Integrating prosodic context in speech perception

Jeremy Steffman

Northwestern University
jeremy.steffman@northwestern.edu

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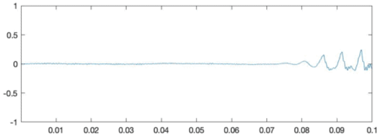
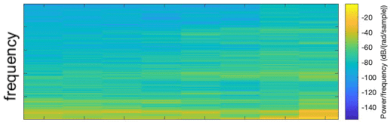
Introduction

Two parts of understanding spoken language

1. perceiving segmental contrasts → lexical items
2. perceiving prosodic features: grouping, prominence relations, etc.

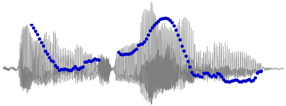
"her name is Marilyn"





(hɚneɪm ɪz meɹɪlɪn)$_{\text{intonational phrase}}$

L+H* L-L%



segmental processing

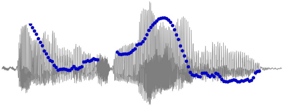
hɚneɪm ɪz meɹɪlɪn

prosodic processing

$(..........)_{IP}$

L+H*L-L%

Prosody and segment usually studied as independent in processing



↙		↘
segmental processing	⟺ ?	prosodic processing
↓		↓
hɚneɪm ɪz meɹɪlɪn		(...........)$_{IP}$ L+H*L-L%

We lack a good understanding of how they interact[1]

[1] Mitterer et al., 2016; Steffman, 2019

This talk

is about one type of interaction: the influence of prosodic context on the perception of segmental contrasts

Why should prosodic context matter?

Acoustic cues vary based on prosody and segment (cf. the notion of "suprasegmentals")

[1] Cho, 2015; Turk and Shattuck-Hufnagel, 2007
[2] Chen, 1970
[3] Lehiste, 1970
[4] Shepherd, 2008; Nakai et al., 2009
[5] Keating et al., 2004

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- before prosodic boundaries[1]

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- before voiced obstruents[2]
- based on vowel height[3]
- in long vowels in languages where vowel length is contrastive[4]

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This is the case for many cues, another well known case: VOT[5]

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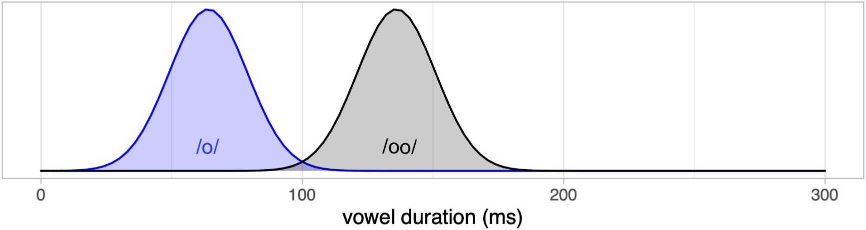
Why should prosodic context matter?

Duration is contrastive in Japanese[1]

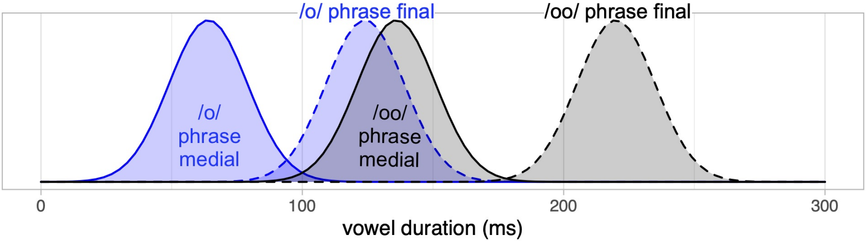


e.g. /dookjo/ "housemate" - /dookjoo/ "townmate"

[1]From Shepherd, 2008

Why should prosodic context matter?

And varies based on phrasing: longer phrase-finally[1]



Dual patterning based on both prosodic and segmental properties

[1] From Shepherd, 2008

Road map

Hypothesis: Determining segmental contrasts in speech involves **interaction** between segmental/prosodic processing

Question: What does does this interaction look like?

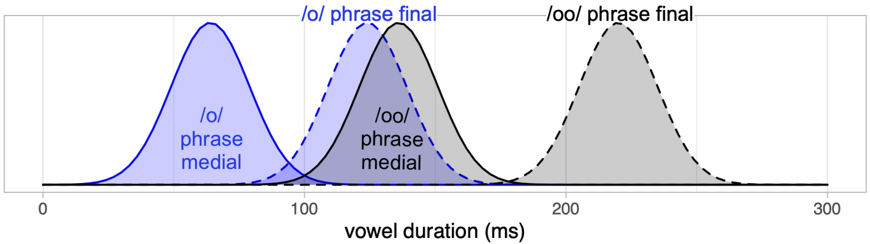
Section I
Do listeners care about prosodic boundaries in their perception of contrastive temporal cues?

Section II
Do listeners care about prosodic *prominence* their perception of spectral cues? (vowel formants)
And how is this information processed online?

I. Prosodic boundaries and contrastive vowel length in Japanese

Experiment 1: Contrastive vowel duration in Japanese

Recall this[1]



Do listeners care?

[1]From Shepherd, 2008

Experiment 1: Contrastive vowel duration in Japanese[1]

Will phrasing mediate listeners' expectation of how long a vowel should be?

Method: forced choice categorization of vowel duration continuum:

- Experiment 1a ($n = 26$): ʃi'ʃoo "master" - ʃi'ʃo "librarian"
- Experiment 1b ($n = 26$): dookjoo "housemate" - dookjo "townmate"

[1] Joint work with Hironori Katsuda (Steffman and Katsuda, 2020)

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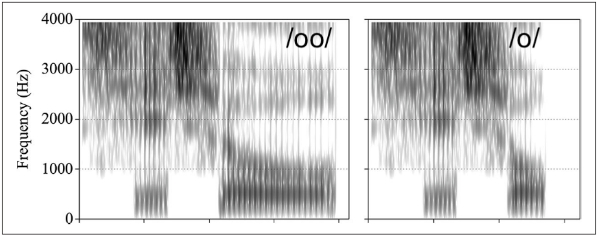

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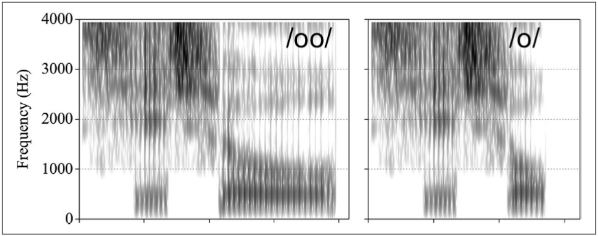

- cued as phrase final or phrase medial by intonational tunes in a phrase
  we are [TARGET] therefore we are reliable
- only pitch varies across phrase final/ phrase medial conditions

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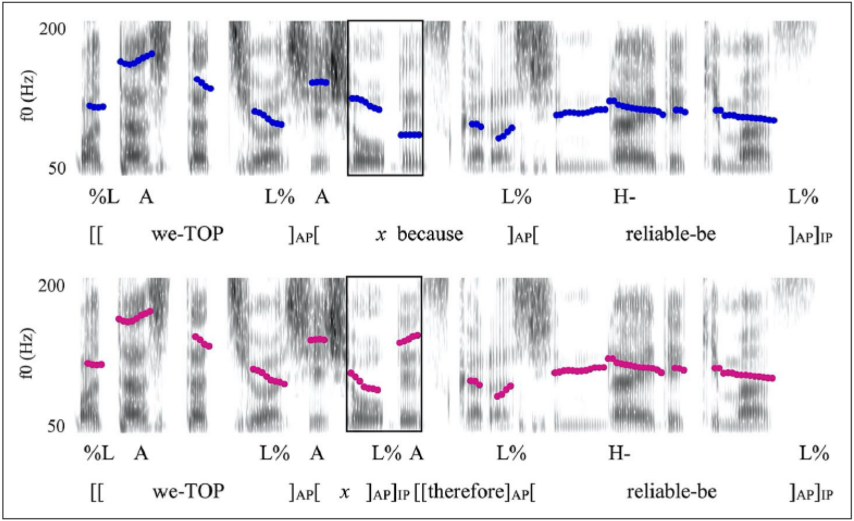
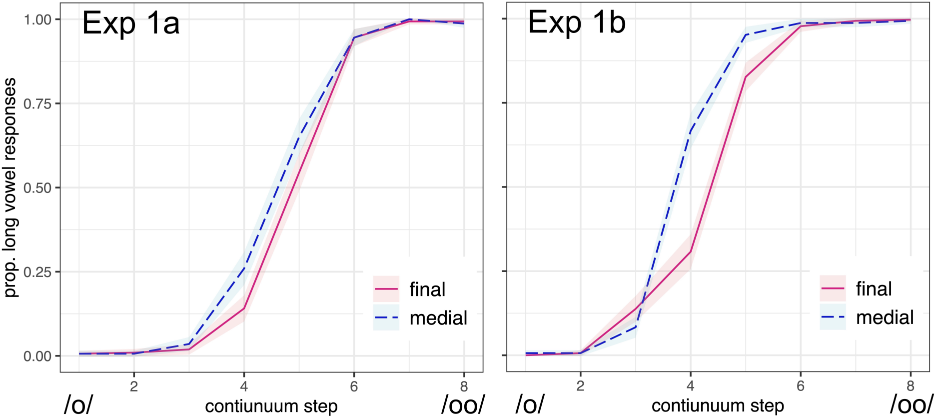
Experiment 1a stimuli



Experiment 1: Results[1]



[1] Exp 1a phrasing β= -0.91; 95%CI = [-1.54,-0.31]
Exp 1b phrasing β= -1.54; 95%CI = [-2.14,-1.06]

What we've seen so far...

Listeners modulate their perception of temporal contrasts as a function of prosodic phrasing

Up next...

- what about non-temporal cues?
- what about prosodic prominence?

II. Contextual prominence in vowel perception

The test case: Prominence strengthening in American English vowels

Vowel articulations/acoustics are modulated by prominence[1]
(= *prominence strengthening*)

Two effects:

1. Sonority expansion: expansion of the oral cavity
   - where "sonorous" = more open[2]
   - makes a louder vowel

[1] e.g., Beckman et al., 1992; Cho, 2005; de Jong et al., 1993; Erickson, 2002
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2. Voice quality strengthening: glottalization
   - glottalization and production of [ʔ] precede prominent vowel-initial words [3]
   - though not always

[1] e.g., Beckman et al., 1992; Cho, 2005; de Jong et al., 1993; Erickson, 2002
[2] Silverman and Pierrehumbert, 1990
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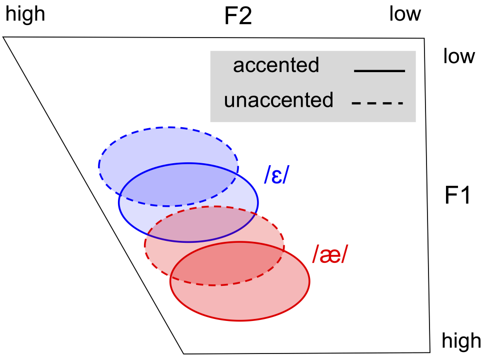
Sonority expansion effects on vowel formants

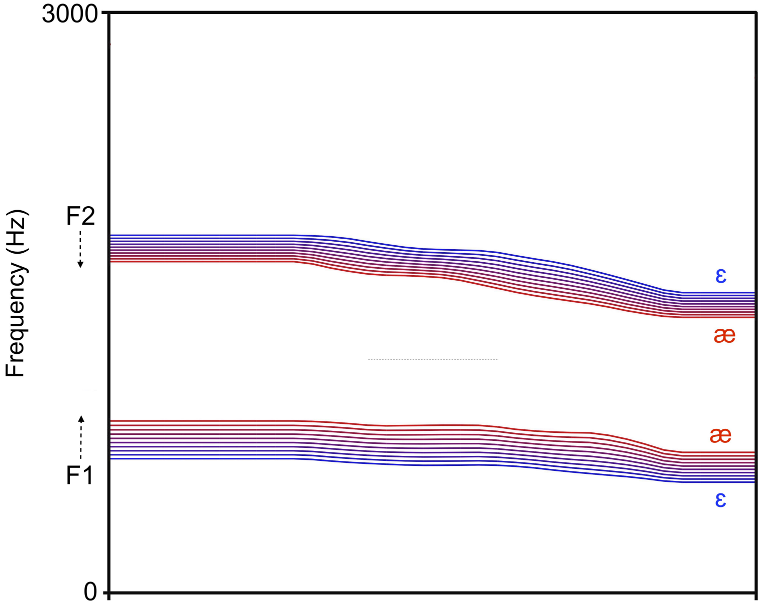
Sonority expansion entails:

- increased opening, jaw lowering: raised F1[1]
- for some vowels, retraction the tongue: lowered F2[2]



[1] Erickson, 2002; Van Summers, 1987

[2] Cho, 2005; Erickson, 2002


3000
F2
Frequency (Hz)
ɛ
æ
æ
F1
ɛ
0

Experiment 2 and 3

Two visual word eyetracking studies (n = 36 in each)

- 6-step continuum categorized as "ebb" /ɛ/ or "ab" /æ/
  - central region of a piloted 10 step continuum - more ambiguous sounds
- Two contextual conditions: prominent/non-prominent

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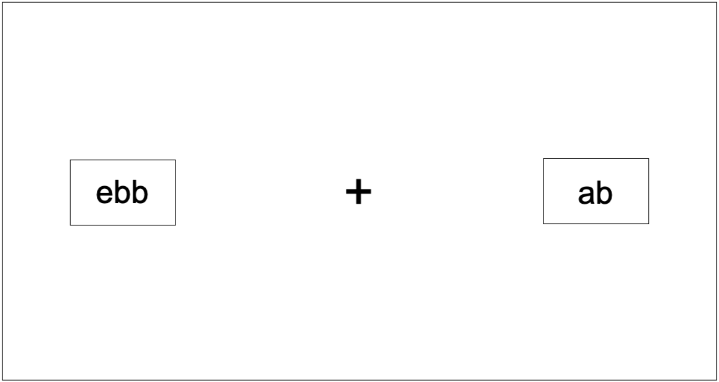

Experiment 2 conditions: "Phrasal prominence"

Two prominence conditions cuing a contrast in accentuation

1. I'll say *X* now *nuclear pitch accent - NPA* (prominent)
   H* H* L-L%
2. I'll SAY *x* now *post-focus* (non-prominent)
   L+H* L-L%

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Prediction

Higher F1/ lower F2 expected in the NPA condition, more tokens mapped to /ɛ/ therein: increased "ebb" responses in NPA.

Experiment 3 conditions: [ʔ] as a cue to prominence

Glottalization often co-occurs with phrasal prominence in vowel-initial words

Prominence manipulation: presence/absence of pre-target [ʔ]

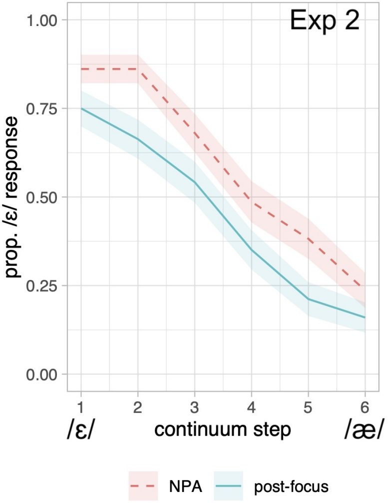
- "say the [target] now"

1. [seɪ ðə ʔ ɛb naʊ] *glottal stop*
   H* H* L-L%
2. [seɪ ðə ɛb naʊ] *no glottal stop*
   H* H* L-L%

Prediction:

if [ʔ] cues prominence, increased "ebb" responses in the glottal stop condition - same as phrasal prominence

Categorization responses[1]



[1] Exp 2 prominence β= 0.91; 95%CI = [0.22,1.59]
Exp 3 prominence β= 2.66; 95%CI = [2.08,3.28]

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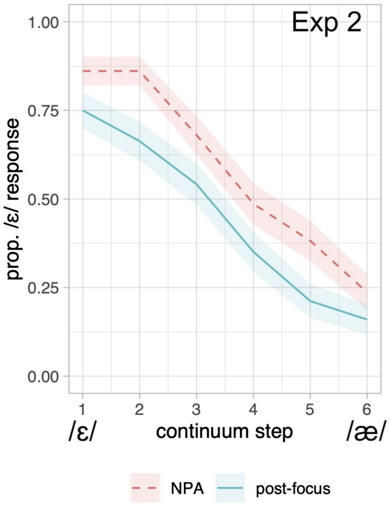

[1] Exp 2 prominence $\beta = 0.91$; 95%CI = [0.22,1.59]
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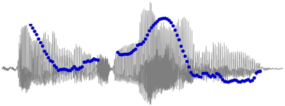
What we've seen so far...

- Prosodic prominence matters in vowel perception
- Both phrasal context (Exp 2) and local context (Exp 3) generate adjustments in categorization

Up next:

- How are listeners integrating these cues as speech unfolds?



↙ ↘

segmental processing $\Longleftrightarrow$??? prosodic processing

Two ways this might work

1. Segments first: 
    - make your best guess about segmental material as soon as you can
    - wait to integrate this information with a prosodic representation, once you know more about utterance prosody

2. All at once: 
    - Why wait? Integrate preceding contextual cues with information about a segment as soon as you can

The segments first model

Prosodic analysis[1]

- simultaneous segmental and prosodic parses of the signal

1. Segmental analysis activates lexical hypotheses
2. Parsed prosody integrated in lexical competition (e.g., alignment of phrasal/word boundaries)

Prediction:

Prosodic context shows a delayed influence in segmental processing

Recent empirical support from prosodic *boundaries*[2]

[1] Cho et al., 2007

[2] Kim et al., 2018a; Mitterer et al., 2019

All at once

On the other hand...

- listeners rapidly integrate temporal and spectral context in perception in general[1]
- and some other contextual prosodic influences occur rapidly[2]

Prediction:

Prosodic context, which precedes segmental material, should show an immediate influence on listeners' interpretation of that material

[1] e.g., Reinisch and Sjerps, 2013
[2] e.g., Brown et al., 2011

"The segmental analysis activates all possible lexical hypotheses, and its activation is further modulated by the prosodic analysis at a relatively late stage in spoken-word recognition." (Mitterer et al., 2019)
(prosodic boundaries)

"listeners integrate [...] cues to prosodic structure in the earliest moments of spoken-word recognition." (Brown et al., 2011)
(rhythmic alternations)

Why prominence is interesting

Prominence in American English can be described in phonological/categorical terms

- nuclear accented > accented > unaccented
- pitch accent categories
  - L+H* > H* > L*

[1] Bishop et al., 2020; Grice et al., 2017

Why prominence is interesting

Prominence in American English can be described in phonological/categorical terms

- nuclear accented > accented > unaccented
- pitch accent categories
  - L+H* > H* > L*

But...

- various phonetic parameters impact prominence perception, including within pitch accent categories[1]
- "a linguistic entity is prosodically prominent when it stands out relative to an entity or a set of entities in its environment." (Terken and Hermes, 2000)

[1] Bishop et al., 2020; Grice et al., 2017

Experiments in this section

In both Experiment 2 and 3:

1. listeners hear variation in formants and contextual prominence
2. prominence cues only *precede* the target

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1. the temporal scope of differences in preceding context
2. the phonological status of prominence differences across conditions?

Prediction in both: prominent contexts should lead to increased looks to "ebb" - same as categorization

Predictions: timecourse

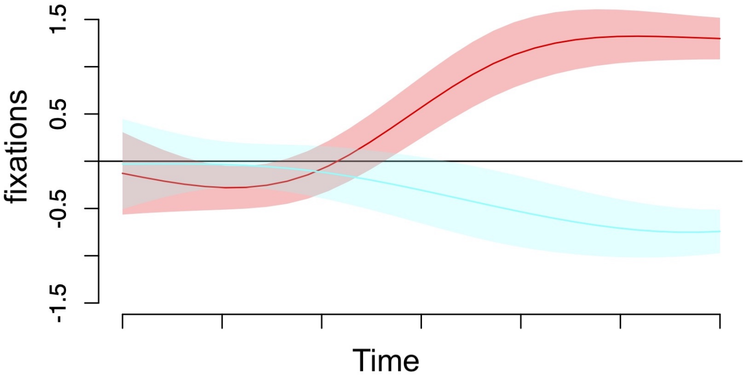
Segments first

- P1 Given (1) formants, and (2) contextual prominence, formants will impact processing *before* prominence asynchronous use of cues
- P2 Perception of formants early in processing *won't vary* across conditions

All at once

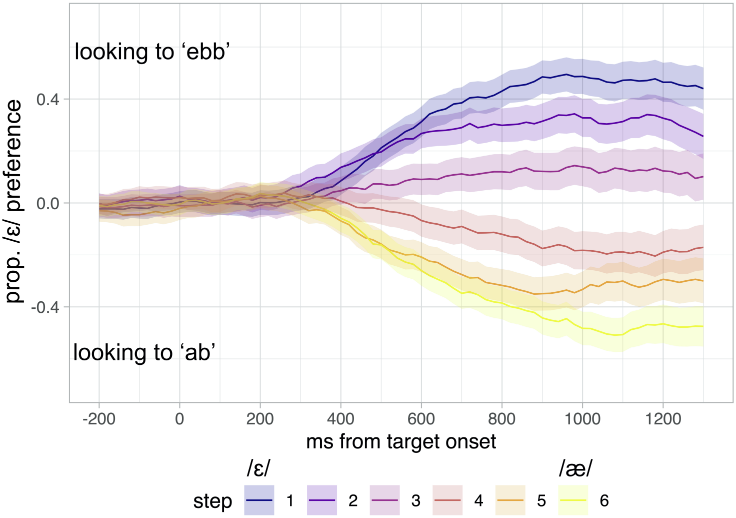
- P1 Given (1) formants, and (2) contextual prominence, both will impact processing immediately synchronous use of cues
- P2 Perception of formants early in processing *will vary* across conditions

GAMM modeling



When in time do smooths diverge, and how do they change over time?

Experiment 2 results: Formants



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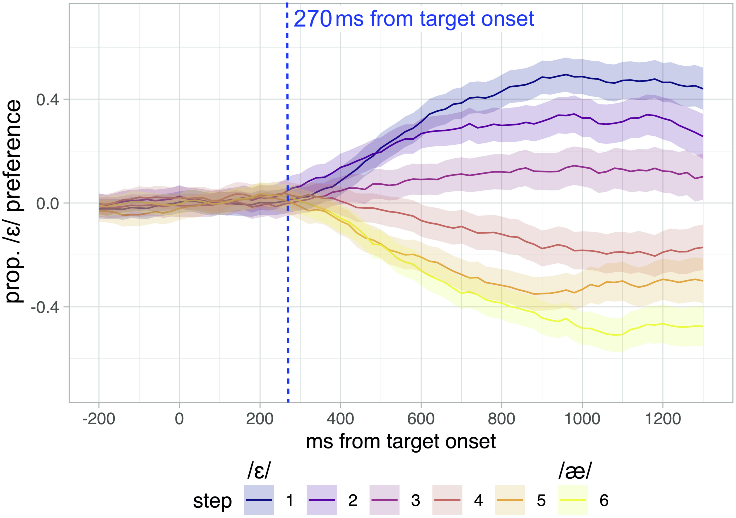
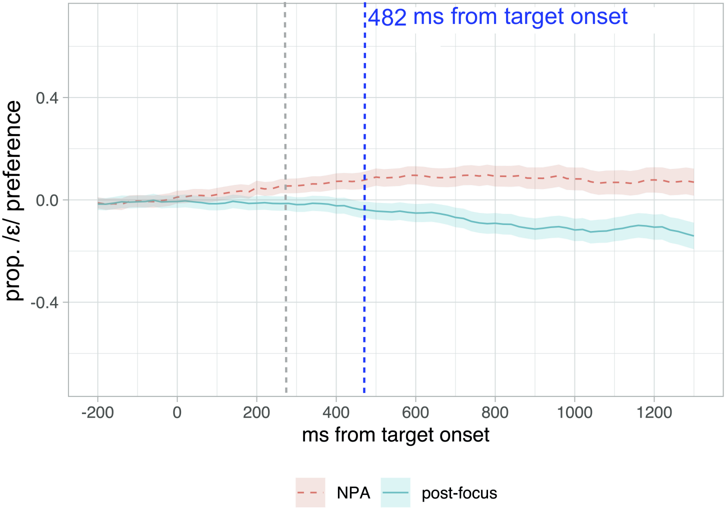
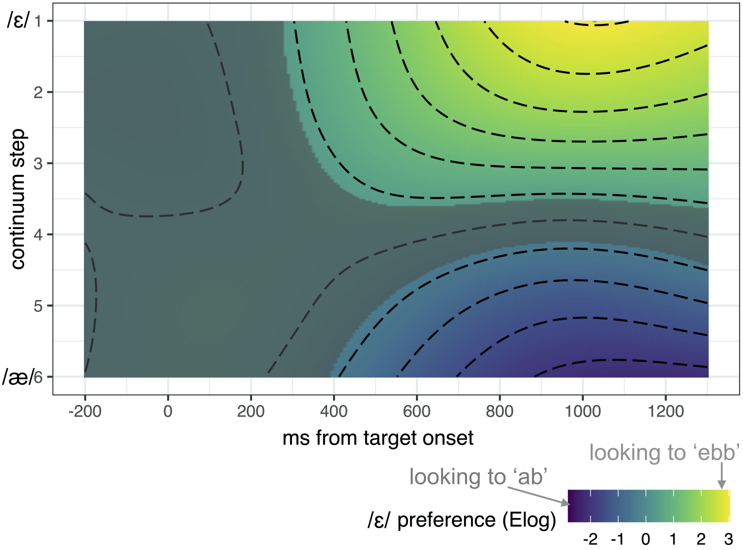
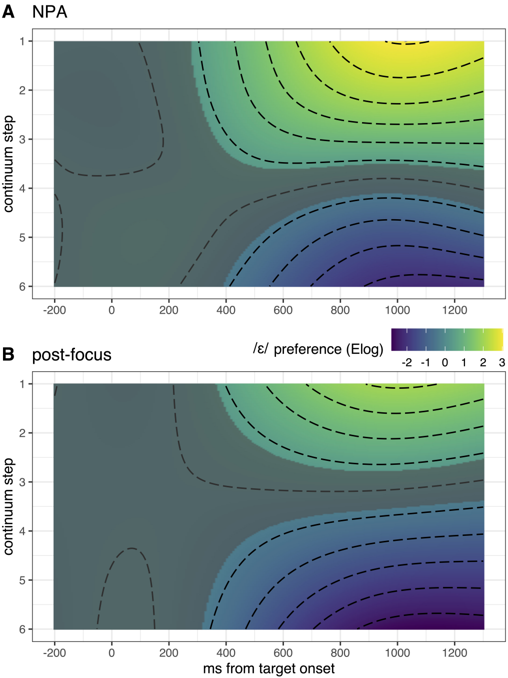


Experiment 2 results: Prominence



Experiment 2 surface plots



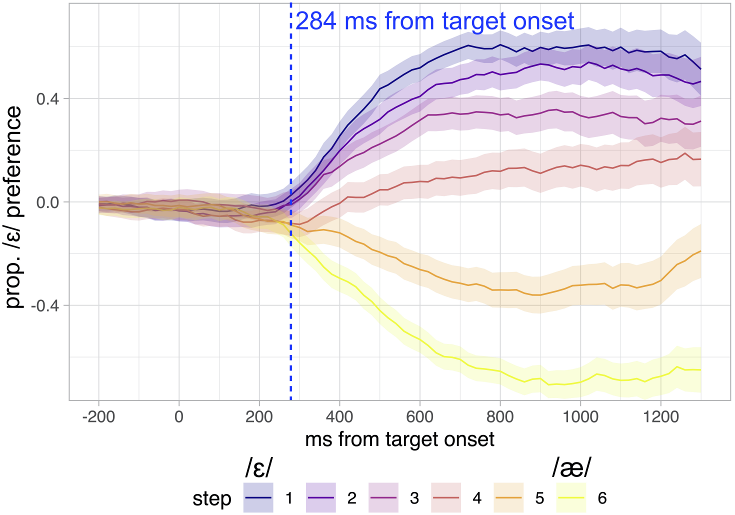

A
NPA
B
post-focus
/ɛ/ preference (Elog)
-2
-1
0
1
2
3
continuum step
1
2
3
4
5
6
-200
0
200
400
600
800
1000
1200
ms from target onset

What we've seen so far...

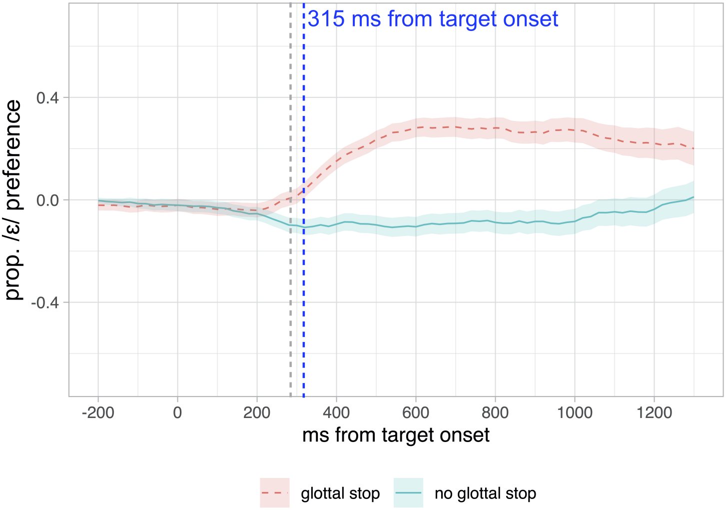
1. Phrasal prominence effects are overall delayed relative to the effect of formant cues
2. But there are subtle immediate impacts on formant perception

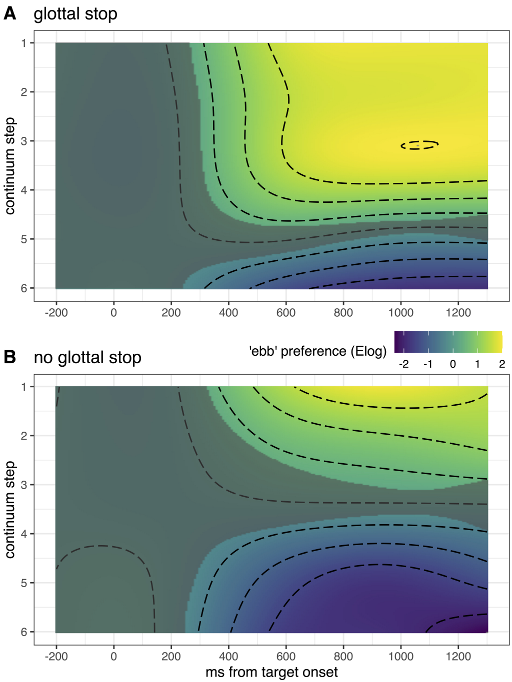
What about [ʔ]?

Experiment 3 results: Formants



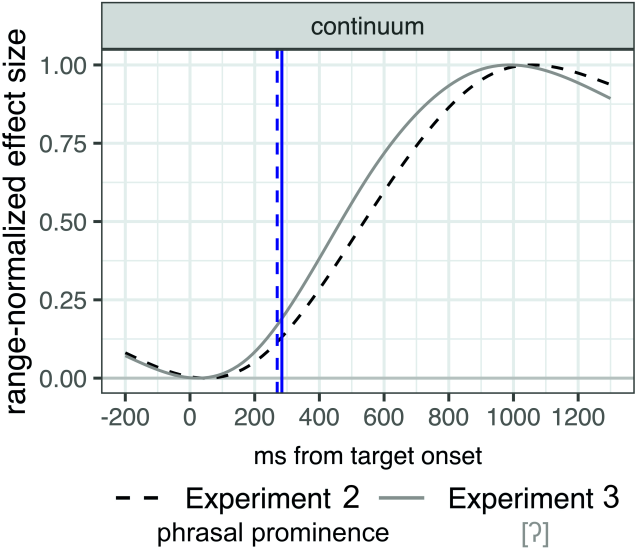
Experiment 3 results: Prominence



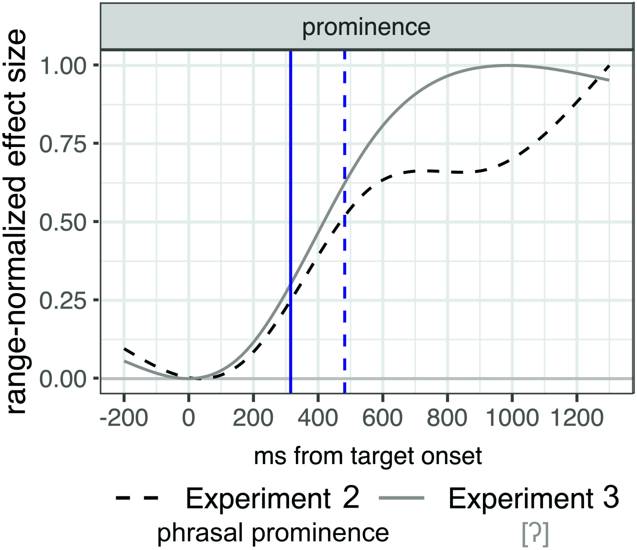


A glottal stop
continuum step
1
2
3
4
5
6
-200
0
200
400
600
800
1000
1200
B no glottal stop
'ebb' preference (Elog)
-2
-1
0
1
2
continuum step
1
2
3
4
5
6
-200
0
200
400
600
800
1000
1200
ms from target onset

Comparing Experiment 2 and 3: Continua



Comparing Experiment 2 and 3: Prominence



Processing prominence and segment

1. When [ʔ] precedes a vowel....

 don’t wait to use prominence information - process in tandem with formant cues

1. When prominence is conveyed by preceding tunes/duration...

  subtler early influences grow slowly reaching a maximum relatively later in processing

This is a notable departure from strictly delayed influence attested for prosodic boundaries[1]

[1] Kim et al., 2018a; Mitterer et al., 2019

Take home messages

1. Does prosodic context shape speech perception?

- Yes
- Both prosodic boundaries (Section I) and prosodic prominence (Section II) mediate perception of segmental contrasts

2. How is prominence processed in relation to segmental material?

- Prominence is integrated immediately with cues to a contrast
- When context is global/phrasal - later-stage reinforcement of prominence effects
- Listeners consider the phonetics and phonology of prominence in processing?

Going forwards

On the processing side:

- Does incoherence between prosodic context and cues hinder processing?
  - Are certain types of incoherence more inhibitory?

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    - Are certain types of incoherence more inhibitory?
- How bidirectional are these influences?
    - How do "segmental" cues influence interpretation of prosodic features? (see Mitterer et al., 2020)

Going forwards

On the processing side:

- Does incoherence between prosodic context and cues hinder processing?
  - Are certain types of incoherence more inhibitory?
- How bidirectional are these influences?
  - How do "segmental" cues influence interpretation of prosodic features? (see Mitterer et al., 2020)
- How do these effects fit into existing models of spoken word recognition?

On the typological side:

- How do language-specific patterns of vowel reduction and strengthening translate to perception?
- How does prominence mediate processing in edge-prominence languages?

An abridged thank you

- To Sun-Ah Jun, Pat Keating, Megha Sundara and Taehong Cho
- To RAs for these projects:

  Danielle Bagnas, Qingxia Guo, Jae Weller and Bryan Gonzalez

- To you all!

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Appendix

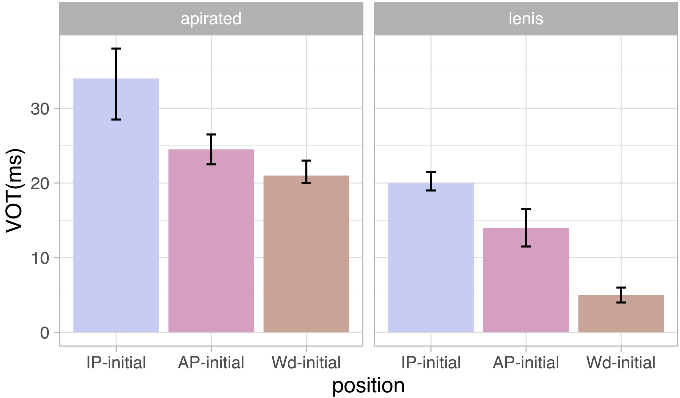
"Segmental" cues vary systematically based on prosody

E.g., voice onset time (VOT) is longer...

- in aspirated vs. unaspirated stops[1]
- in prominent syllables[2]
- at the beginning of prosodic domains[3]

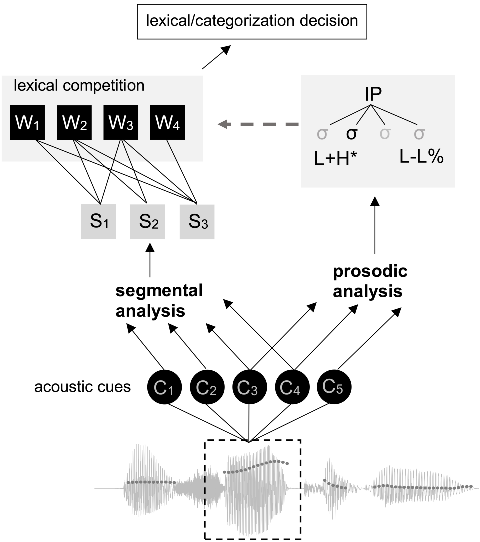
[1] Abramson, 1976; Abramson and Whalen, 2017
[2] Cole et al., 2007; Cho, 2015
[3] Keating et al., 2004

Dual patterning: Korean VOT

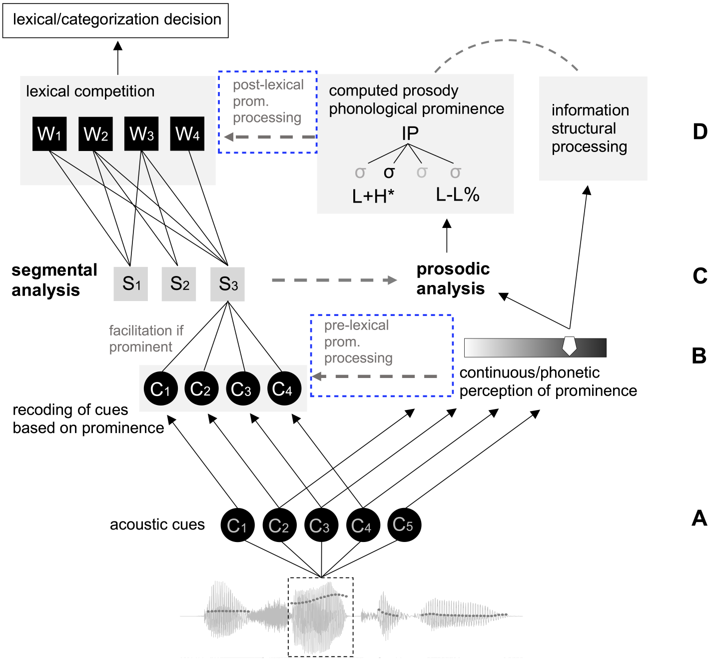


VOT from Korean /t^h/ and /t/, adopted from Cho and Keating (2001)

Schematic of the prosodic analysis model[1]

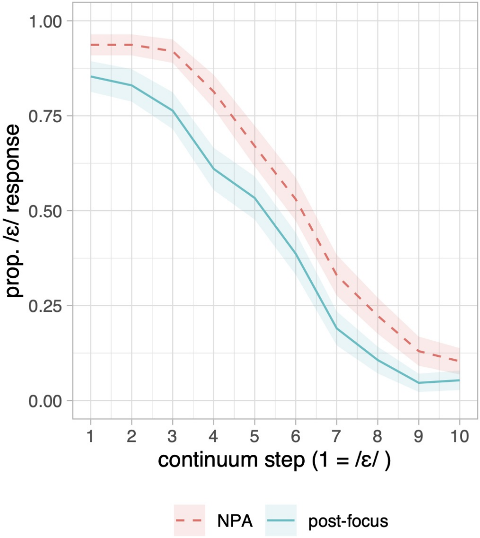


[1] Cho et al., 2007; Kim et al., 2018b; Mitterer et al., 2019



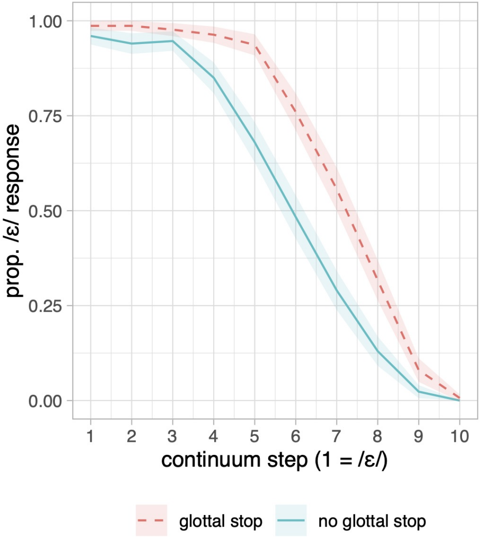
Multistage Assessment of Prominence in Processing (MAPP)

Offline pre-Experiment 2 results



main effect of prom.
$\beta = 0.83$; 95%CI = [0.27,1.39]

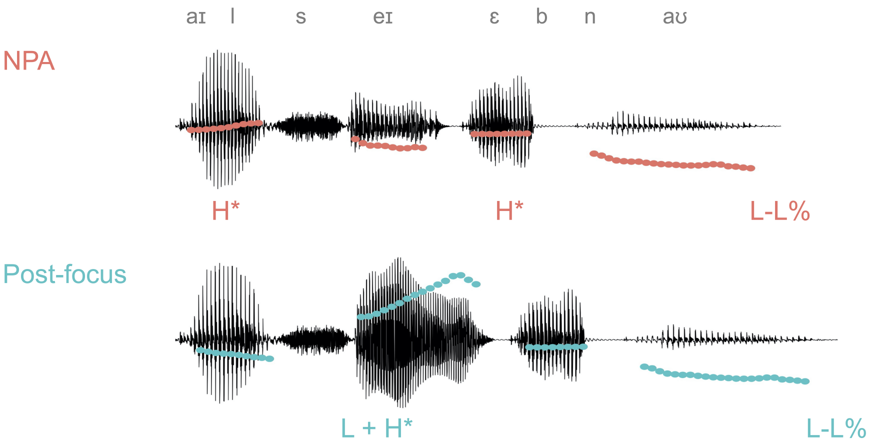
Offline pre-Experiment 3 results



main effect of prom.

$\beta = 1.75$; 95%CI = [1.31,2.22]

Experiment 2 stimuli



Experiment 3 stimuli

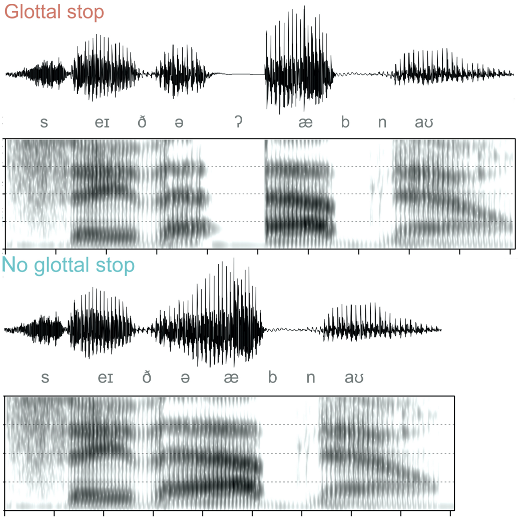
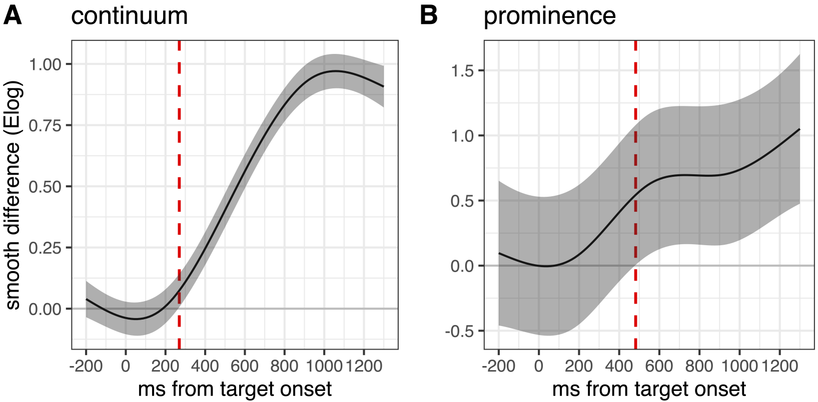
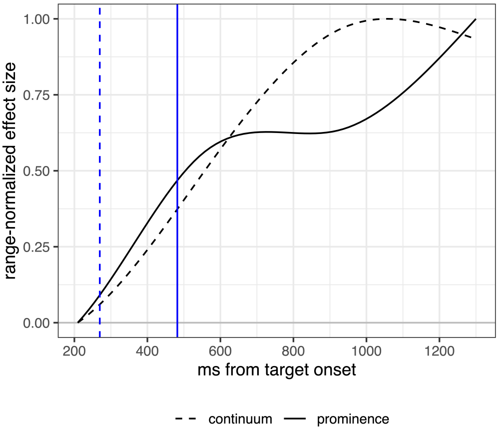


Figure: Waveforms and spectrograms of the Experiment 3 stimuli

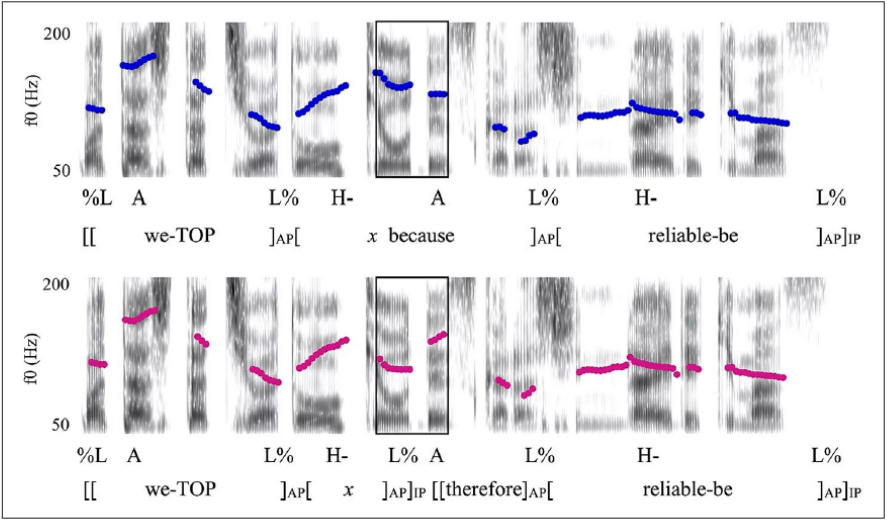
Exp 2 difference smooths



Range-normalized effects Experiment 2



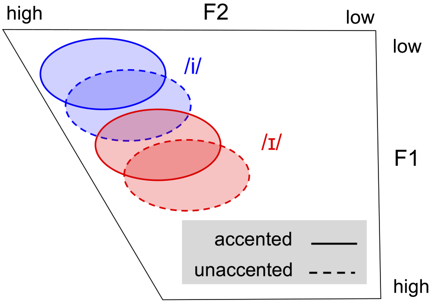
Experiment 1b stimuli



Bonus Experiment: High front vowels

High front vowels, contra sonority expansion, often show:

- Hyperarticulation: enhance features [+high, -back] - raise/front tongue (lower F1/higher F2)



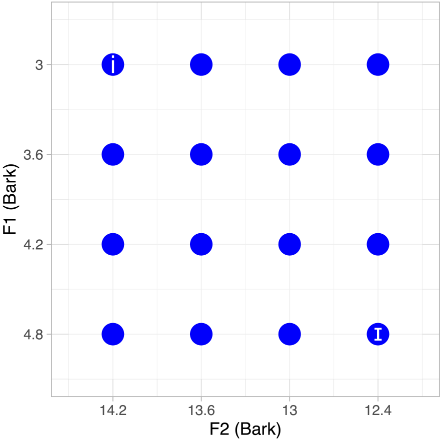
Tests perception of an /ɪ/ to /i/ continuum

Prediction

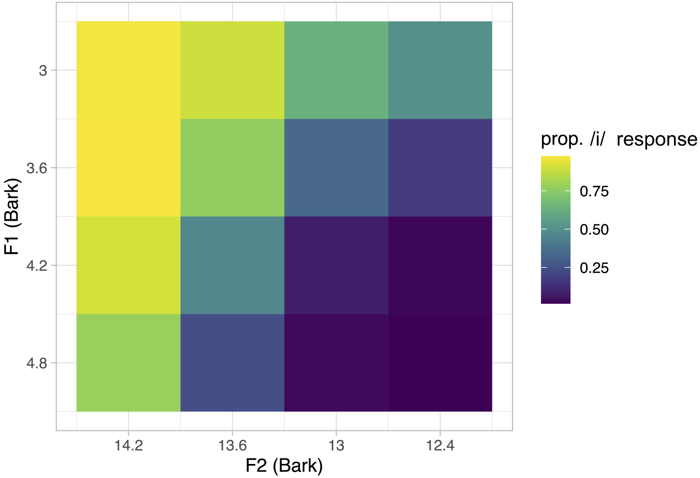
Lower F1/ Higher F2 expected in the NPA condition, fewer tokens mapped to /i/ therein:
decreased /i/ responses in NPA

Bonus Experiment

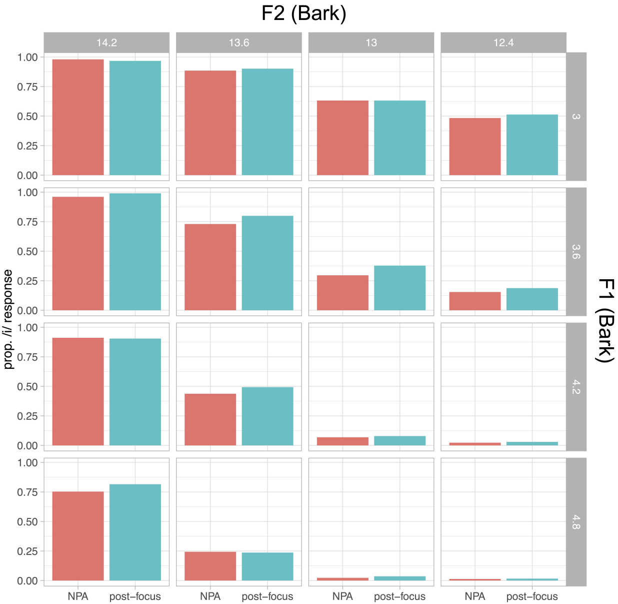
- "sit" to "seat" (/ɪ/ to /i/) continuum
- Same prominence manipulation as Experiment 1: NPA / post-focus



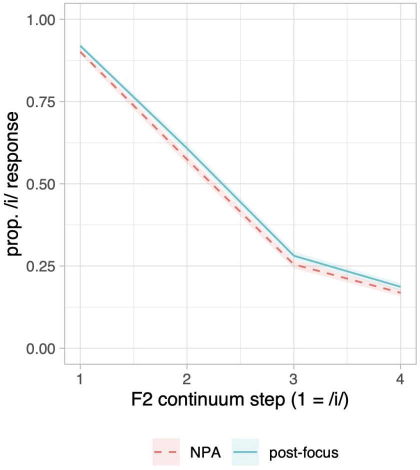
Bonus experiment results: Continuum



Bonus experiment results: Continuum/prominence



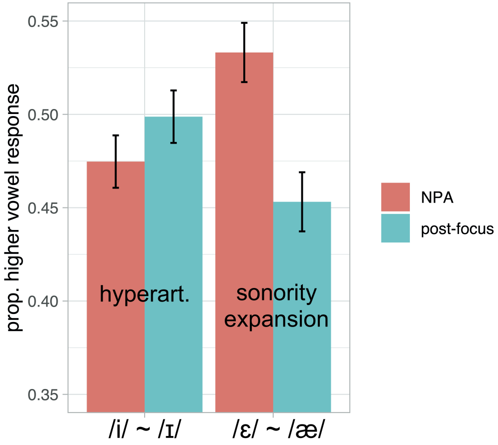
Bonus experiment results: Prominence



main effect of prom. β= -0.26; 95%CI = [-0.42,-0.10]

hyperarticulation expected under prominence

high vowels and non-high vowels



Evidence for contrast-specific expectations of prominence strengthening

Model outputs

Table: Experiment 3

	Estimate	Est. Error	L-95% CI	U-95%CI	credible?
intercept	0.05	0.17	-0.29	0.39	
prominence	0.83	0.28	0.27	1.39	✓
continuum	-2.57	0.28	-3.15	-2.03	✓
prom:cont	-0.24	0.13	-0.50	0.01	

Table: Experiment 5 click responses

	Estimate	Est. Error	L-95% CI	U-95%CI	credible?
intercept	0.09	0.16	-0.21	0.40	
prominence	0.91	0.35	0.22	1.59	✓
continuum	-1.56	0.20	-1.96	-1.17	✓
prom:cont	-0.13	0.12	-0.37	0.11	

Model outputs

Table: Experiment 4

	Estimate	Est. Error	L-95% CI	U-95%CI	credible?
intercept	1.18	0.16	0.87	1.50	✓
glottal stop	1.75	0.23	1.31	2.22	✓
continuum	-3.35	0.17	-3.71	-3.02	✓
glot:cont	-0.79	0.20	-1.20	-0.41	✓

Table: Experiment 6 click responses

	Estimate	Est. Error	L-95% CI	U-95%CI	credible?
intercept	1.11	0.17	0.78	1.45	✓
glottal stop	2.66	0.30	2.08	3.28	✓
continuum	-2.89	0.22	-3.33	-2.49	✓
glot:cont	-0.56	0.23	-1.03	-0.13	✓

Model outputs

Table: Bonus Experiment

	Estimate	Est. Error	L-95% CI	U-95%CI	credible?
intercept	-0.54	0.15	-0.84	-0.25	✓
prominence	-0.26	0.08	-0.42	-0.10	✓
F1	-1.80	0.15	-2.10	-1.52	✓
F2	2.63	0.18	2.28	2.99	✓
F1:F2	0.78	0.11	0.57	1.00	✓
F1:prominence	-0.01	0.10	-0.19	0.19	
F2:prominence	0.01	0.11	-0.20	0.22	
F1:F2:prominence	-0.01	0.10	-0.20	0.19	

Model outputs

Table: Experiment 6

	Estimate	Est. Error	L-95% CI	U-95%CI	credible?
intercept	-0.14	0.16	-0.44	0.17	
prominence	0.49	0.24	0.01	0.95	✓
continuum	-2.61	0.22	-3.05	-2.18	✓
prom:cont	-0.46	0.12	-0.71	-0.25	✓

Model outputs

Table: Model output for the GAMM used in Experiment 2

Parametric terms	Estimate	Est. Error	t-value	p-value
intercept	0.24	0.16	1.50	0.14
continuum	-1.63	0.09	-18.04	< 0.001
prominence	0.45	0.23	1.91	0.05
Smooth terms	**edf**	**ref df**	**F-value**	**p-value**
te(time, continuum; condition = NPA)	17.09	19.71	38.27	< 0.001
te(time, continuum; condition = post-focus)	8.99	9.52	66.32	< 0.001
s(time, participant; condition = NPA)	228.11	323.00	3.91	< 0.001
s(time, participant; condition = post-focus)	231.32	323.00	4.97	< 0.001

Model outputs

Table: Model output for the GAMM used in Experiment 4

Parametric terms	Estimate	Est. Error	t-value	p-value
intercept	0.37	0.08	4.39	< 0.001
continuum	-1.01	0.10	-9.86	< 0.001
glottal stop	0.52	0.12	4.45	< 0.001
Smooth terms	**edf**	**ref df**	**F-value**	**p-value**
te(time, continuum; condition = GS)	21.85	22.48	333.36	< 0.001
te(time, continuum; condition = no GS)	22.00	23.05	282.845	< 0.001
s(time, participant; condition = GS)	268.60	358.00	9.38	< 0.001
s(time, participant; condition = no GS)	284.13	358.00	10.24	< 0.001