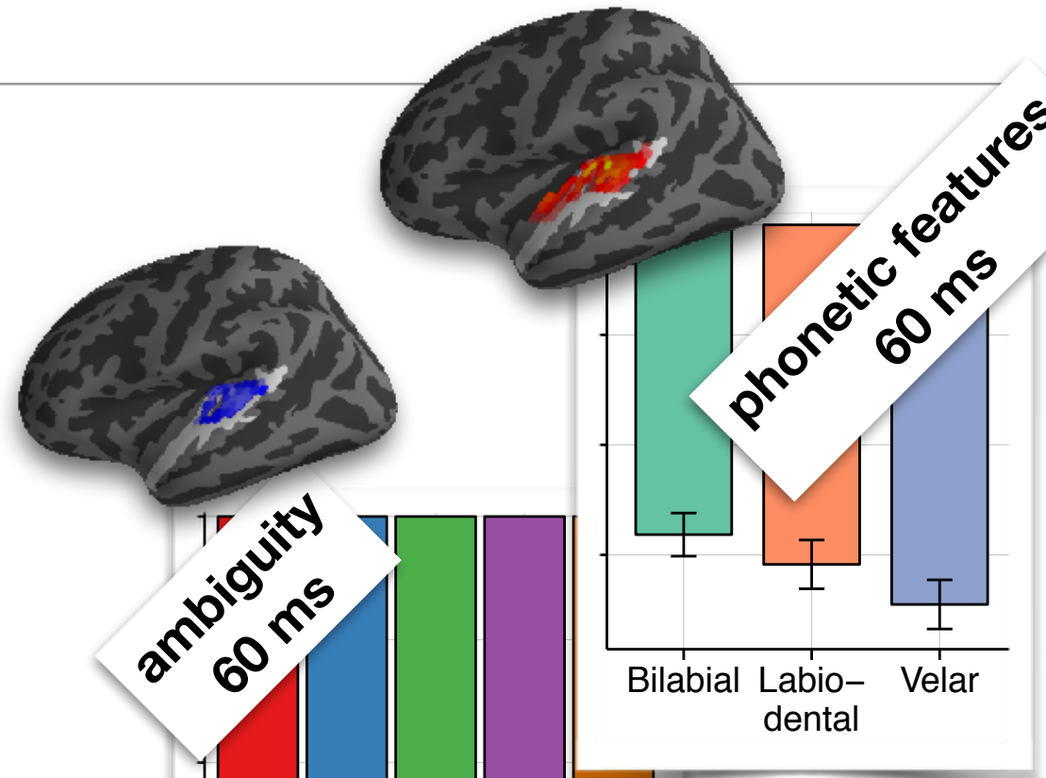
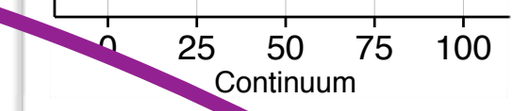
# Interim Conclusion




**onset phoneme re-evoked at all tested delays (150-750 ms)**

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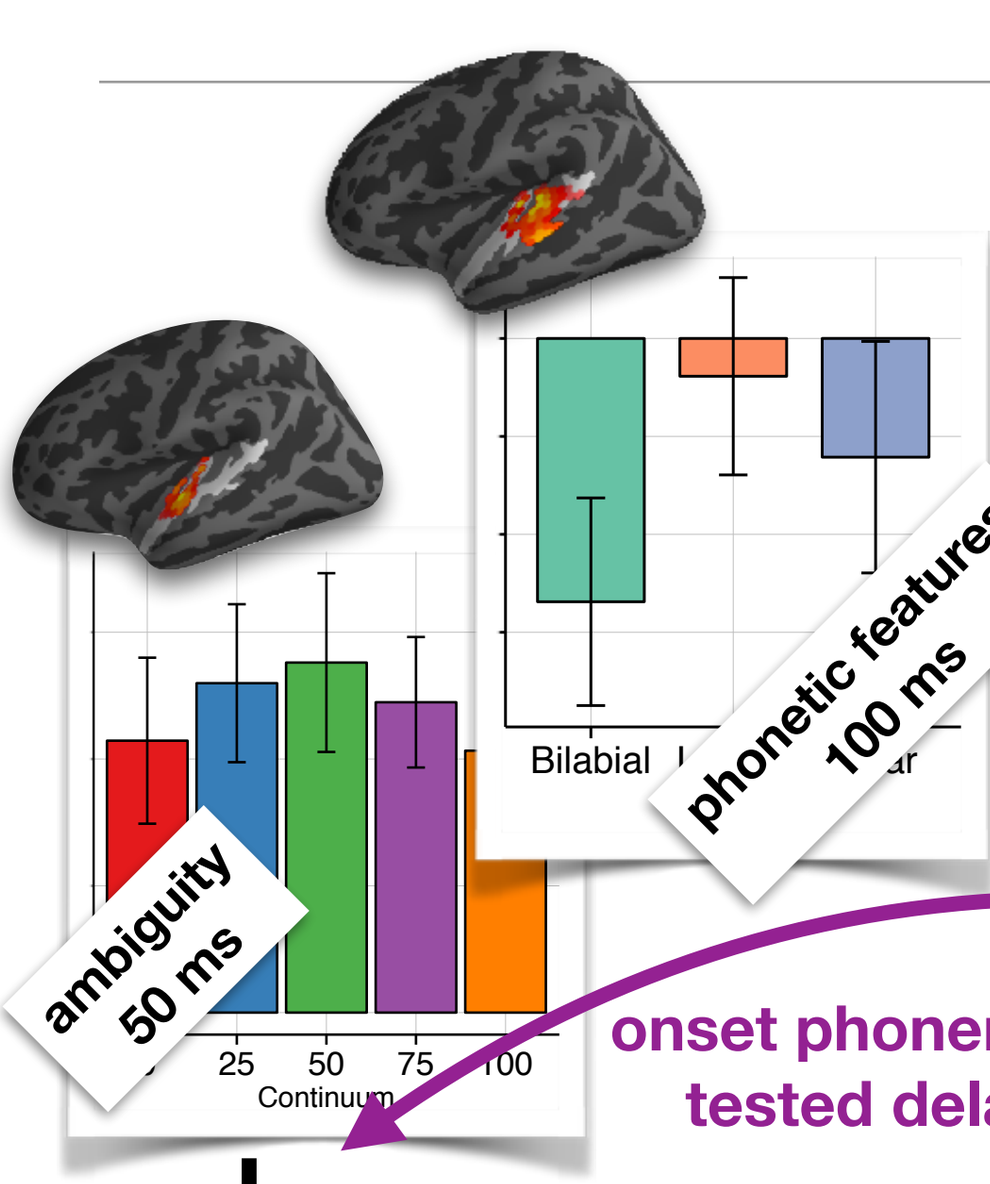
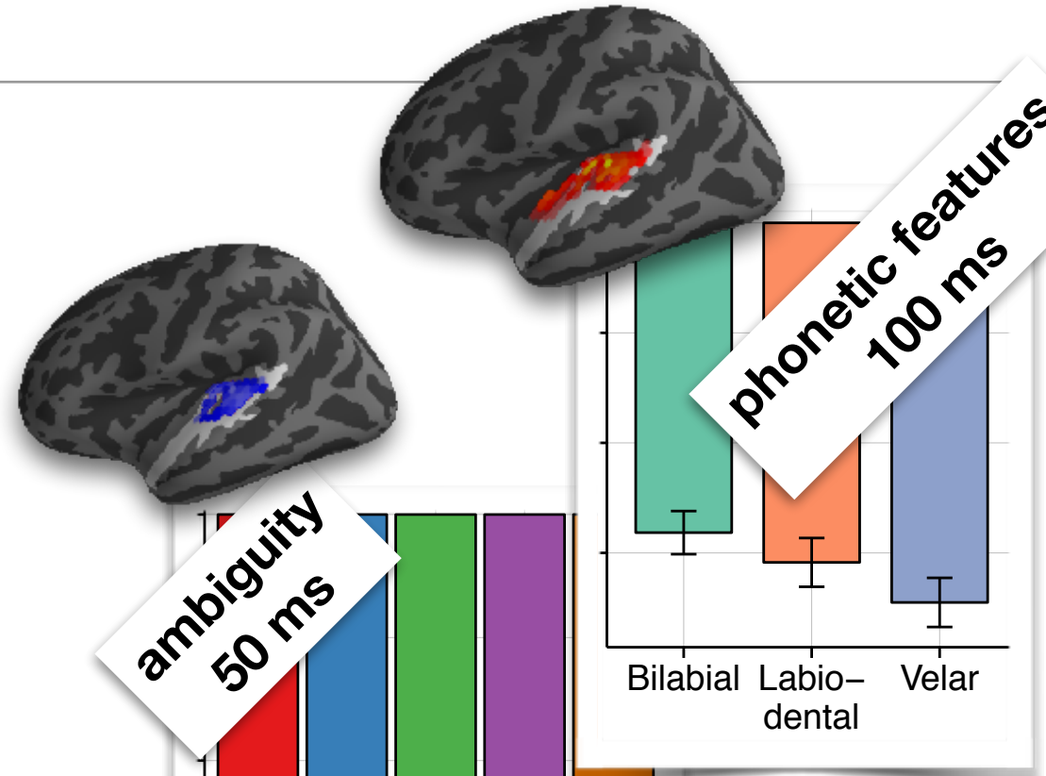
# Interim Conclusion




onset phoneme re-evoked at all tested delays (150-750 ms)

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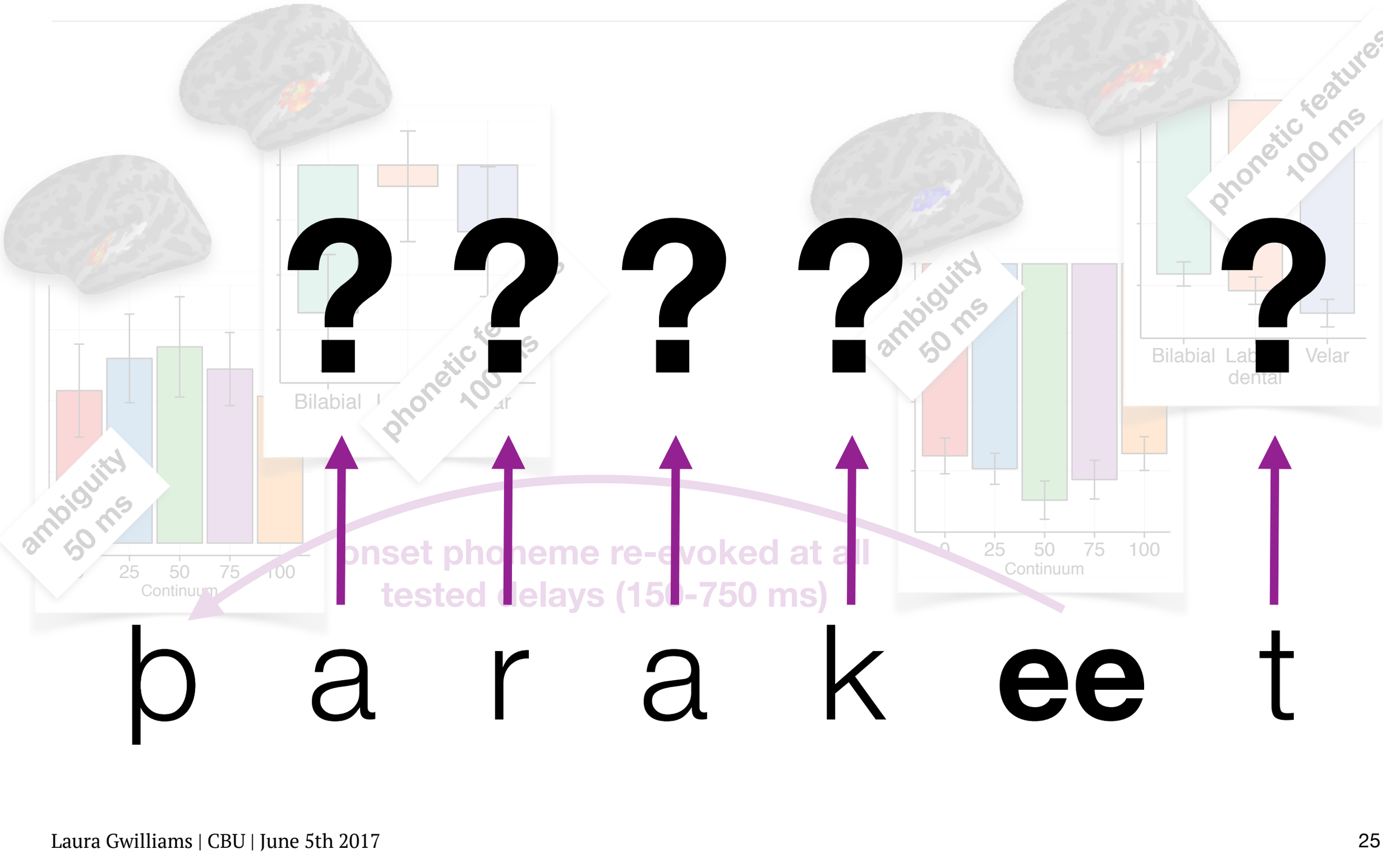
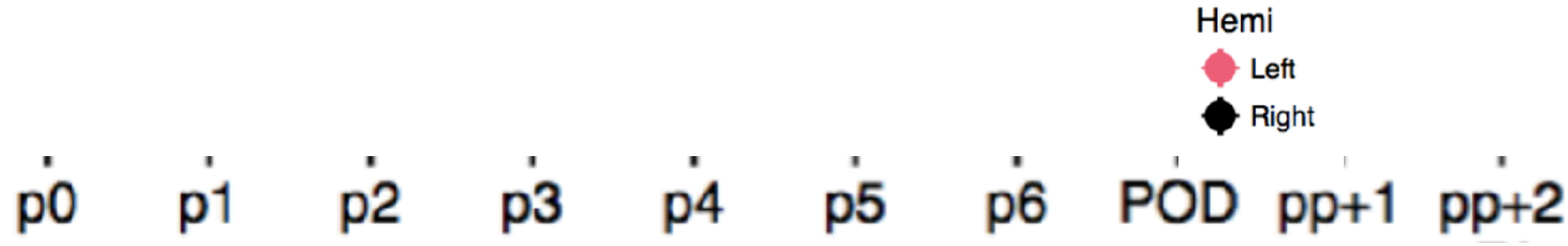
# Interim Conclusion



# Reactivation in Intermediate Positions



# Reactivation in Intermediate Positions

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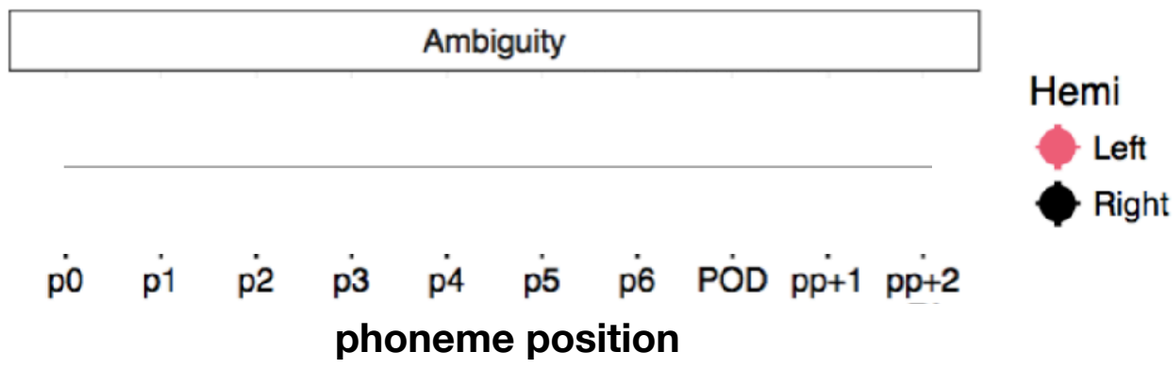

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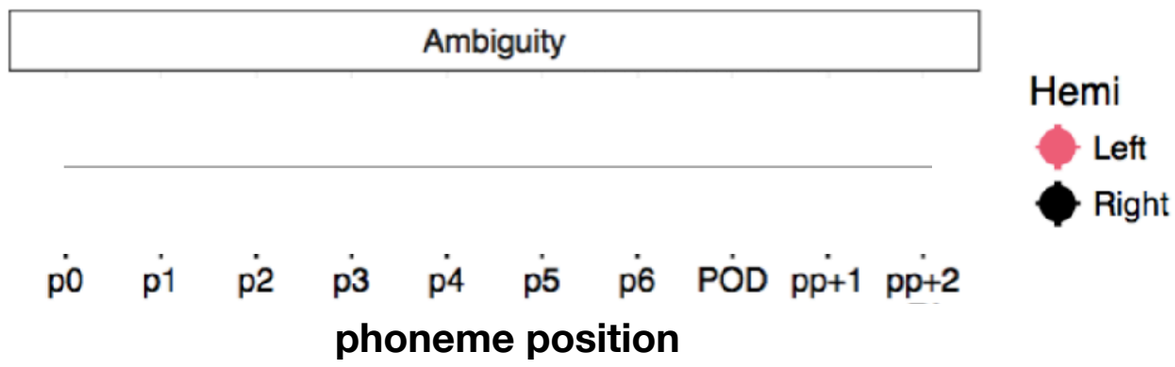

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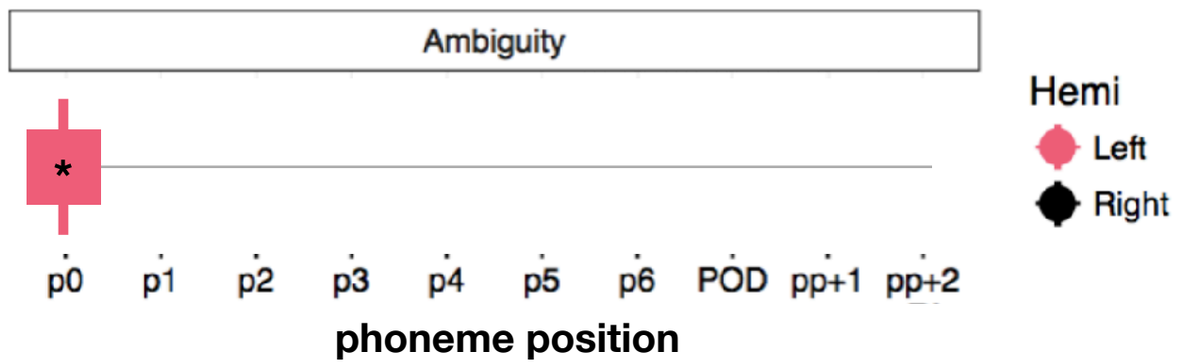

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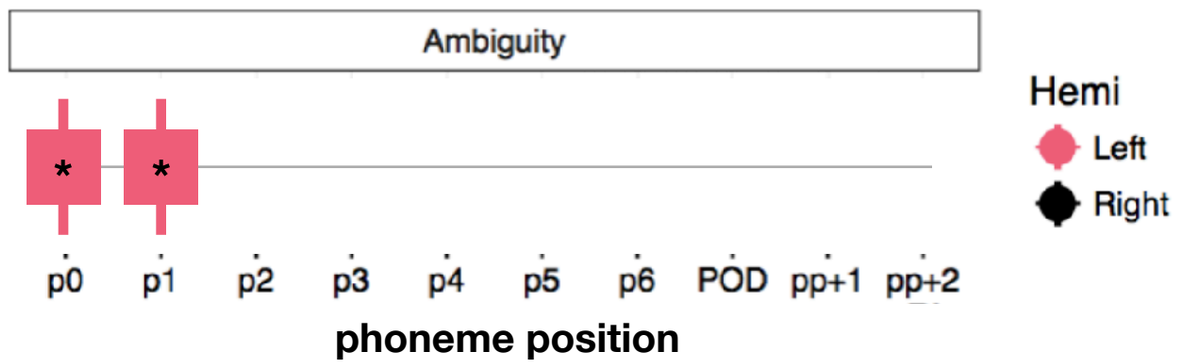

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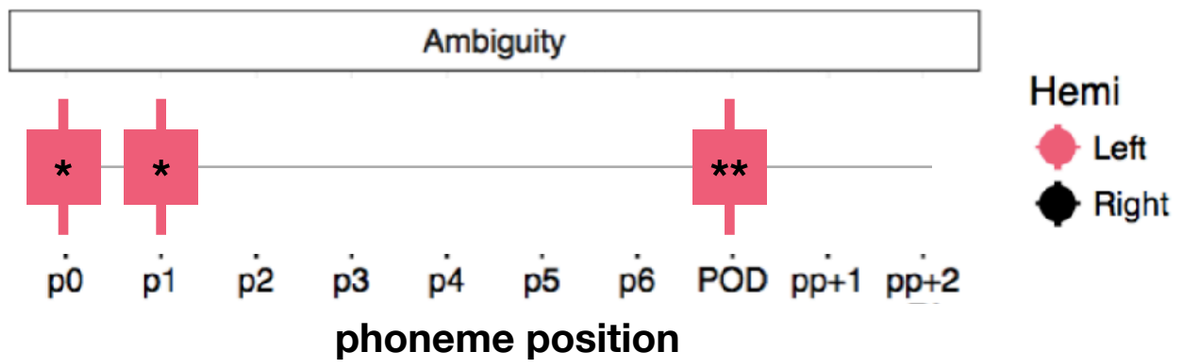

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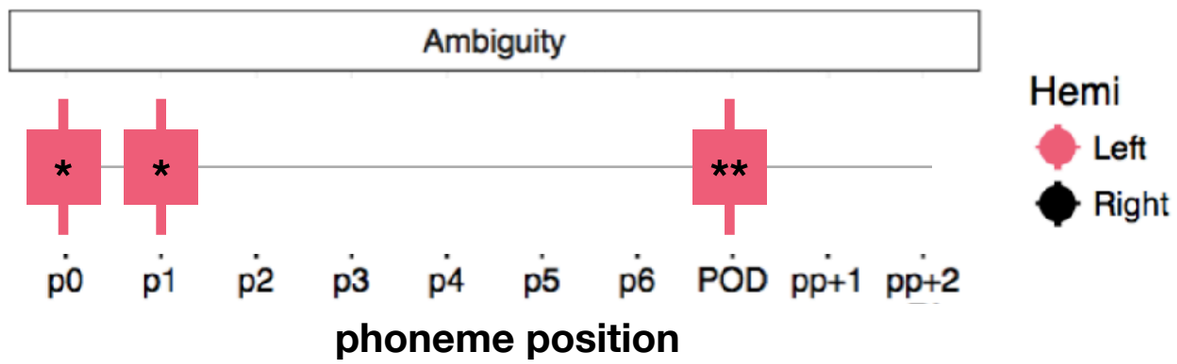

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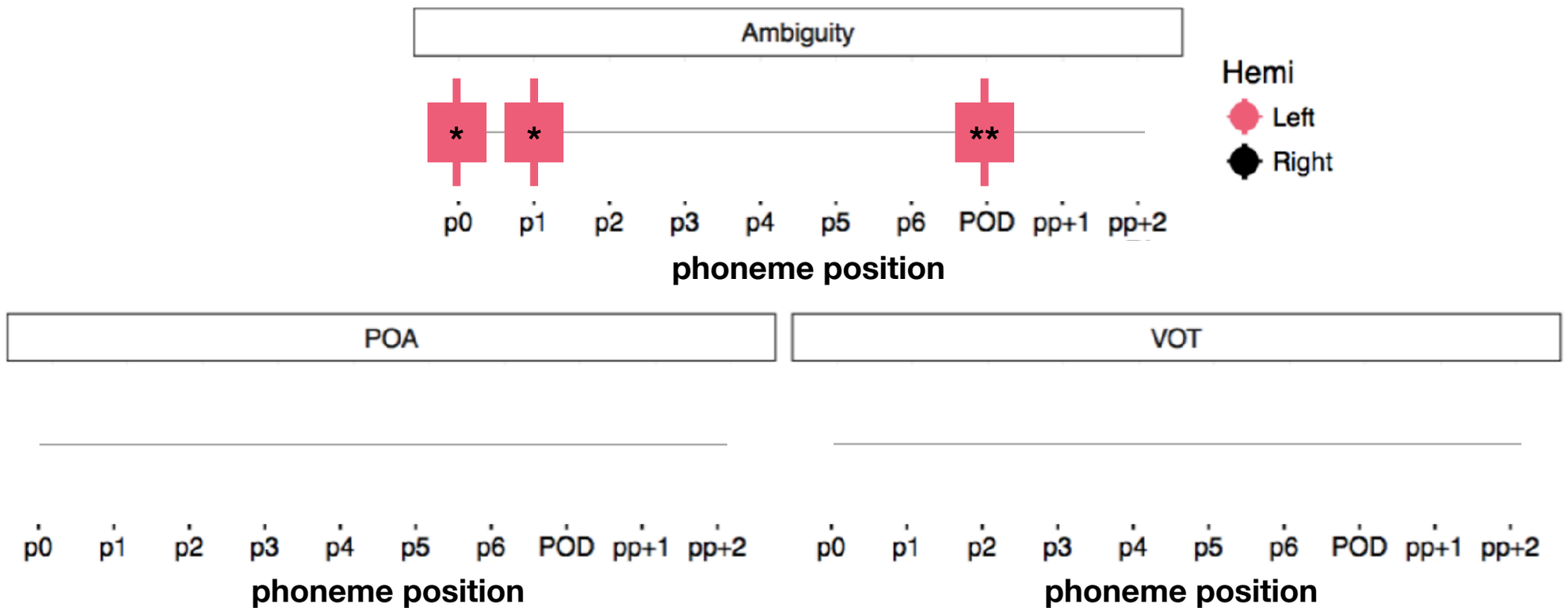

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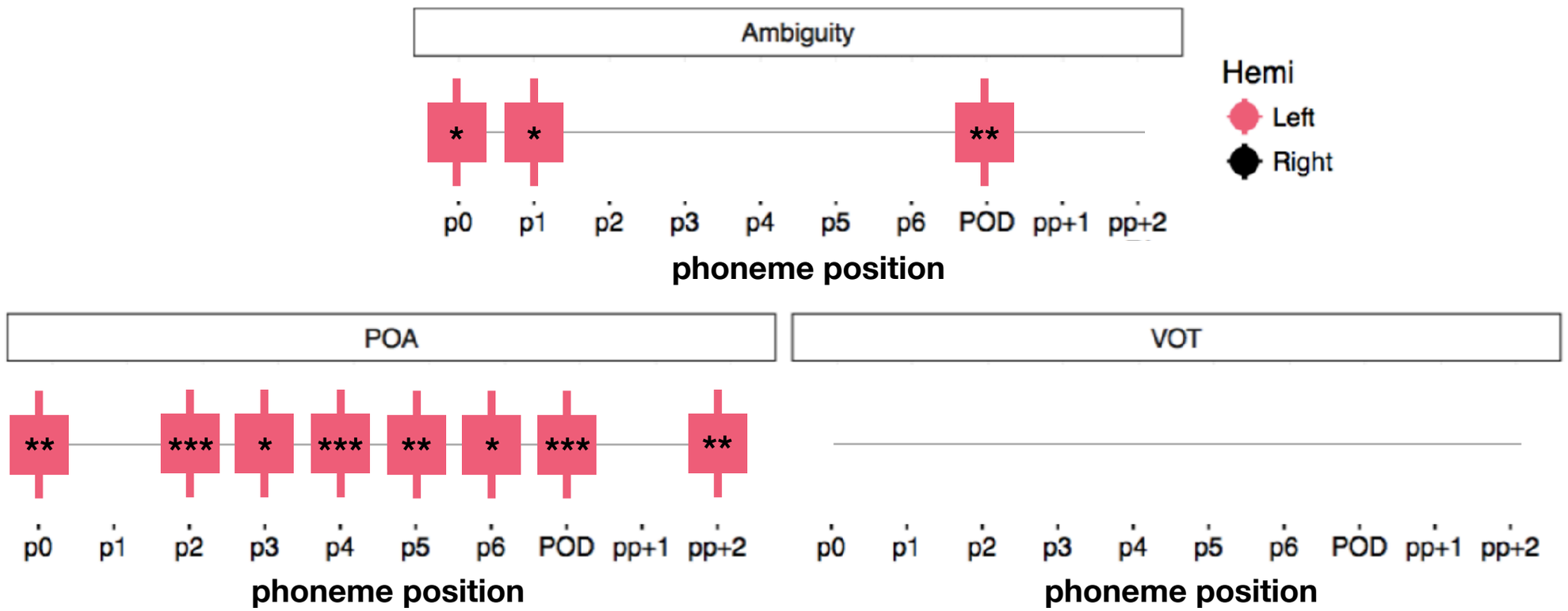

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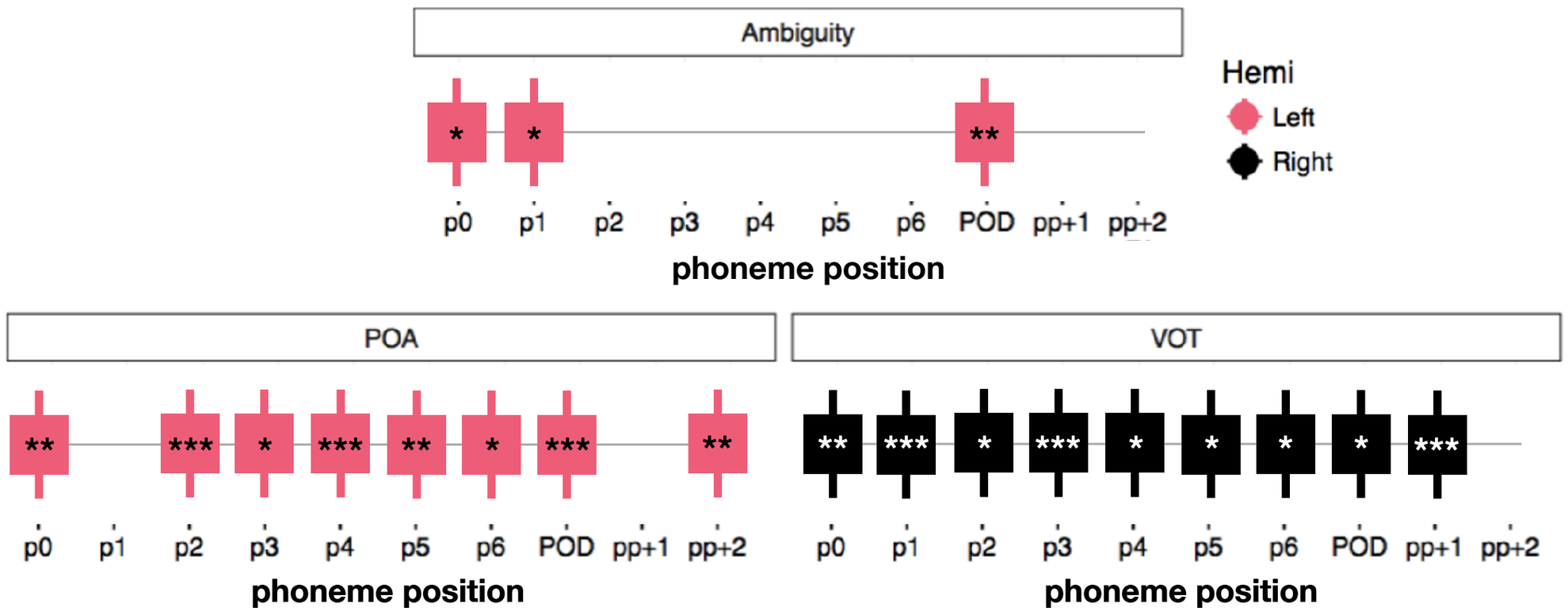

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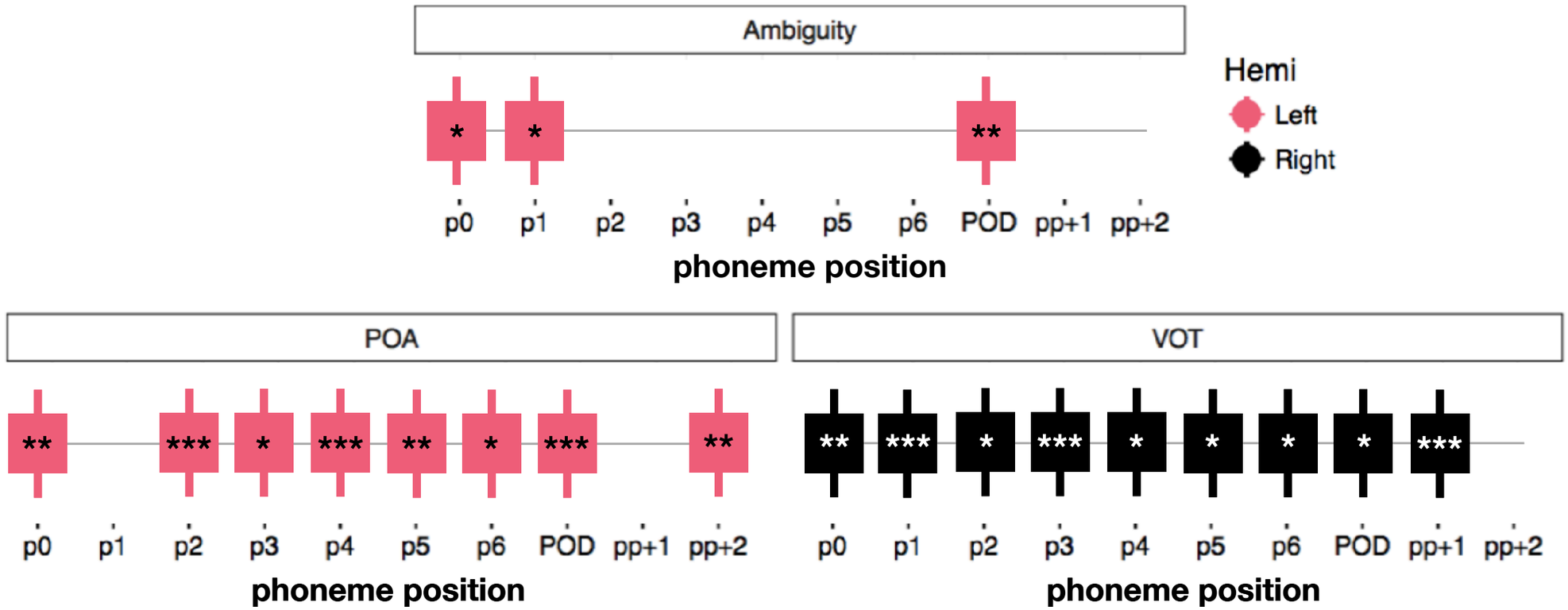

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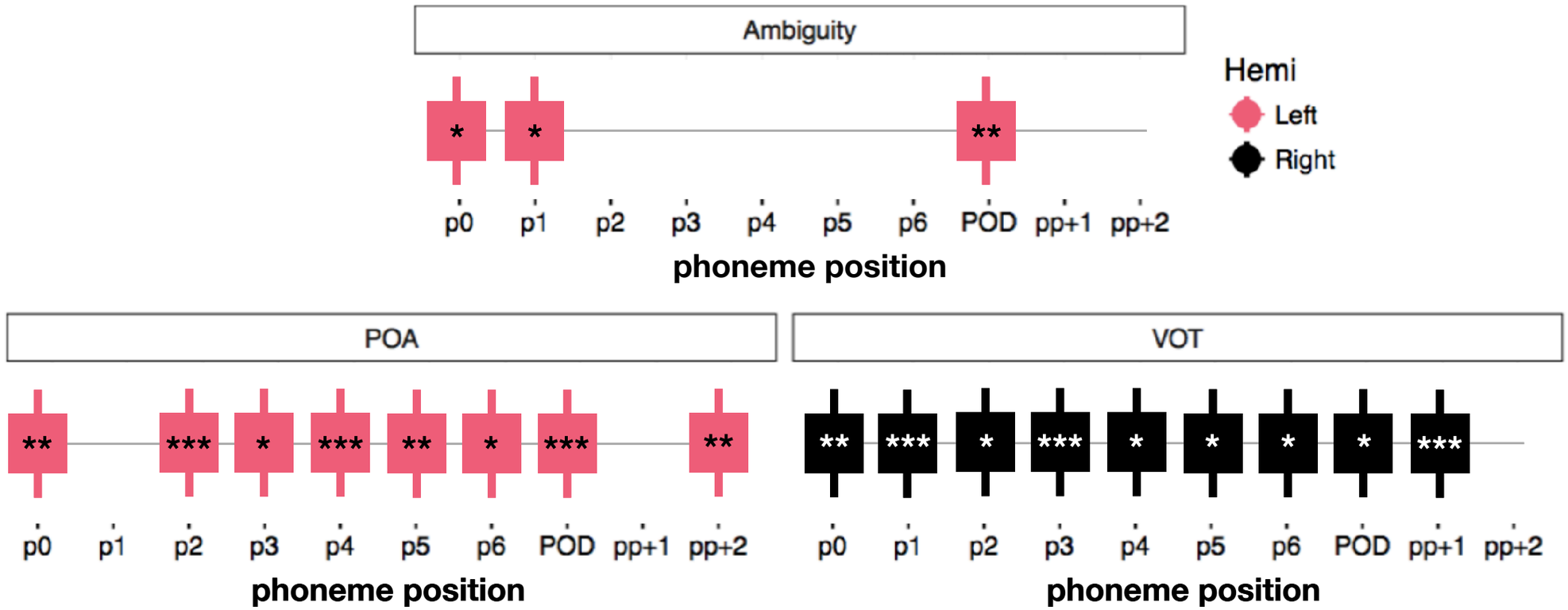
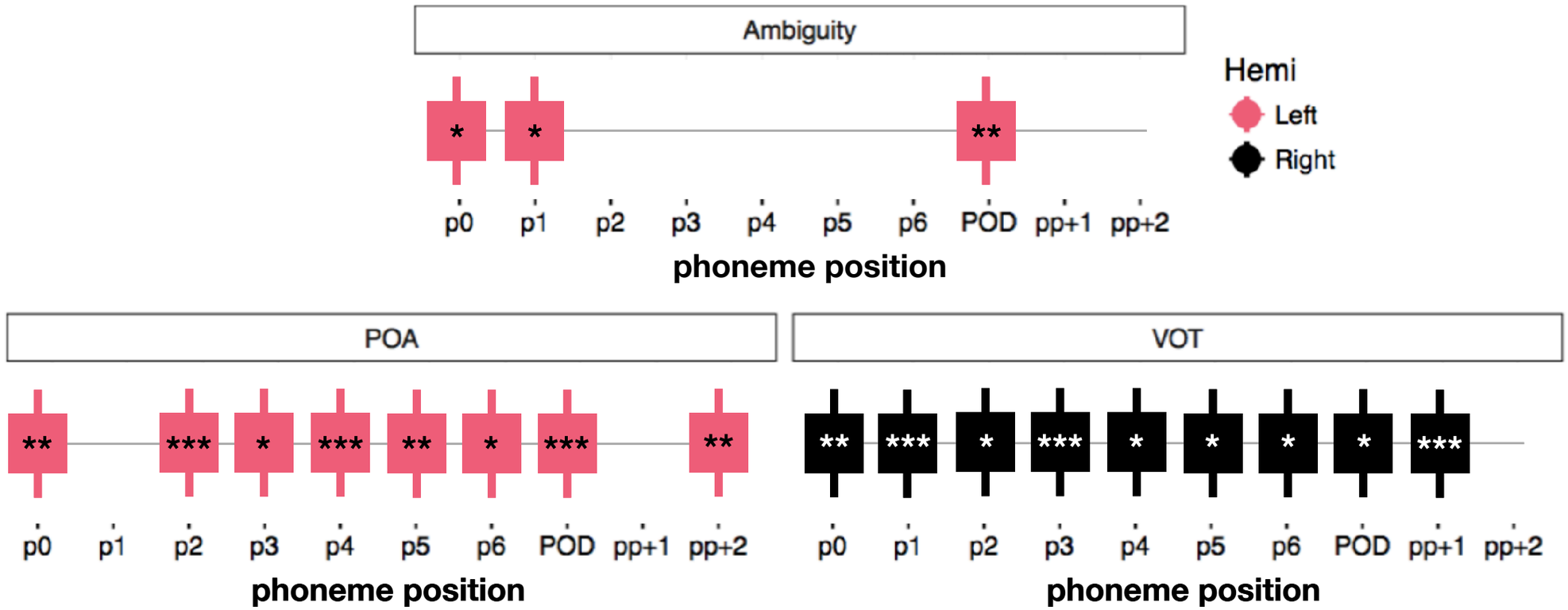


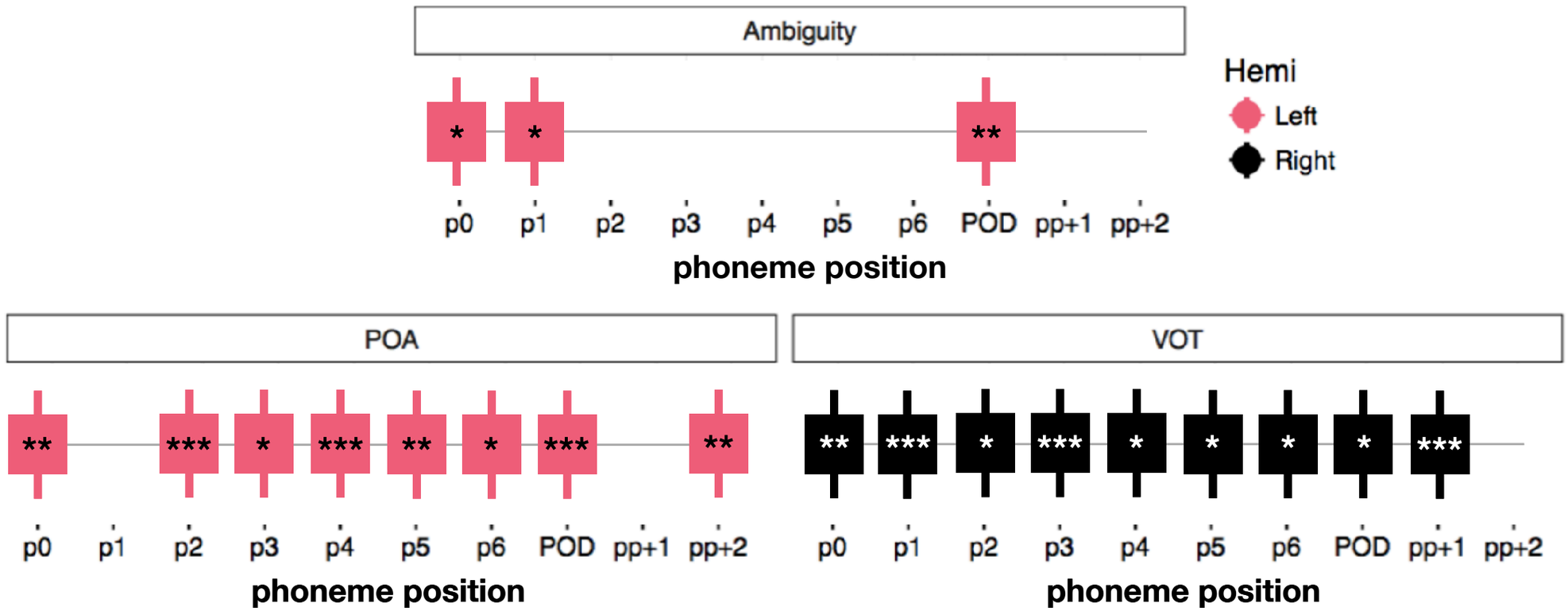

- Information is re-evoked in auditory cortex

# Reactivation in Intermediate Positions



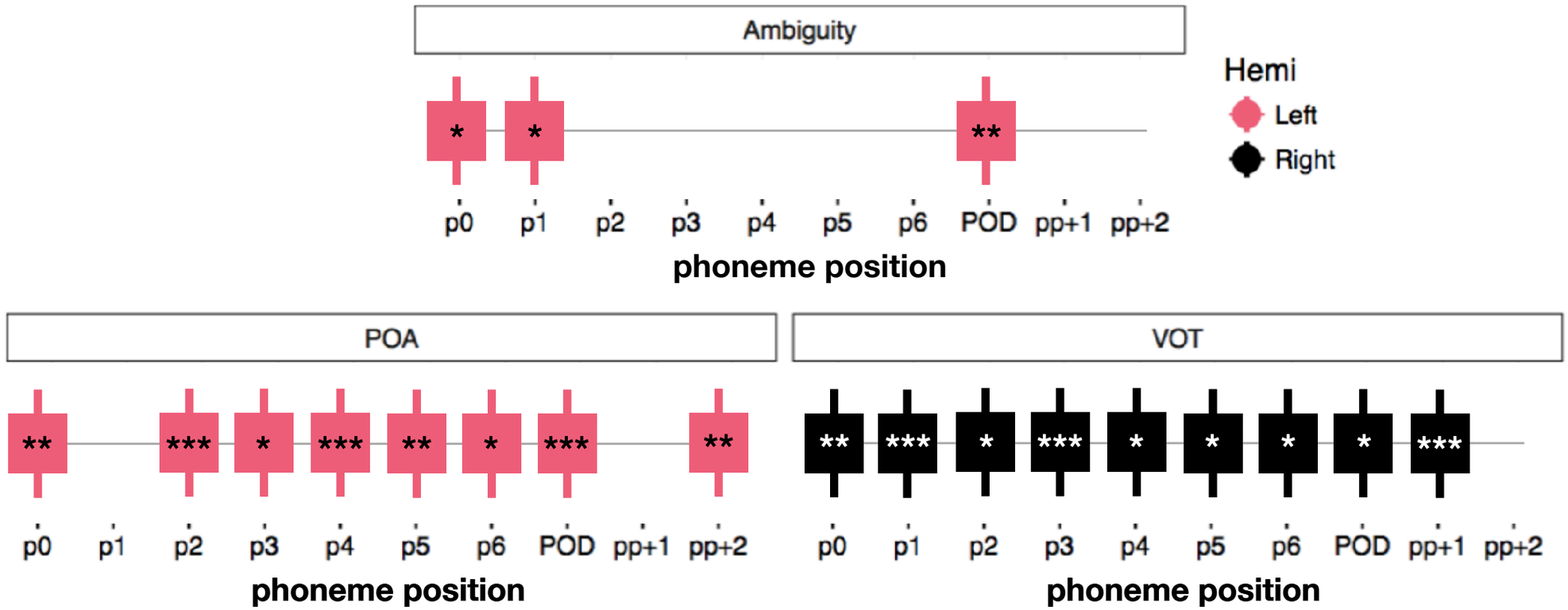

- Information is re-evoked in auditory cortex
- Specifically time-locked to the onset of subsequent phonemes

# Reactivation in Intermediate Positions



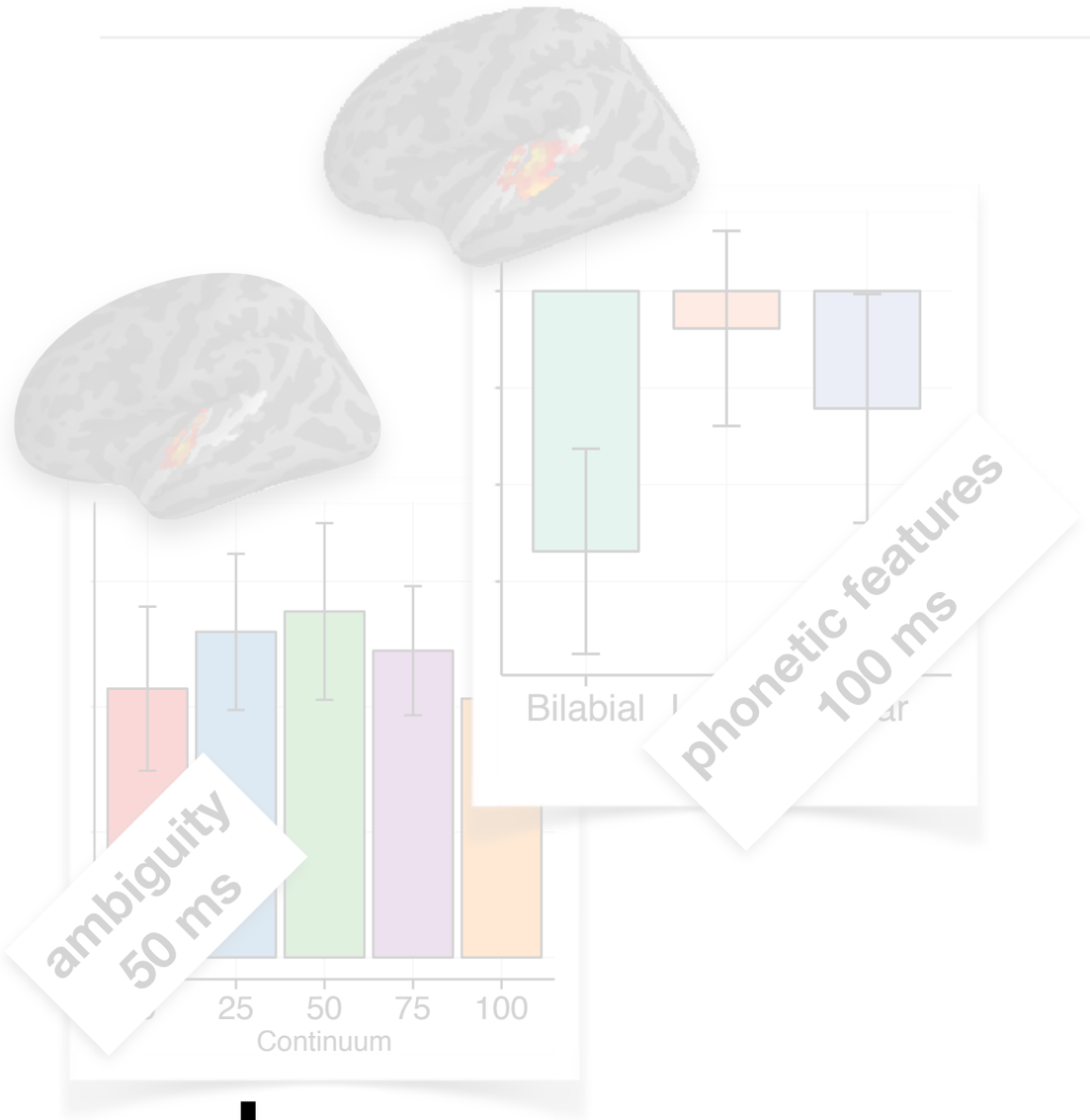

- Information is re-evoked in auditory cortex
- Specifically time-locked to the onset of subsequent phonemes
  - Not driven by residual information in the acoustic signal

# Reactivation in Intermediate Positions




- Information is re-evoked in auditory cortex
- Specifically time-locked to the onset of subsequent phonemes
- Not driven by residual information in the acoustic signal
- Not specific to the ambiguous tokens — general to language processing

# Interim Conclusion

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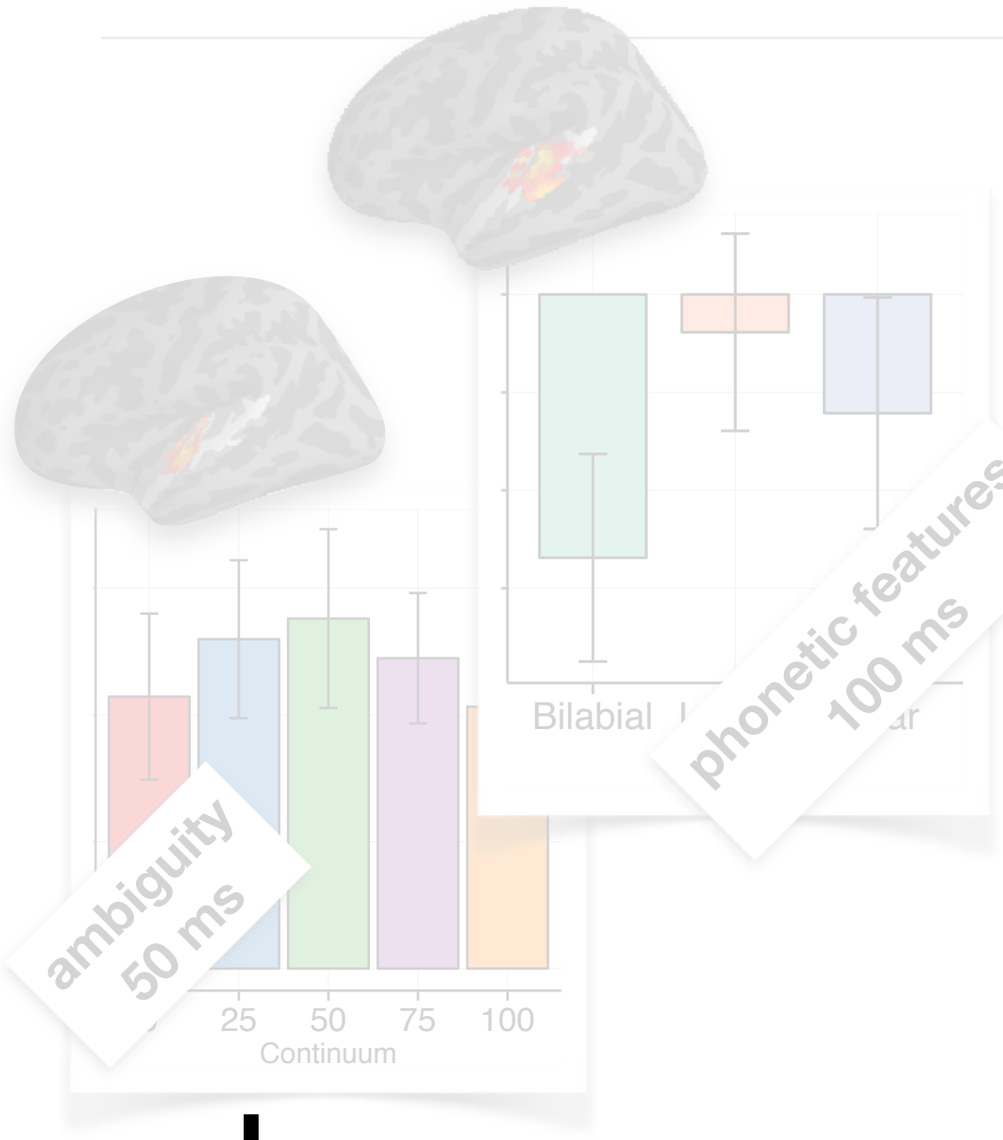
# Interim Conclusion

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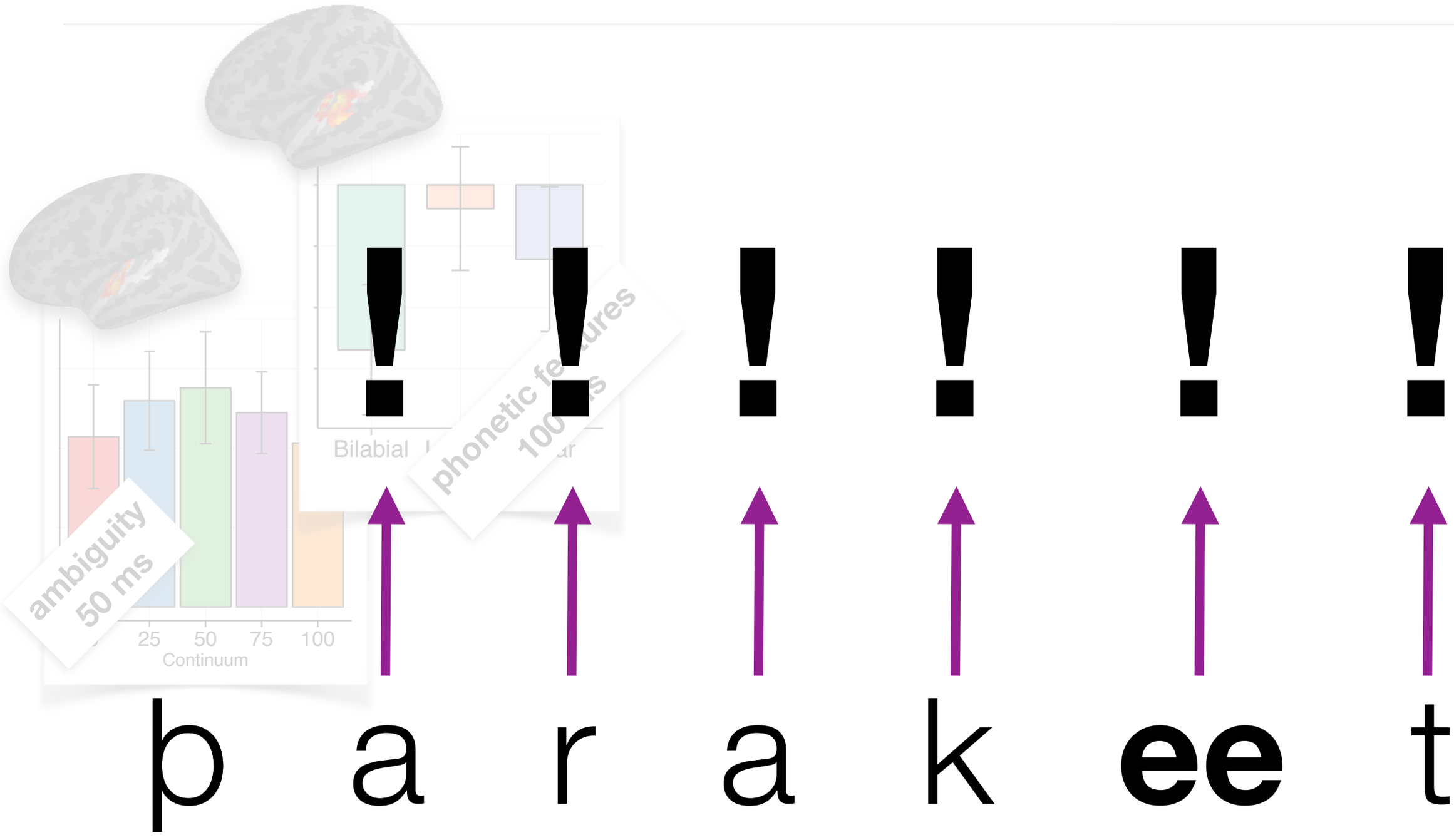
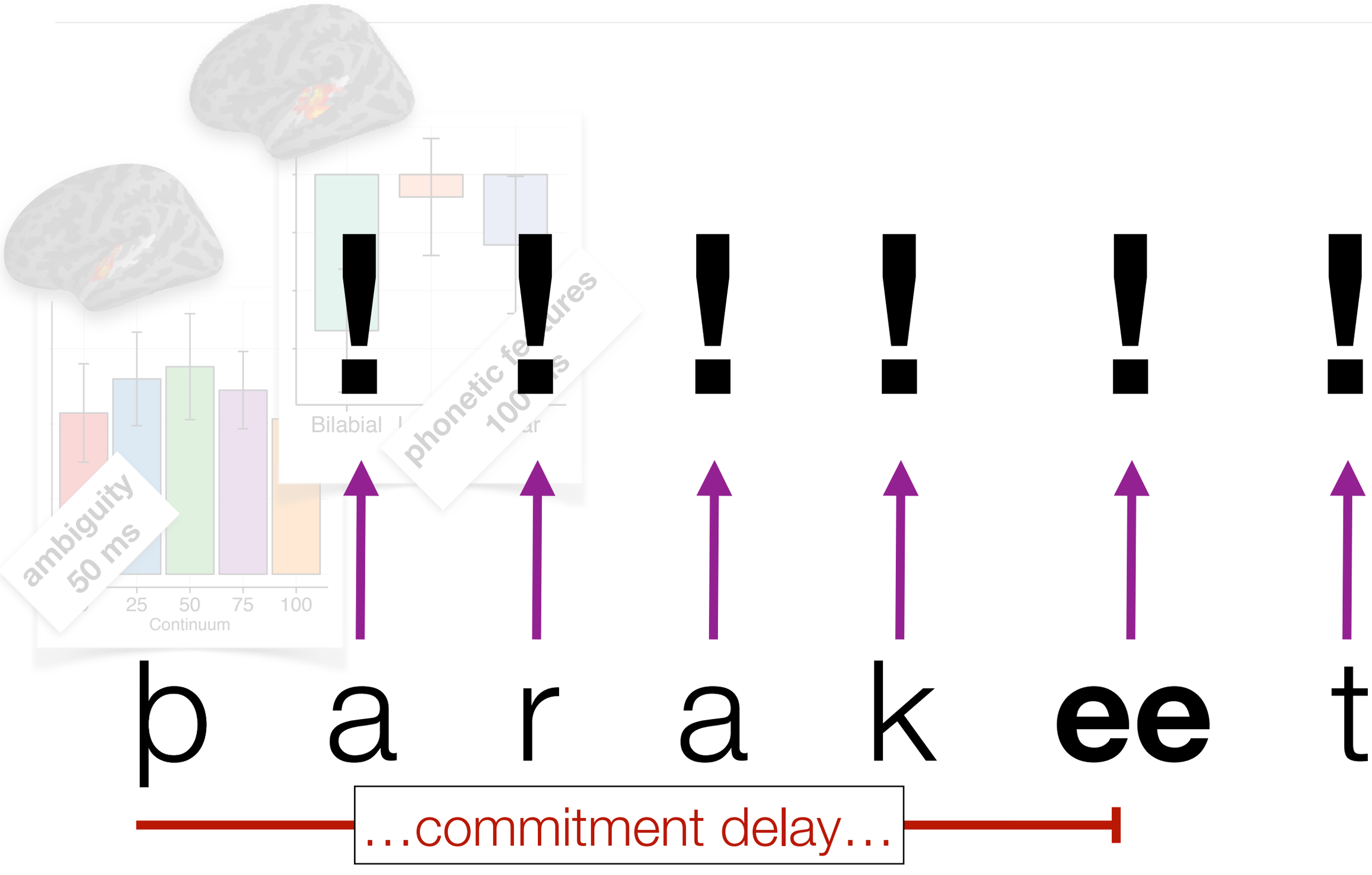
# Interim Conclusion



# Interim Conclusion



# Today's Questions

## How long can the system delay **phonological commitment?**

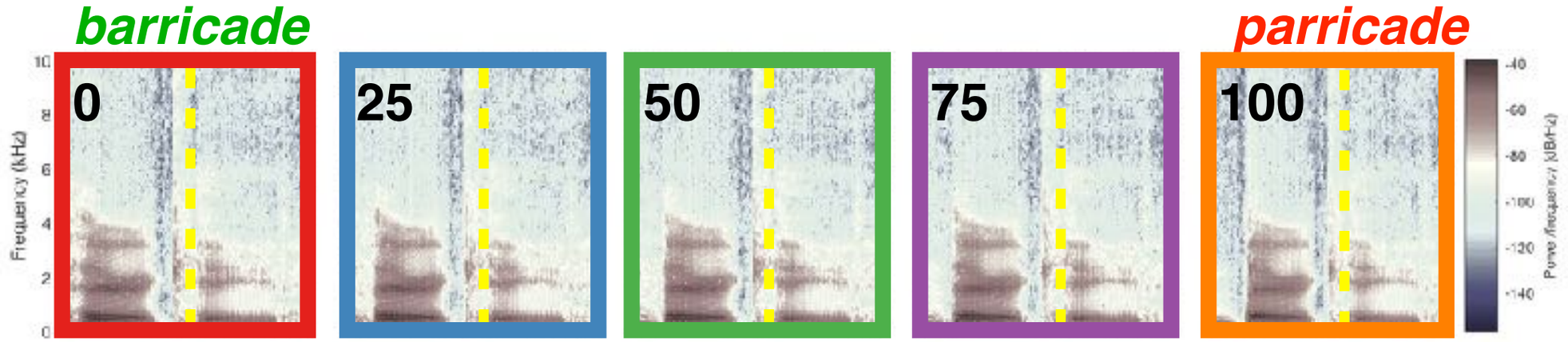
# Today's Questions

## How long can the system delay phonological commitment?

**Psycholinguistic investigations into this question:**

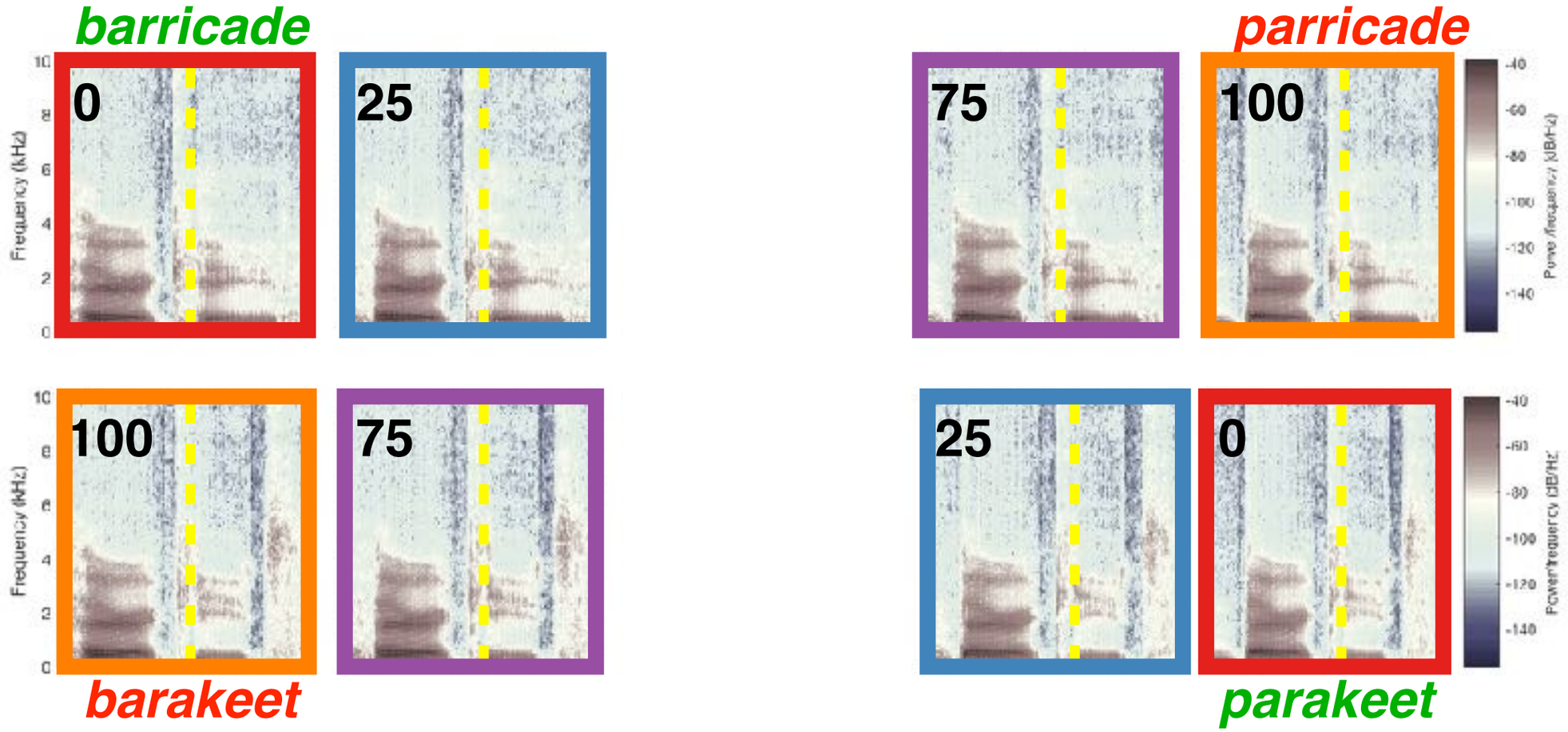
Connine et al. 1991; Samuel 1991; McMurray et al. 2009; Szostak and Pitt 2013

# Example Continuum Pair




- Point of Disambiguation (POD) ranged 3-8 phonemes / 150-750 ms

# Example Continuum Pair

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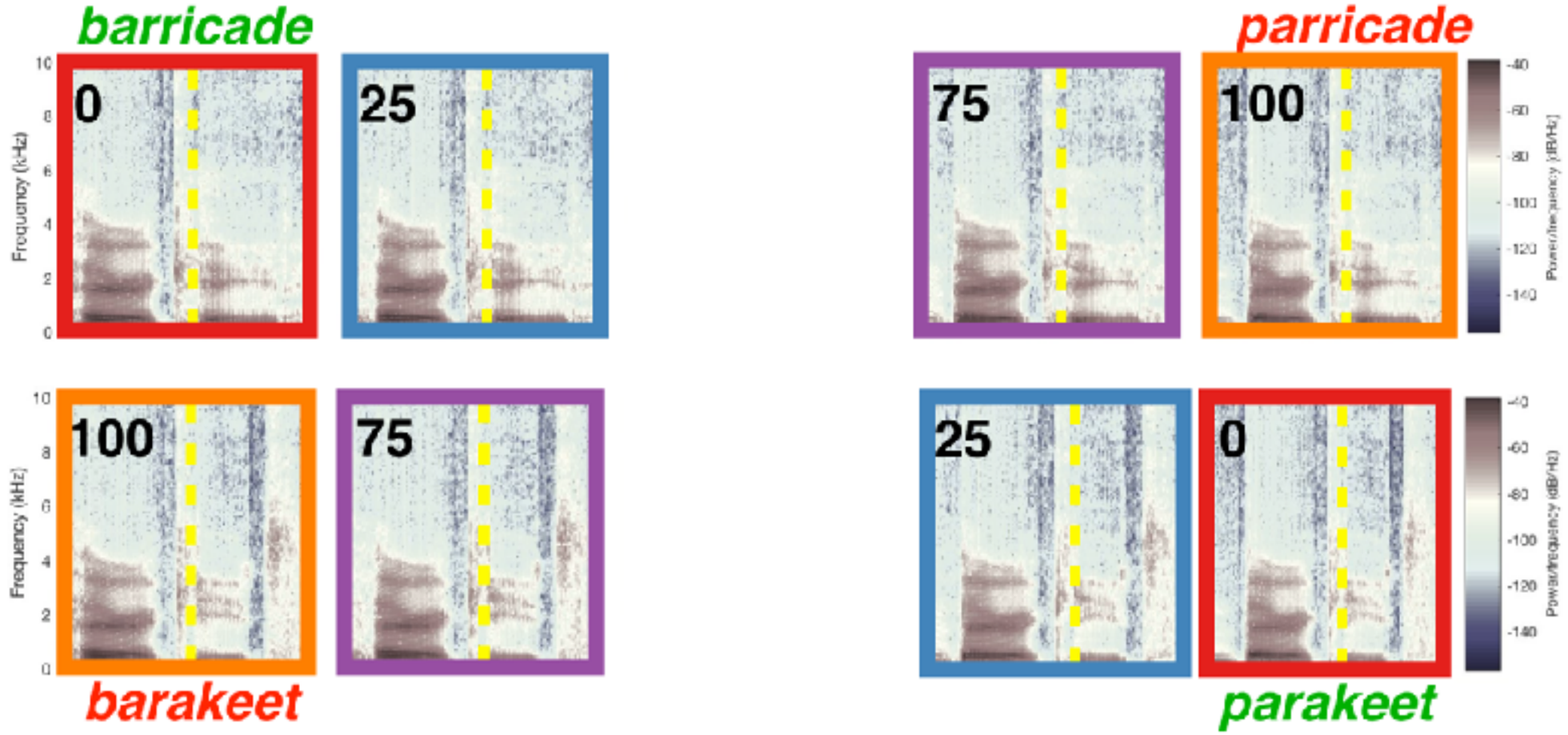


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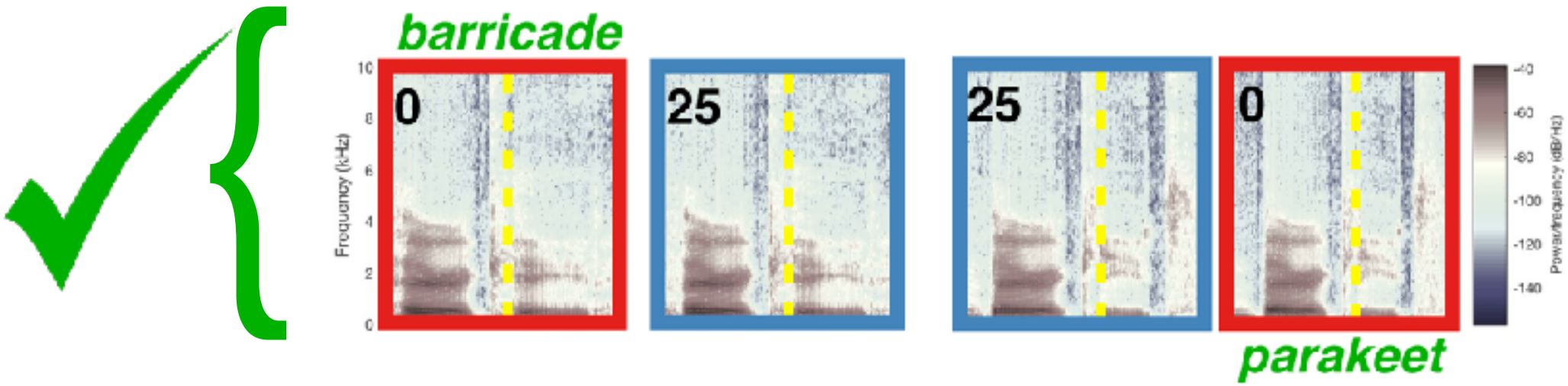
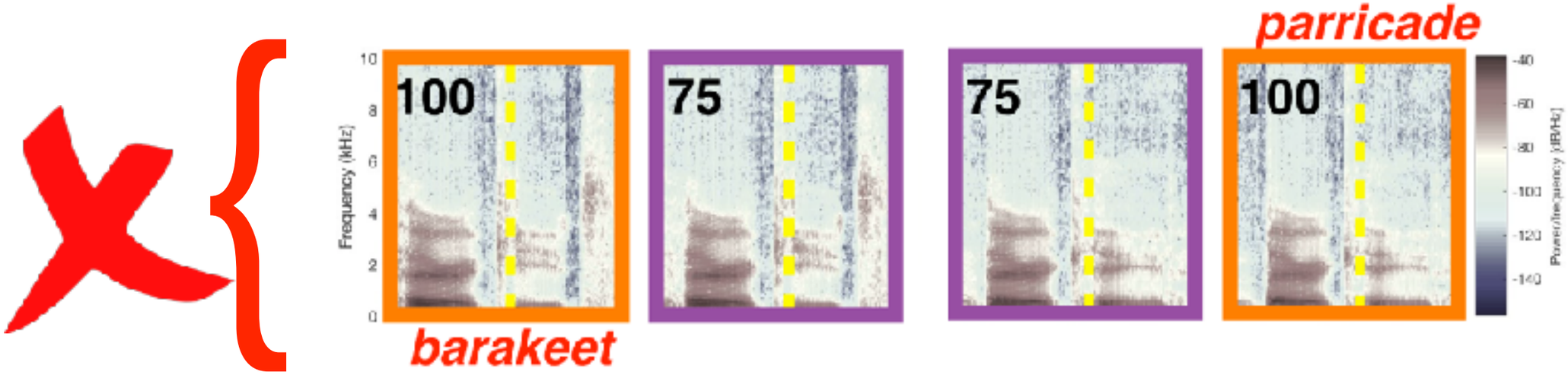



vs.

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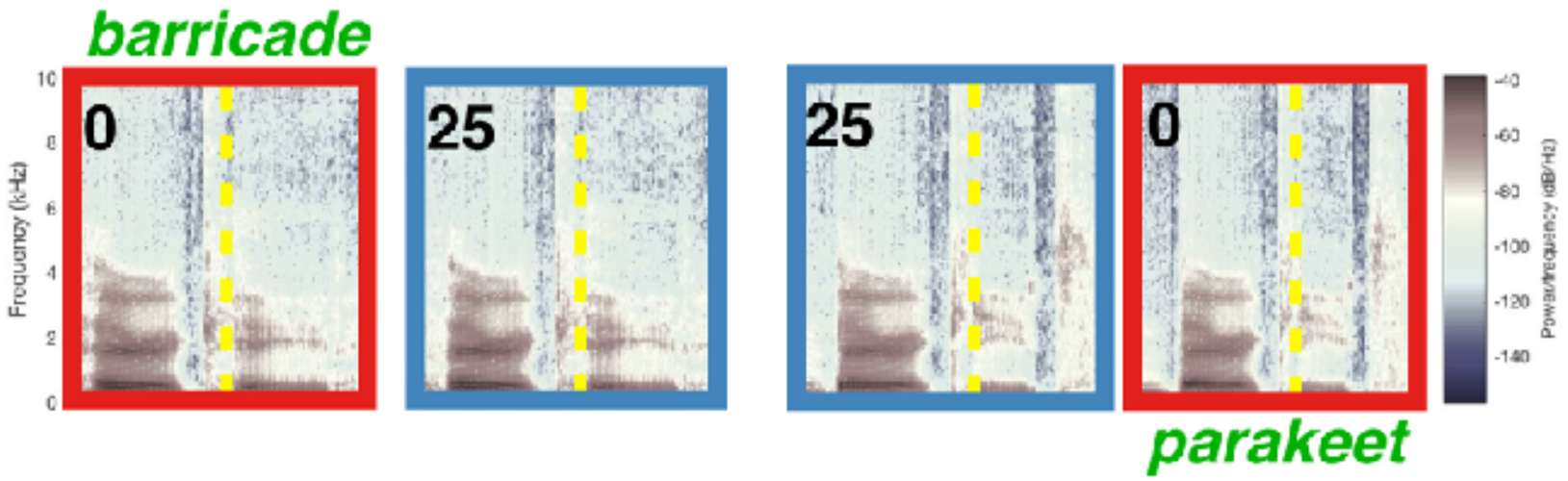
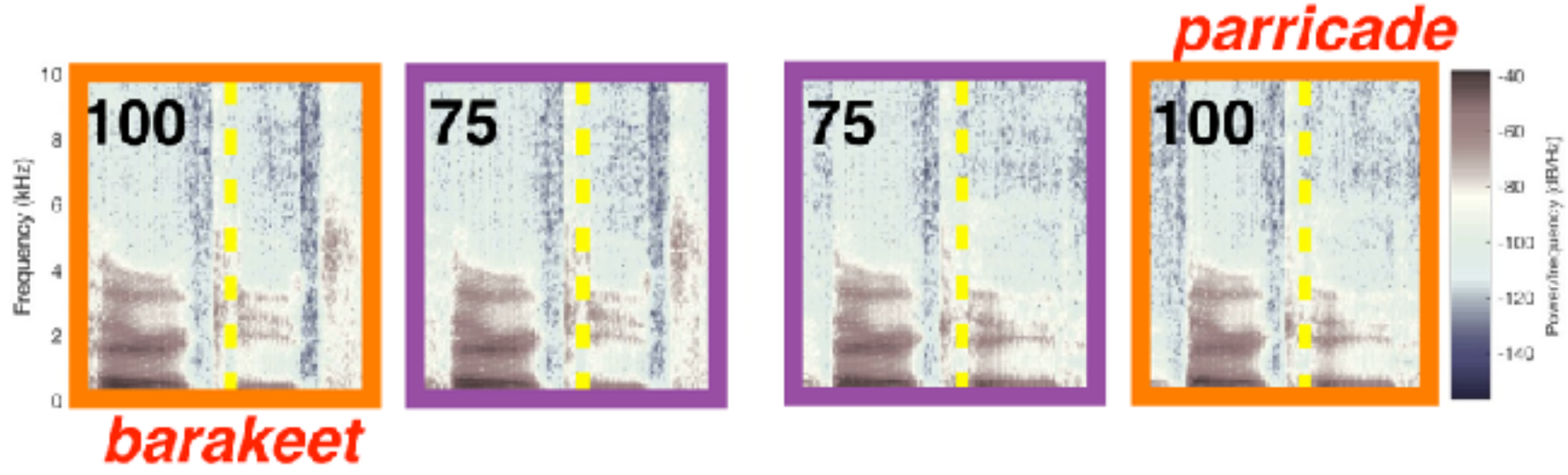
# Example Continuum Pair

word




vs.

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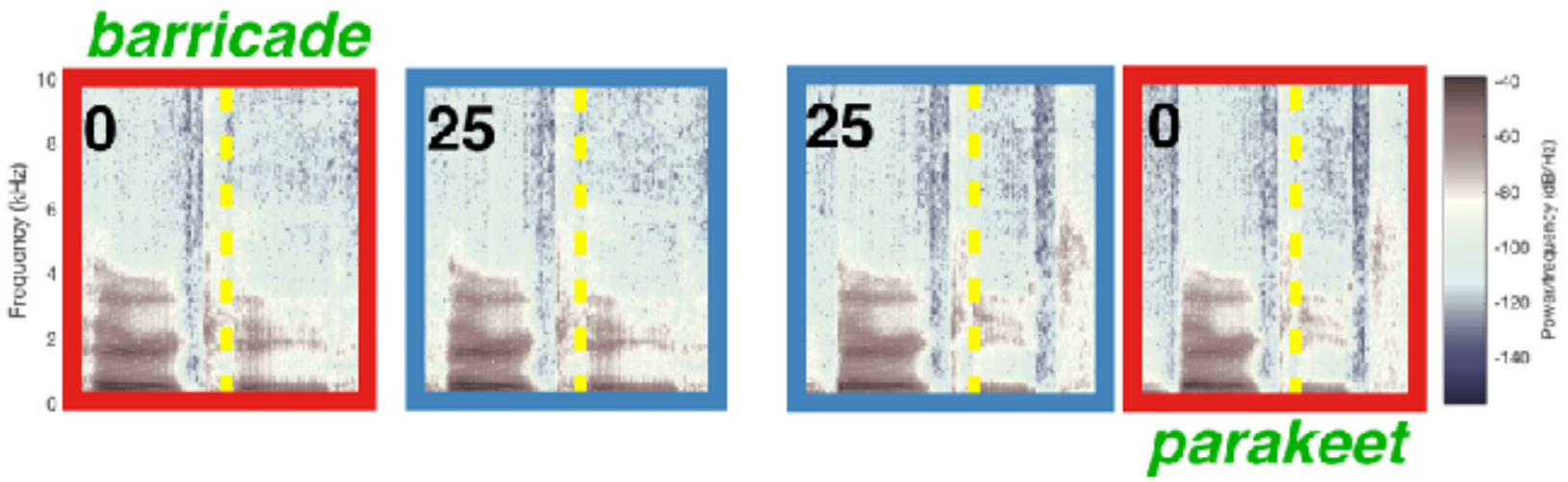
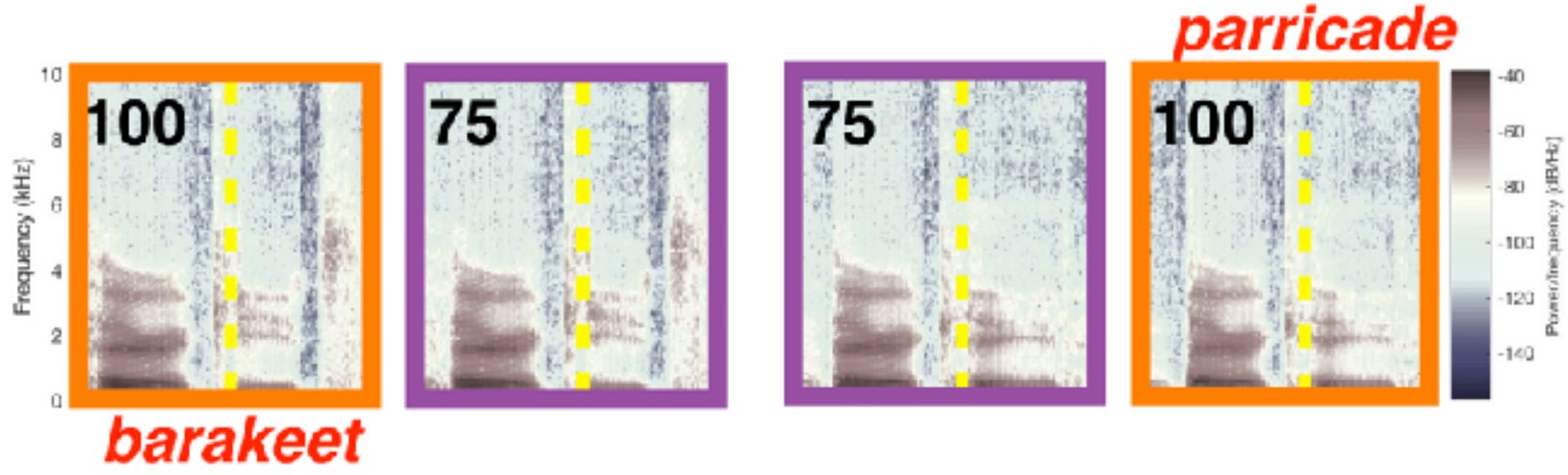
word




VS.

non-word

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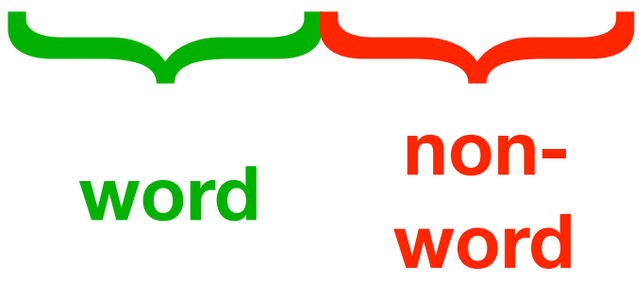


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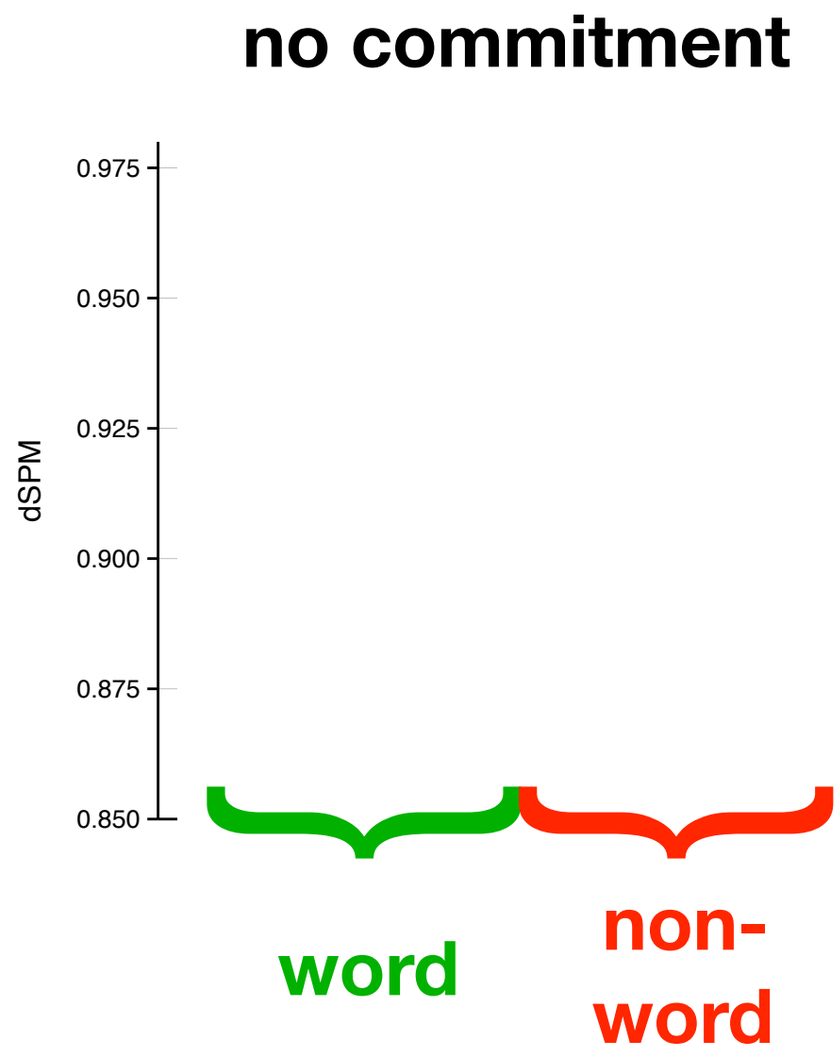


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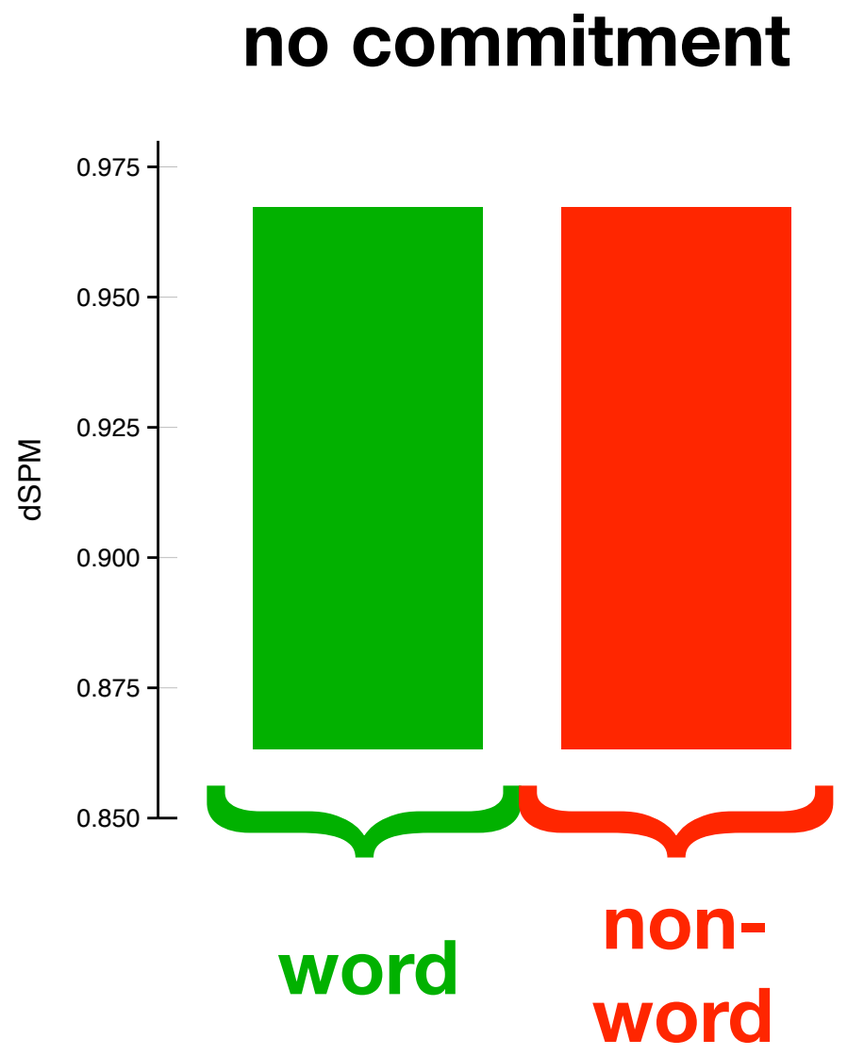


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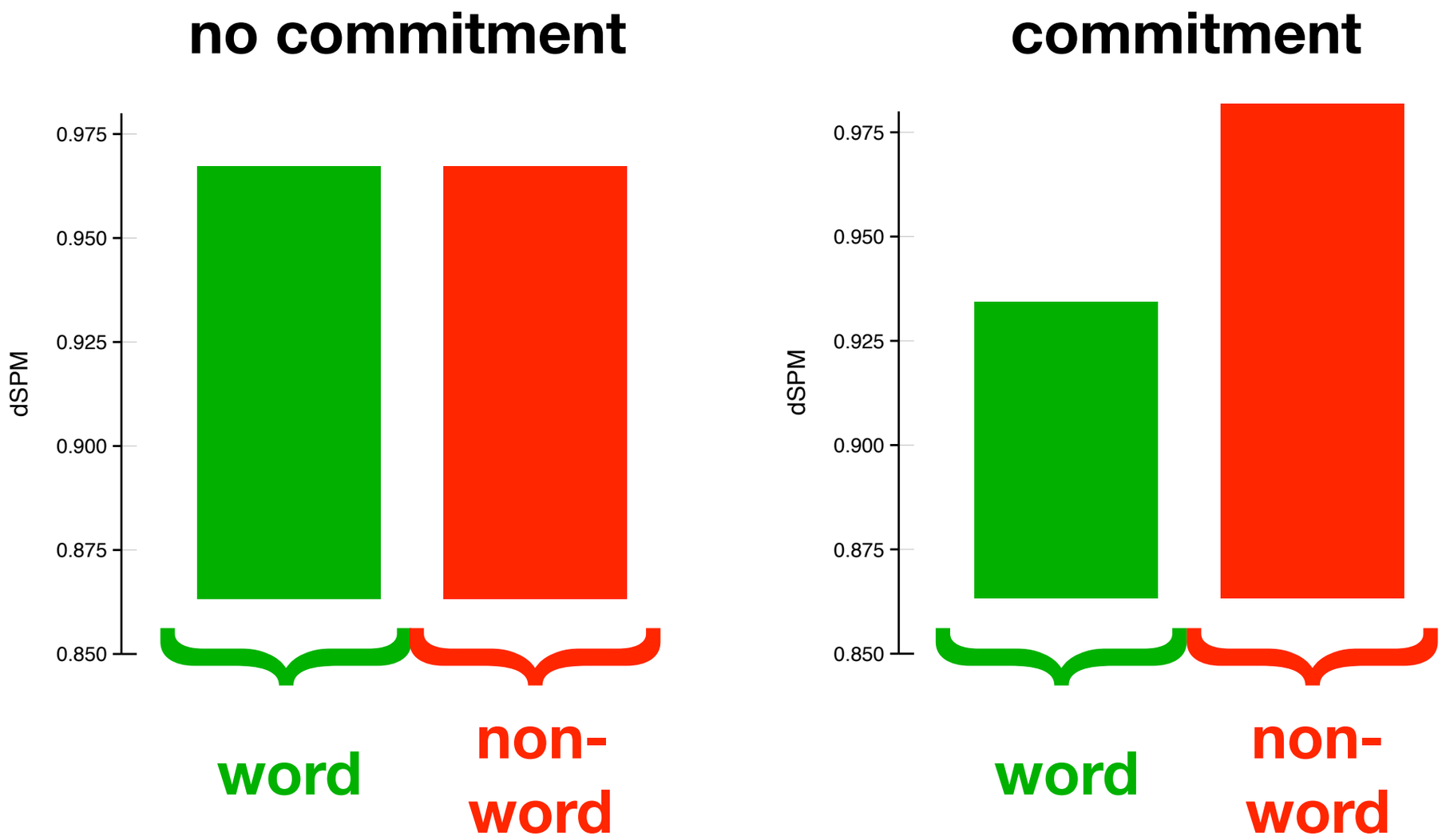


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# Commitment Before POD

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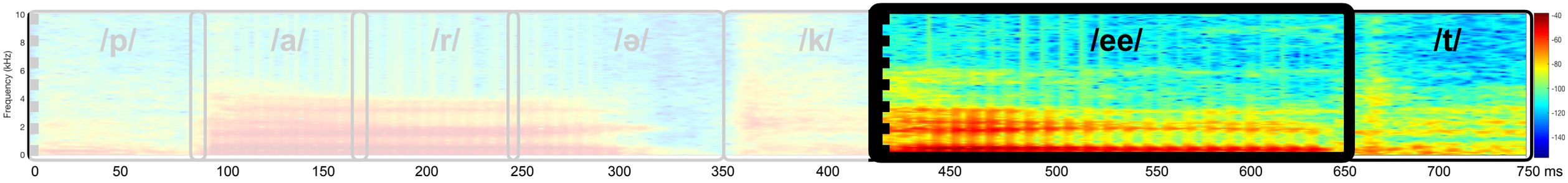

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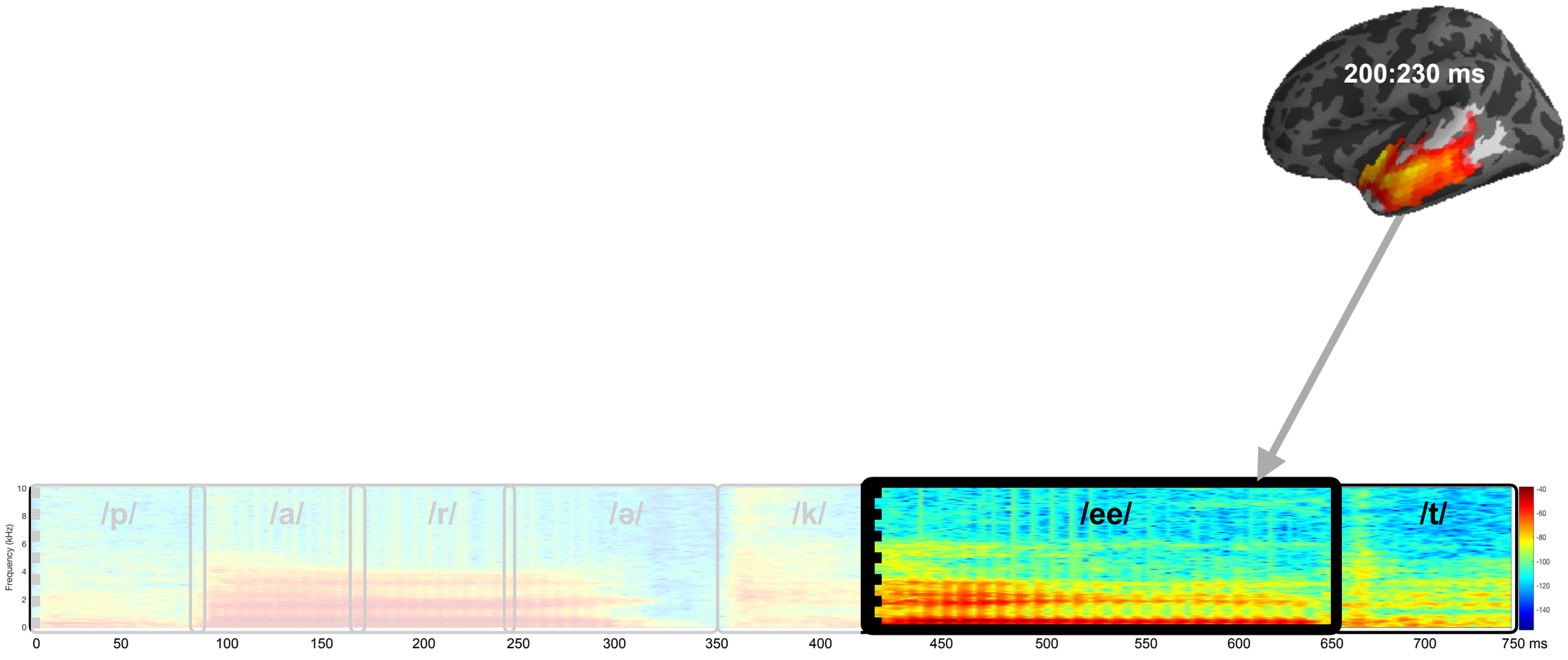

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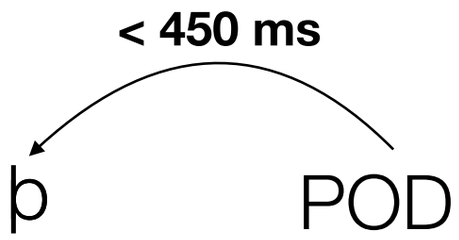


**Early**: POD <u>earlier</u> than 450 ms after word onset

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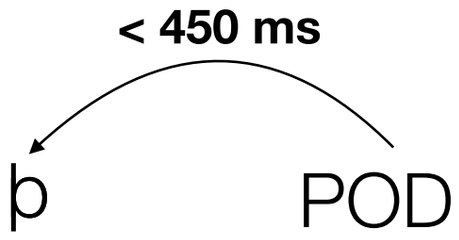
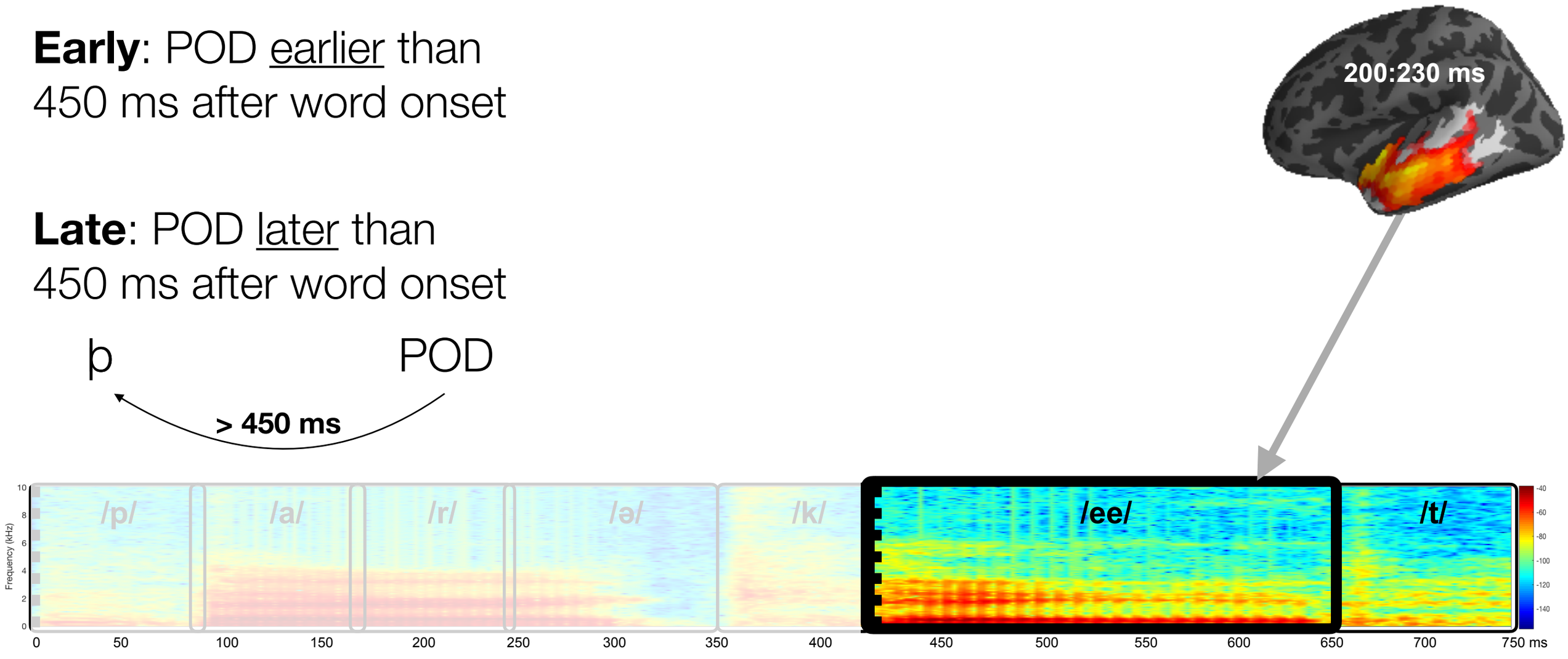
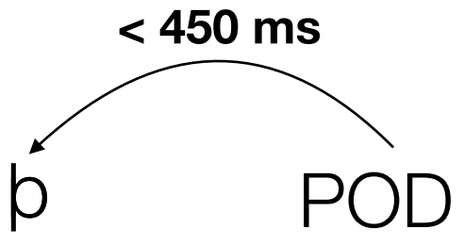



**Early**: POD <u>earlier</u> than 450 ms after word onset

**Late**: POD <u>later</u> than 450 ms after word onset



# Commitment Before POD

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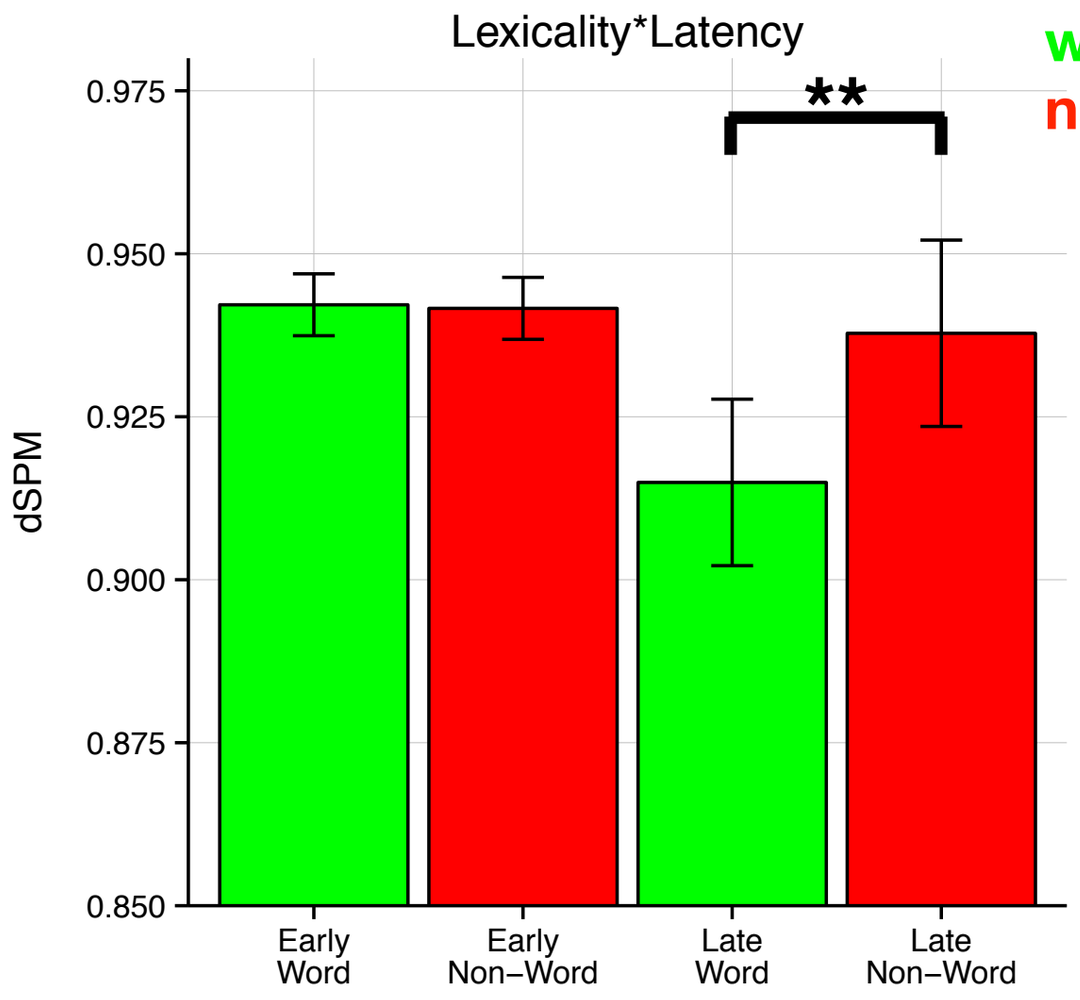
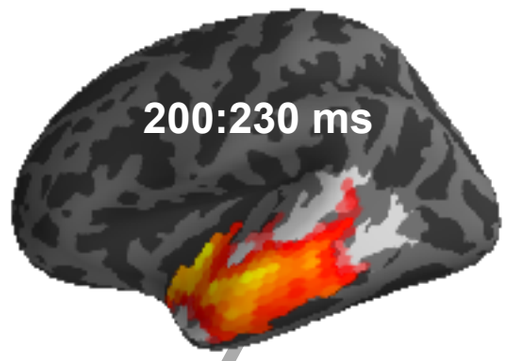
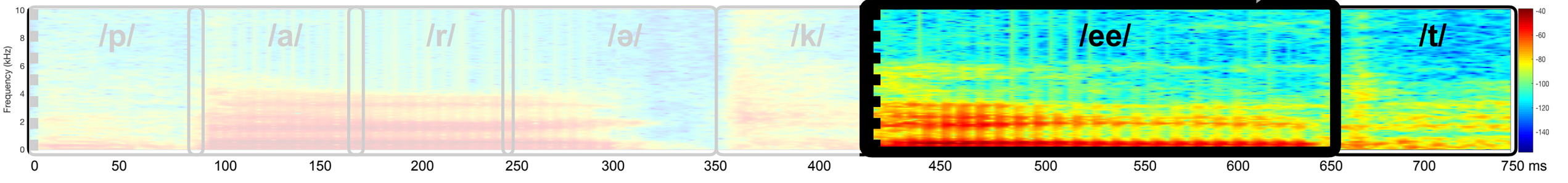


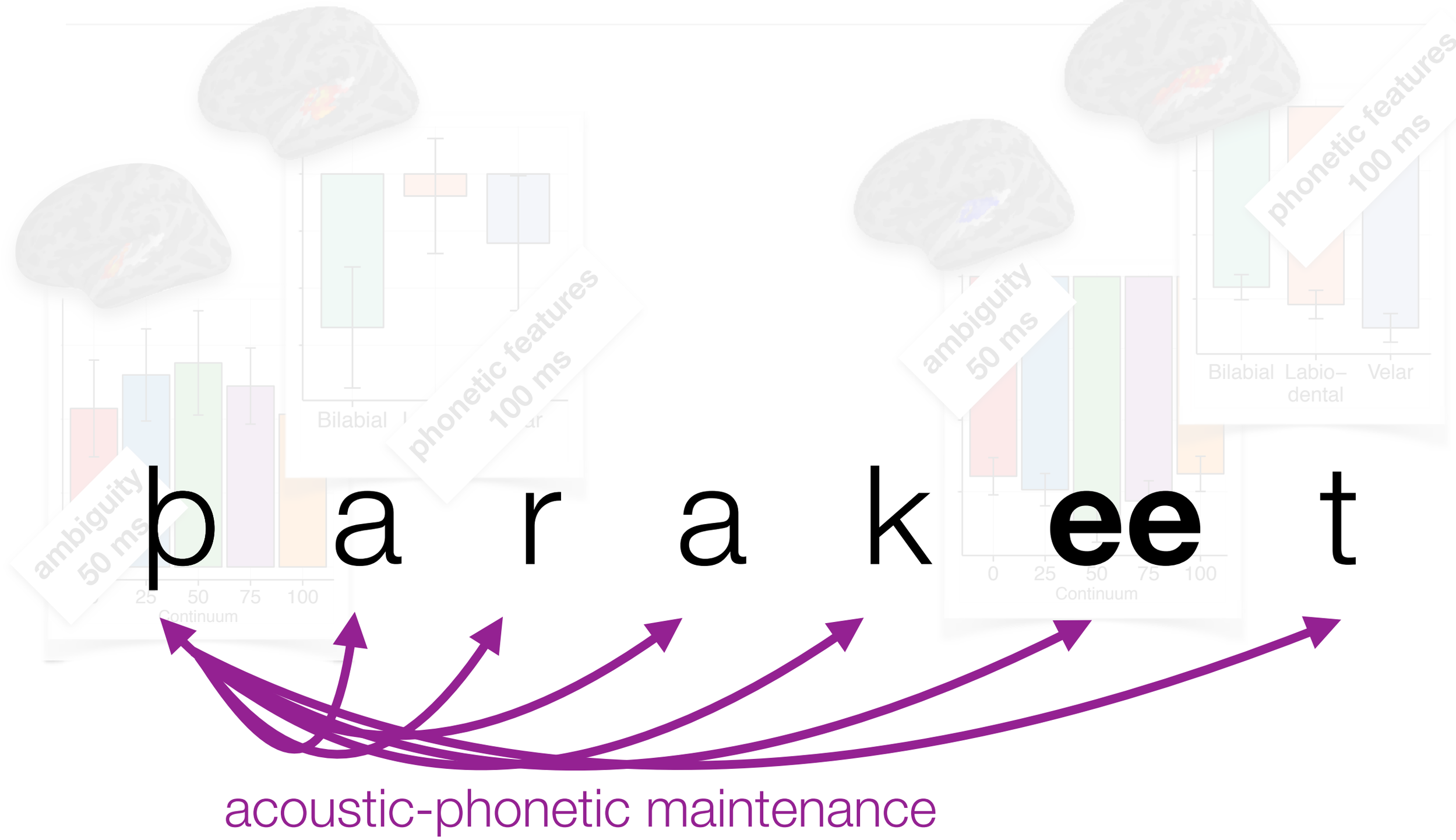



# Interpretation


p a r a k **ee** t

# Interpretation



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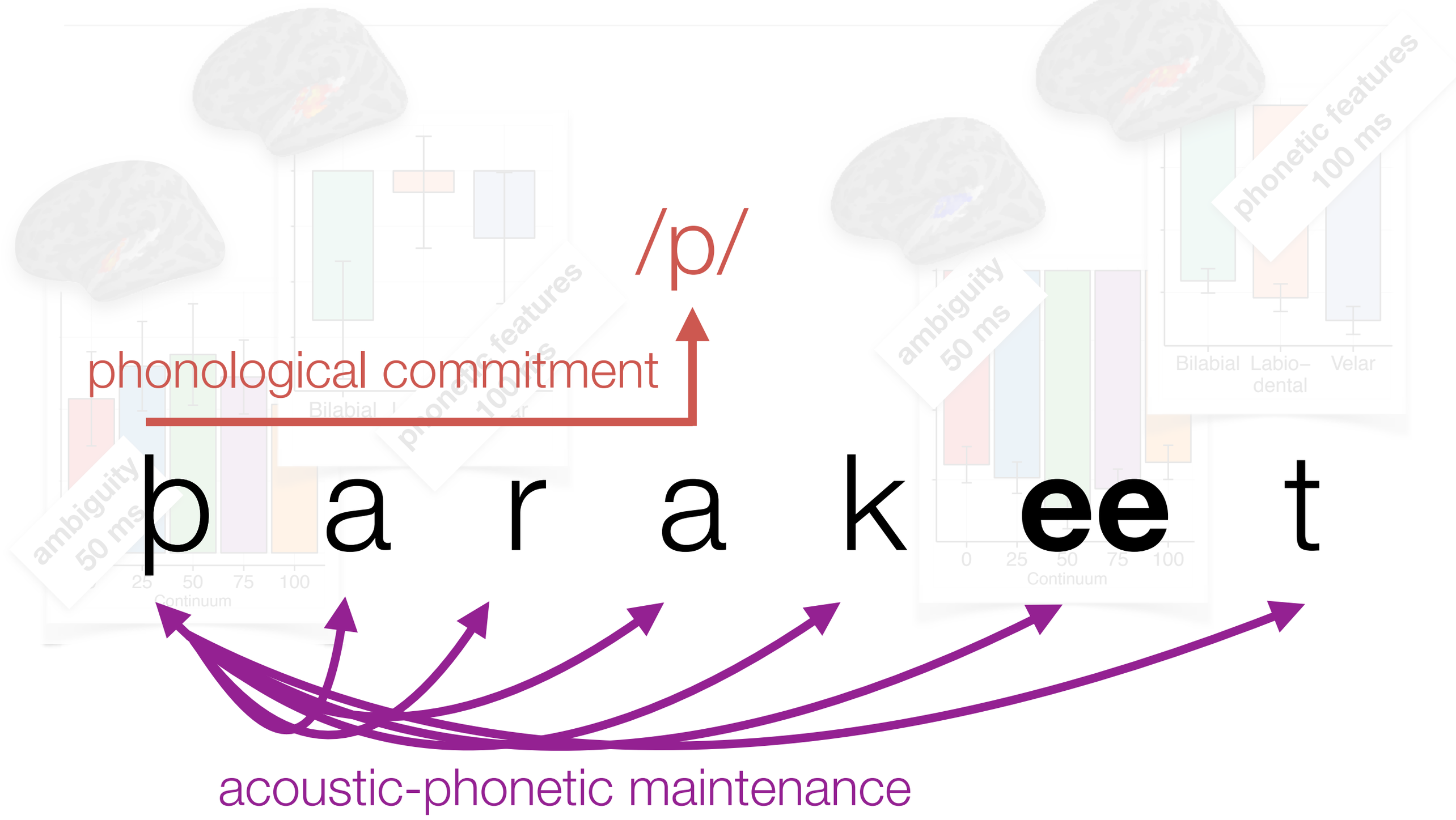

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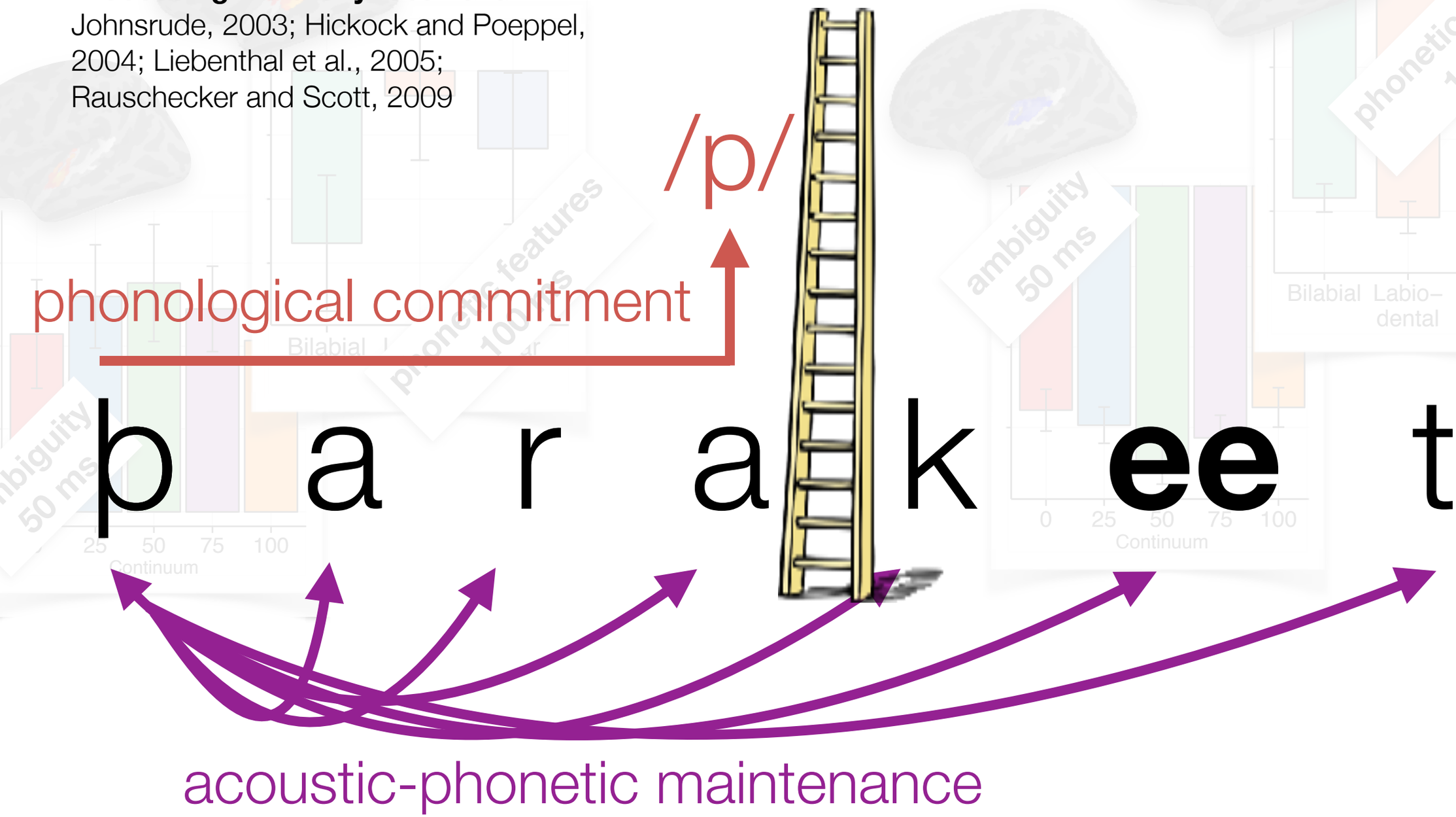
**Processing hierarchy:** Scott and Johnsrude, 2003; Hickock and Poeppel, 2004; Liebenthal et al., 2005; Rauschecker and Scott, 2009



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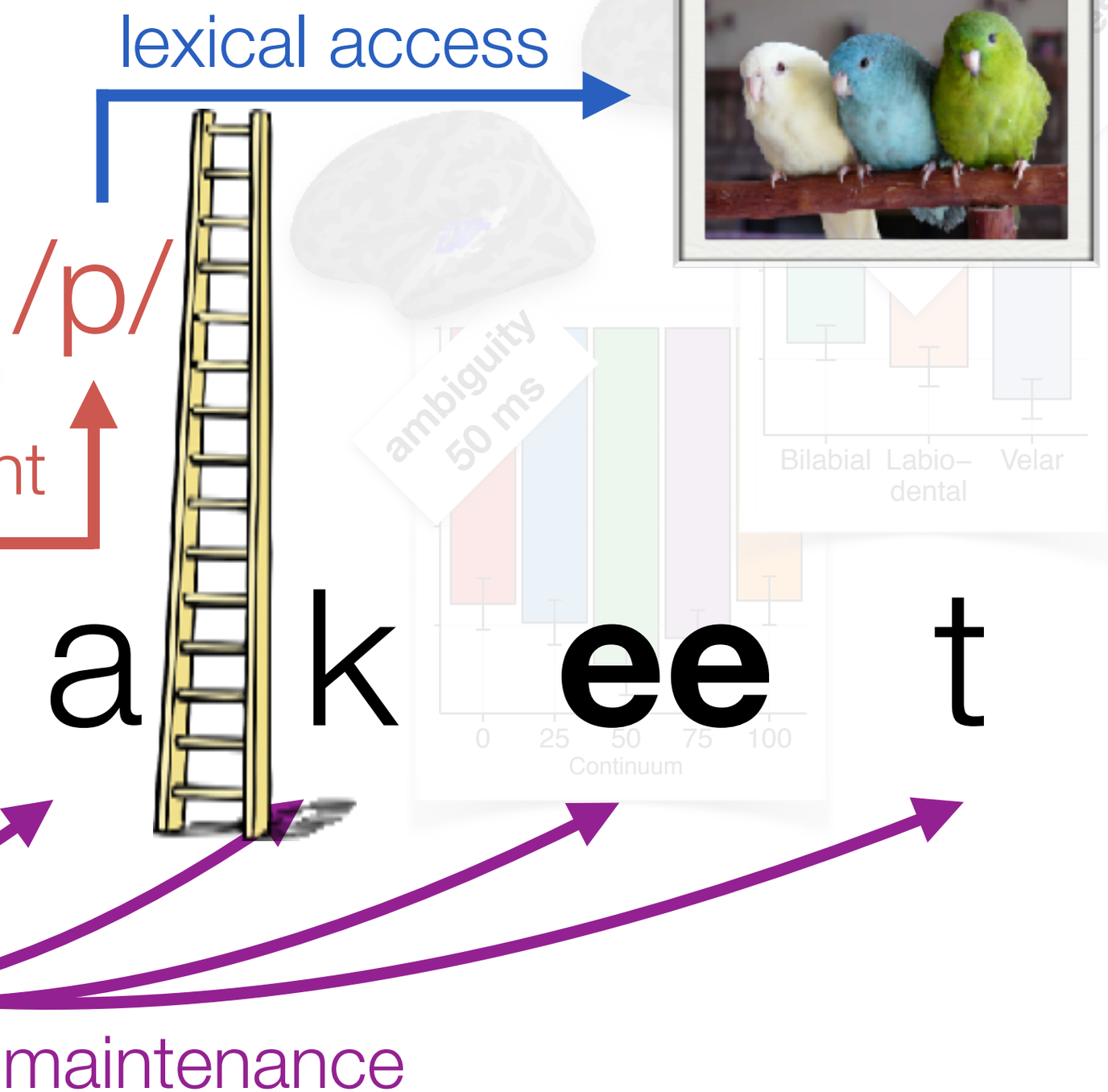

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lexical access

/p/

phonological commitment

b a r a k **ee** t

acoustic-phonetic maintenance

# Interpretation

lexical access

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# Interpretation

**Processing is not purely feedforward, or feed "up":** TRACE model: McClelland and Elman, 1986; McMurray et al. 2009. cf. MERGE: Norris et al. 2000

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# Interpretation

lexical access

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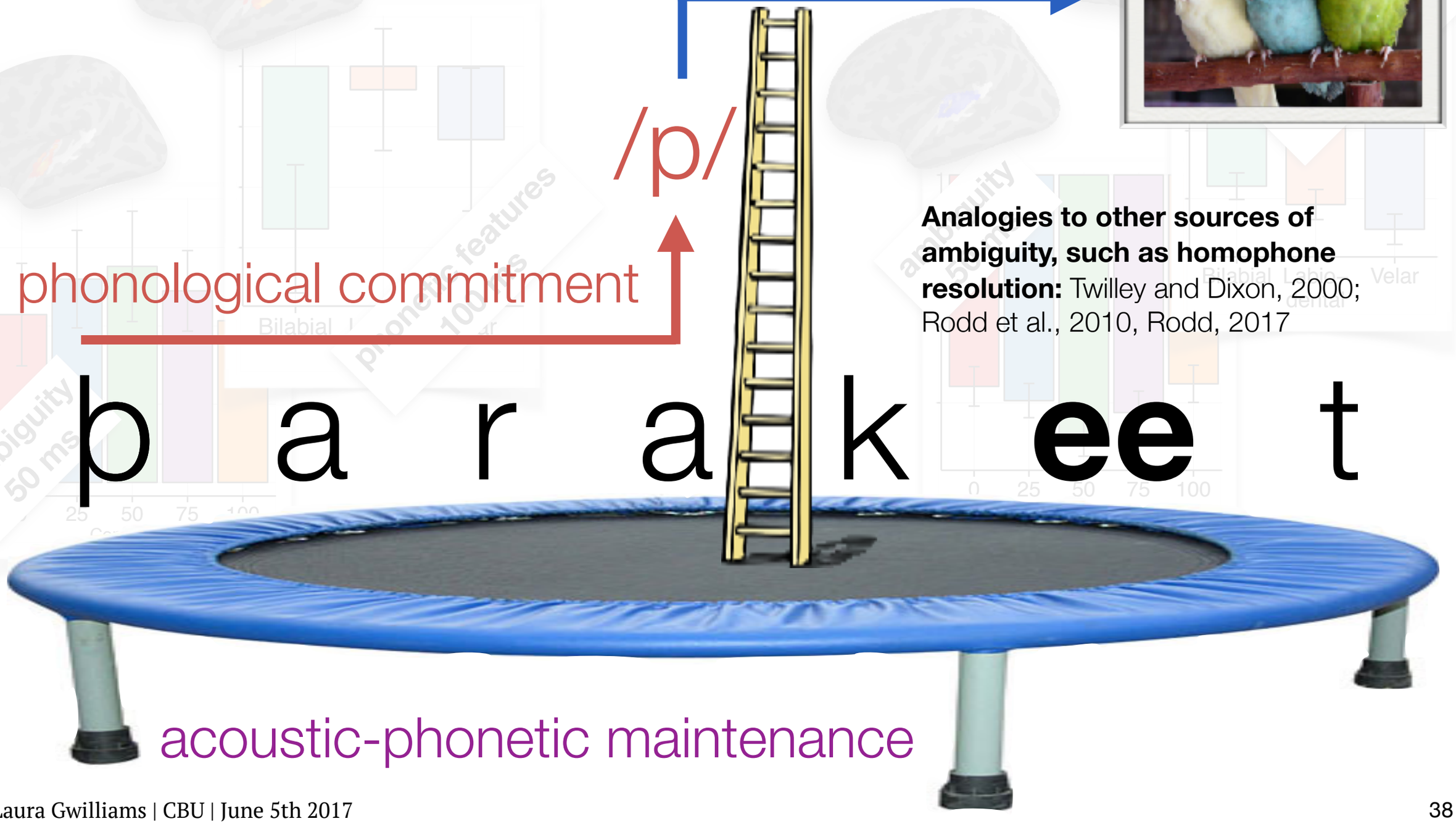

**Analogies to other sources of ambiguity, such as homophone resolution:** Twilley and Dixon, 2000; Rodd et al., 2010, Rodd, 2017

p a r a k **ee** t

acoustic-phonetic maintenance

# Conclusion Part 1

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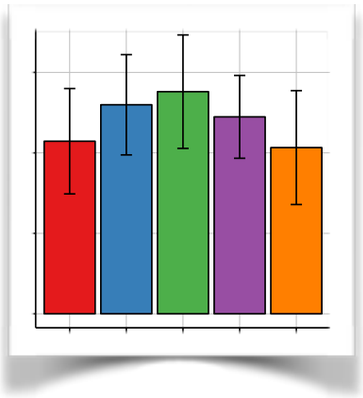
- Sensitivity to phoneme ambiguity ~50 ms after onset in primary auditory cortex



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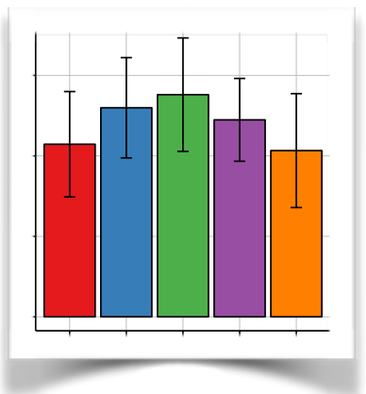
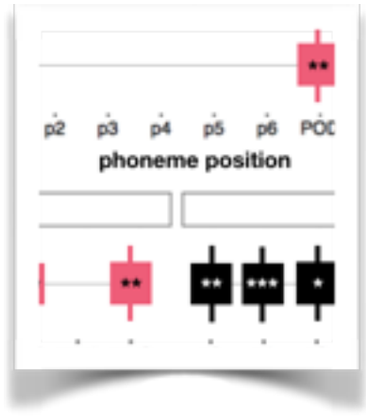


- Subphonemic detail is maintained over long time-scales (+700 ms) and re-evoked at subsequent phoneme positions



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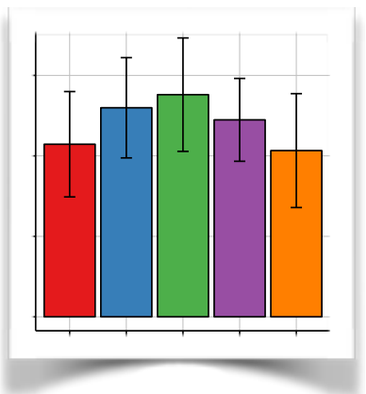

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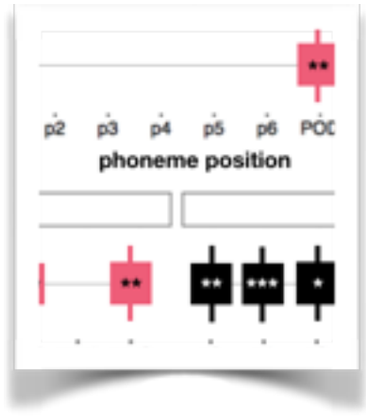
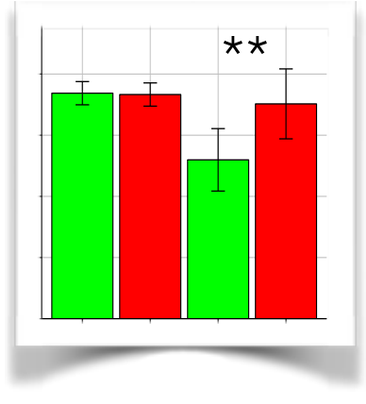



- Phonological commitment resolves ~450 ms after phoneme onset in superior temporal gyrus



*Future Directions*

# Applying machine-learning analysis tools to uncover the dynamics of phonological processing

# Research Question

# Research Question

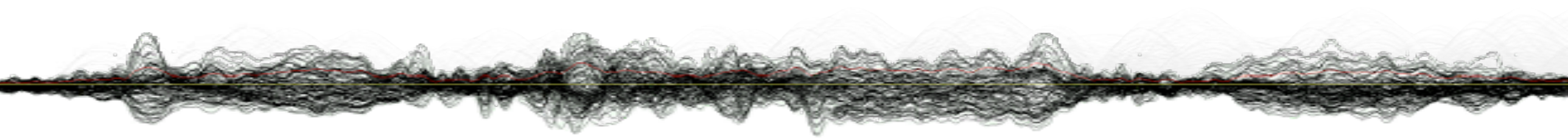
How is sub-phonemic information maintained when listening to continuous speech?

# Collaborator

**ME** **JEAN-RÉMI KING**

# Setup

we take continuous speech, and annotate it for phoneme boundaries and phonetic information



- 24 participants
- 1 hour recording
- ~40,000 phonemes per participant

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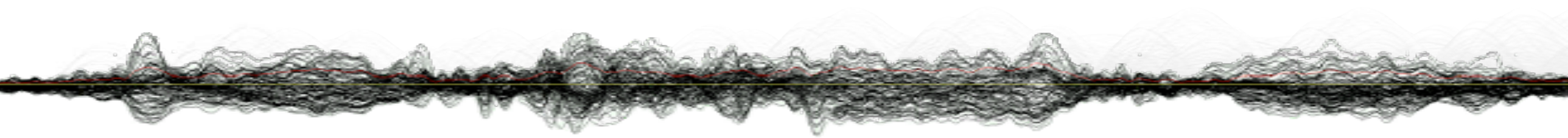

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# Decoding from the MEG Signal

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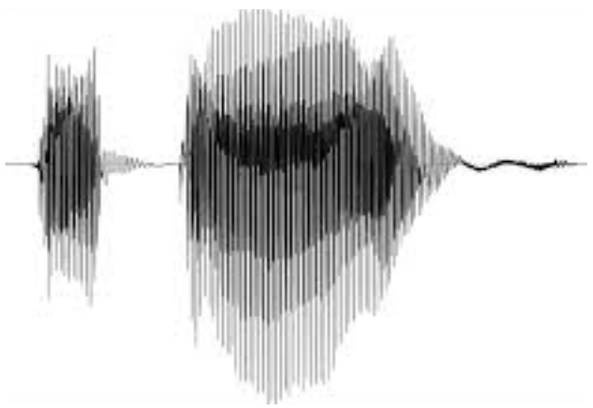
**/b/ /f/**
**/m/**

+bilabial
+ fricative
- voiced

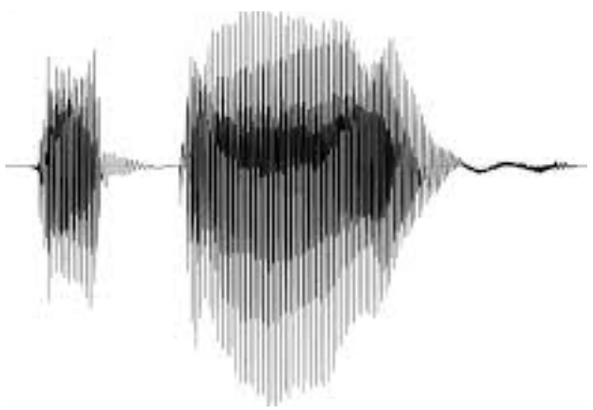


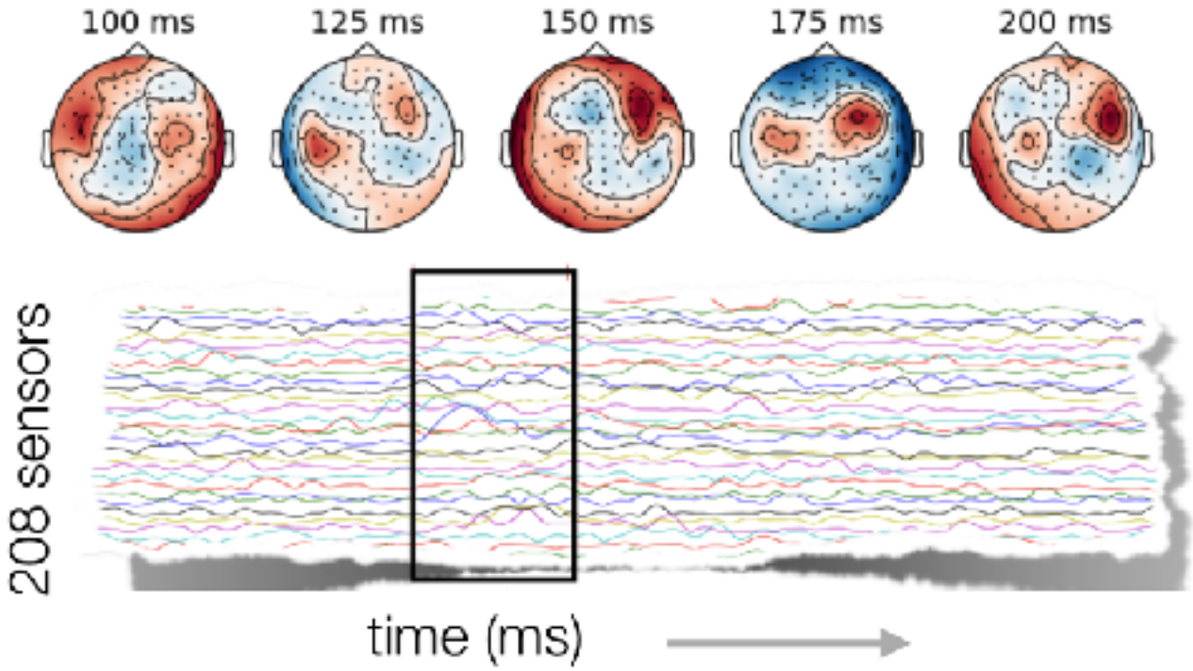
# Decoding from the MEG Signal

**/b/ /f/**
**/m/**

encode
stimulus

+bilabial
+ fricative
- voiced





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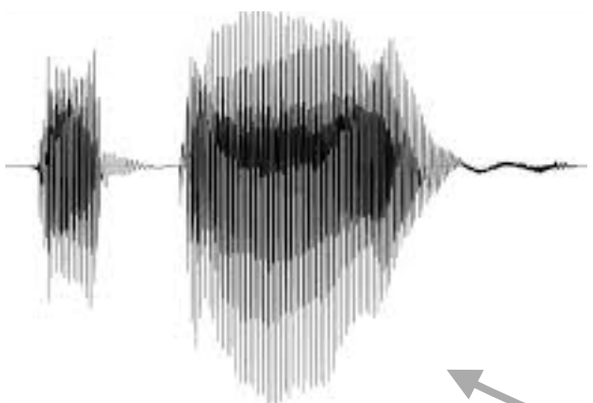

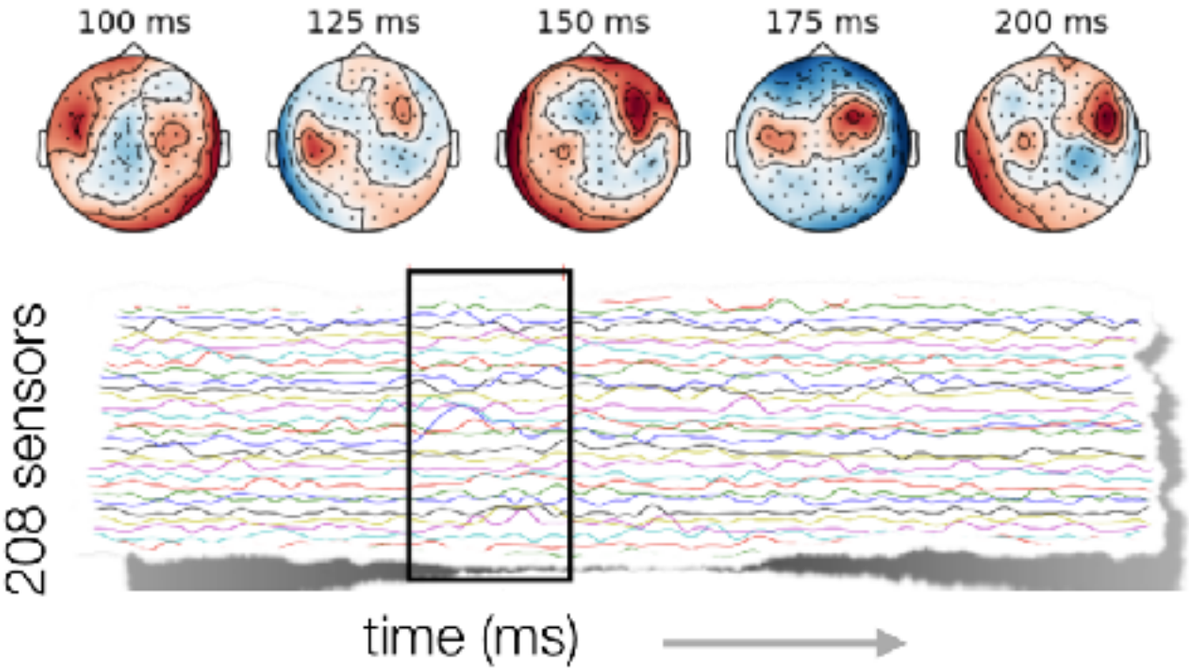


decode stimulus

# Decode Phonetic Features from the MEG Signal

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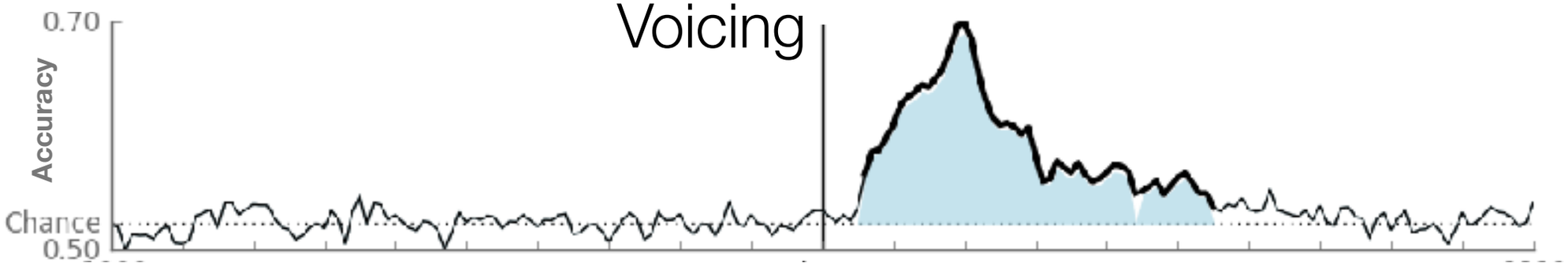

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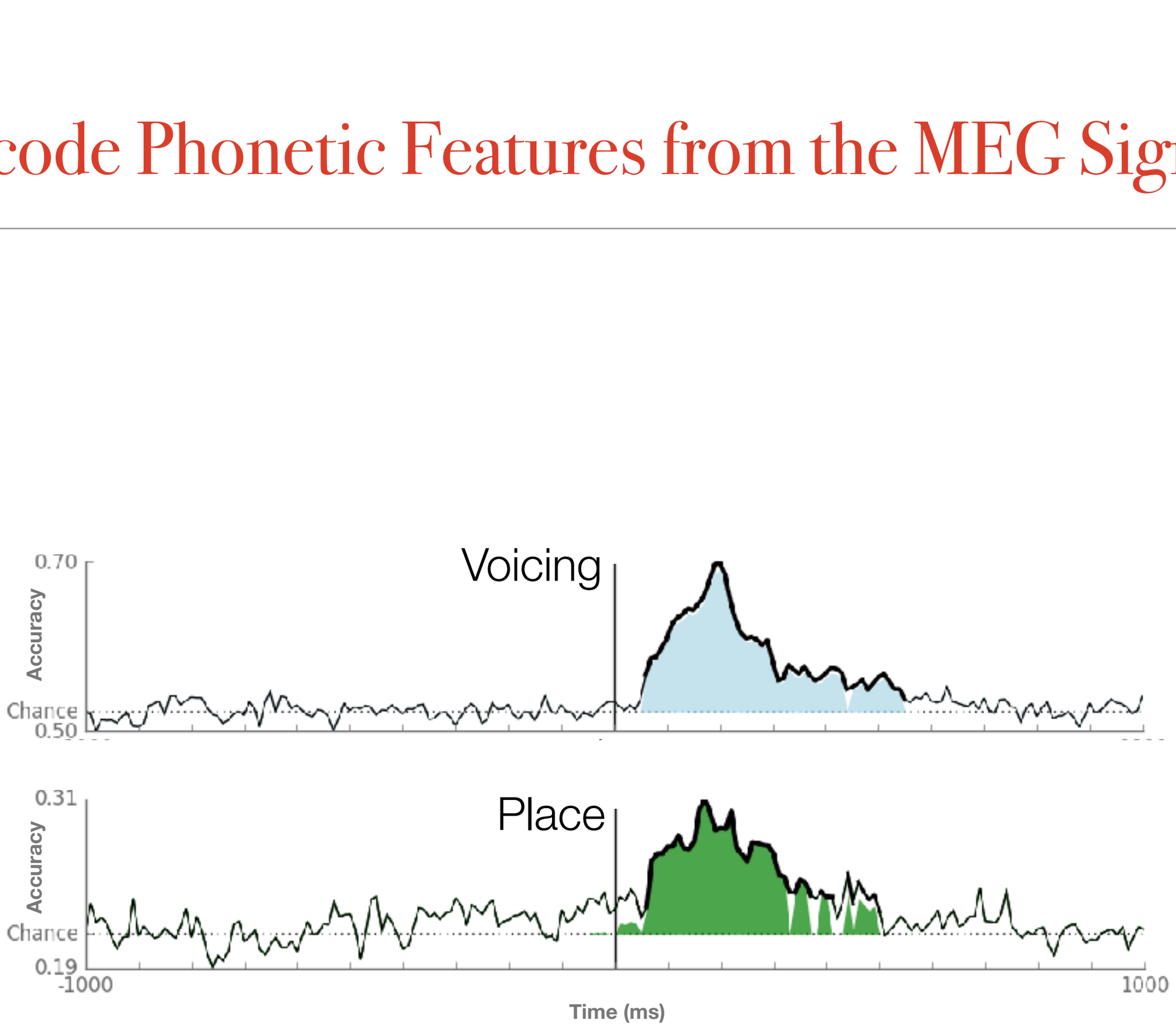

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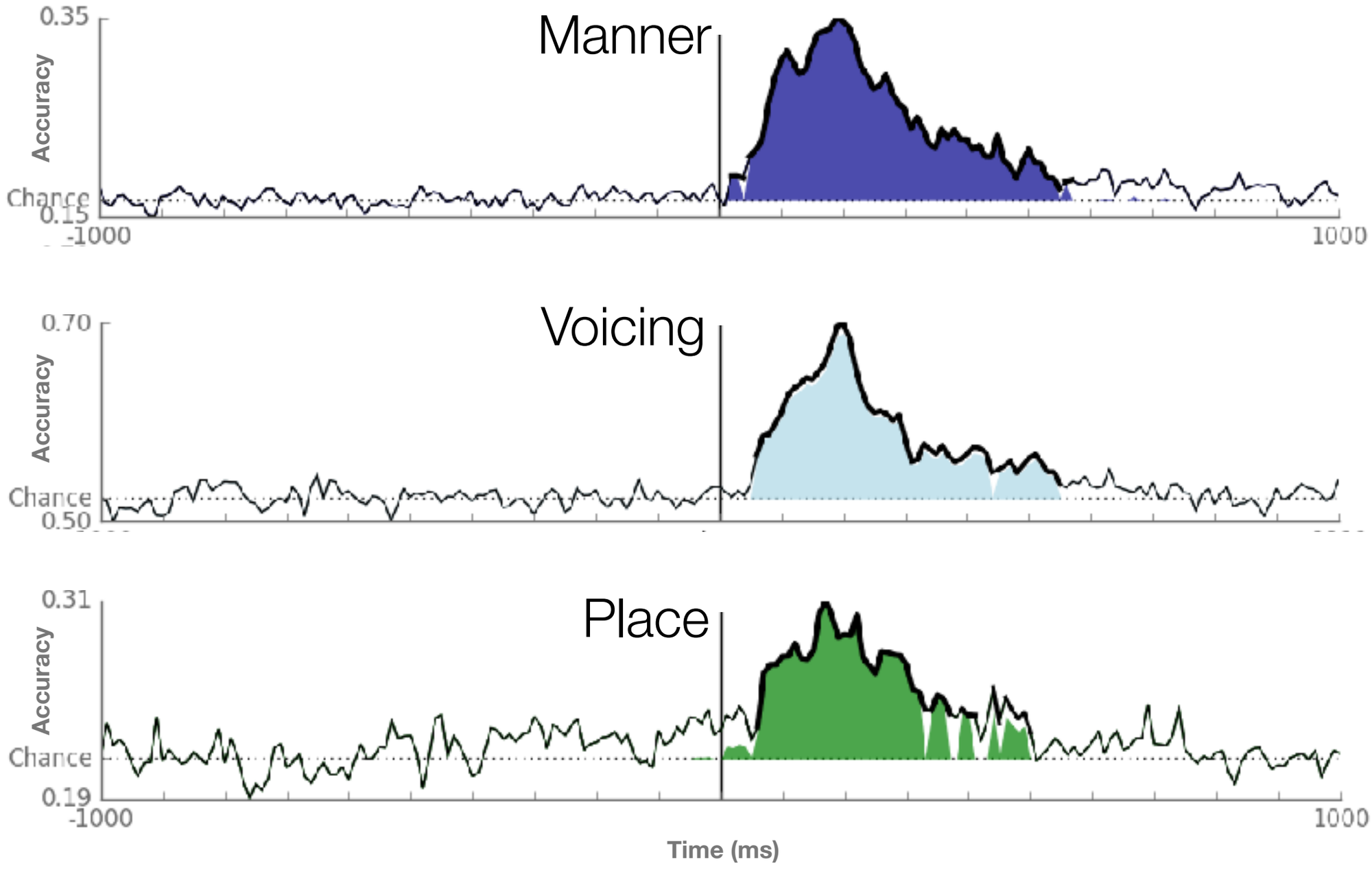
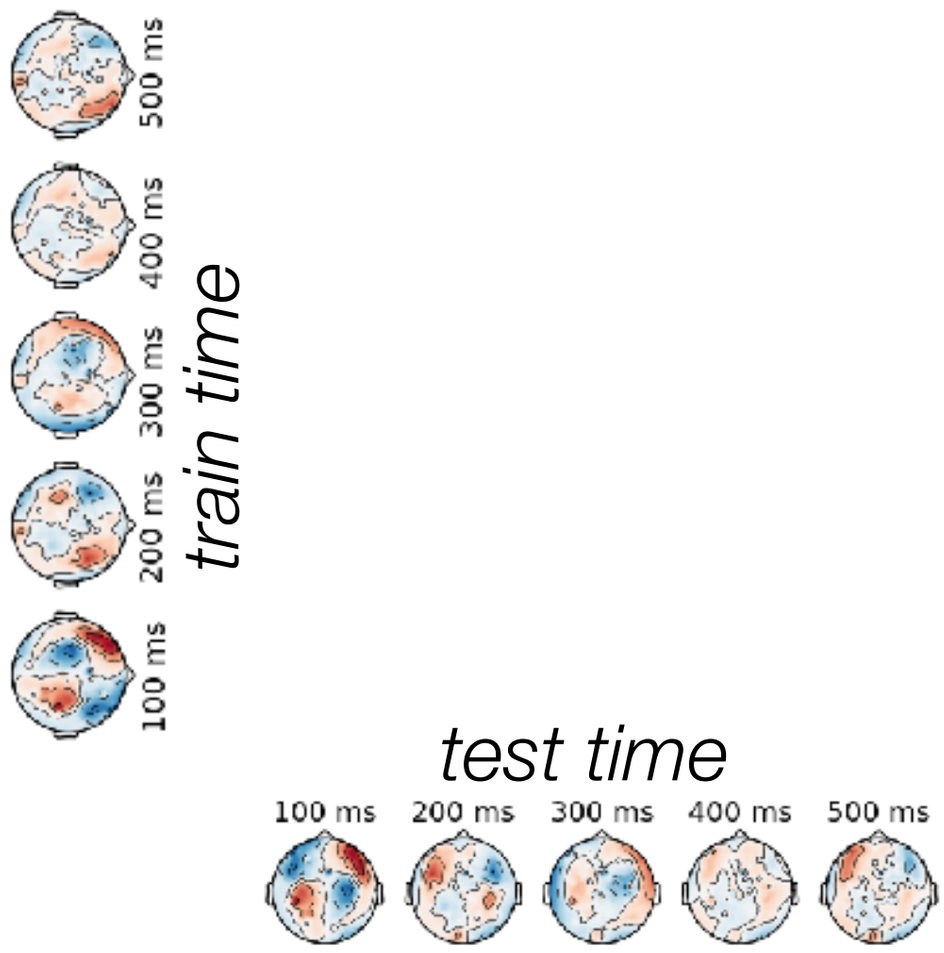


# Decode the *Dynamics* of Phonetic Feature Processing



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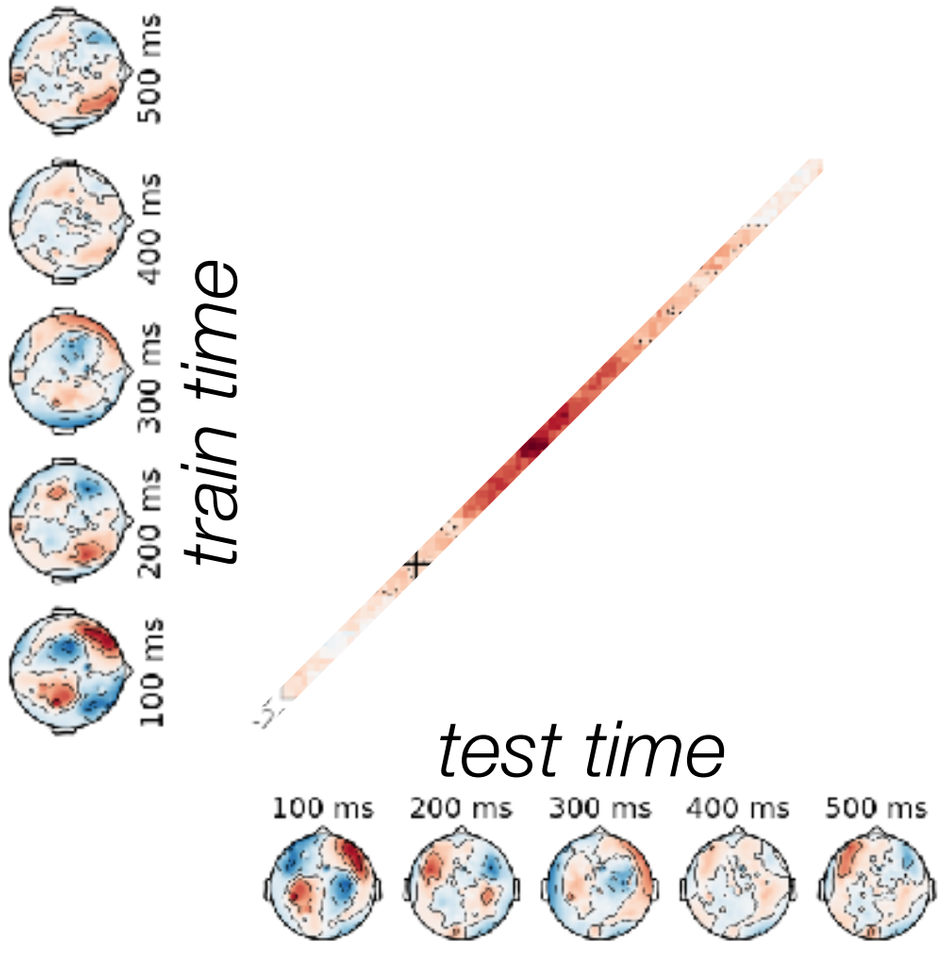

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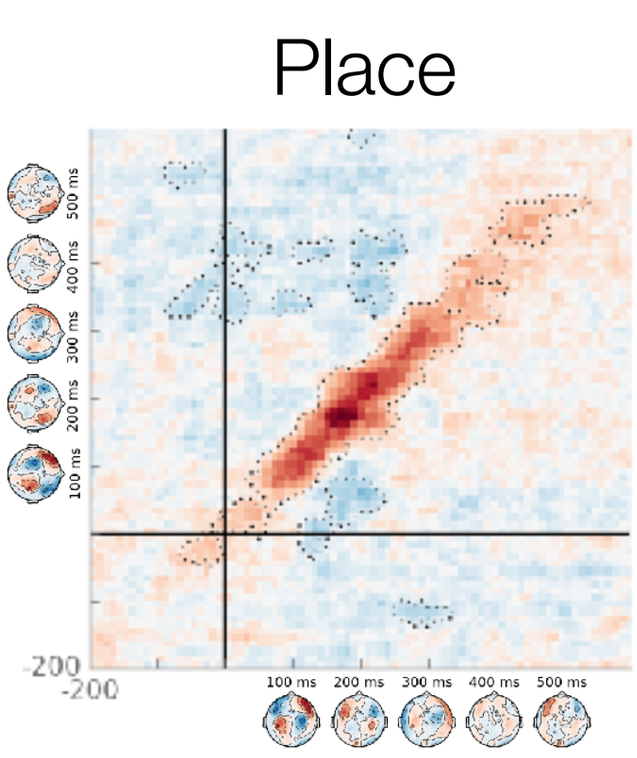

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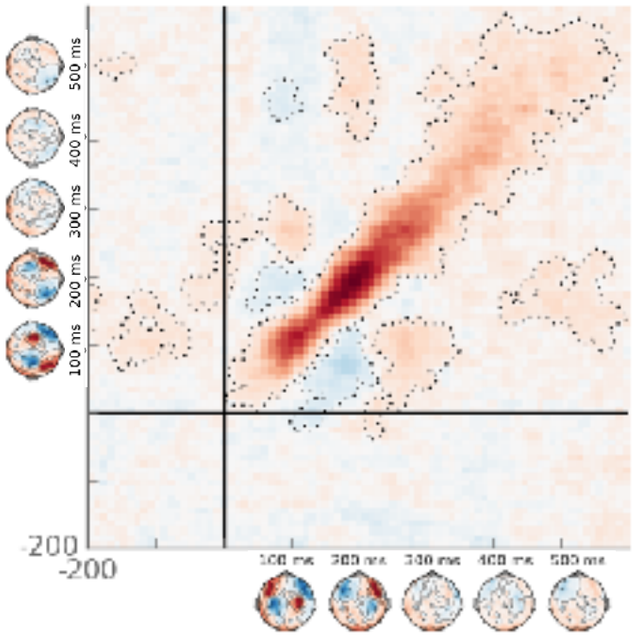
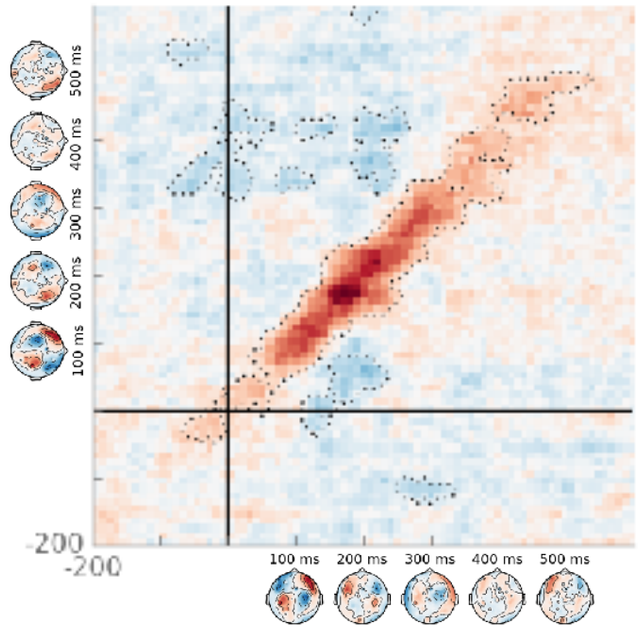
Manner




Place



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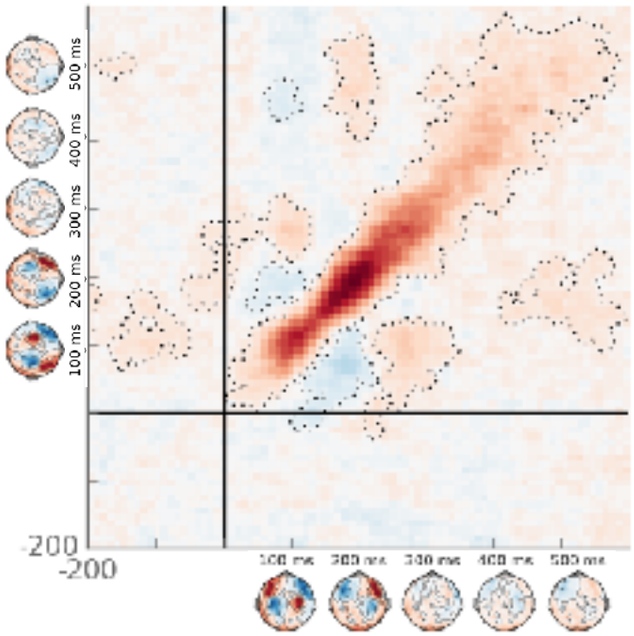
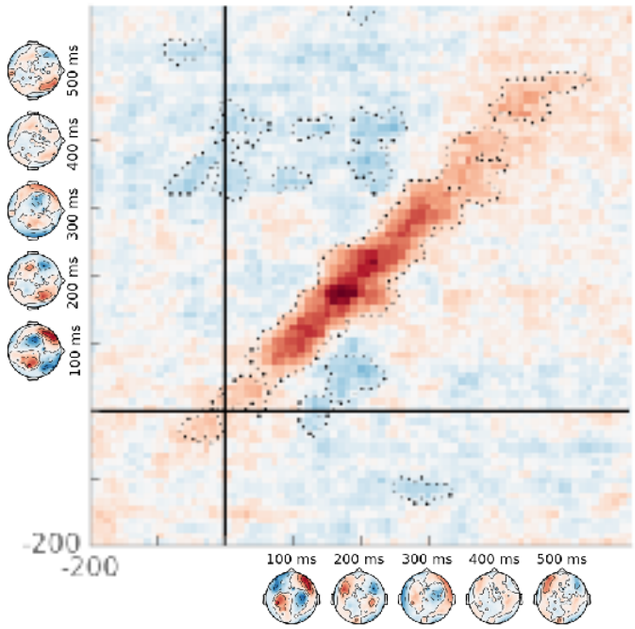
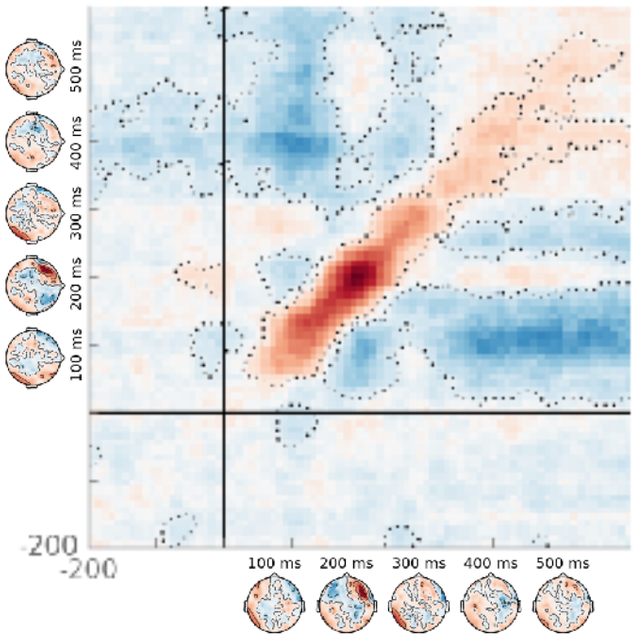
Manner




Place

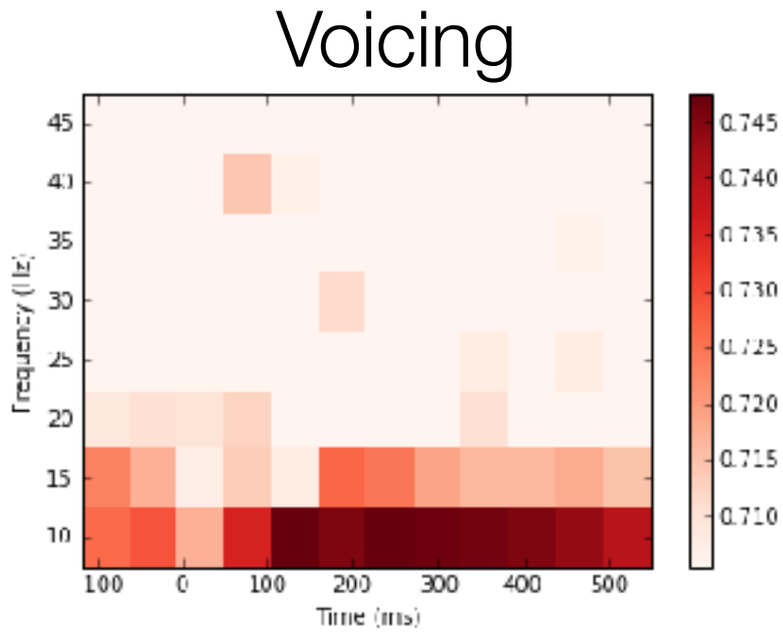



Voicing



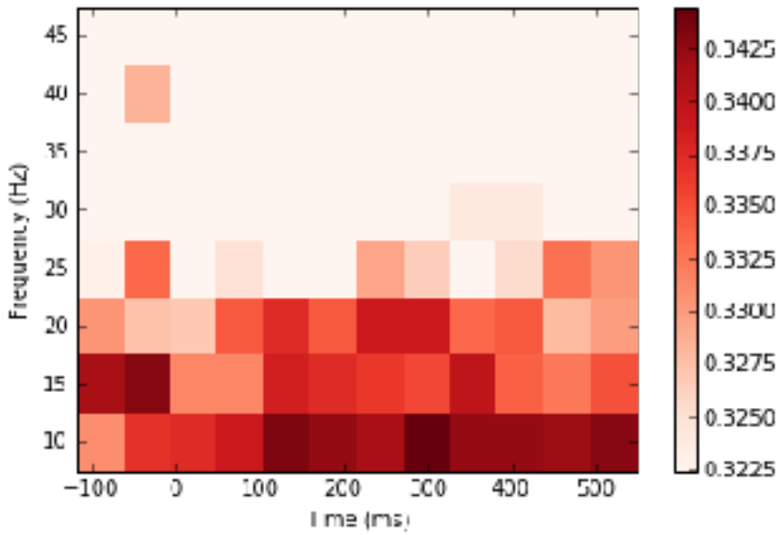
# Decode the *Frequency* of Phonetic Feature Processing

# Decode the *Frequency* of Phonetic Feature Processing

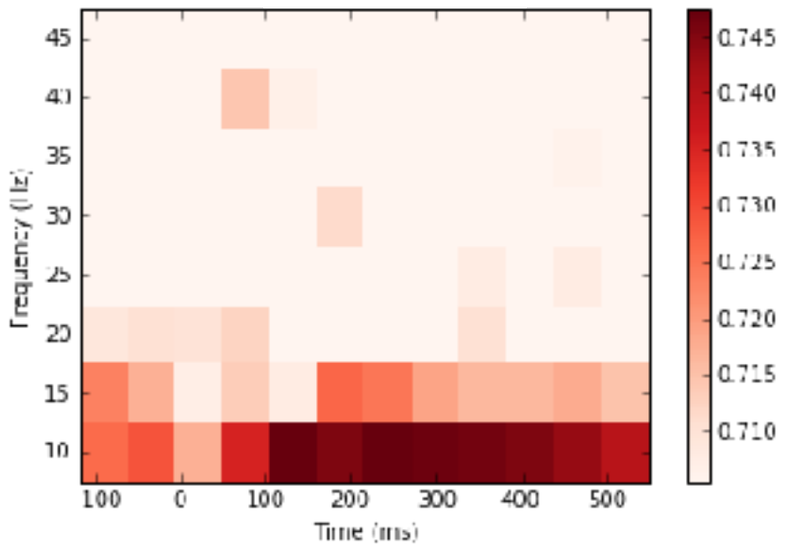


# Decode the *Frequency* of Phonetic Feature Processing

## Manner

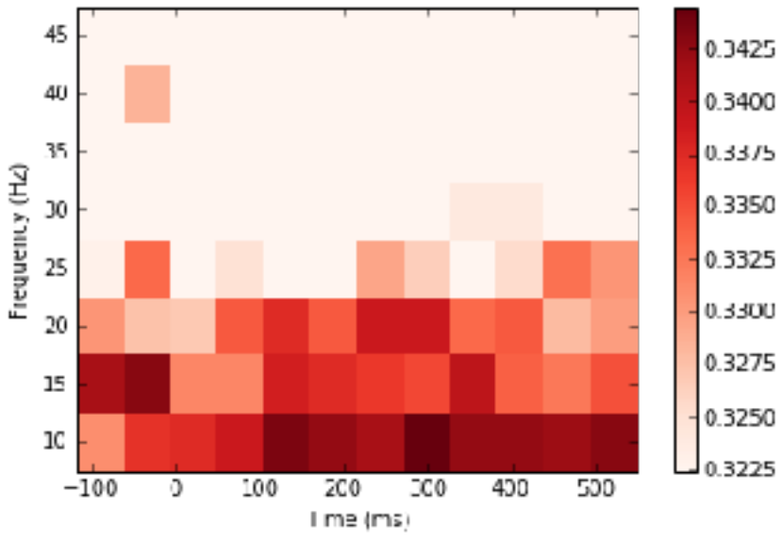



## Voicing

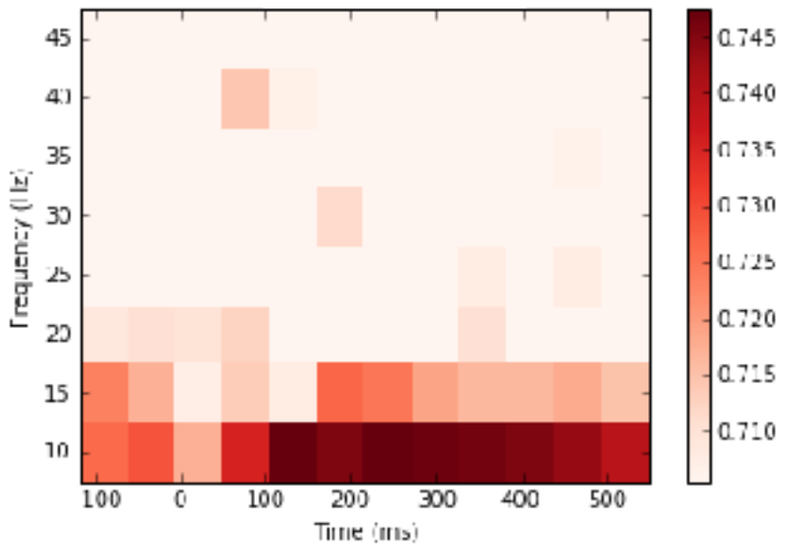



# Decode the *Frequency* of Phonetic Feature Processing

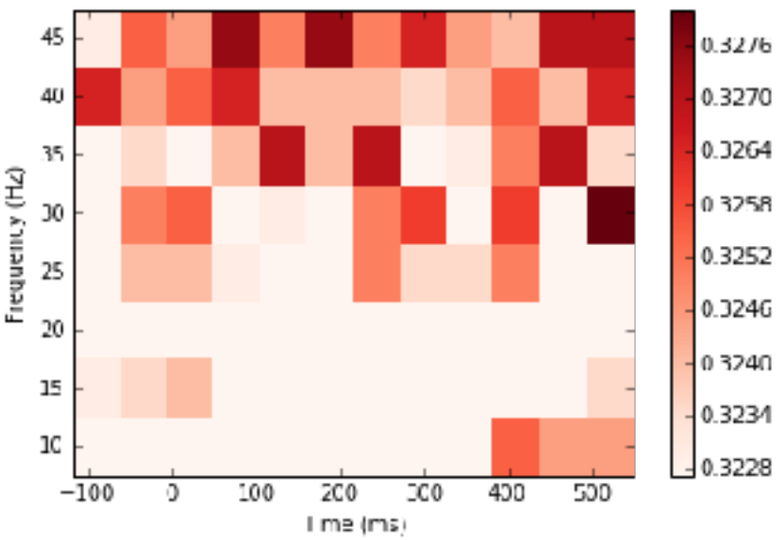
## Manner




## Voicing



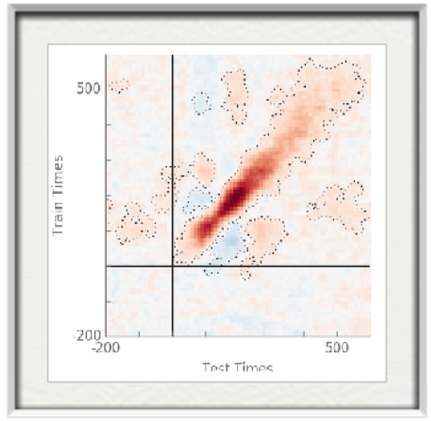

## Place



# Promising Work in Progress

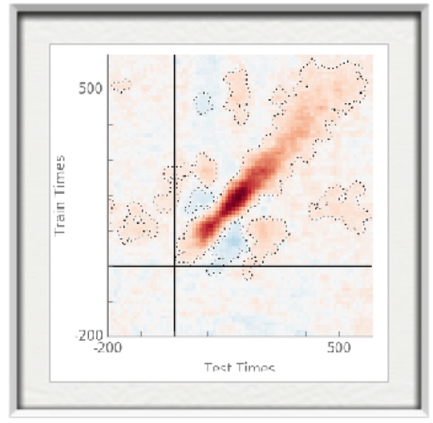
# Promising Work in Progress

- Phonetic features appear to elicit different temporal dynamics

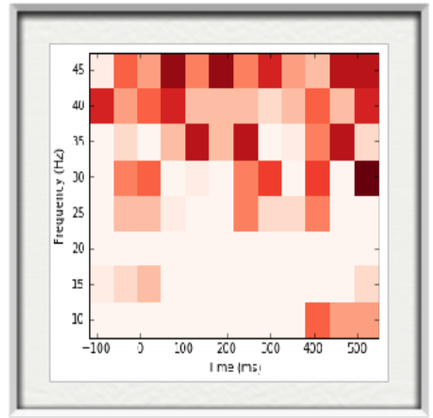


# Promising Work in Progress

- Phonetic features appear to elicit different temporal dynamics

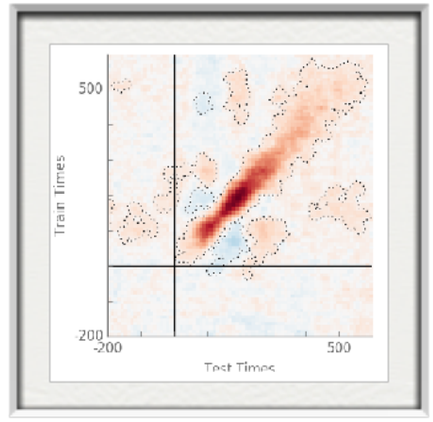



- And different spectral profiles

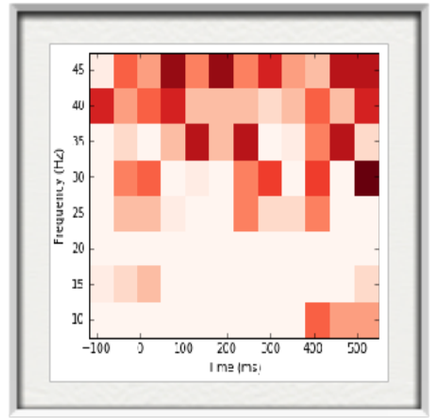


# Promising Work in Progress

- Phonetic features appear to elicit different temporal dynamics




- And different spectral profiles




- There is great utility in applying machine-learning analyses to spatiotemporally resolved MEG data

# Finish Line

# Finish Line

## Completed Research:

- Sensitivity to **phonological ambiguity** is reflected in the very initial stages (~50 ms) of processing a speech sound

- Sub-phonemic information is **maintained** for long periods of time, and is **re-evoked** at subsequent phoneme positions in the spoken word

- The system **commits to phonological interpretations** on a shorter time-scale in parallel to phonetic maintenance

## Future Directions:

- Can we apply **machine-learning** analysis techniques to MEG data to unveil the dynamics with which sub-phonemic information is processed?

# With big thanks to:

- My supervisors, **Alec Marantz** and **David Poeppel**, as well as everyone in the **Neuroscience of Language Lab** and **Poeppel Lab**!

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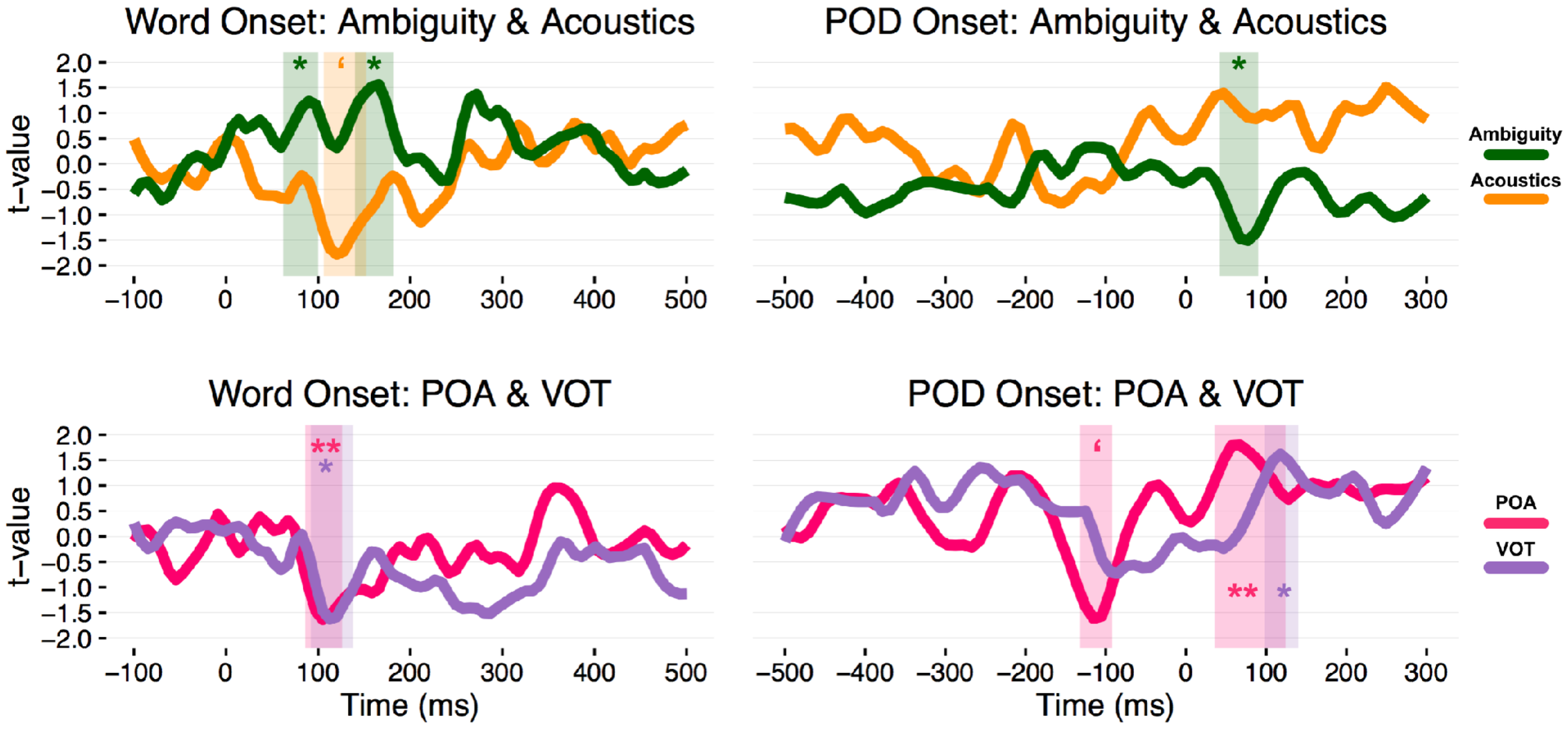
NEW YORK UNIVERSITY

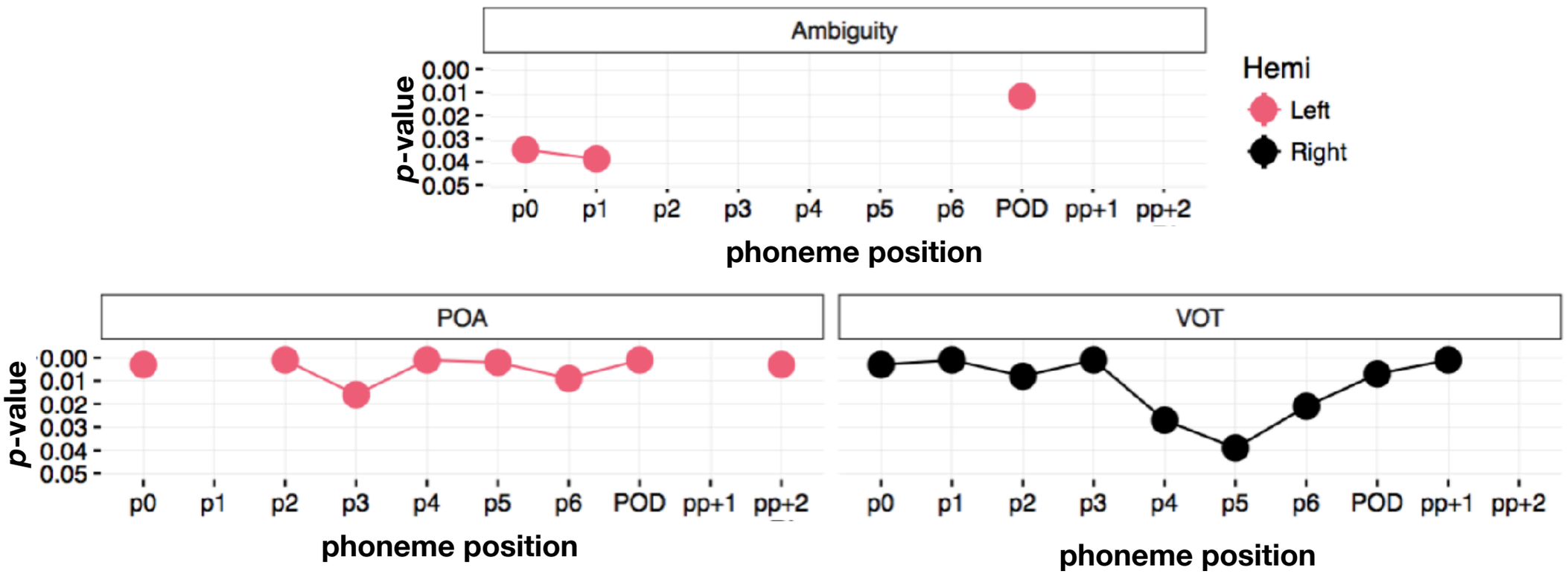
# Example Stimuli Pairs

| | |
|---|---|
| potent | total |
| dwindle | twinkle |
| bubbly | publish |
| primal | triumph |
| direct | tirade |
| crash | grasp |
| democratic | temporary |
| chemically | temperature |
| commodity | tomorrow |
| badger | pageant |
| percolate | turkeys |
| crochet | grotesque |

| | |
|---|---|
| bazaar | position |
| choir | twilight |
| decades | technician |
| dreadlock | treadmill |
| delaware | telephone |
| capitalise | tapestries |
| curling | girlish |
| depositor | topography |
| balloon | pollute |
| caucuses | talkative |
| blunt | plunge |
| beneficial | penicillin |

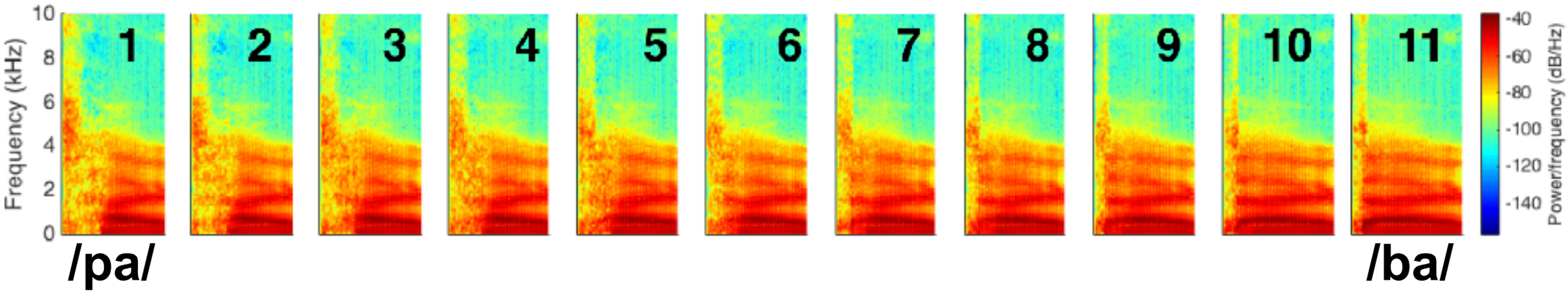

Word Onset: Ambiguity & Acoustics
POD Onset: Ambiguity & Acoustics
t–value
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
−100
0
100
200
300
400
500
−500
−400
−300
−200
−100
0
100
200
300
Ambiguity
Acoustics
Word Onset: POA & VOT
POD Onset: POA & VOT
t–value
Time (ms)
Time (ms)
POA
VOT

# Reactivation in Intermediate Positions

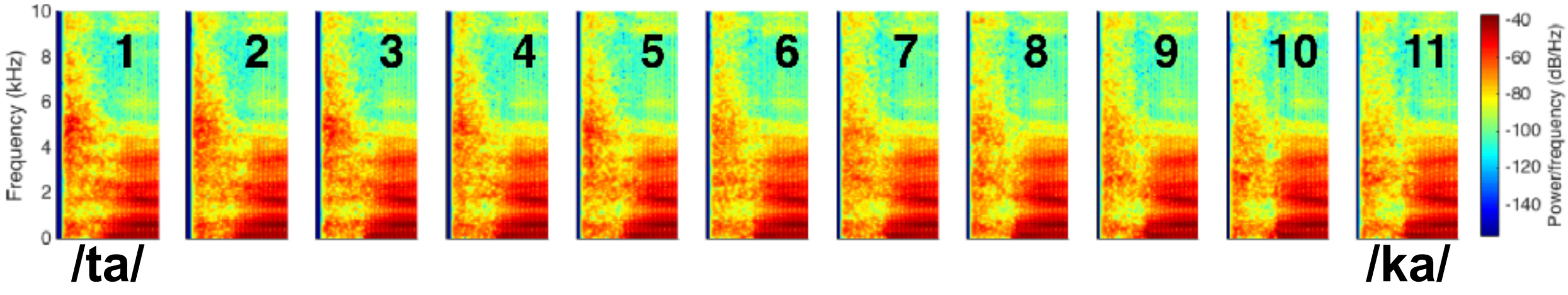


# Experiment 1: Design & Materials

- Voice onset time (VOT) - {p-b, t-d, k-g}

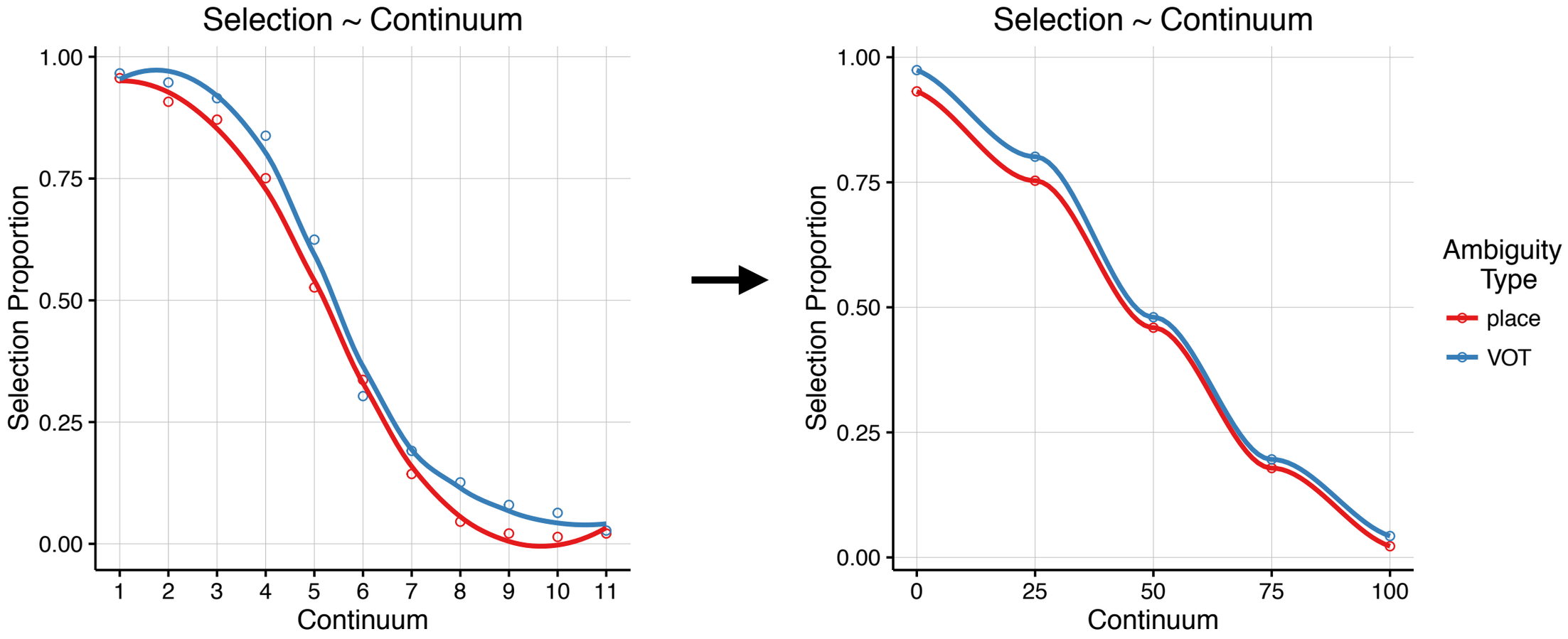



- Place of articulation (PoA) - {t-k, p-t}

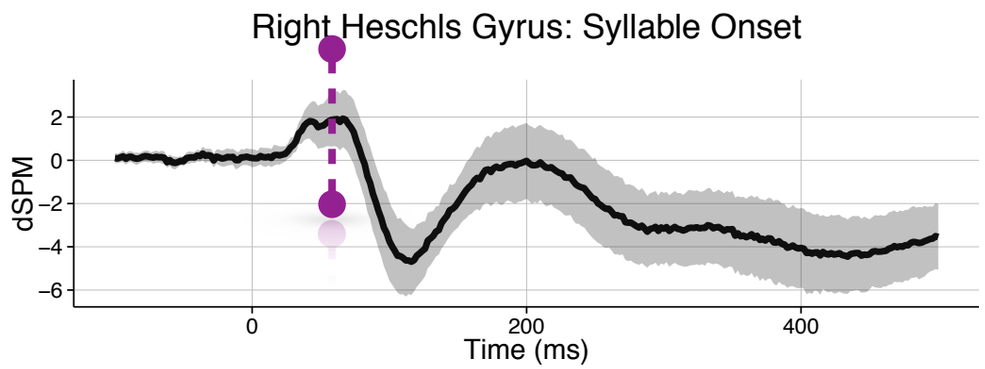


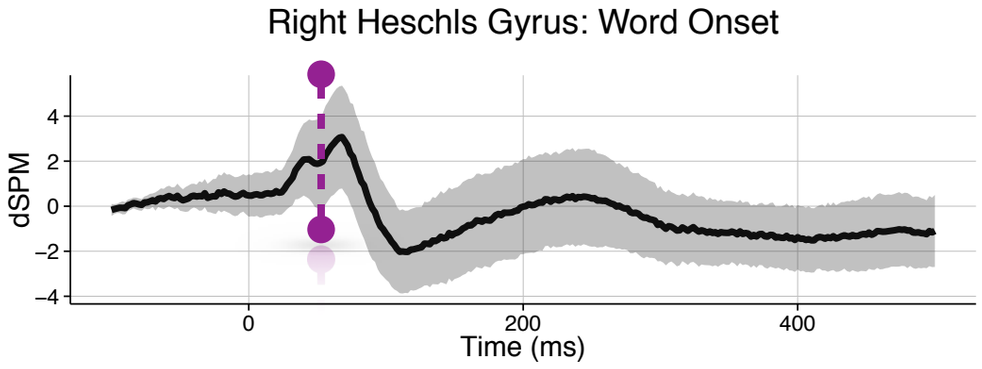
# Experiment 1: Design & Materials

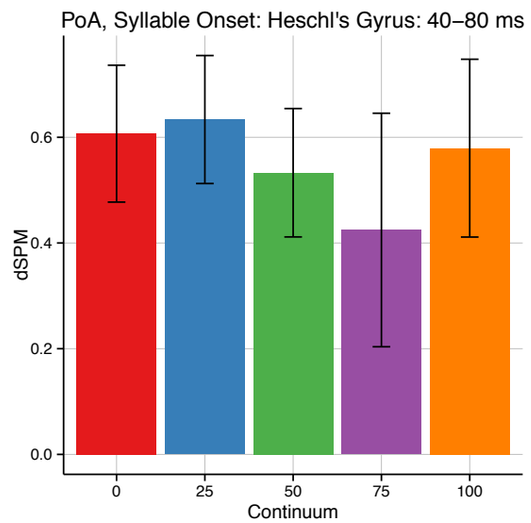
- Re-sampled the continuum to match perceptual categorisation

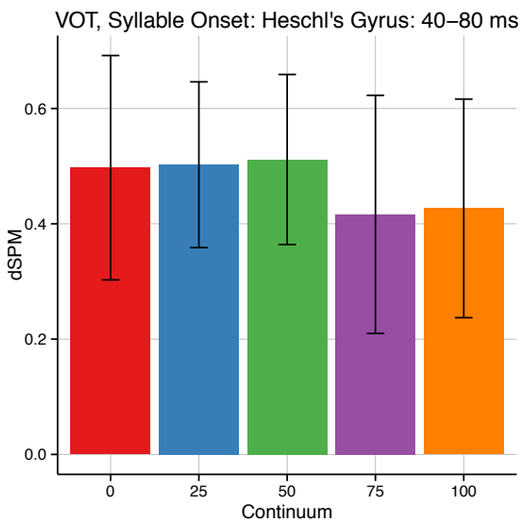


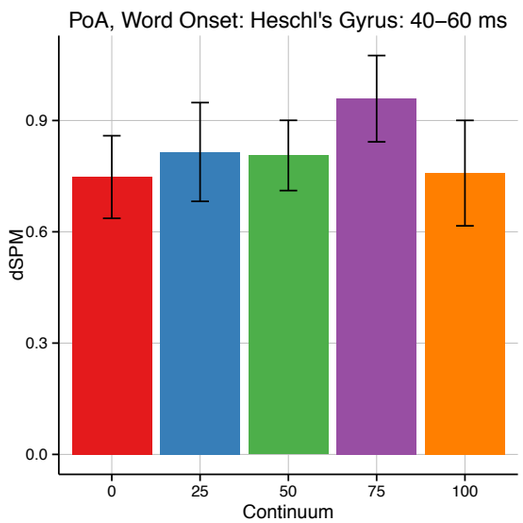
# No Ambiguity Effect in Right Hemisphere

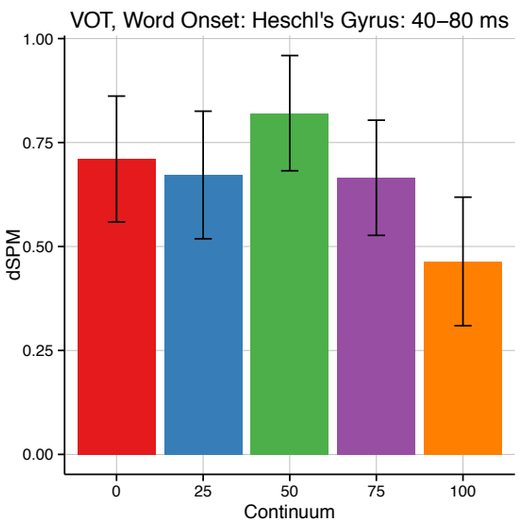


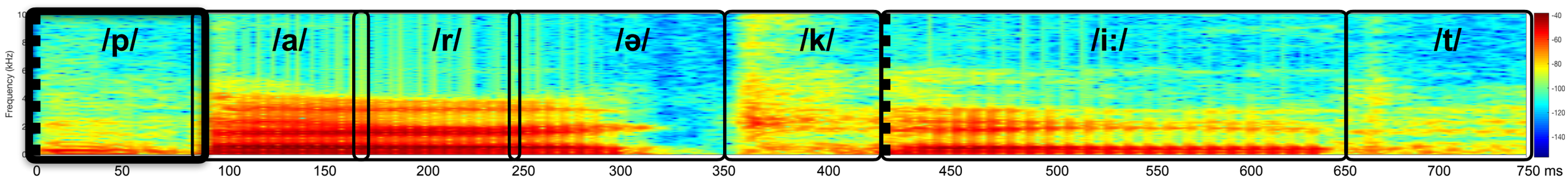



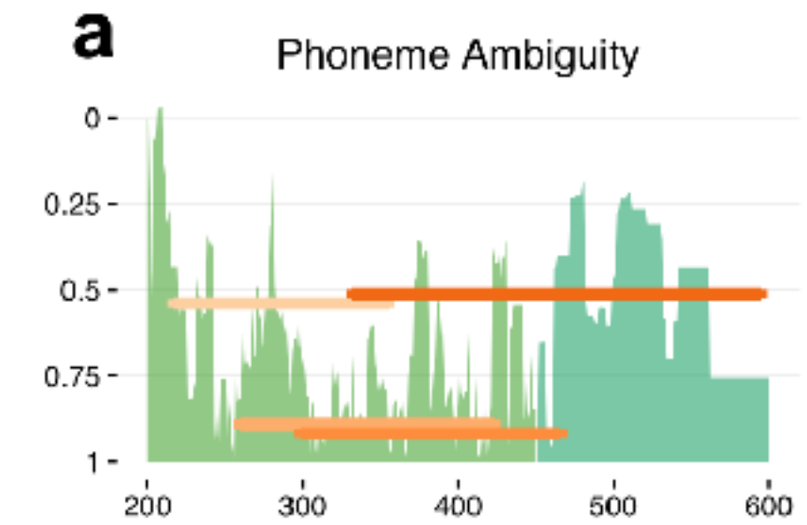



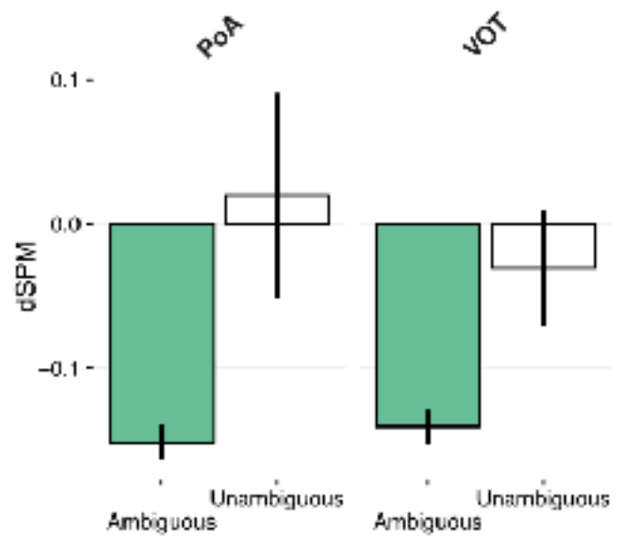



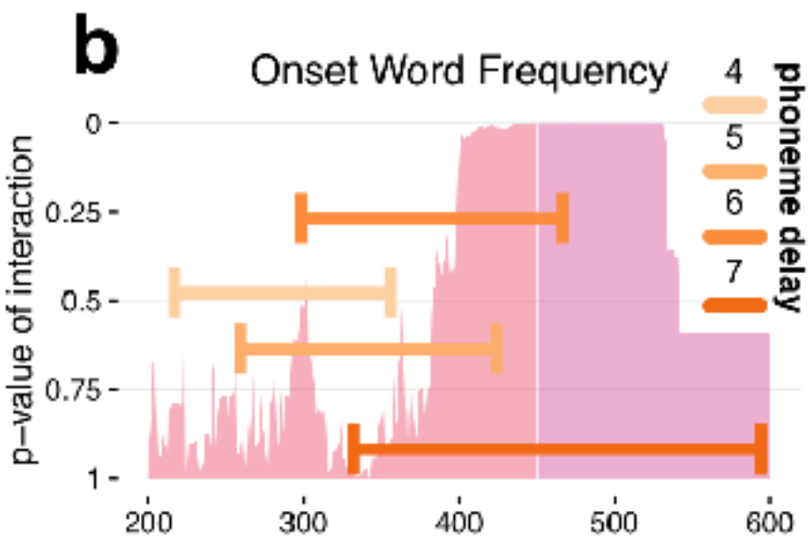



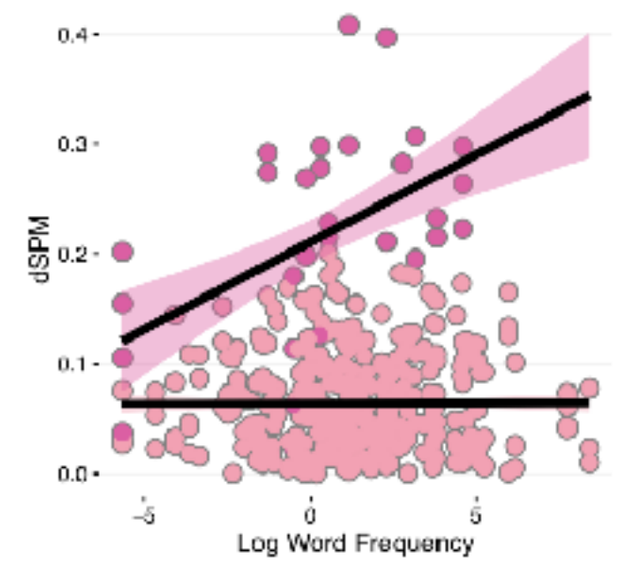



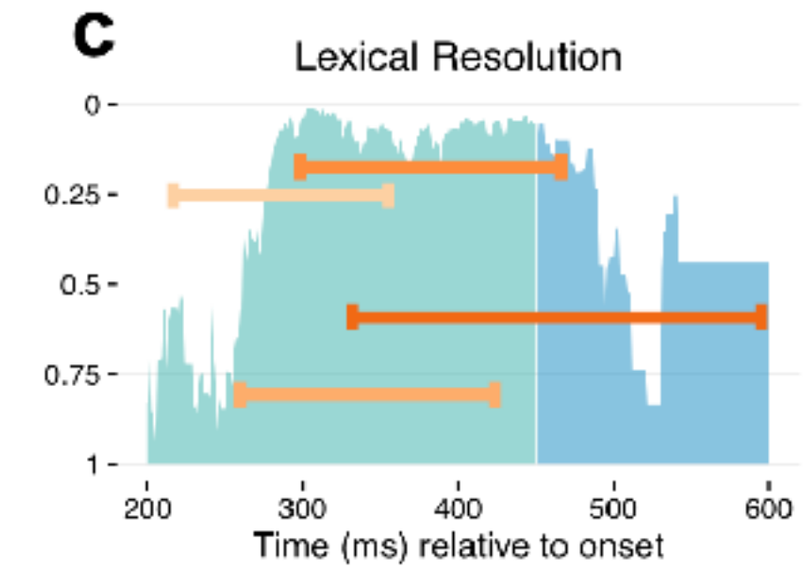



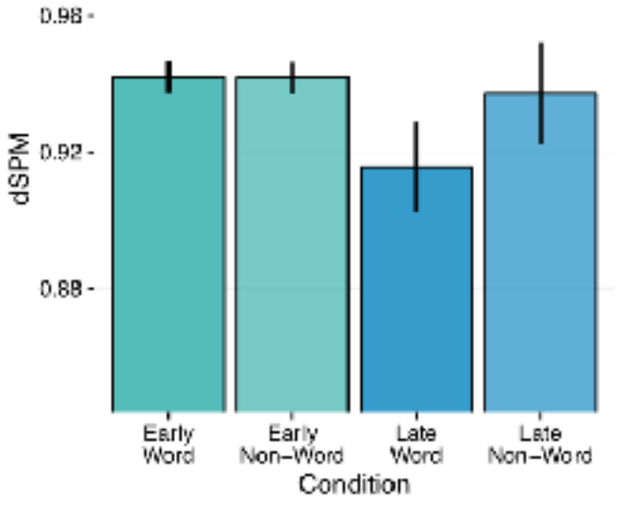

a
Phoneme Ambiguity
0
0.25
0.5
0.75
1
200
300
400
500
600


PoA
VOT
0.1
0.0
−0.1
dSPM
Ambiguous
Unambiguous
Ambiguous
Unambiguous


b
Onset Word Frequency
p−value of interaction
0
0.25
0.5
0.75
1
200
300
400
500
600
4
5
6
7
phoneme delay


0.4
0.3
0.2
0.1
0.0
dSPM
−5
0
5
Log Word Frequency


c
Lexical Resolution
0
0.25
0.5
0.75
1
200
300
400
500
600
Time (ms) relative to onset


0.98
0.92
0.88
dSPM
Early Word
Early Non−Word
Late Word
Late Non−Word
Condition