

Integrating prosodic context in speech perception

Jeremy Steffman

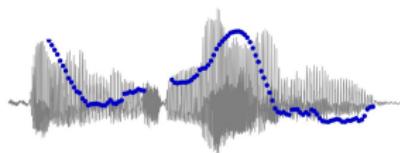
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Introduction

Two parts of understanding spoken language

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



segmental processing

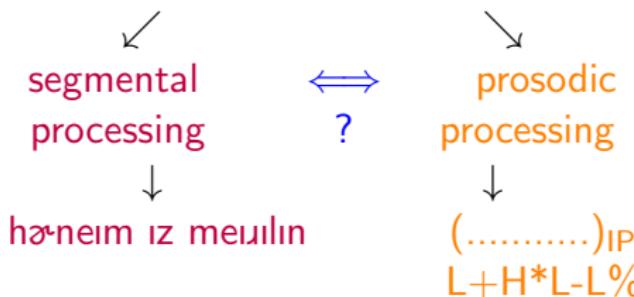
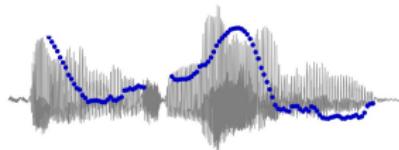
prosodic processing

↓
hə-neɪm ɪz meɪ-lɪn

↓
(.....)IP
L+H*L-L%

Prosody and segment usually studied as independent in processing





We lack a good understanding of how they interact¹

¹Mitterer 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”)

¹Cho, 2015; Turk and Shattuck-Hufnagel, 2007

²Chen, 1970

³Lehiste, 1970

⁴Shepherd, 2008; Nakai et al., 2009

⁵Keating et al., 2004

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For example, vowel duration is longer...

- in prominent syllables¹
- before prosodic boundaries¹

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- before voiced obstruents²
- based on vowel height³
- in long vowels in languages where vowel length is contrastive⁴

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(This is the case for many cues, another well known case is VOT⁵)

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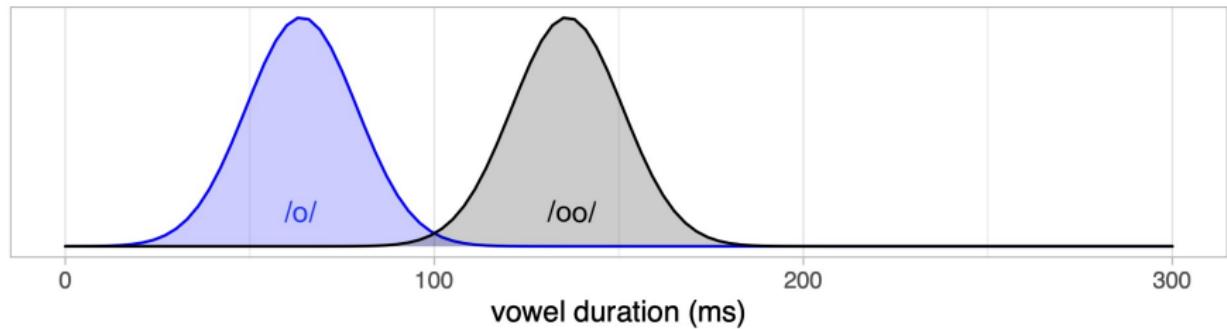
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Why should prosodic context matter?

Duration is contrastive in Japanese¹

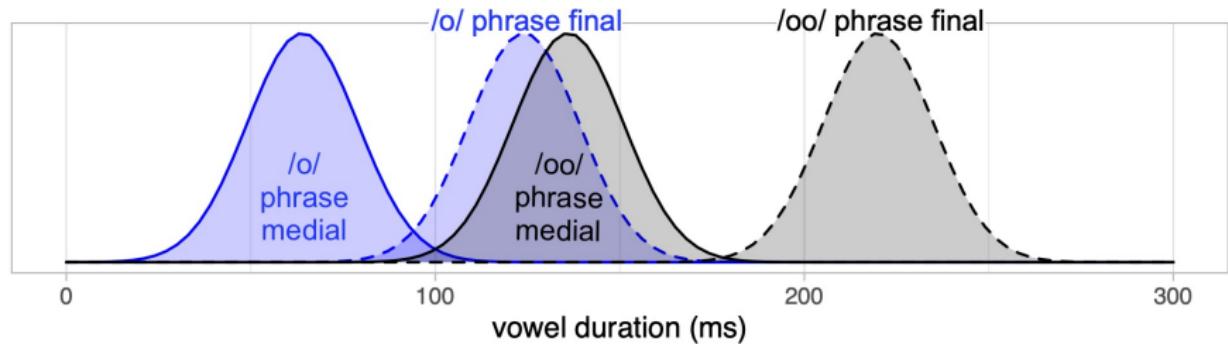


e.g. /dookjo/ “housemate” - /dookjoo/ “townmate”

¹From Shepherd, 2008

Why should prosodic context matter?

And varies based on phrasing: longer phrase-finally¹



Dual patterning based on both **prosodic** and **segmental** properties

¹From Shepherd, 2008

Road map

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

Question: What does this interaction look like?

Section I

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

Section II

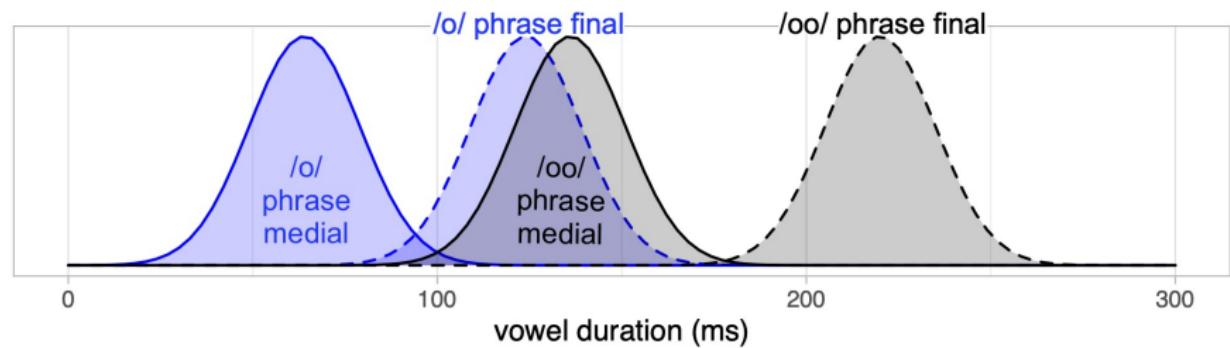
Do listeners care about prosodic *prominence* their perception of spectral cues? (vowel formants)

And how is this information processed online?

I. Prosodic boundaries and contrastive vowel length in Japanese

Experiment 1: Contrastive vowel duration in Japanese

Recall this¹



Do listeners care?

¹From Shepherd, 2008

Experiment 1: Contrastive vowel duration in Japanese¹

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”

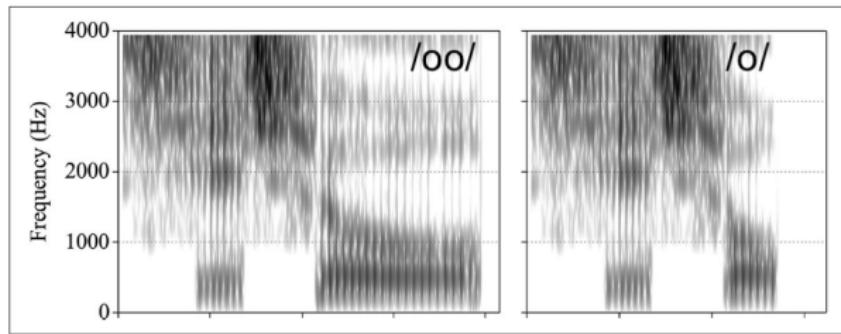
¹Joint work with Hironori Katsuda (Steffman and Katsuda, 2020)

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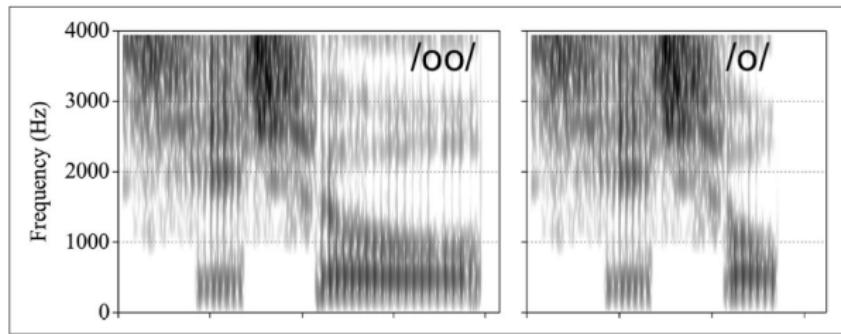
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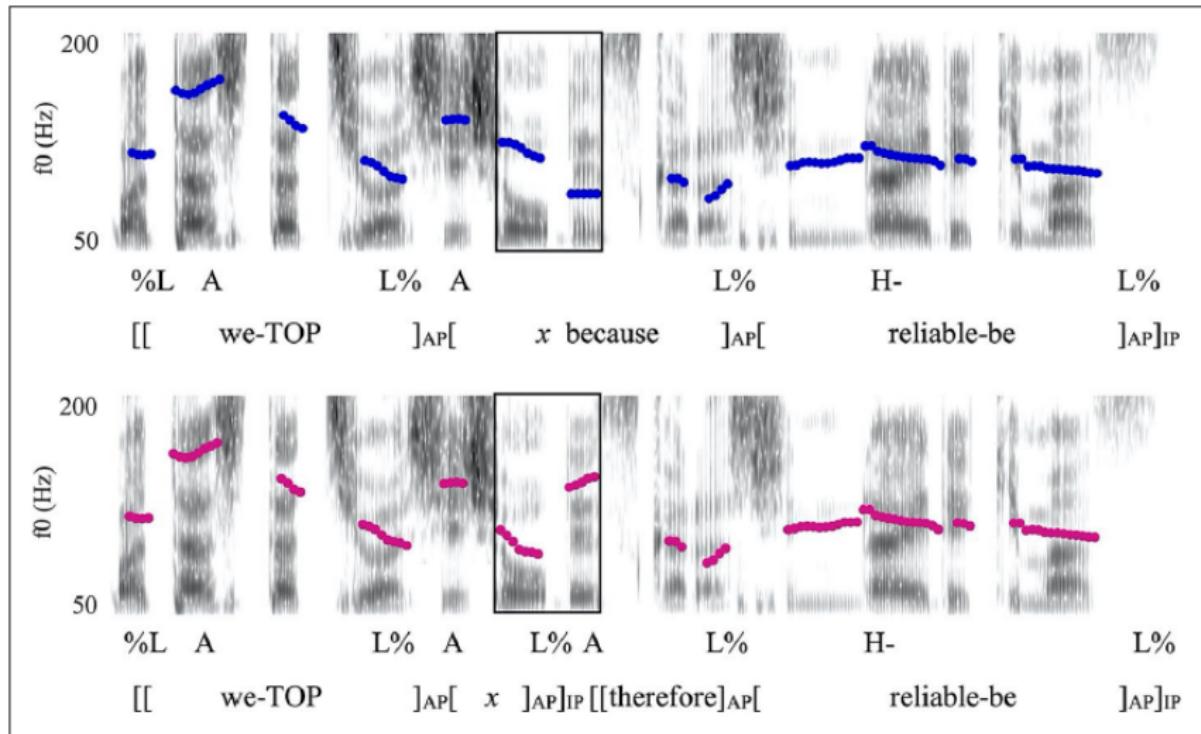
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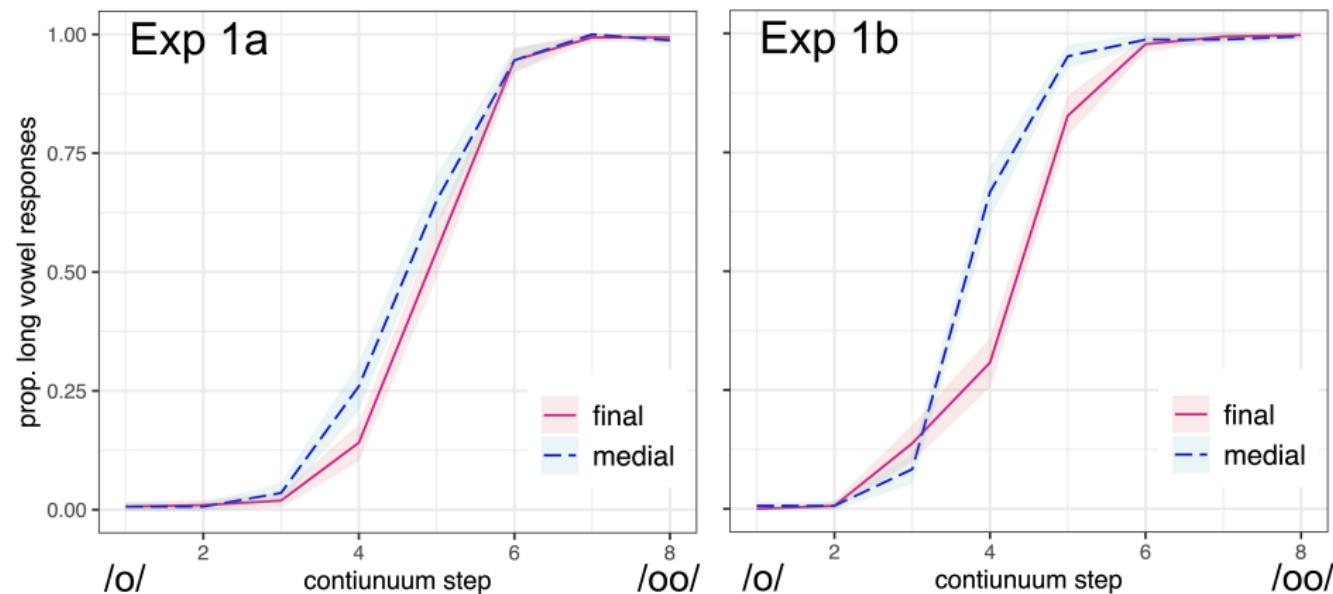
- cued as **phrase final** or **phrase medial** by intonational tunes in a phrase
we are [TARGET] therefore we are reliable
- only pitch varies across phrase final/ phrase medial conditions

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

Experiment 1a stimuli



Experiment 1: Results¹



¹Exp 1a phrasing $\beta = -0.91$; 95%CI = [-1.54,-0.31]
Exp 1b phrasing $\beta = -1.54$; 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 prominence¹
(= *prominence strengthening*)

Two effects:

- ① **Sonority expansion:** expansion of the oral cavity
 - where “sonorous” = more open²
 - makes a louder vowel

¹e.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 [?] precede prominent vowel-initial words³
 - though not always

¹e.g., Beckman et al., 1992; Cho, 2005; de Jong et al., 1993; Erickson, 2002

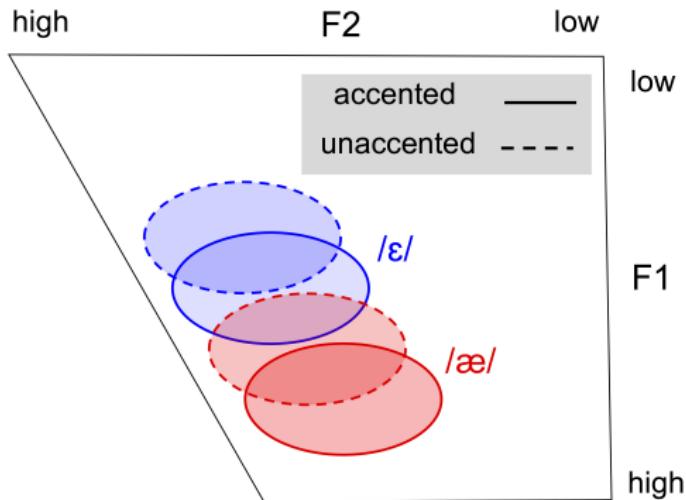
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Sonority expansion effects on vowel formants

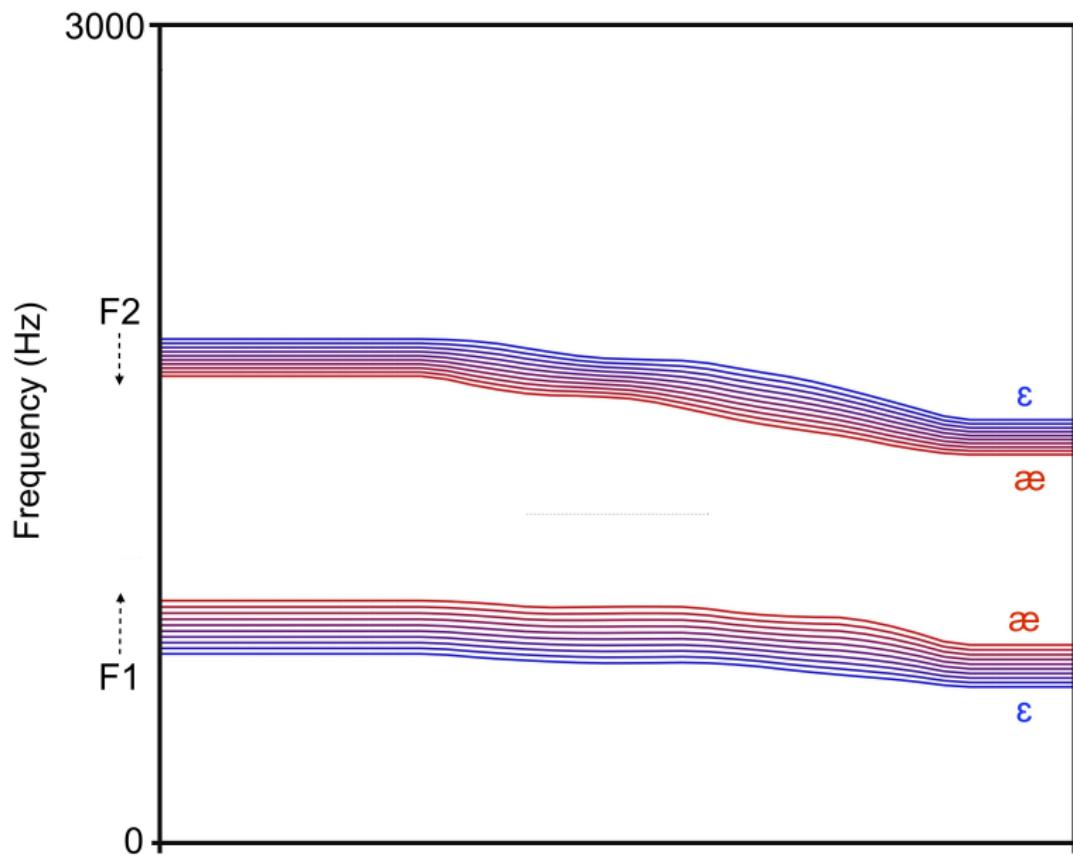
Sonority expansion entails:

- increased opening, jaw lowering: raised F1¹
- for some vowels, retraction the tongue: lowered F2²



¹Erickson, 2002; Van Summers, 1987

²Cho, 2005; Erickson, 2002



Experiment 2 and 3

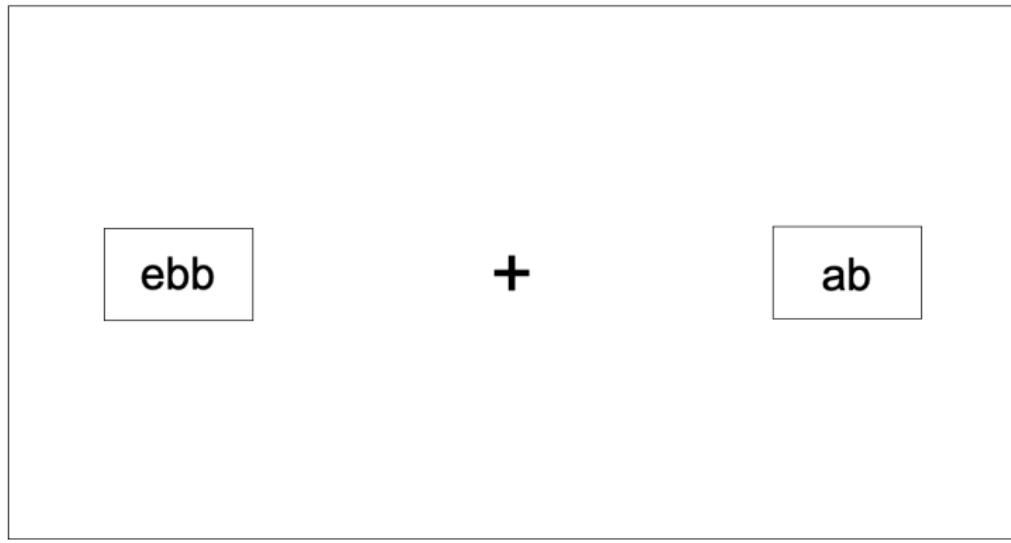
Two visual word eyetracking studies ($n = 36$ in each)

- 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: [?] as a cue to prominence

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

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

- “say the [target] now”

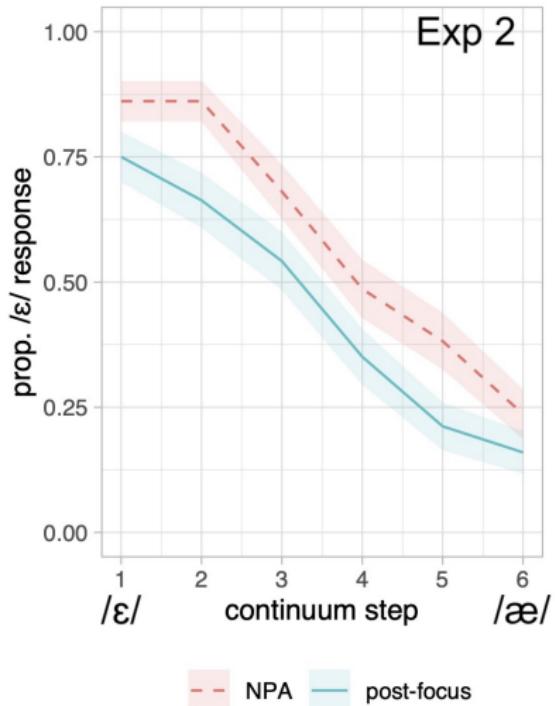
① [sei ðə ? εb nau] *glottal stop*
H* H* L-L%

② [sei ðə εb nau] *no glottal stop*
H* H* L-L%

Prediction:

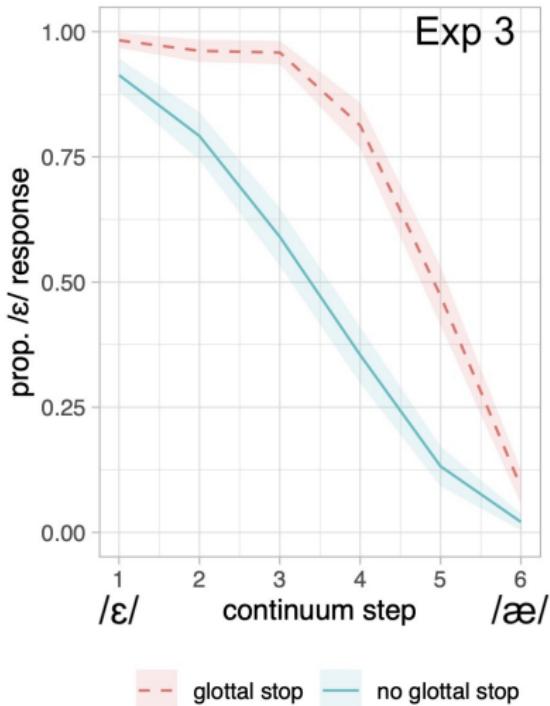
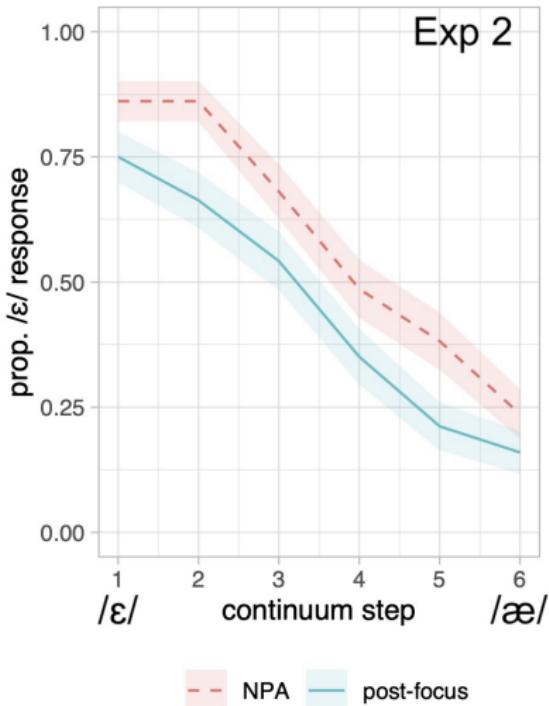
if [?] cues prominence, increased “ebb” responses in the *glottal stop* condition - same as phrasal prominence

Categorization responses¹



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

Categorization responses¹



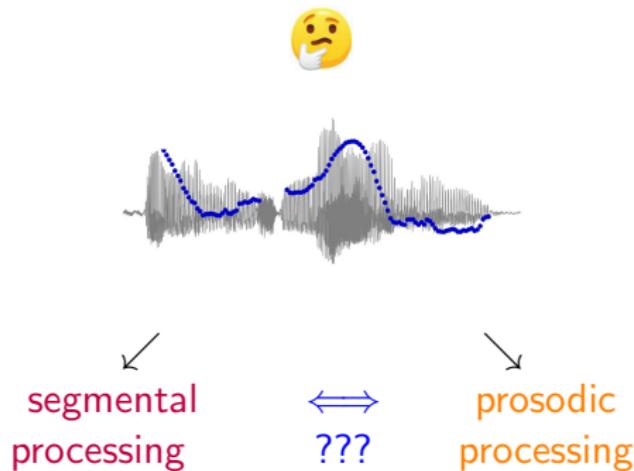
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What we've seen so far...

- 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?



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 analysis¹

- 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

¹Cho et al., 2007

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

All at once



On the other hand...

- listeners rapidly integrate temporal and spectral context in perception in general¹
- and some other contextual prosodic influences occur rapidly²

Prediction:

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

¹e.g., Reinisch and Sjerps, 2013

²e.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*

¹Bishop 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 categories¹
- “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)

¹Bishop 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**
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- ② the phonological status of prominence differences across conditions?

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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

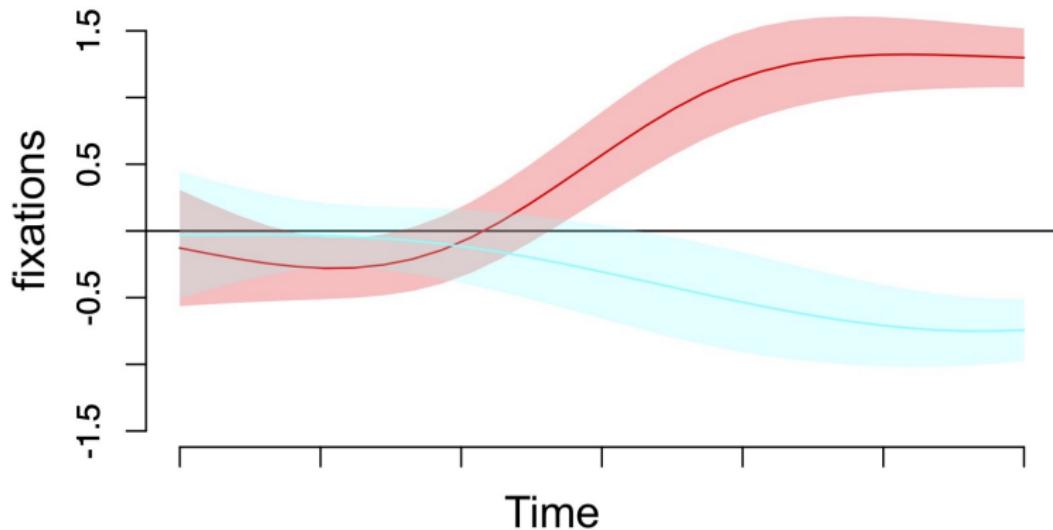
- P1 Given (1) formants, and (2) contextual prominence, formants will impact processing *before* prominence **asynchronous use of cues**
- P2 Perception of formants early in processing *won't vary* across conditions



All at once

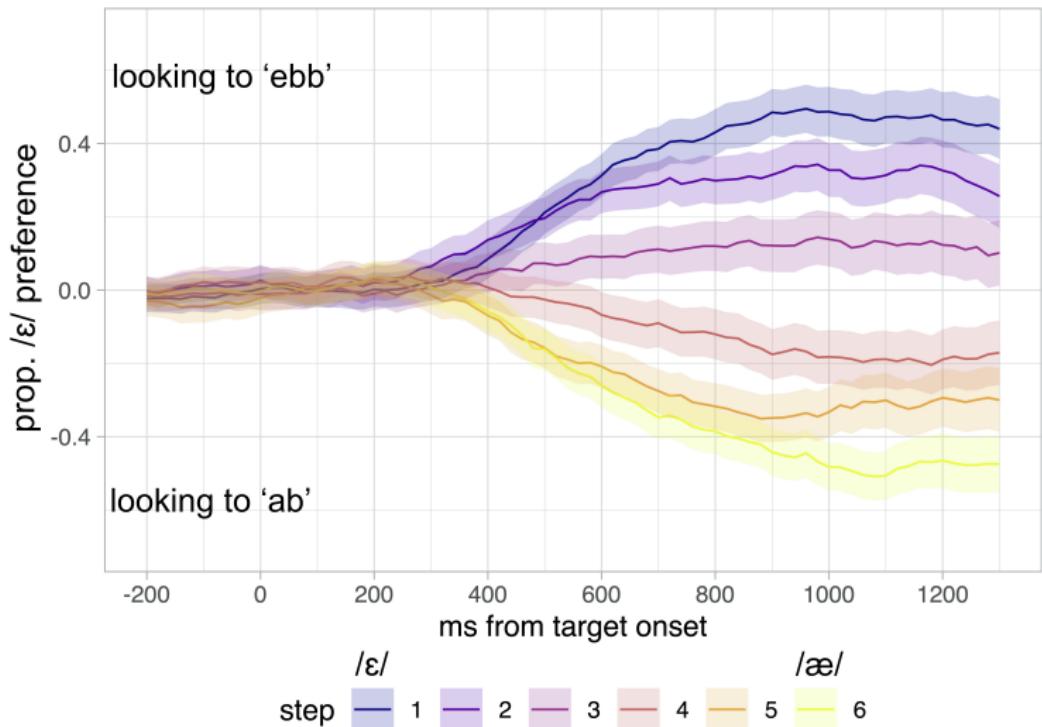
- P1 Given (1) formants, and (2) contextual prominence, both will impact processing immediately **synchronous use of cues**
- P2 Perception of formants early in processing *will vary* across conditions

GAMM modeling

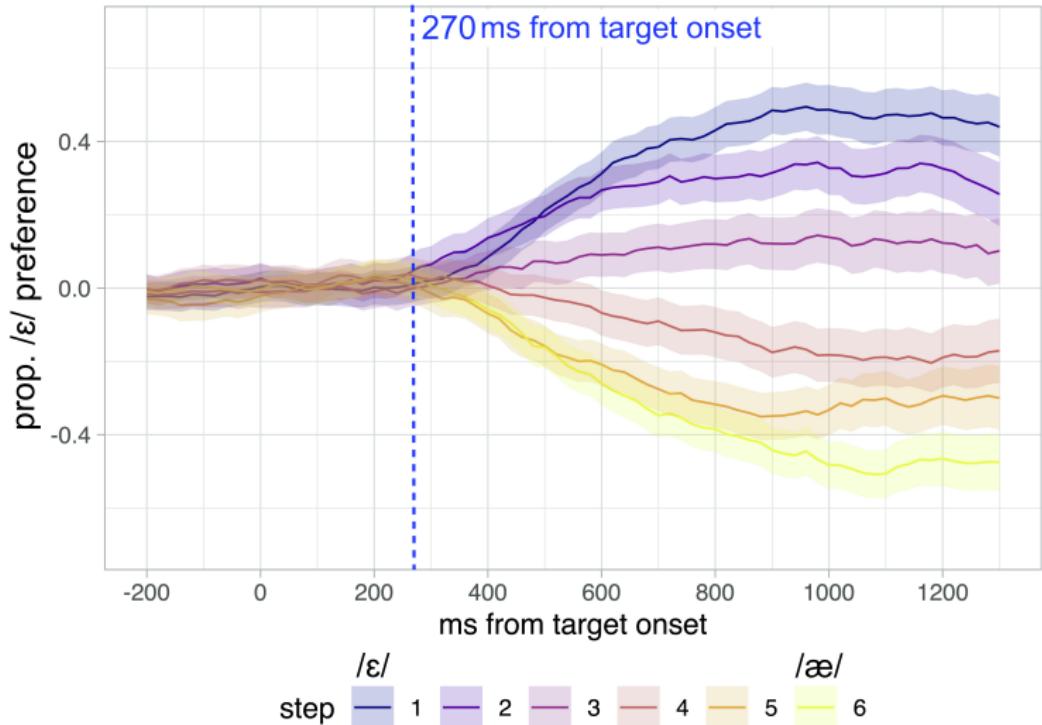


When in time do smooths diverge, and how do they change over time?

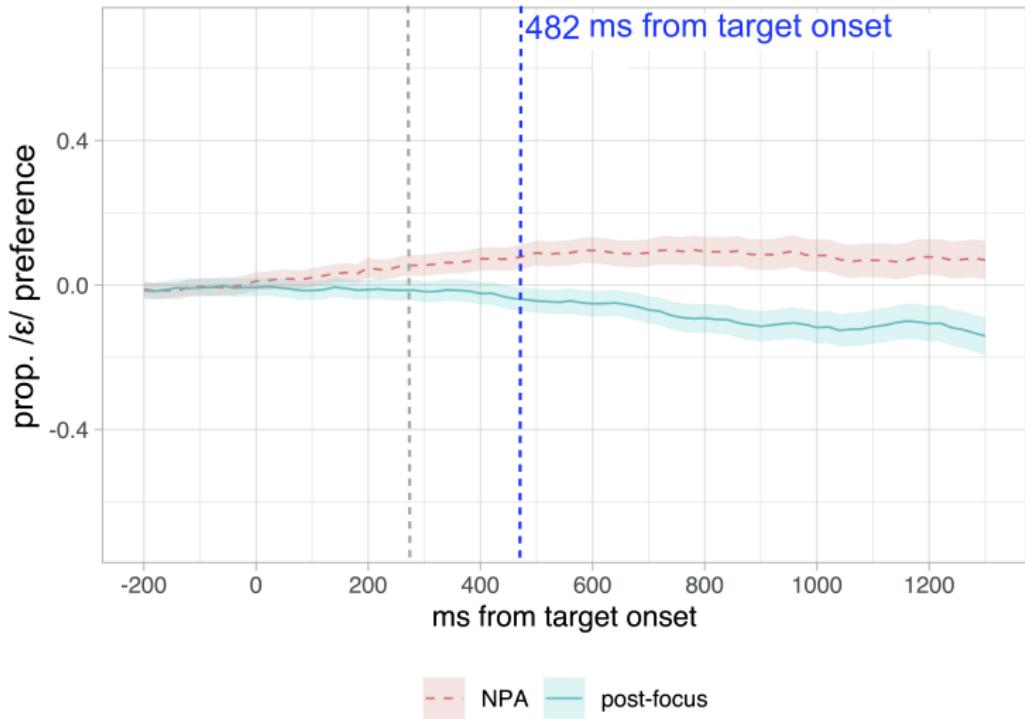
Experiment 2 results: Formants



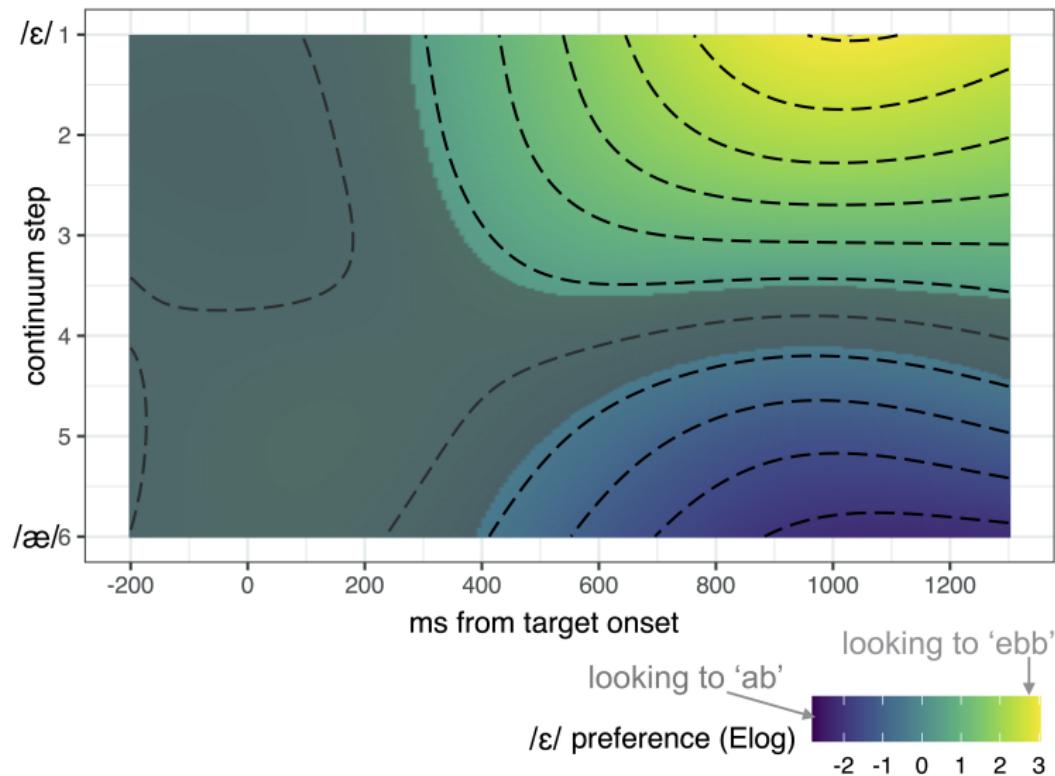
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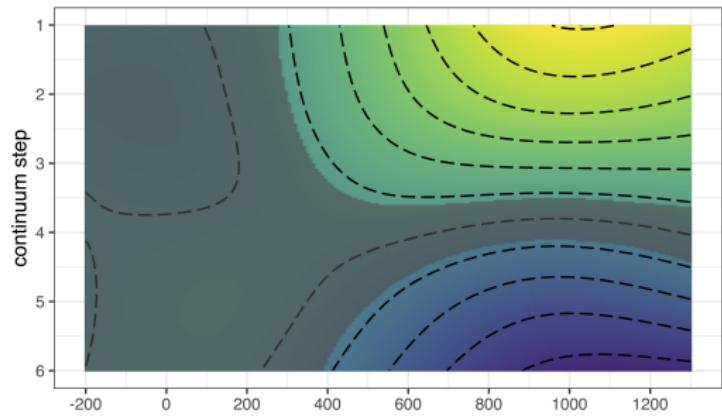
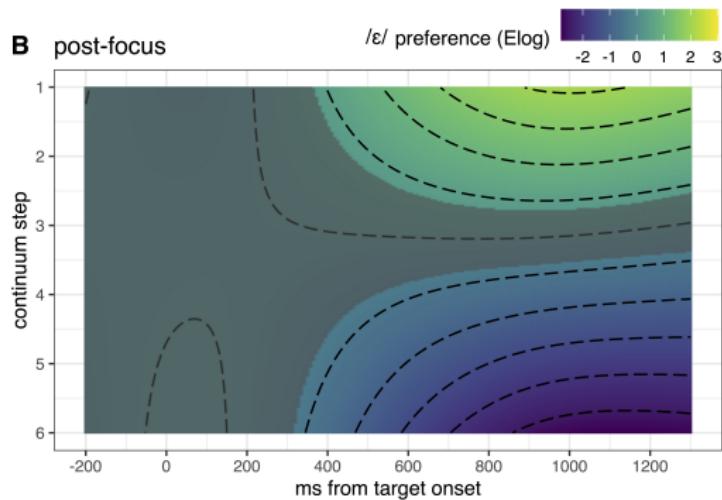


Experiment 2 results: Prominence



Experiment 2 surface plots



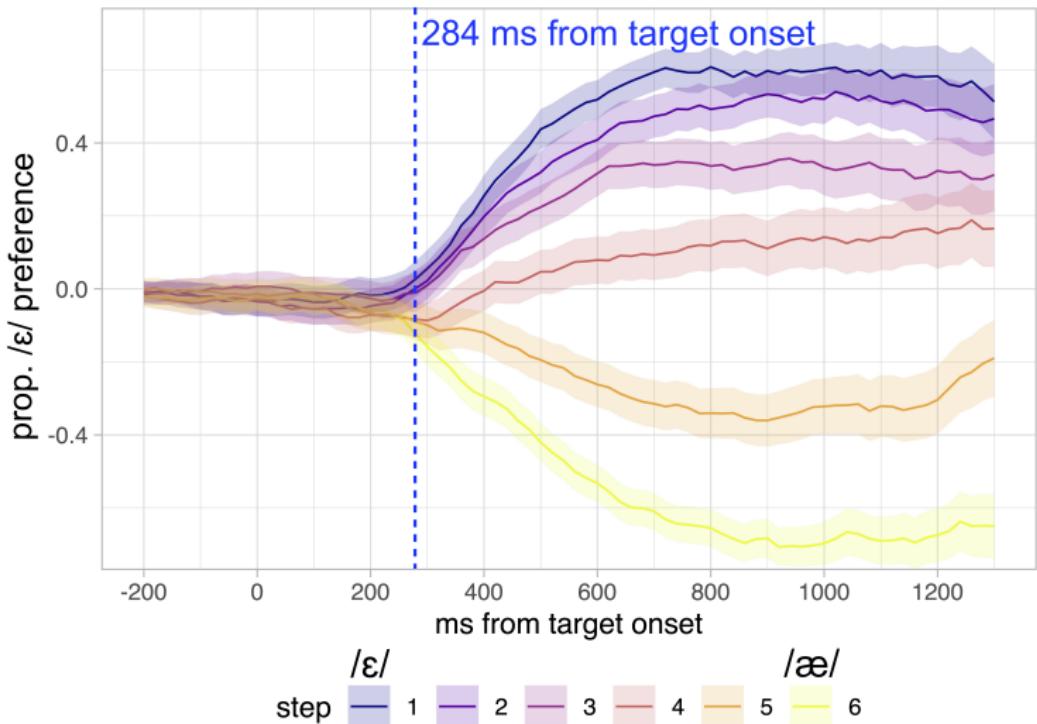
A NPA**B post-focus**

What we've seen so far...

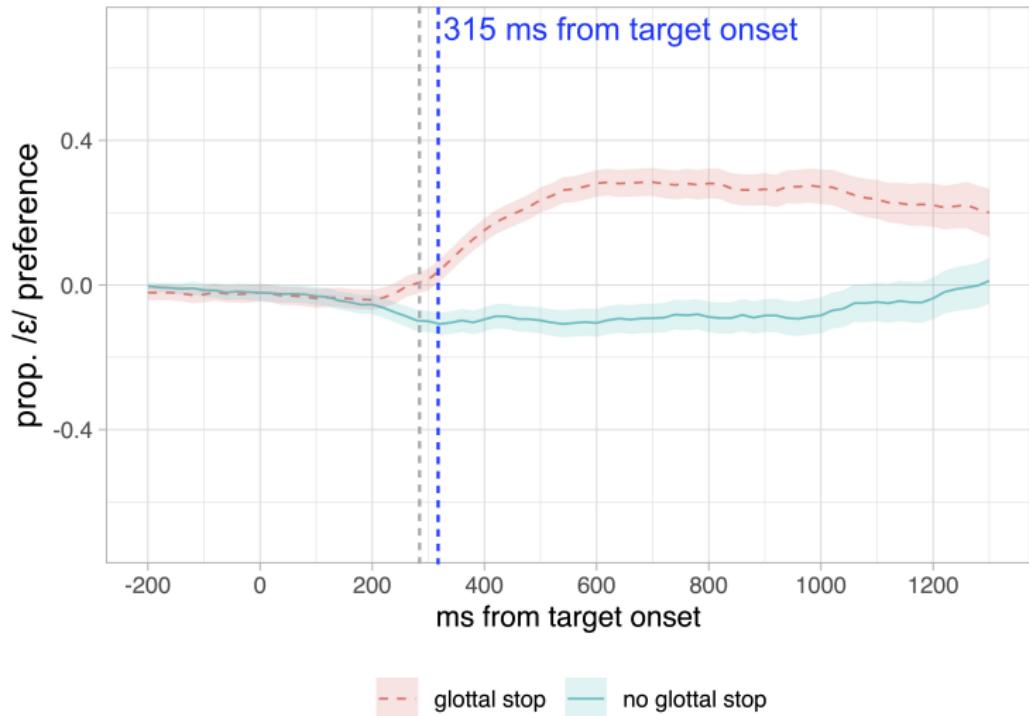
- ① Phrasal prominence effects are overall delayed relative to the effect of formant cues 🐹
- ② But there are subtle immediate impacts on formant perception 🐰

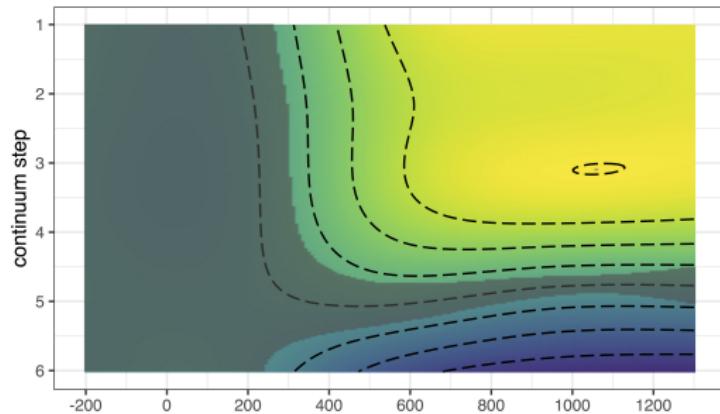
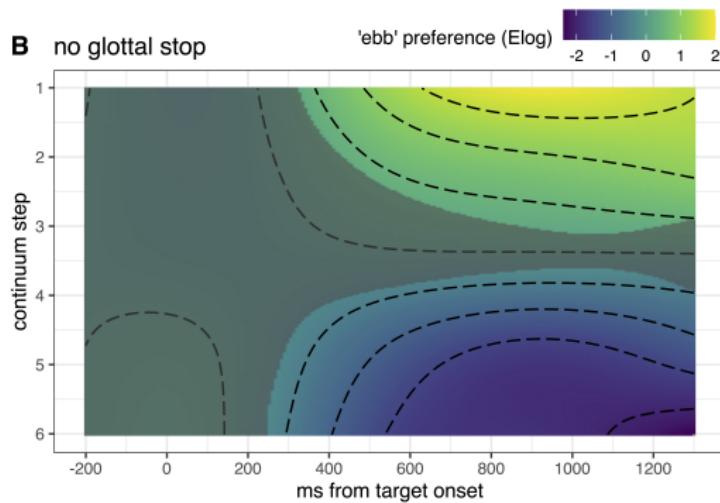
What about [?]?

Experiment 3 results: Formants

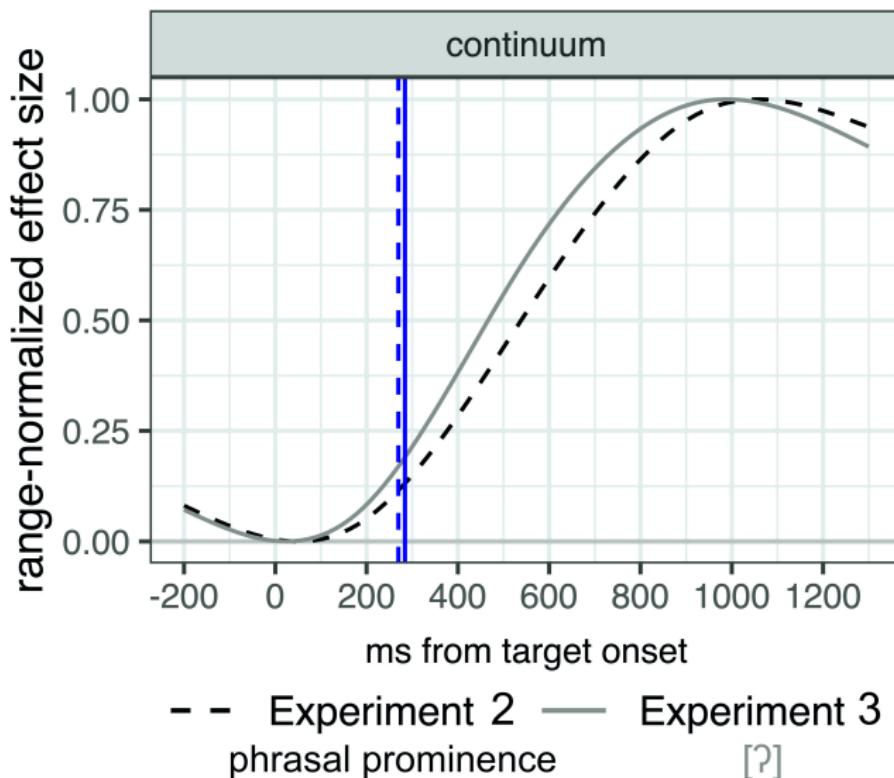


Experiment 3 results: Prominence

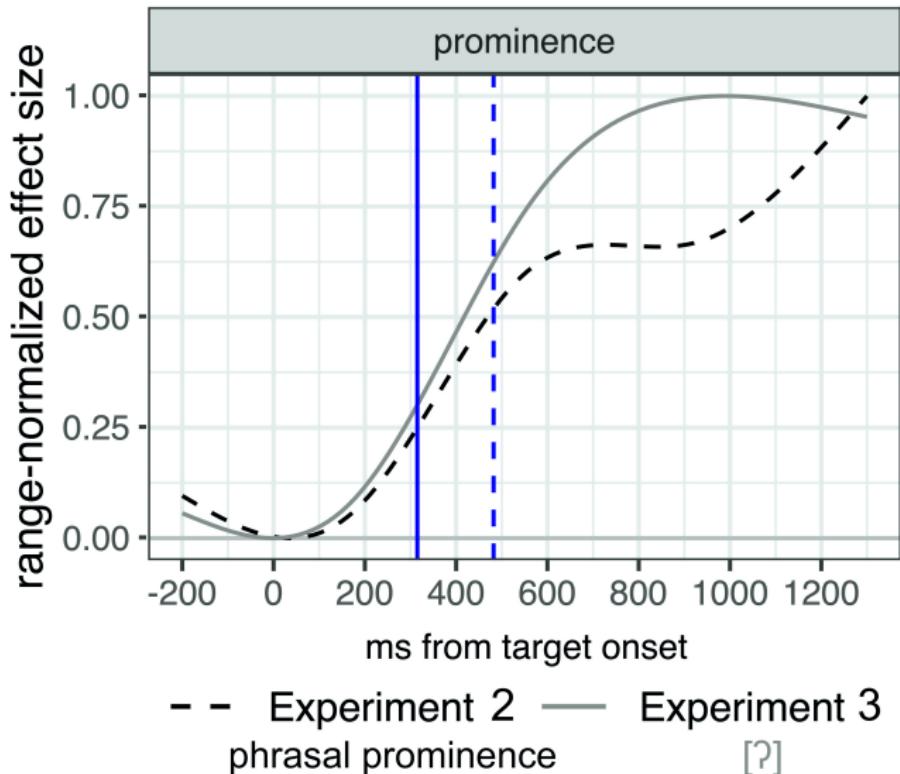


A glottal stop**B** no glottal stop

Comparing Experiment 2 and 3: Continua



Comparing Experiment 2 and 3: Prominence



Processing prominence and segment

- When [?] precedes a vowel....

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

- 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 boundaries¹

¹Kim 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:

- How bidirectional are these influences?
- How do “segmental” cues influence interpretation of prosodic features?
(see Mitterer et al., 2020)

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On the processing side:

- 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!

References

References I

- Abramson, A. S. (1976). Laryngeal timing in consonant distinctions. *Haskins Laboratory Status Report on Speech Research, SR-47*, pages 105–112.
- Abramson, A. S. and Whalen, D. H. (2017). Voice Onset Time (VOT) at 50: Theoretical and practical issues in measuring voicing distinctions. *Journal of phonetics*, 63:75–86.
- Beckman, M. E. (1996). The parsing of prosody. *Language and cognitive processes*, 11(1-2):17–68.
- Beckman, M. E., Edwards, J., and Fletcher, J. (1992). *Prosodic structure and tempo in a sonority model of articulatory dynamics*, page 68–89. Papers in Laboratory Phonology. Cambridge University Press.
- Bishop, J., Kuo, G., and Kim, B. (2020). Phonology, phonetics, and signal-extrinsic factors in the perception of prosodic prominence: Evidence from rapid prosody transcription. *Journal of Phonetics*, 82:100977.
- Brown, M., Salverda, A. P., Dilley, L. C., and Tanenhaus, M. K. (2011). Expectations from preceding prosody influence segmentation in online sentence processing. *Psychonomic bulletin & review*, 18(6):1189–1196.
- Chen, M. (1970). Vowel length variation as a function of the voicing of the consonant environment. *Phonetica*, 22(3):129–159.
- Cho, T. (2005). Prosodic strengthening and featural enhancement: Evidence from acoustic and articulatory realizations of /a, i/ in english. *The Journal of the Acoustical Society of America*, 117(6):3867–3878.

References II

- Cho, T. (2015). Language Effects on Timing at the Segmental and Suprasegmental Levels. In Redford, M. A., editor, *The Handbook of Speech Production*, pages 505–529. John Wiley & Sons, Inc.
- Cho, T. and Keating, P. (2001). Articulatory and acoustic studies on domain-initial strengthening in Korean. *Journal of phonetics*, 29(2):155–190.
- Cho, T., McQueen, J. M., and Cox, E. A. (2007). Prosodically driven phonetic detail in speech processing: The case of domain-initial strengthening in English. *Journal of Phonetics*, 35(2):210–243.
- Cole, J., Kim, H., Choi, H., and Hasegawa-Johnson, M. (2007). Prosodic effects on acoustic cues to stop voicing and place of articulation: Evidence from radio news speech. *Journal of Phonetics*, 35(2):180–209.
- de Jong, K., Beckman, M. E., and Edwards, J. (1993). The interplay between prosodic structure and coarticulation. *Language and speech*, 36(2-3):197–212.
- Dilley, L., Shattuck-Hufnagel, S., and Ostendorf, M. (1996). Glottalization of word-initial vowels as a function of prosodic structure. *Journal of phonetics*, 24(4):423–444.
- Erickson, D. (2002). Articulation of extreme formant patterns for emphasized vowels. *Phonetica*, 59(2-3):134–149.
- Garellek, M. (2013). *Production and perception of glottal stops*. PhD thesis, UCLA.
- Garellek, M. (2014). Voice quality strengthening and glottalization. *Journal of Phonetics*, 45:106–113.
- Grice, M., Ritter, S., Niemann, H., and Roettger, T. B. (2017). Integrating the discreteness and continuity of intonational categories. *Journal of Phonetics*, 64:90–107.

References III

- Keating, P., Cho, T., Fougeron, C., and Hsu, C.-S. (2004). Domain-initial articulatory strengthening in four languages. *Phonetic interpretation: Papers in laboratory phonology VI*, pages 143–161.
- Kim, S., Kim, J., and Cho, T. (2018a). Prosodic-structural modulation of stop voicing contrast along the vot continuum in trochaic and iambic words in american english. *Journal of Phonetics*, 71:65–80.
- Kim, S., Mitterer, H., and Cho, T. (2018b). A time course of prosodic modulation in phonological inferencing: The case of Korean post-obstruent tensing. *PloS one*, 13(8).
- Lehiste, I. (1970). *Suprasegmentals*. Massachusetts Institute of Technology Press.
- Mitterer, H., Cho, T., and Kim, S. (2016). How does prosody influence speech categorization? *Journal of Phonetics*, 54:68–79.
- Mitterer, H., Kim, S., and Cho, T. (2019). The glottal stop between segmental and suprasegmental processing: The case of maltese. *Journal of Memory and Language*, 108:104034.
- Mitterer, H., Kim, S., and Cho, T. (2020). The role of segmental information in syntactic processing through the syntax–prosody interface. *Language and Speech*, page 0023830920974401.
- Nakai, S., Kunnari, S., Turk, A., Suomi, K., and Ylitalo, R. (2009). Utterance-final lengthening and quantity in northern finnish. *Journal of phonetics*, 37(1):29–45.
- Reinisch, E. and Sjerps, M. J. (2013). The uptake of spectral and temporal cues in vowel perception is rapidly influenced by context. *Journal of Phonetics*, 41(2):101–116.

References IV

- Shepherd, M. A. (2008). The scope and effects of preboundary prosodic lengthening in japanese. *USC Working Papers in Linguistics*, 4:1–14.
- Silverman, K. and Pierrehumbert, J. (1990). The timing of prenuclear high accents in English. In Beckman, M. E. and Kingston, J., editors, *Papers in Laboratory Phonology*, Papers in Laboratory Phonology, pages 72–106.
- Steffman, J. (2019). Intonational structure mediates speech rate normalization in the perception of segmental categories. *Journal of Phonetics*, 74:114–129.
- Steffman, J. and Katsuda, H. (2020). Intonational structure influences perception of contrastive vowel length: The case of phrase-final lengthening in tokyo japanese. *Language and Speech*, page 0023830920971842. PMID: 33251945.
- Terken, J. and Hermes, D. (2000). The perception of prosodic prominence. In *Prosody: Theory and experiment*, pages 89–127. Springer.
- Turk, A. E. and Shattuck-Hufnagel, S. (2007). Multiple targets of phrase-final lengthening in american english words. *Journal of Phonetics*, 35(4):445–472.
- Van Summers, W. (1987). Effects of stress and final-consonant voicing on vowel production: Articulatory and acoustic analyses. *The Journal of the Acoustical Society of America*, 82(3):847–863.

Appendix

“Segmental” cues vary systematically based on prosody

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

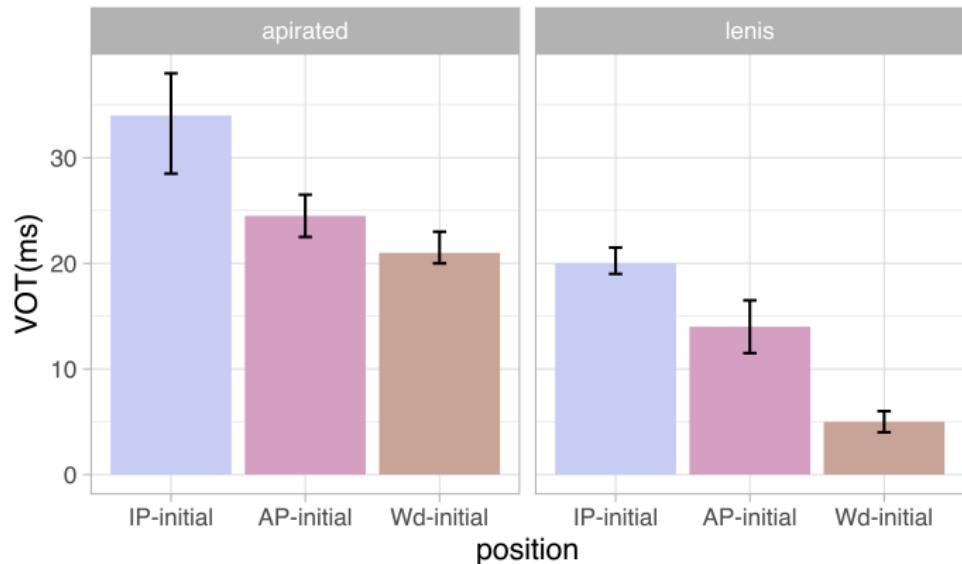
- in aspirated vs. unaspirated stops¹
- in prominent syllables²
- at the beginning of prosodic domains³

¹Abramson, 1976; Abramson and Whalen, 2017

²Cole et al., 2007; Cho, 2015

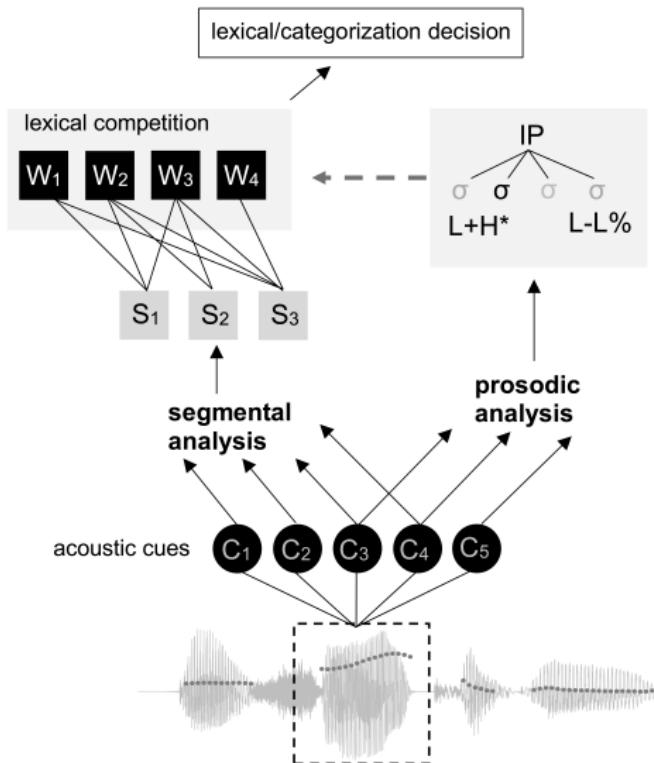
³Keating et al., 2004

Dual patterning: Korean VOT

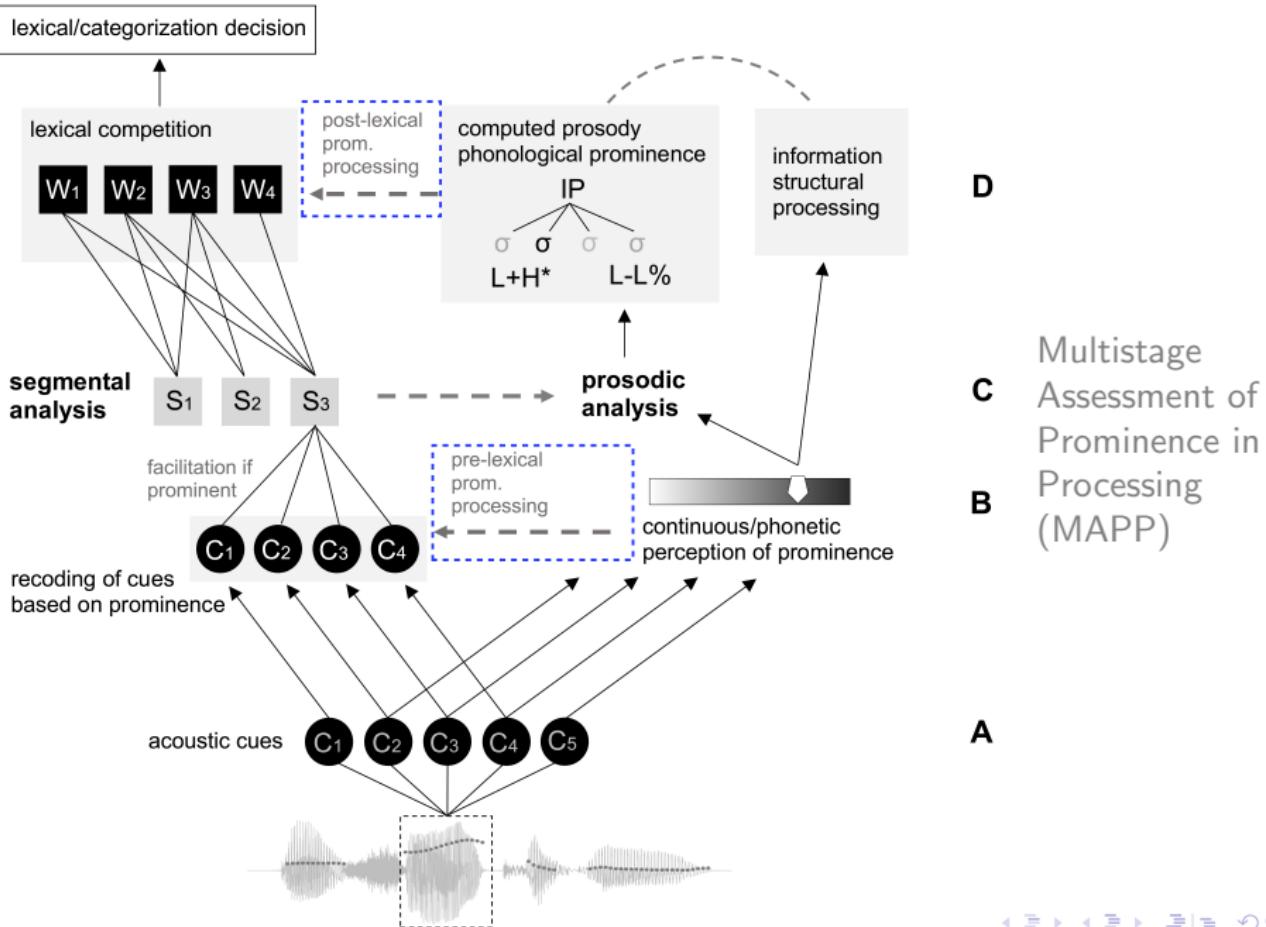


VOT from
Korean /t^h/ and
/t/, adopted
from Cho and
Keating (2001)

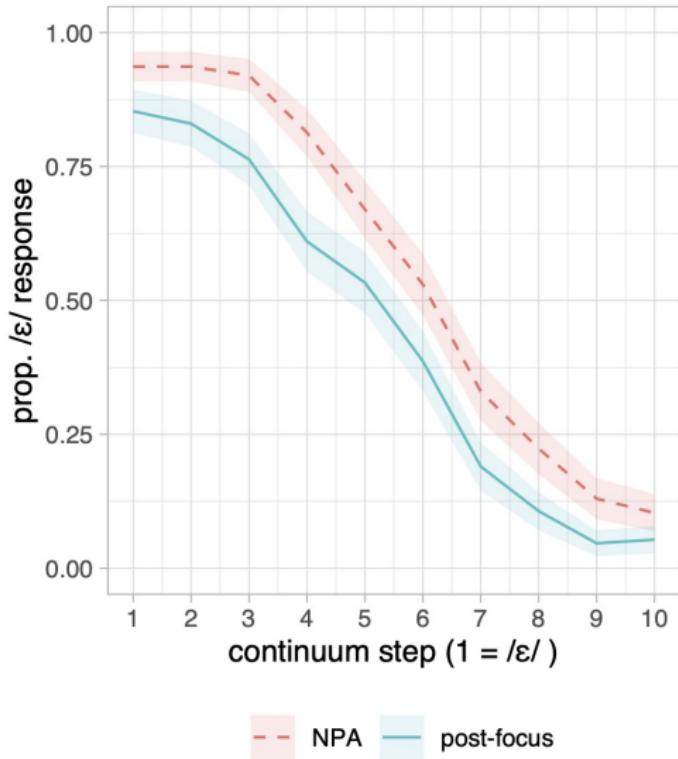
Schematic of the prosodic analysis model¹



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

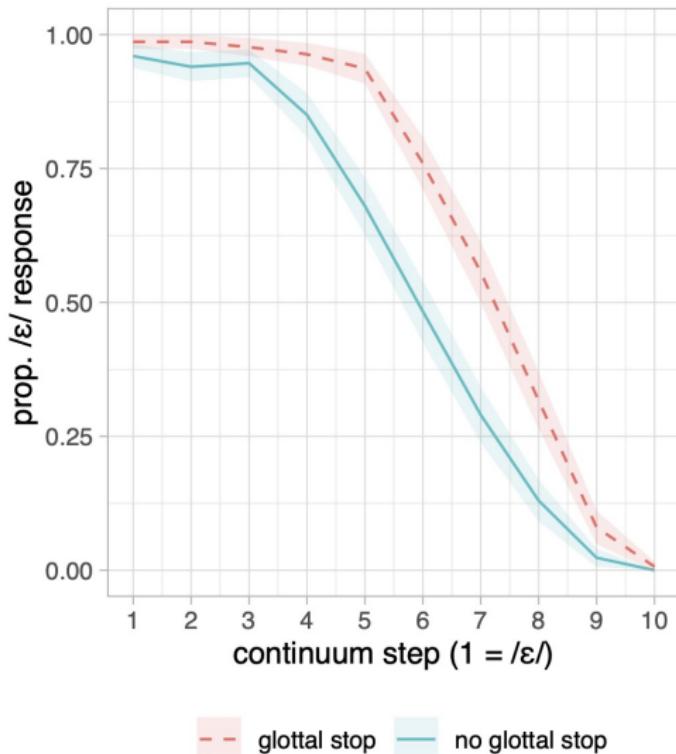


Offline pre-Experiment 2 results



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

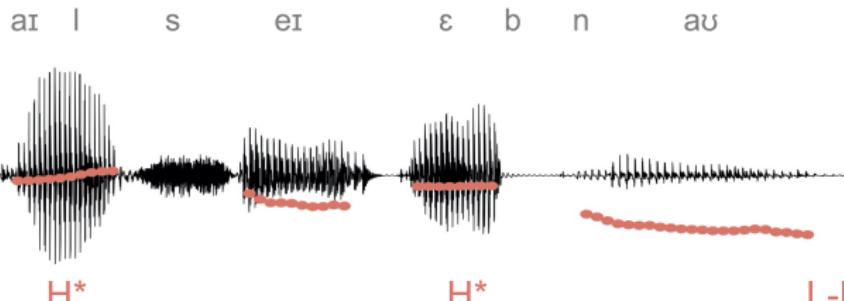
Offline pre-Experiment 3 results



main effect of prom.
 $\beta = 1.75$; 95%CI = [1.31,2.22]

Experiment 2 stimuli

NPA



Post-focus



Experiment 3 stimuli

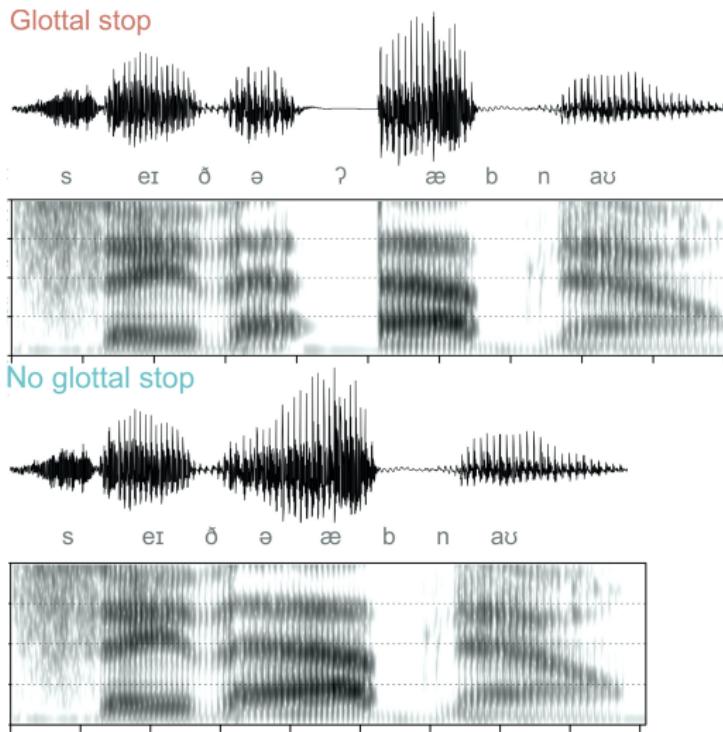
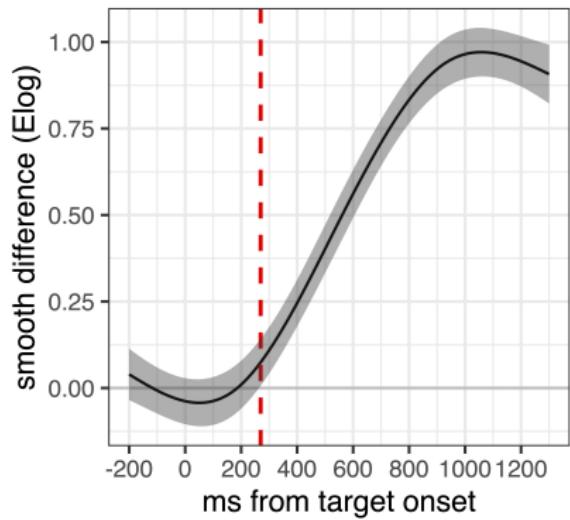


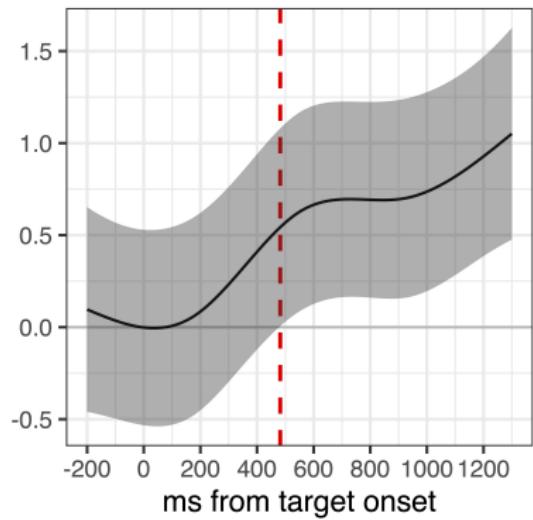
Figure: Waveforms and spectrograms of the Experiment 3 stimuli

Exp 2 difference smooths

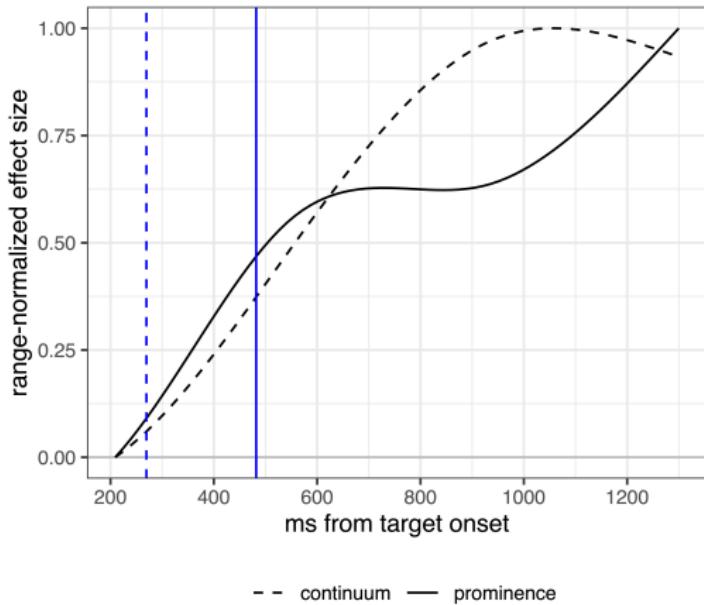
A continuum



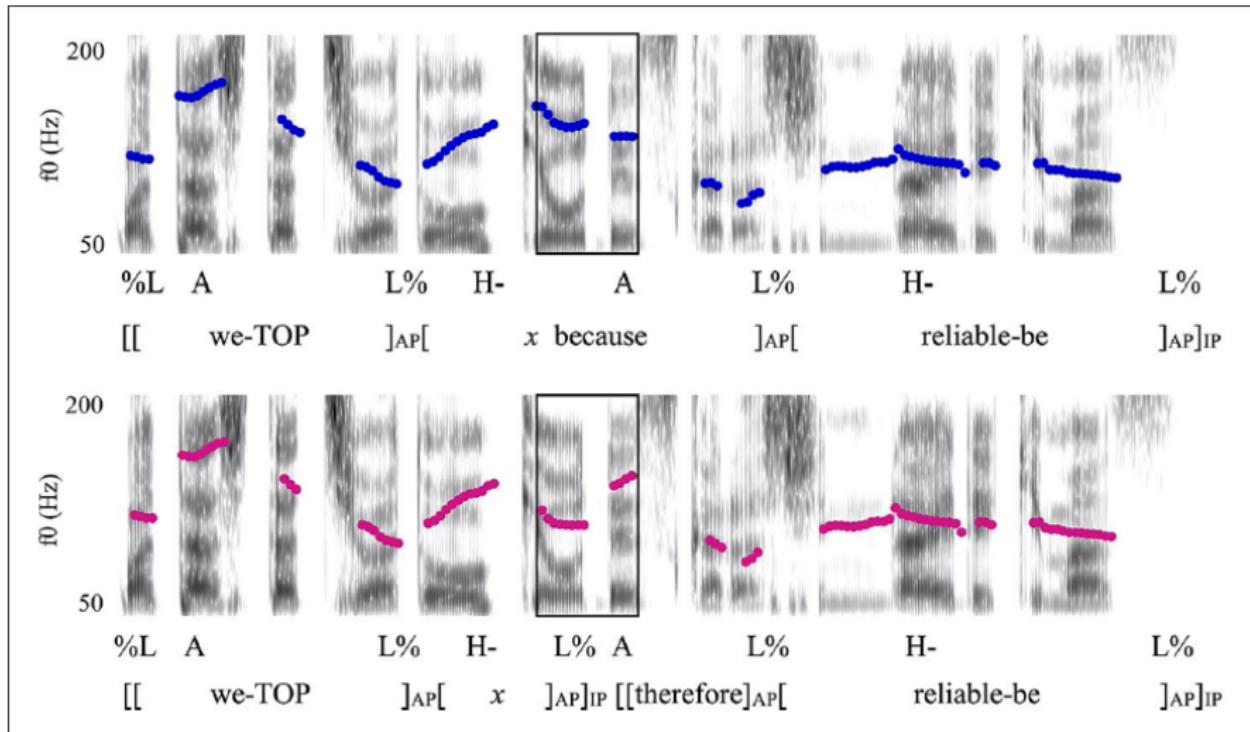
B prominence



Range-normalized effects Experiment 2



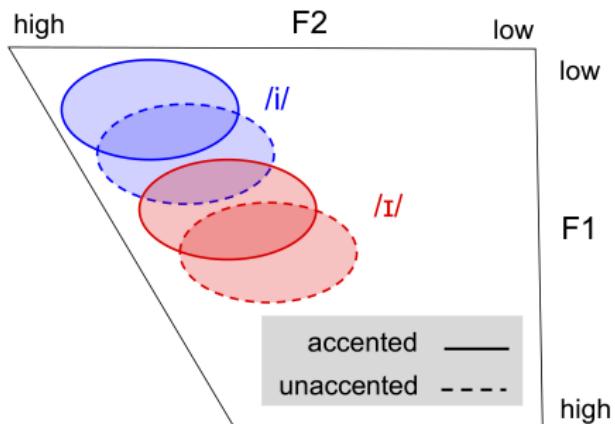
Experiment 1b stimuli



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)



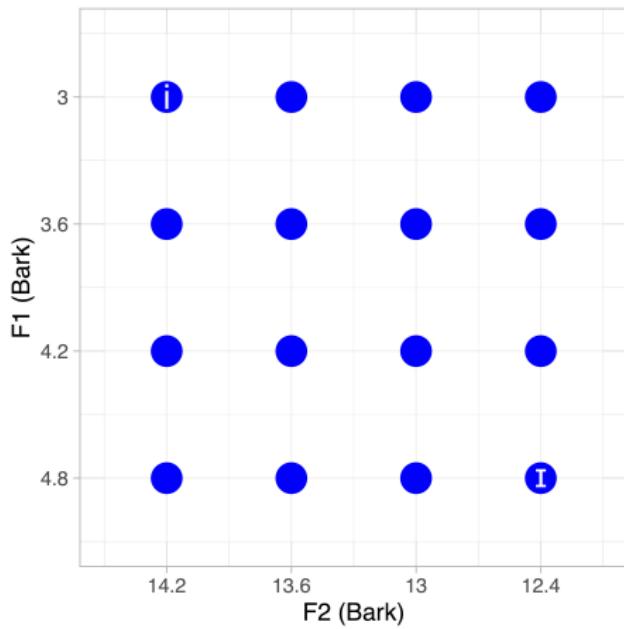
Tests perception of an /ɪ/ to /i/ continuum

Prediction

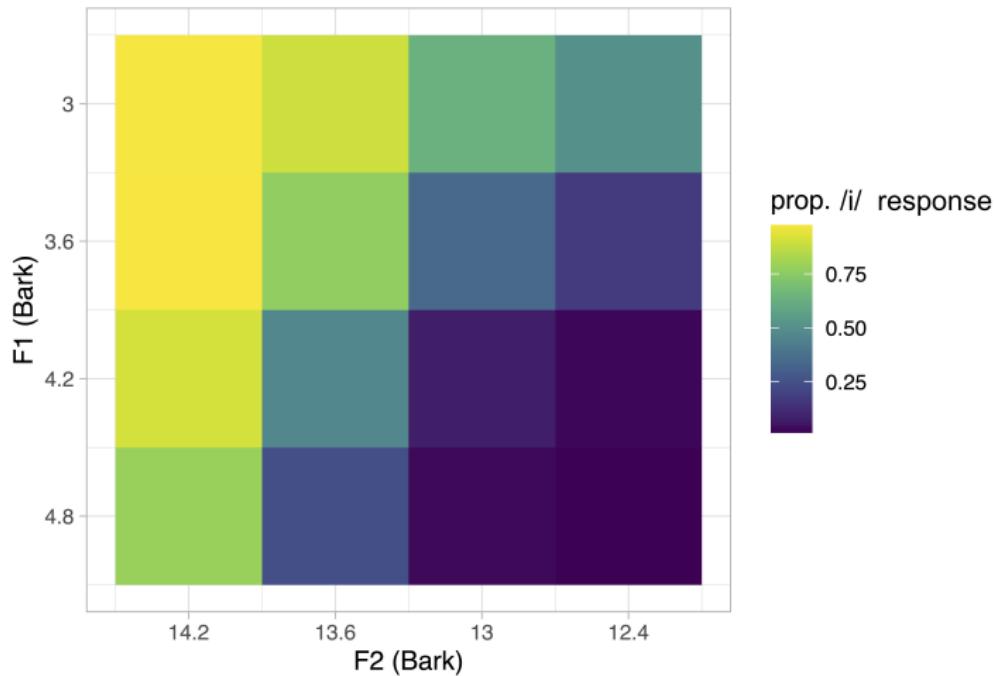
Lower F1/ Higher F2 expected in the **NPA** condition, fewer tokens mapped to /i/ therein:
decreased /i/ responses in NPA

Bonus Experiment

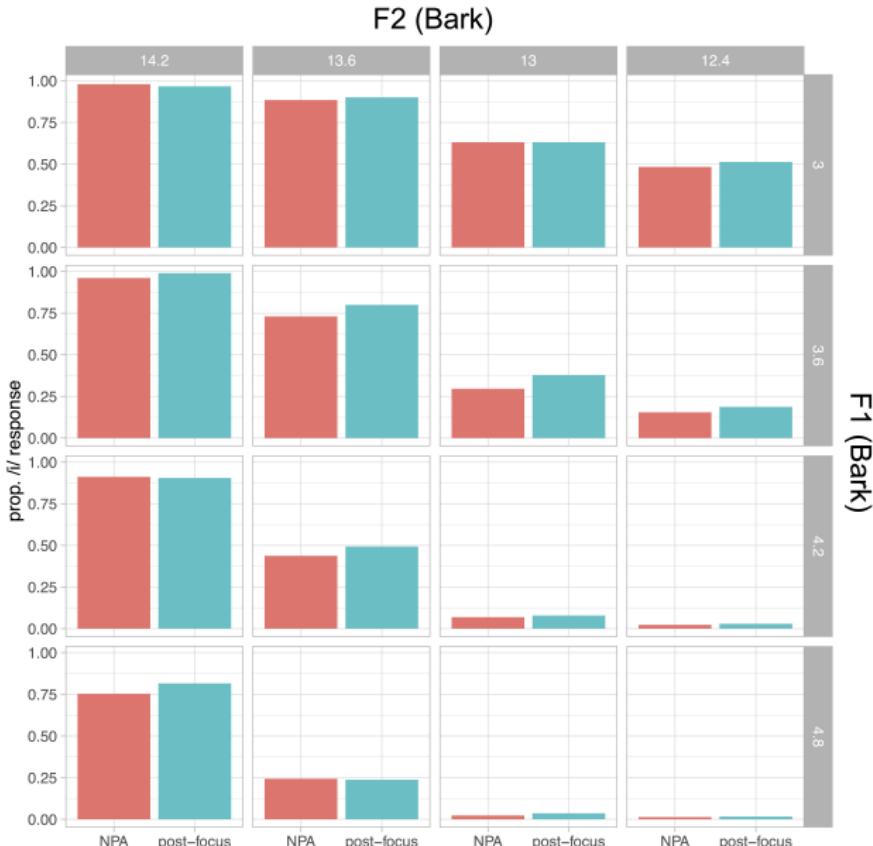
- “sit” to “seat” (/ɪ/ to /i/) continuum
- Same prominence manipulation as Experiment 1: NPA / post-focus



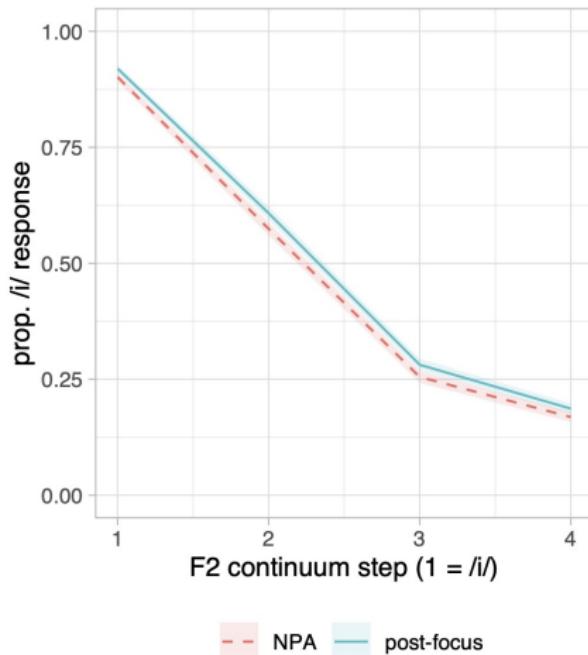
Bonus experiment results: Continuum



Bonus experiment results: Continuum/prominence



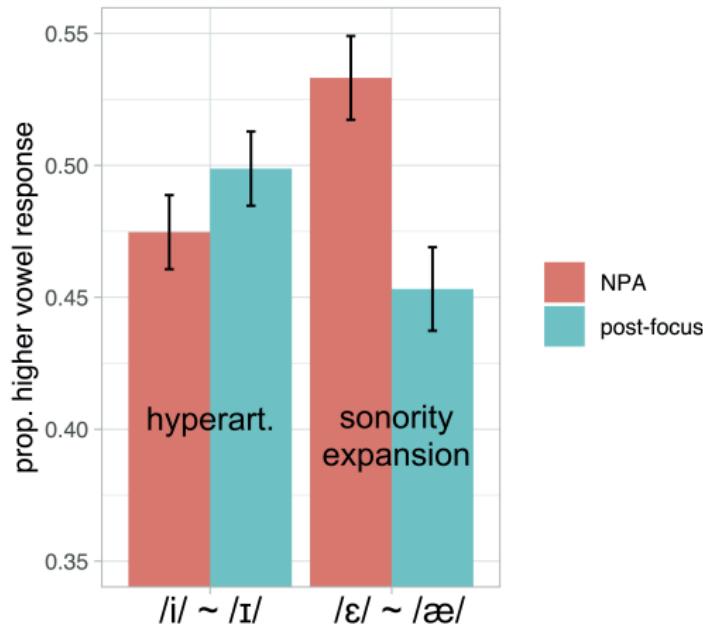
Bonus experiment results: Prominence



main effect of prom.
 $\beta = -0.26$; 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