

# Non-generalization of a phonetically natural pattern in Mixtec tone sandhi

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Many thanks to the San Martín Peras community in Oaxaca and California for their generosity in sharing their language with us. Thanks especially to Natalia Gracida Cruz, who recorded all of the audio for the wug test, and to Lorena Espinosa Rivera, who recruited many of the participants.

# Introduction

Some phonological patterns are easier to learn than others, potentially due to **learning biases**:

- **Structural bias**: Patterns that are structurally simple are easier to learn than patterns that are structurally complex (Moreton & Pater 2012a)
  - Simpler natural class = easier to learn (Saffran & Thiessen, 2003)

# Introduction

Some phonological patterns are easier to learn than others, potentially due to **learning biases**:

- **Substantive bias**: Patterns that are phonetically natural are easier to learn than patterns that are phonetically unnatural (Moreton & Pater 2012b; Zheng & Do 2025)
  - Vowel **harmony** easier to learn than vowel **disharmony** (Martin & Peperkamp, 2020)

# Introduction

Lots of evidence for **structural bias** (Moreton & Pater 2012a), but less for **substantive bias** (Moreton & Pater 2012b; cf. Zheng & Do 2025)

**Conclusion:** Substantive bias, if it exists, is weaker than structural bias

Most evidence from artificial grammar learning (AGL) studies (cf. Becker et al. 2011  
Becker et al. 2012)

- Limited and often made-up data sets, laboratory setting, often adult learners
- Can we replicate this finding with patterns in participants' native language?

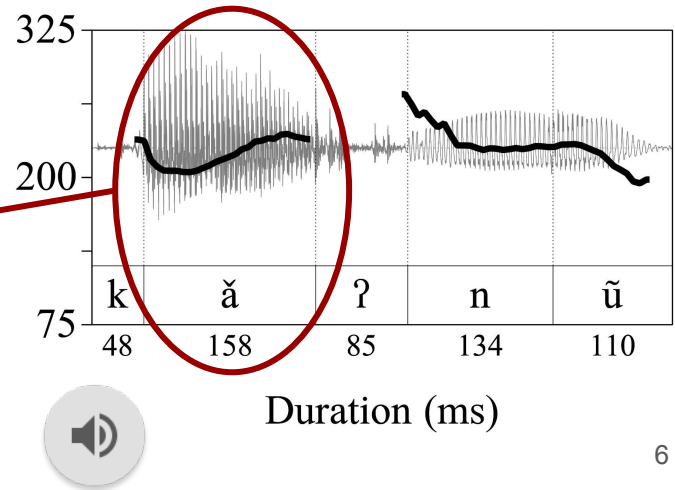
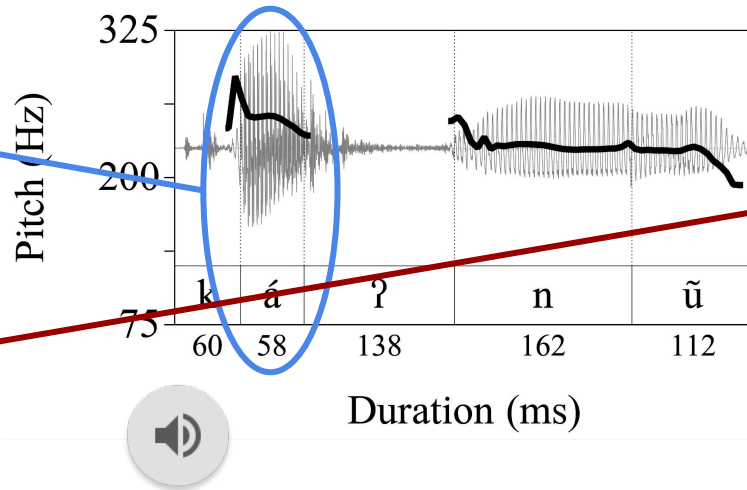
# Introduction

**This presentation:** A naturally-occurring, lexically-specific process of tone sandhi in San Martín Peras Mixtec (SMP Mixtec)

- Some adjectives have an initial **High** tone, but with an initial **Low-to-High Rising** tone when preceded by a L tone

1. Ká'nu  
[káʔnũ]  
'big'

2. Kîni kǎ'nu  
[kîni kǎʔnũ]  
pig big  
'a big pig'



# Introduction

This sandhi process is...

- Lexically specific, but exceptions are phonetically grounded
  - Potentially subject to **substantive bias**
- Optional and subject to variation, making the process more difficult to learn

A case where substantive bias is up against a difficult learning situation

## Question

Is substantive bias strong enough to drive learning of lexical tendencies in SMP Mixtec tone sandhi?

# Background

# Background

SMP Mixtec is an Otomanguean language of western Oaxaca, Mexico

Spoken by about 11,500 in Oaxaca  
(INEGI, 2020)

Many speakers of SMP Mixtec live in  
Oxnard, Santa Maria, Salinas, and  
Watsonville, CA



# Background

There are (at least) five tones: High (´), Mid (v), Low (̀), Rising (ˇ), and Falling (˘) (Peters, 2018).

- The tone-bearing unit is the mora, and tri-tonal contours are only found on long vowels.

<b>H-L</b>	<b>M-L</b>	<b>L-L</b>	<b>LH-L</b>	<b>HL-L</b>
Kuáàn [k <sup>w</sup> áà̃̃] ‘yellow’	Saà [saà] ‘bird’	Ntàà [n <sup>t</sup> àà] ‘flat’	Ntsĩ [n <sup>t</sup> sĩ̃] ‘sad’	Xânù [ʃânũ] ‘cigarette’

# Background

Another important feature:

- There is a contrast between **modal** and **glottalized** vowels (Eischens and Hedding, 2025; cf. Macaulay and Salmons, 1995).

1. ìvì  
[ìβì]  
'two'



2. ì'vì  
[ìʔβì]  
'pain'

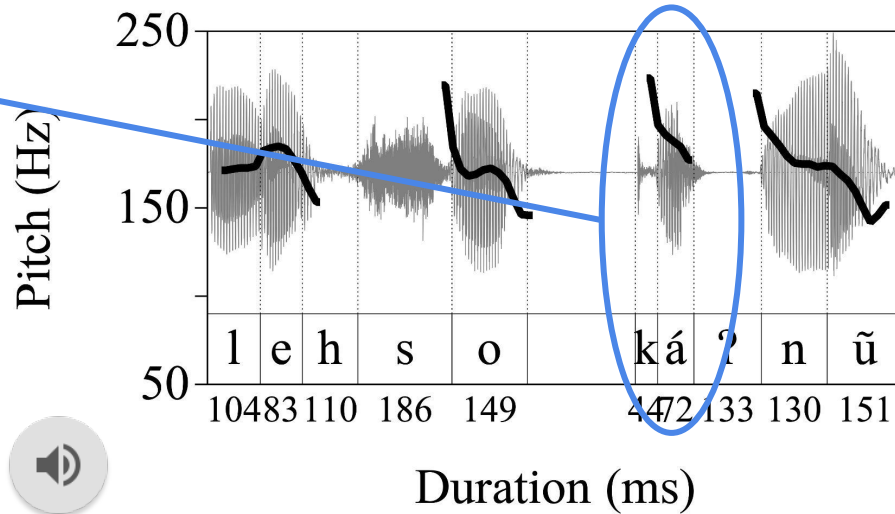


# Tone sandhi

# Tone sandhi

Many adjectives begin with a **High** tone

1. Leso ká'nu  
[le<sup>h</sup>so **ká**?nũ]  
rabbit big  
'A big rabbit'



# Tone sandhi

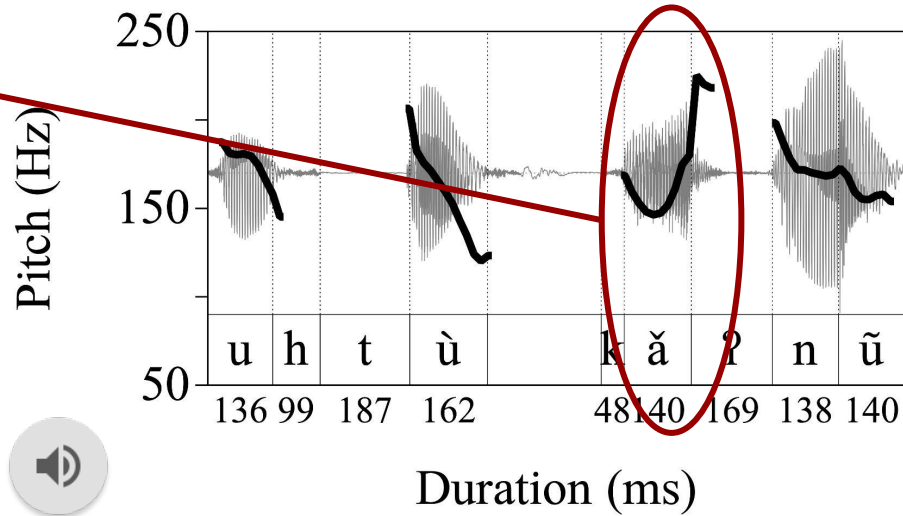
When preceded by a Low tone, the initial **High** becomes a Low-High **Rise**

1. Utù kǎ'nu

[uhtù **kǎ**?nũ]

cornfield big

'A big cornfield'



# Tone sandhi

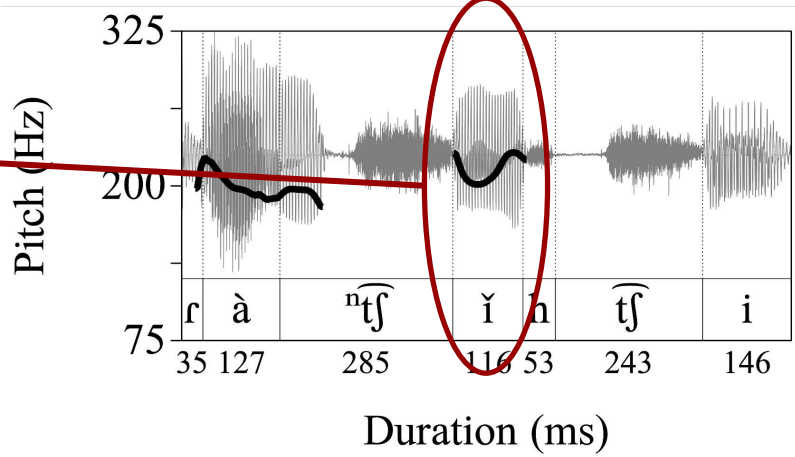
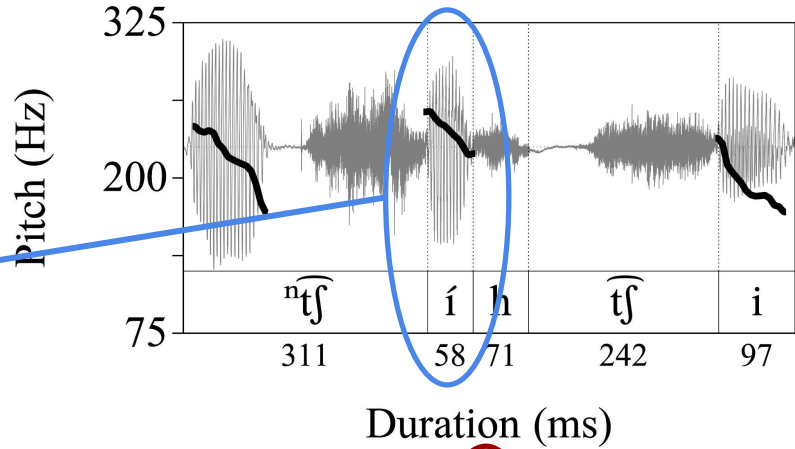
But the process is **lexically exceptional**

## Application

1. Nchíchi  
[ntʃi<sup>h</sup>tʃi]  
'Miraculous'



2. Rà nchǐchi  
[rà ntʃi<sup>h</sup>tʃi]  
he miraculous  
'A miraculous man'



# Tone sandhi

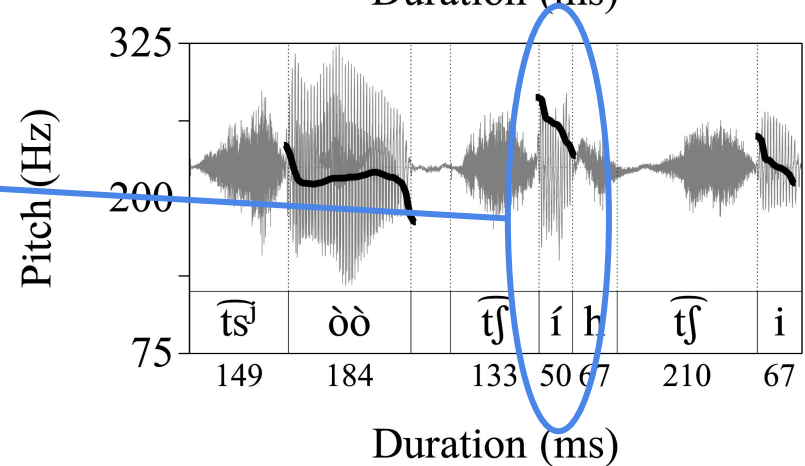
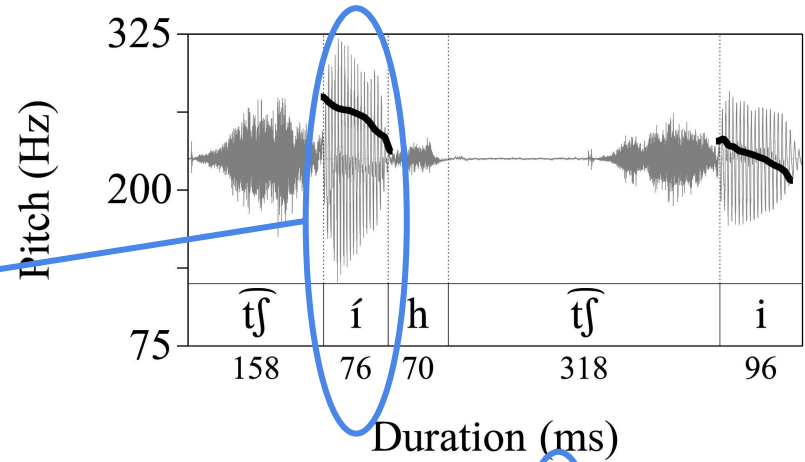
But the process is **lexically exceptional**

## Non-application

1. Chíchi  
[tʃi<sup>h</sup>tʃi]  
'Ripe'



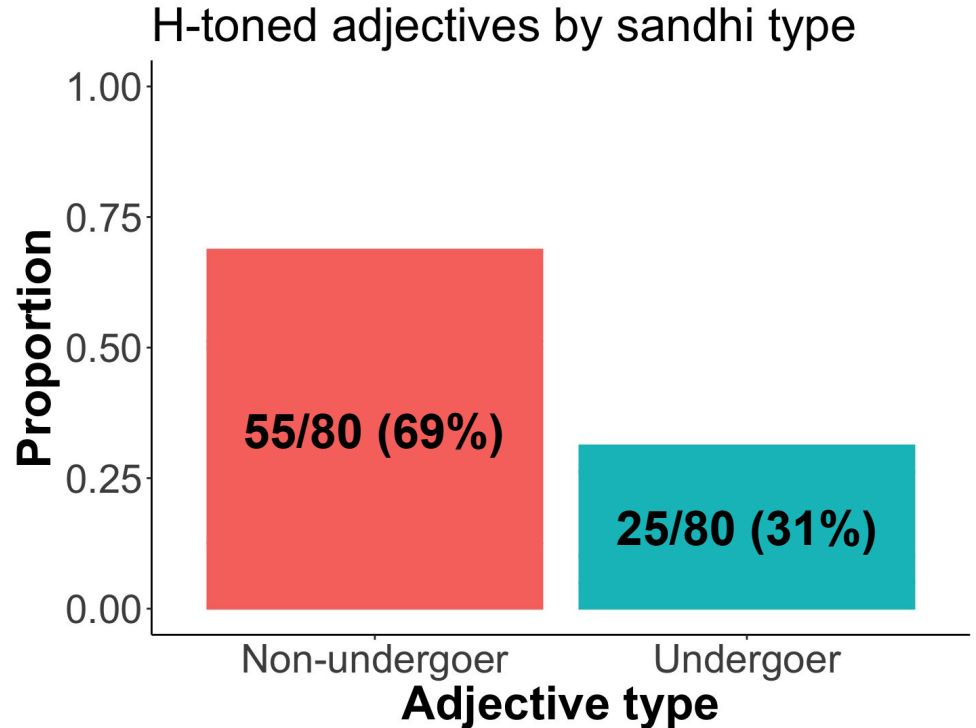
2. Tsiòò chíchi  
[tʃi<sup>h</sup>tʃi]  
passion.fruit ripe  
'A ripe passion fruit'



# Tone sandhi

In fact, only a minority of High-tone-initial adjectives undergo this sandhi process

- **Non-undergoers:** 55/80 (69%)
- **Undergoers:** 25/80 (31%)



# Tone sandhi

Whether an adjective undergoes sandhi is not predictable

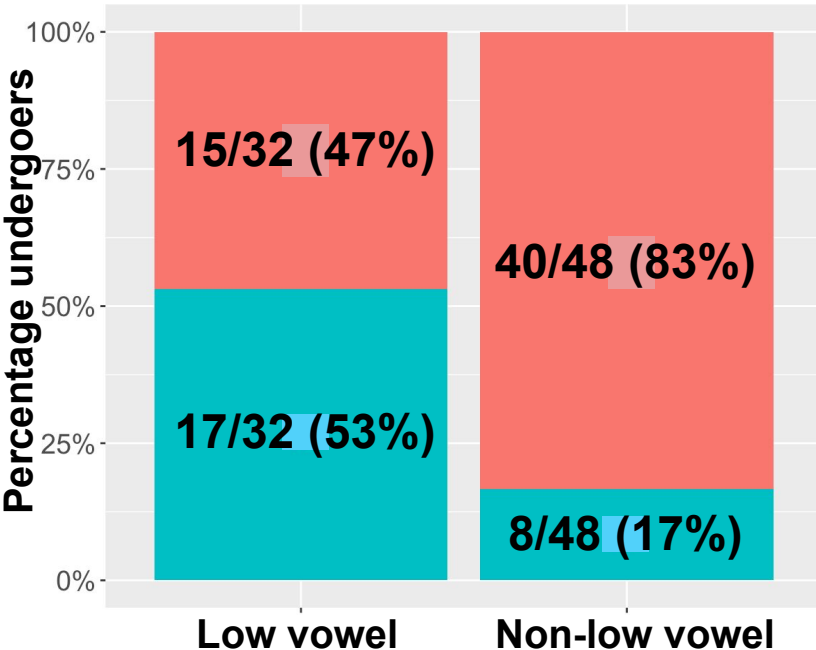
But two features increase the likelihood that an adjective undergoes tone sandhi:

1. The first vowel of the adjective is **low** ([a])
2. The first vowel of the adjective is **glottalized** ([vʔ])

# Tone sandhi

Sandhi is much more likely on adjectives that begin with a **low vowel**

High-toned adjectives by vowel height



Undergoer?



[káʔnũ] ~ [kǎʔnũ]

‘big’

[kwǎǎ] ~ [kwǎǎ]

‘yellow’

[βálí] ~ [βǎlí]

‘small (pl)’

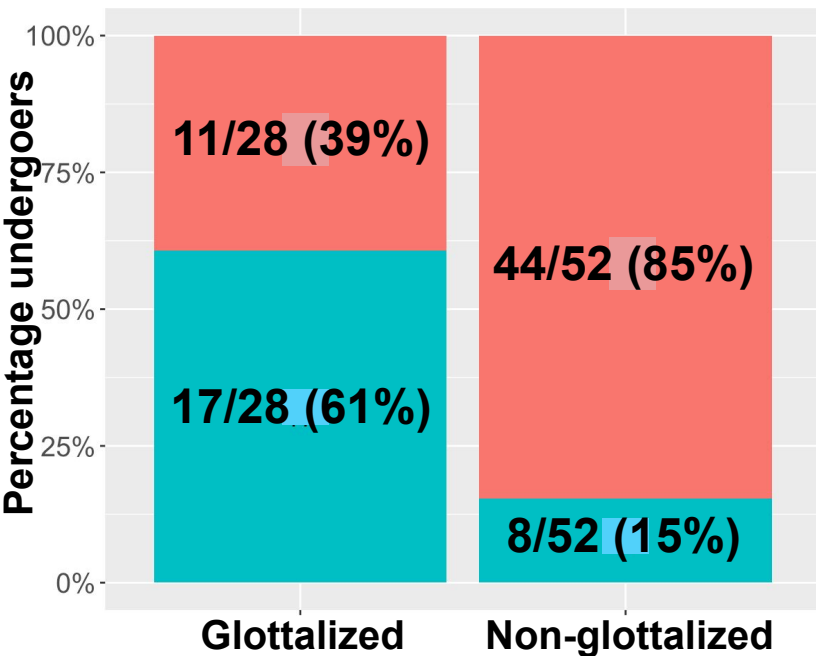
[tjáhtũ] ~ [tǎhtũ]

‘from Petlacala’

# Tone sandhi

Sandhi is much more likely on adjectives that begin with a **glottalized vowel**

High-toned adjectives by glottalization



[káʔnũ] ~ [kǎʔnũ] 'big'

[síʔi] ~ [sǐʔi] 'female'

[túʔũ] ~ [tǔʔũ] 'liar'

[láʔntʂia] ~ [lǎʔntʂia] 'torn'

# Tone sandhi

Two factors **increase** likelihood of application of tone sandhi:

1. If the first vowel of the adjective is **low** ([a])
2. If the first vowel of the adjective is **glottalized** ([vʔ])

These factors have **phonetic grounding**

- Connection between **long duration** of Rising tones (Zhang, 2004) and **longer intrinsic duration** of low vowels (Lehiste, 1970)
- Connection between the **lower f<sub>0</sub>** of Rising tones, **low intrinsic f<sub>0</sub>** of low vowels (Whalen and Levitt, 1995), and **pitch lowering** on glottalized vowels (Eischens, 2022).

# Tone sandhi

The phonological tendencies in undergoers of tone sandhi are phonetically grounded

Presumably subject to **substantive bias**

- Since the pattern is natural, it should be easier to learn than if it were phonetically arbitrary or unnatural
- Exceptional patterns are learned in a number of languages (Zuraw, 2000; Albright & Hayes, 2003; Hayes & Londe, 2006; Becker et al., 2011)
- But there are reasons to think they aren't learned in SMP Mixtec

# Tone sandhi

SMP Mixtec learners may **not** internalize the phonological tendencies in undergoers of tone sandhi.

- In fact, some speakers learn the sandhi form as the citation form

[kwí <sup>h</sup> ka] 'rich'		[kwá <sup>?</sup> à] 'red'		[já <sup>?</sup> à] 'brown'	
7 speakers: [kwí <sup>h</sup> ka]	RMR: [kwǐ <sup>h</sup> ka]	8 speakers: [kwá <sup>?</sup> à]	AMR: [kwǎ <sup>?</sup> à]	4 speakers: [já <sup>?</sup> à]	RDC: [jǎ <sup>?</sup> à]



# Learning difficulties

This may reflect difficulties in learning, since the data are...

- Variable
  - Optional, even on adjectives to which the process applies
  - Subject to interspeaker variation, with speakers applying sandhi to different sets of adjectives
- Subject to opacity
  - Underlying Low tones trigger tone sandhi, but derived Low tones don't
- Sparse
  - Only 25 adjectives have been observed to undergo the process

# Tone sandhi

Competing pressures:

**Substantive bias**  
should make the  
process **easier** to  
learn

**Variability/sparsity**  
should make the  
process **harder** to  
learn

**Which wins?**

# Wug test

# Wug test: Participants

We recruited 23 SMP Mixtec-speaking participants in the US and in Oaxaca

- They completed the task online using computers or their cell phone

We excluded the results of 2 participants who reported hearing problems

- 21 left for analysis

# Wug test: Materials

Auditory stimuli made up of Noun + Adjective constructions

- Nouns were four real, common SMP Mixtec animals
- Adjectives were a mix of real and nonce adjectives
- All stimuli made in collaboration with a speaker of SMP Mixtec

Each N + Adj construction was presented with and without a rise on the adjective

- Participants instructed to indicate which pronunciation sounded more like 'their Mixtec'

# Wug test: Materials

Kîni sî'i  
[kînĩ sí?i]  
pig female  
'A female pig'

The diagram illustrates the materials for the Wug test. It features two green rectangular boxes labeled '1' and '2'. Below box '1' is a solid blue horizontal bar. Below box '2' is a horizontal bar that is partially blue on the left and grey on the right. In the center of the diagram is a blue circular button with a white refresh icon. At the bottom of the diagram are two grey circular volume control icons, one centered under each box.

Kîni sǐ'i  
[kînĩ sǐ?i]  
pig female  
'A female pig'

# Wug test: Materials

Included 64 trials with nonce adjectives

- Varied in vowel height and glottalization (4 conditions)

	<b>Low vowel</b>	<b>Non-low vowel</b>
<b>Glottalized vowel</b>	[ʃáʔjì]	[ʃúʔù]
<b>Non-glottalized vowel</b>	[káá]	[kwíní]

# Wug test: Materials

Also varied preceding tone between **Low tone** and **non-Low tone** (8 conditions)

- 8 observations per participant per condition (64 trials)

	Low vowel	Non-low vowel
Glottalized vowel	[[áʔjì]	[[úʔù]
Non-glottalized vowel	[káá]	[k <sup>w</sup> íní]
	Preceding L tone	

**Sandhi-triggering context**

	Low vowel	Non-low vowel
Glottalized vowel	[[áʔjì]	[[úʔù]
Non-glottalized vowel	[káá]	[k <sup>w</sup> íní]
	Preceding non-L tone	

**Non-triggering context**

# Wug test: Materials

Allows us to answer two questions:

1. Do participants generalize tone sandhi as a process?
  - Do they prefer the rising-tone-initial response more after Low tones than after non-Low tones?
2. If so, is their generalization influenced by the lexical generalizations?
  - Do they prefer the rising-tone-initial response **even more** when the adjective has a low and/or glottalized vowel?

# Wug test: Statistical Analysis

We analyzed responses to nonce words using a hierarchical Bayesian logistic regression model.

- **Dependent variable:** Rising-tone-initial responses
- **Fixed effects:** Preceding tone, vowel height, glottalization, and their two-way and three-way interactions
- **Random intercepts:** Participant and item
- **Priors:** Weakly informative
- **Baseline condition:** Nonce adjectives with a non-low, non-glottalized vowel preceded by a non-Low tone – the condition in which we expect the **fewest rises**

## Question 1: Did

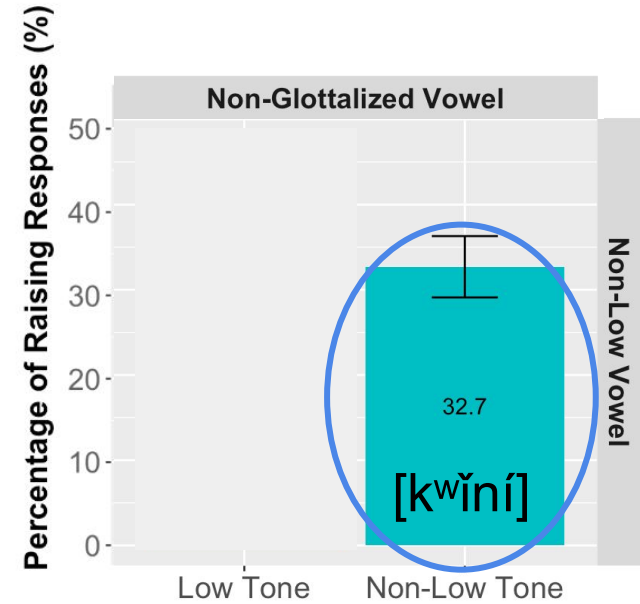
participants generalize tone sandhi as a process?

### Yes:

More rises  
after Low  
tones

### No:

No difference,  
or fewer rises  
after Low  
tones



Preceding Tone

**Question 1:** Did participants generalize tone sandhi as a process?

**Yes:**

More rises  
after Low  
tones

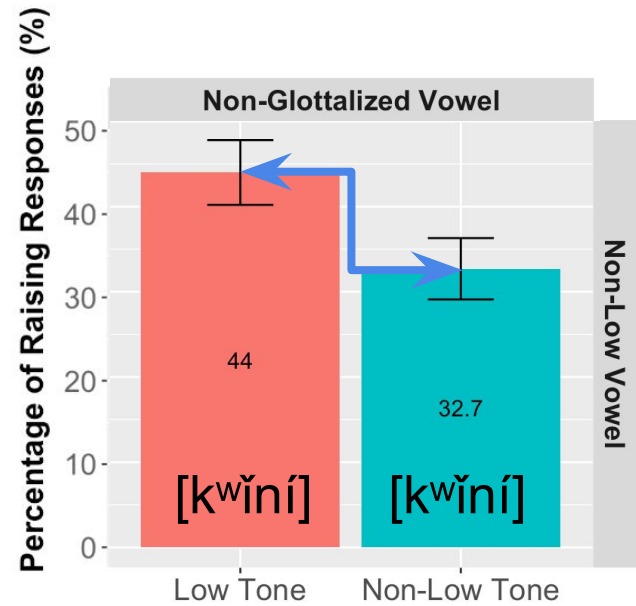
**No:**

No difference,  
or fewer rises  
after Low  
tones

Preceding tone showed a credible **positive** effect:

Estimate = 0.54

95% CrI [0.08, 1.01]



Preceding Tone

### Question 1: Did

participants generalize tone sandhi as a process?

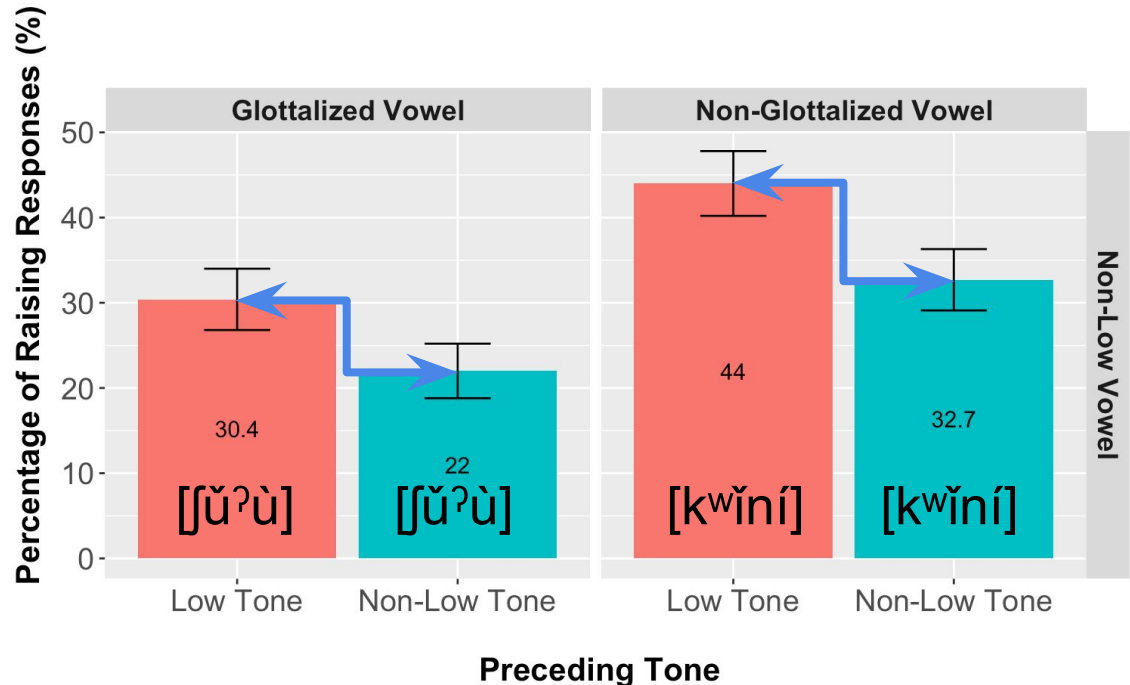
**Yes:**

More rises  
after Low  
tones

**No:**

No difference,  
or fewer rises  
after Low  
tones

Similar effect of preceding tone was also observed in the glottalized, non-low vowel condition (left panel).



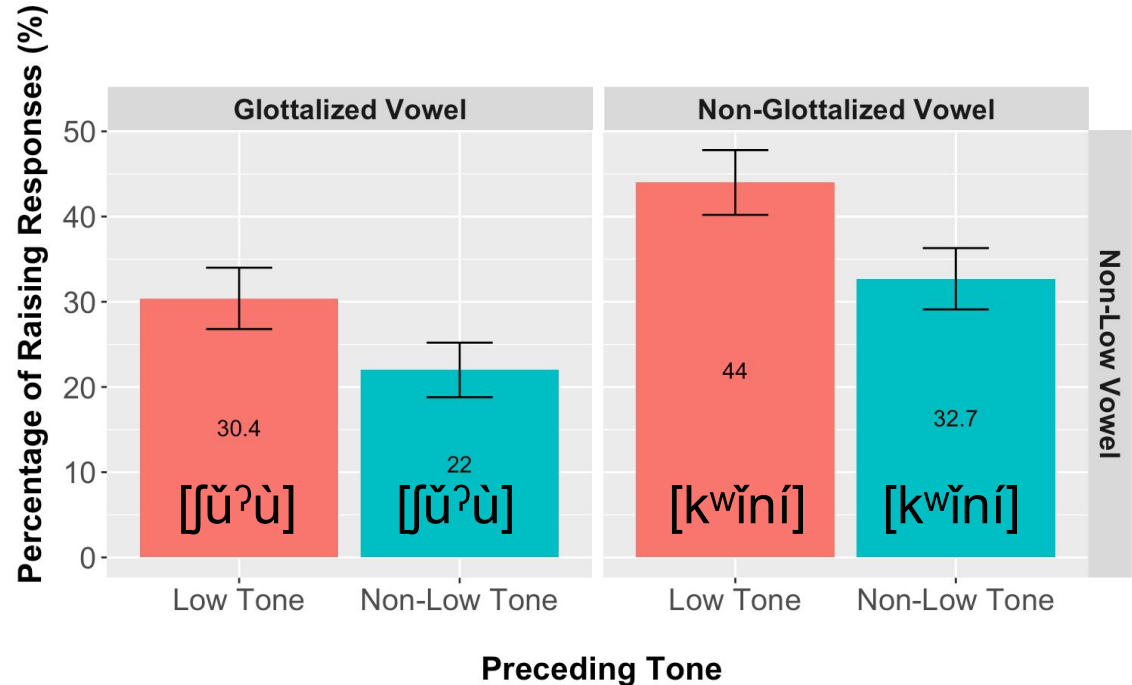
**Question 2a:** Did participants generalize the **glottalization** tendency?

**Yes:**

Even more rises for **glottalized vowels** after Low tone

**No:**

Same or fewer rises for **glottalized vowels** after Low tone



**Question 2a:** Did participants generalize the **glottalization** tendency?

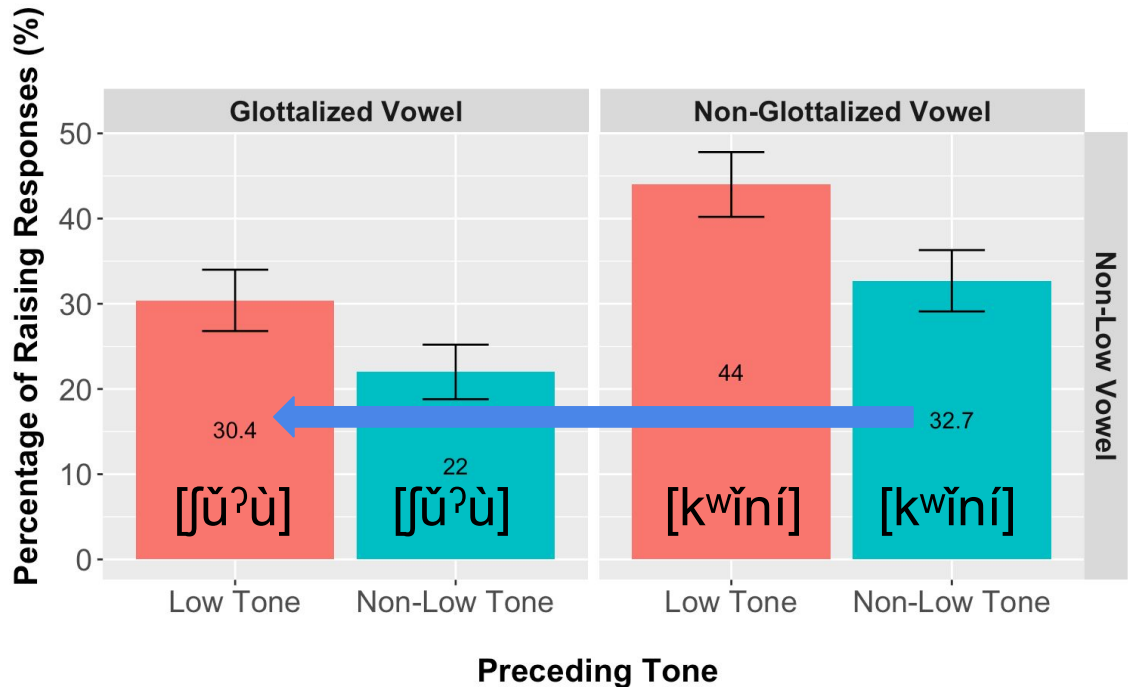
**Yes:**  
Even more rises for **glottalized vowels** after Low tone

**No:**  
Same or fewer rises for **glottalized vowels** after Low tone

**No interaction** between preceding Low tone and glottalization.

Estimate = -0.06

95% CrI [-0.76, 0.63]



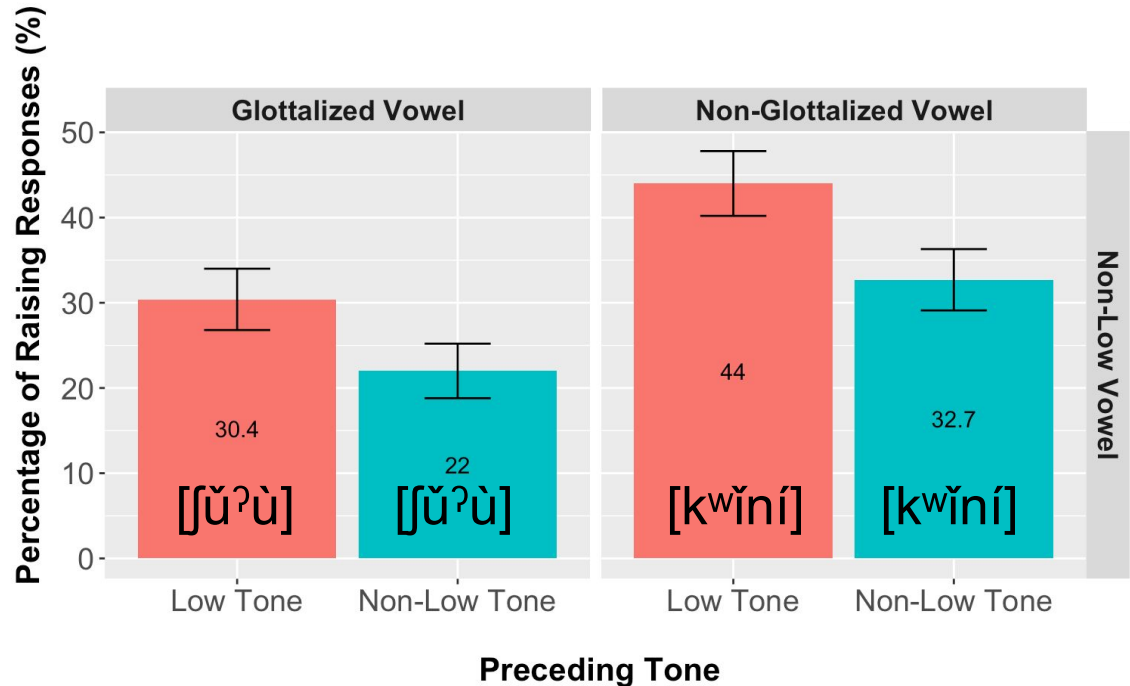
**Question 2b:** Did participants generalize the **vowel height** tendency?

**Yes:**

Even more rises for **low vowels** after Low tone

**No:**

Same or fewer rises for **low vowels** after Low tone



**Question 2b:** Did participants generalize the **vowel height** tendency?

**Yes:**

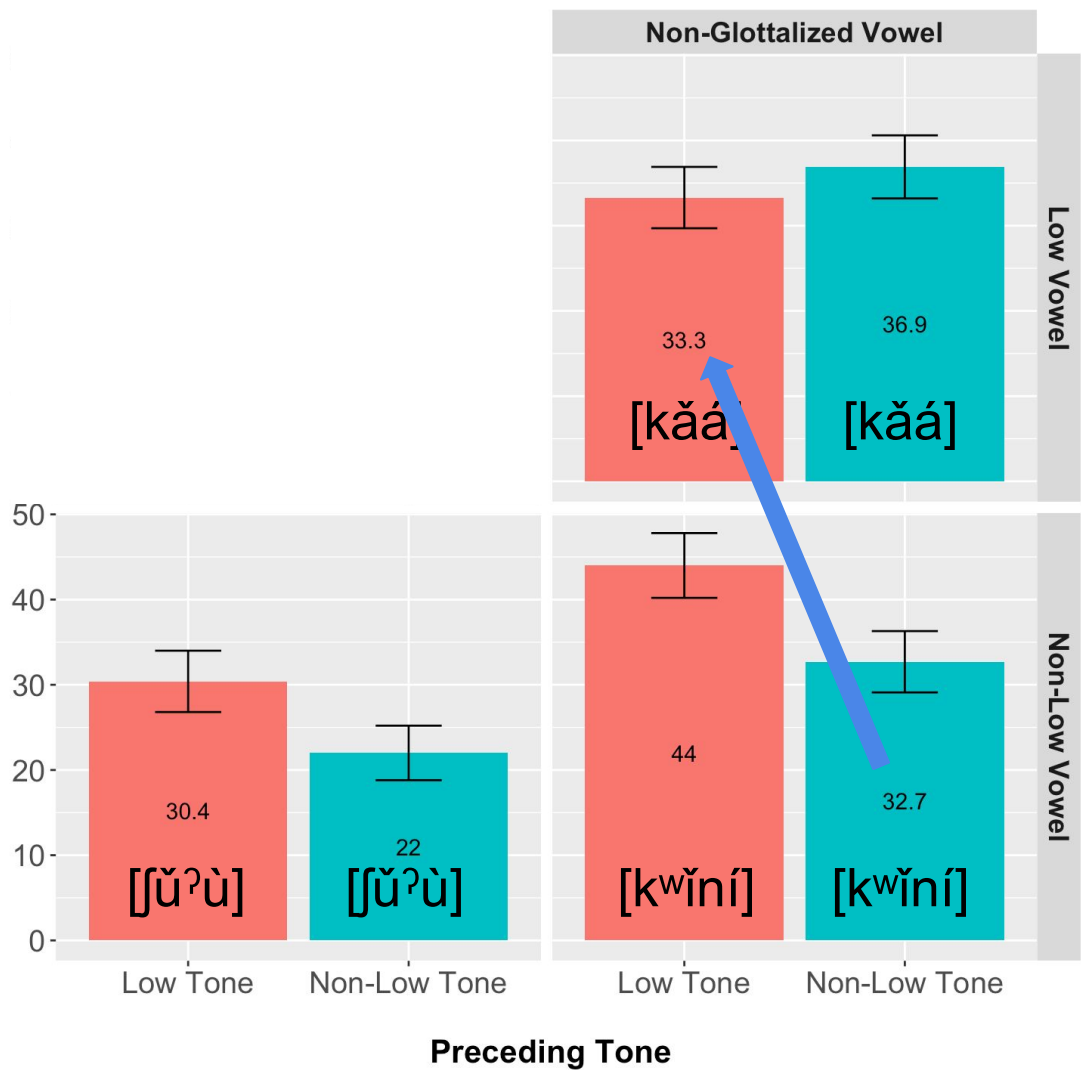
Even more rises for **low vowels** after Low tone

**No:**

Same or fewer rises for **low vowels** after Low tone

Preceding Low tone and low vowel showed a credible **negative** interaction:  
 Estimate = -0.71  
 95% CrI [-1.40, -0.05]

Percentage of Raising Responses (%)



**Question 2b:** Did participants generalize the **vowel height** tendency?

**Yes:**

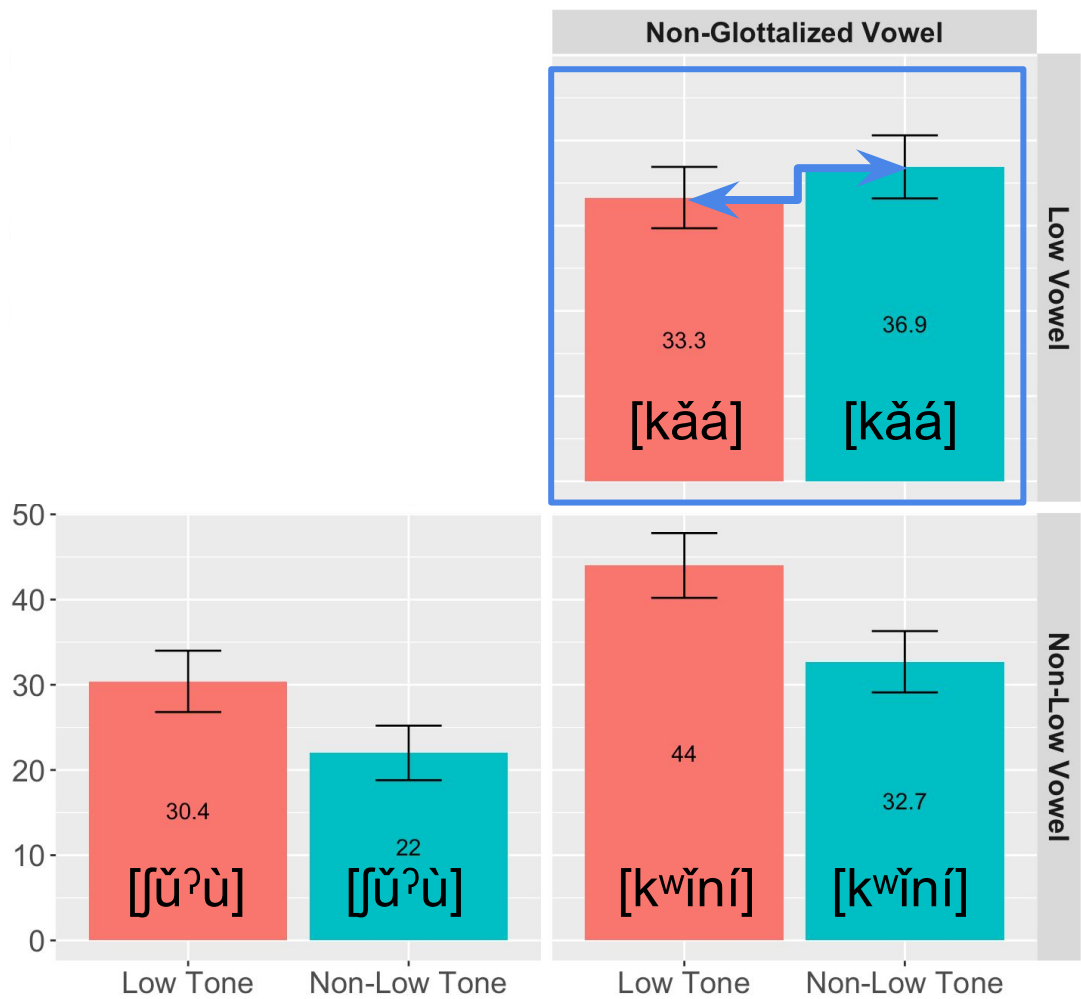
Even more rises for **low vowels** after Low tone

**No:**

Same or fewer rises for **low vowels** after Low tone

Preceding Low tone and low vowel showed a credible **negative** interaction:  
 Estimate = -0.71  
 95% CrI [-1.40, -0.05]

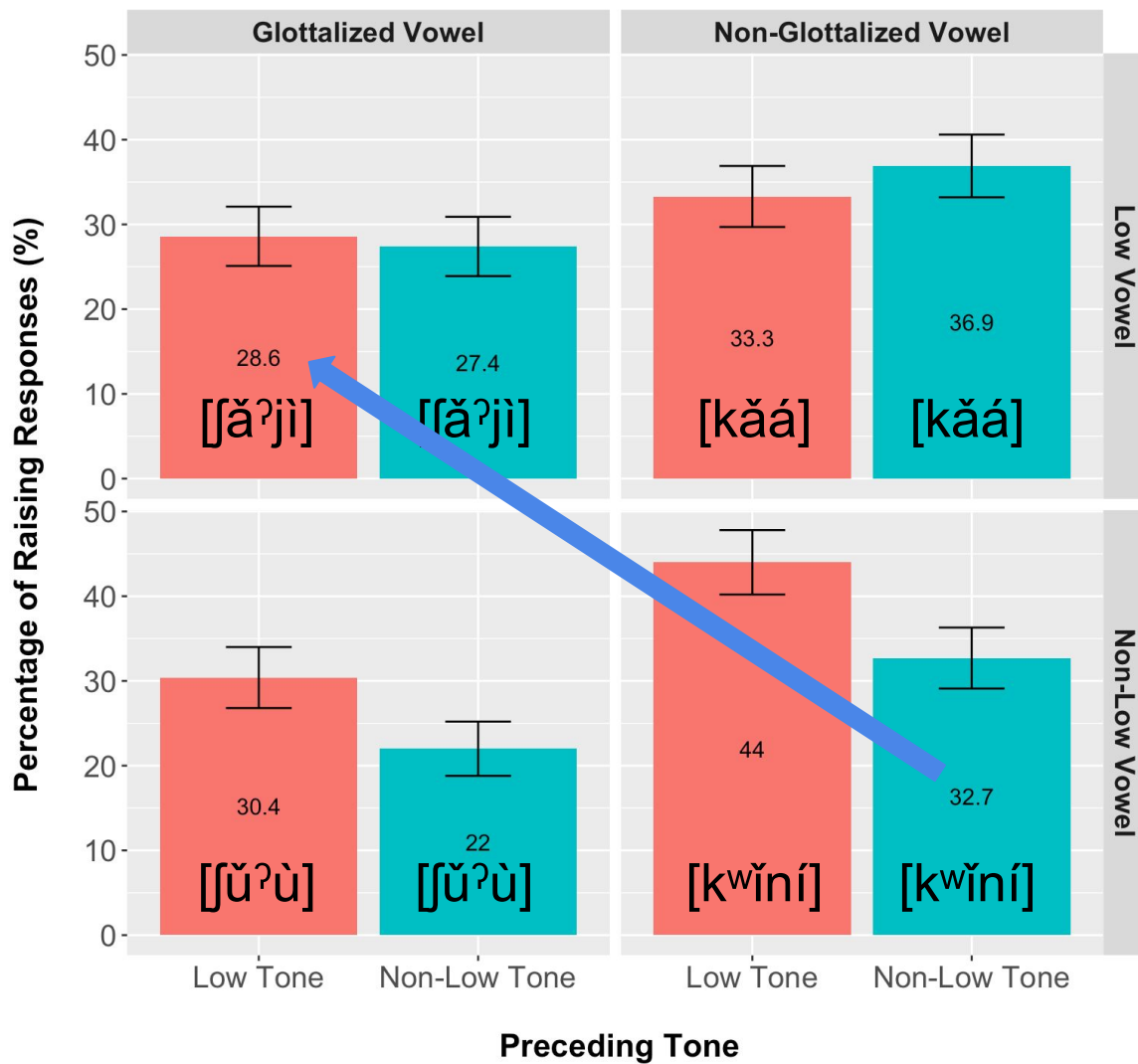
Percentage of Raising Responses (%)



No evidence for **cumulative** effect of vowel height and glottalization.

The three-way interaction between preceding tone, glottalization and vowel height overlapped with 0:

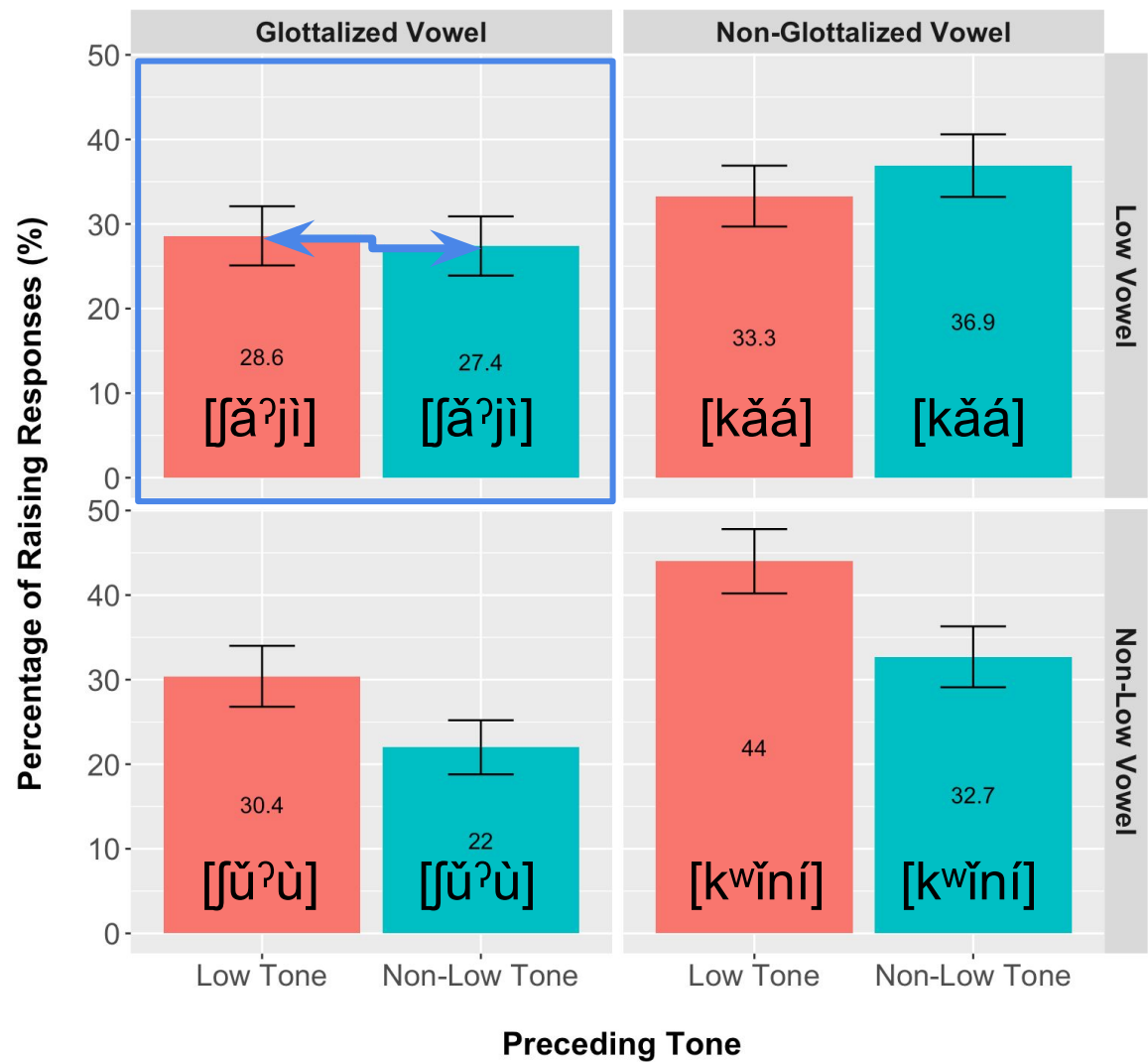
Estimate = 0.29  
95% CrI [-0.66, 1.26]



No evidence for **cumulative** effect of vowel height and glottalization.

The three-way interaction between preceding tone, glottalization and vowel height overlapped with 0:

Estimate = 0.29  
95% CrI [-0.66, 1.26]



# Wug test: Results and discussion

**Question 1:** Do participants generalize tone sandhi as a process?

**Yes**, to some extent

In some conditions, a preceding Low tone increases Rising-tone responses.

# Wug test: Results and discussion

**Question 2:** Do participants generalize the lexical tendencies?

**No**

Effect of preceding Low tone the same or smaller for low and glottalized vowels

# Summary and conclusion

**Driving question:** Is substantive bias strong enough to drive learning of lexical tendencies in an exceptional sandhi process in SMP Mixtec?

**Answer:** Apparently not

- The process is internalized to some extent, but the lexical tendencies are not
- In fact, generalization of sandhi is clear only for adjectives with a **non-low vowel**, counter to the lexical trends

# Summary and conclusion

Our results support previous findings that **substantive bias is relatively weak**, at least compared to structural bias (Moreton & Pater 2012b; Glewwe 2019; cf. Zheng & Do 2025).

- It does not appear to drive learning in the face of variable and/or sparse data

Importantly, this was shown with a naturally-occurring phonological process in participants' native language (cf. Becker et al. 2011; Becker et al. 2012)

- Convergent evidence for conclusions based on AGL studies

# Summary and conclusion

## Outstanding question:

- Why was the effect of preceding Low tone clear only for adjectives with **non-low vowels**?
  - This runs counter to phonetic grounding *and* lexical trends

But we can conclude that **the phonological characteristics of undergoers of tone sandhi in SMP Mixtec are not extended to novel forms.**

**Thank you!**

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# Appendix

# Appendix: Predictability

Whether or not an adjective will undergo sandhi is not predictable:

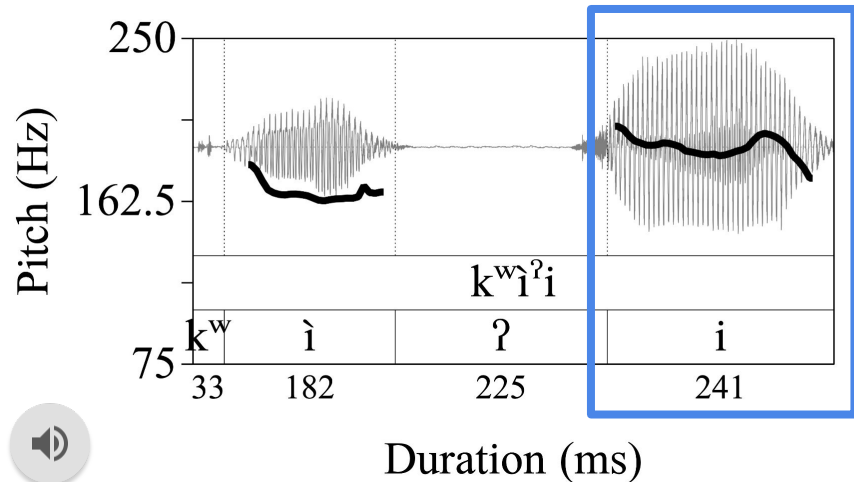
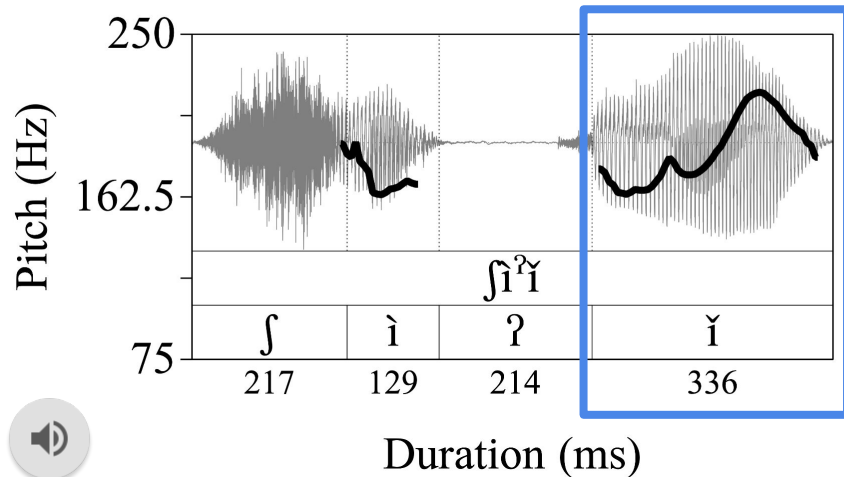
	<b>Undergoer</b>	<b>Non-undergoer</b>
<b>Phonologically similar</b>	[sɪʔi] 'female'	[nʈsɪʔi] 'blue'
<b>Deverbal adjectives</b>	[ʈsɪáʔji] 'rotten'	[ʃáà] 'overripe'

Other factors like frequency cannot currently be tested due to a lack of corpus data

# Appendix: Phonetic grounding

Low tone spread involves the creation of a **Low-to-High rising tone**

- Rising tones have a longer duration than level tones cross-linguistically (Zhang 2004) and in SMP Mixtec



# Appendix: Phonetic grounding

## Phonetic grounding

<b>Rising tones</b>
Longer duration (Zhang, 2004)

# Appendix: Phonetic grounding

## Phonetic grounding

<b>Rising tones</b>	<b>Low vowels</b>
Longer duration (Zhang, 2004)	Longer intrinsic duration (Lehiste, 1970)

# Appendix: Phonetic grounding

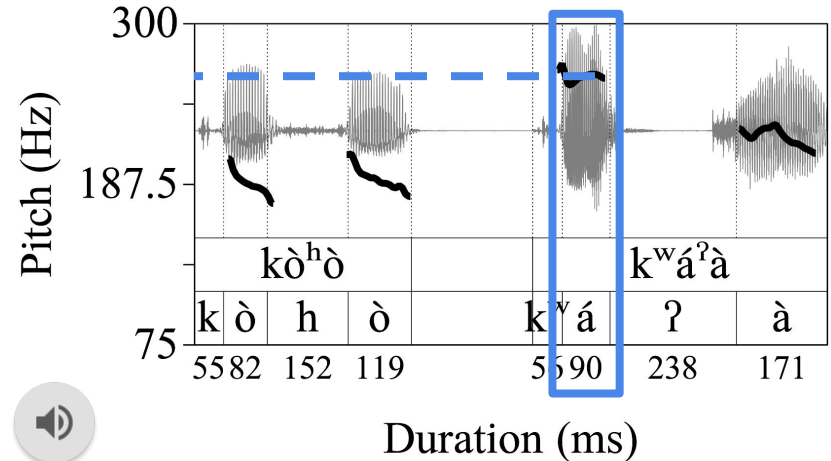
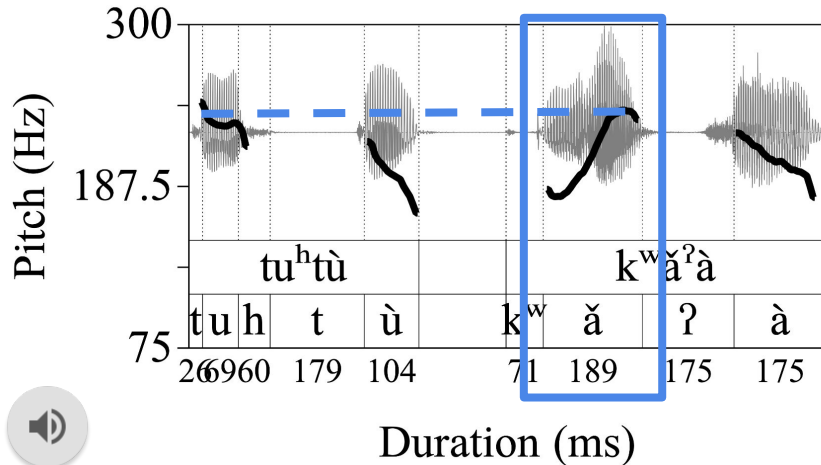
## Phonetic grounding

<b>Rising tones</b>	<b>Low vowels</b>
Longer duration (Zhang, 2004)	Longer intrinsic duration (Lehiste, 1970)

# Appendix: Phonetic grounding

Low tone spread involves the creation of a **Low-to-High rising tone**

- The rising-tone-initial version of adjectives always has a lower peak f0 than the high-tone-initial version



# Appendix: Phonetic grounding

## Phonetic grounding

<b>Rising tones</b>	<b>Low vowels</b>
Longer duration (Zhang, 2004)	Longer intrinsic duration (Lehiste, 1970)
Lower peak f <sub>0</sub> (in SMP Mixtec)	

# Appendix: Phonetic grounding

## Phonetic grounding

<b>Rising tones</b>	<b>Low vowels</b>
Longer duration (Zhang, 2004)	Longer intrinsic duration (Lehiste, 1970)
Lower peak f0 (in SMP Mixtec)	Lower intrinsic f0 (Whalen & Levitt, 1995)

# Appendix: Phonetic grounding

## Phonetic grounding

<b>Rising tones</b>	<b>Low vowels</b>	<b>Glottalized vowels</b>
Longer duration (Zhang, 2004)	Longer intrinsic duration (Lehiste, 1970)	—
Lower peak f0 (in SMP Mixtec)	Lower intrinsic f0 (Whalen & Levitt, 1995)	f0 lowering (Eischens, 2022)

# Appendix: Phonetic grounding

## Phonetic grounding

<b>Rising tones</b>	<b>Low vowels</b>	<b>Glottalized vowels</b>
Longer duration (Zhang, 2004)	Longer intrinsic duration (Lehiste, 1970)	—
Lower peak f0 (in SMP Mixtec)	Lower intrinsic f0 (Whalen & Levitt, 1995)	f0 lowering (Eischens, 2022)

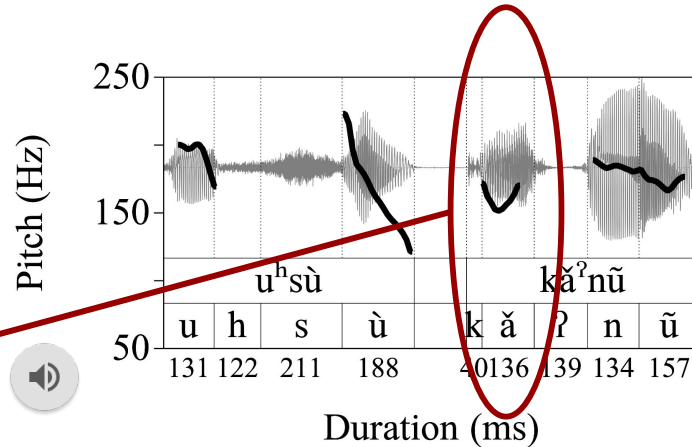
# Appendix: Optionality

## Variability:

Tone sandhi is **optional**

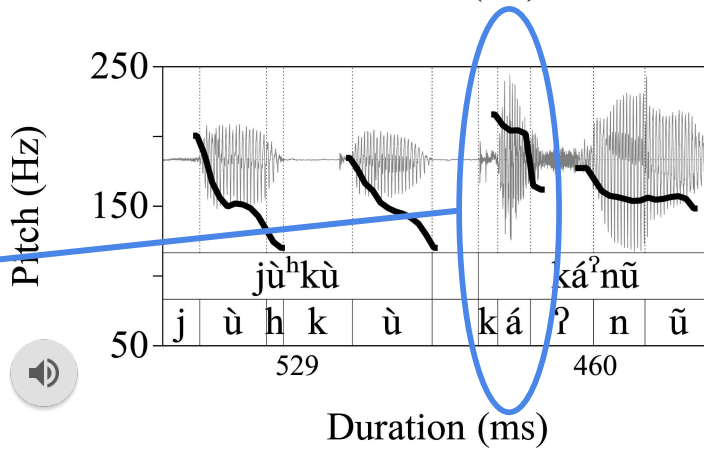
### 1. Application

Usù kǎ'nu  
[u<sup>h</sup>sù **kǎ'?**nũ]  
deer big  
'A big deer'



### 2. Non-application

Yùkù ká'nu  
[jù<sup>h</sup>kù **ká'?**nũ]  
leaf big  
'A big leaf'



# Appendix: Opacity

## Opacity:

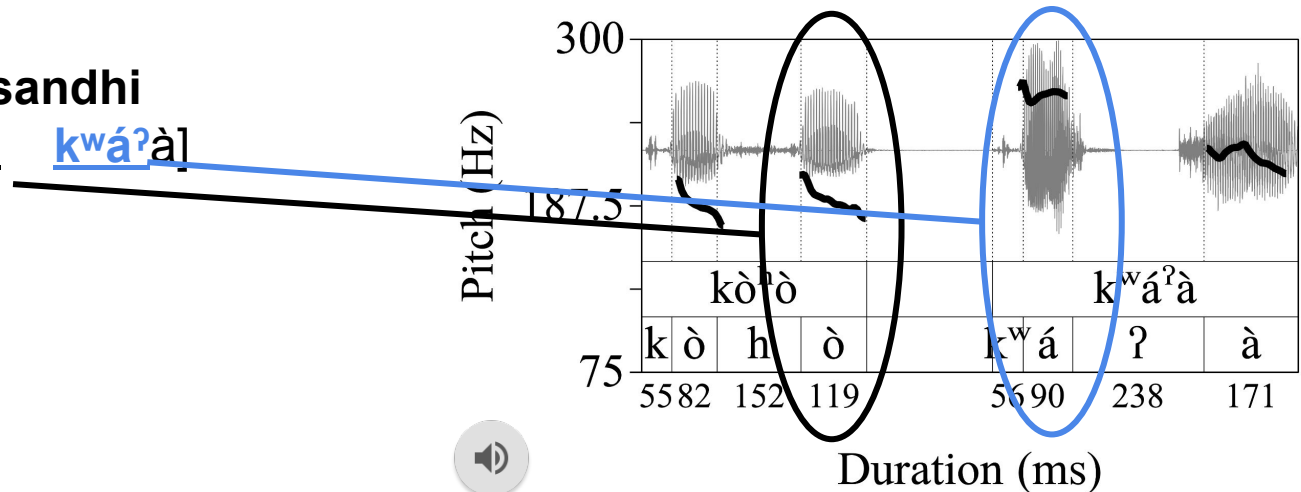
While **underlying** low tones trigger sandhi, **derived** low tones do not

### 1. Derived final L, no sandhi

/kò<sup>h</sup>ò kwá<sup>?</sup>à/ → [kò<sup>h</sup>ò kwá<sup>?</sup>à]

snake red

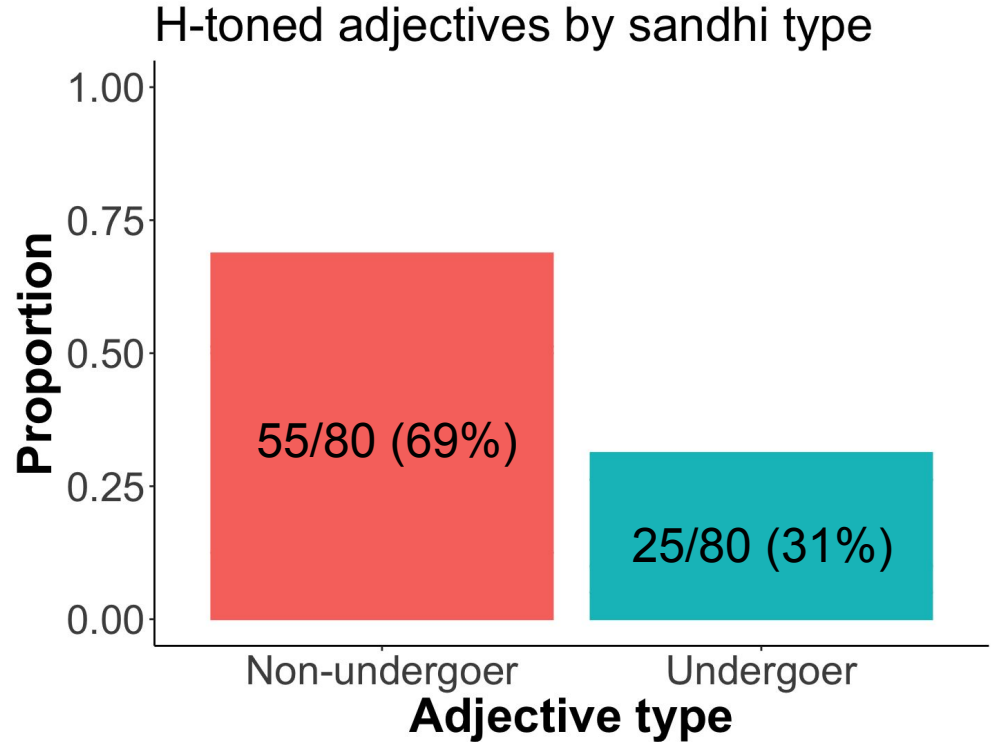
'A red snake'



# Learning difficulties

## Sparsity:

There aren't *that* many undergoers of tone sandhi to begin with



# Appendix: Individual variation

## Variability:

Tone sandhi is subject to **interspeaker variation**

	Speaker 1	Speaker 2	Speaker 3	Speaker 4	Speaker 5
Adjectives that undergo sandhi for	<b>23/25 (92%)</b>	<b>13/25 (52%)</b>	<b>19/25 (76%)</b>	<b>18/25 (72%)</b>	<b>11/25 (44%)</b>

# Appendix: Individual variation

Word	NGC	JGO	LER	LA	RDC
[káʔnũ] ('big')	Y	Y	Y	Y	Y
[kʷáʔà] ('red')	Y	Y	Y	Y	Y
[kʷáà] ('blind')	Y	N	Y	N	N
[ʔsiáʔji] ('rotten')	Y	N	N	N	Y
[ʔsiáʔá] ('stained')	Y	N	N	N	N
[kʷîî] ('striped')	Y	Y	N	N	N
[túʔũ] ('dishonest')	Y	Y	N	N	Y
[ʔtʃíʔtʃi] ('miraculous')	Y	Y	N	Y	N
[jáʔnũ] ('old')	N	N	N	N	Y

# Appendix: Real adjectives

Included 36 trials with real SMP Mixtec adjectives, split up into three classes:

- “Categorical” undergoers: Adjectives to which all consultants have applied tone sandhi
- “Variable” undergoers: Adjectives to which some, but not all, consultants have applied tone sandhi
- Non-undergoers: Adjectives to which no consultants have applied tone sandhi

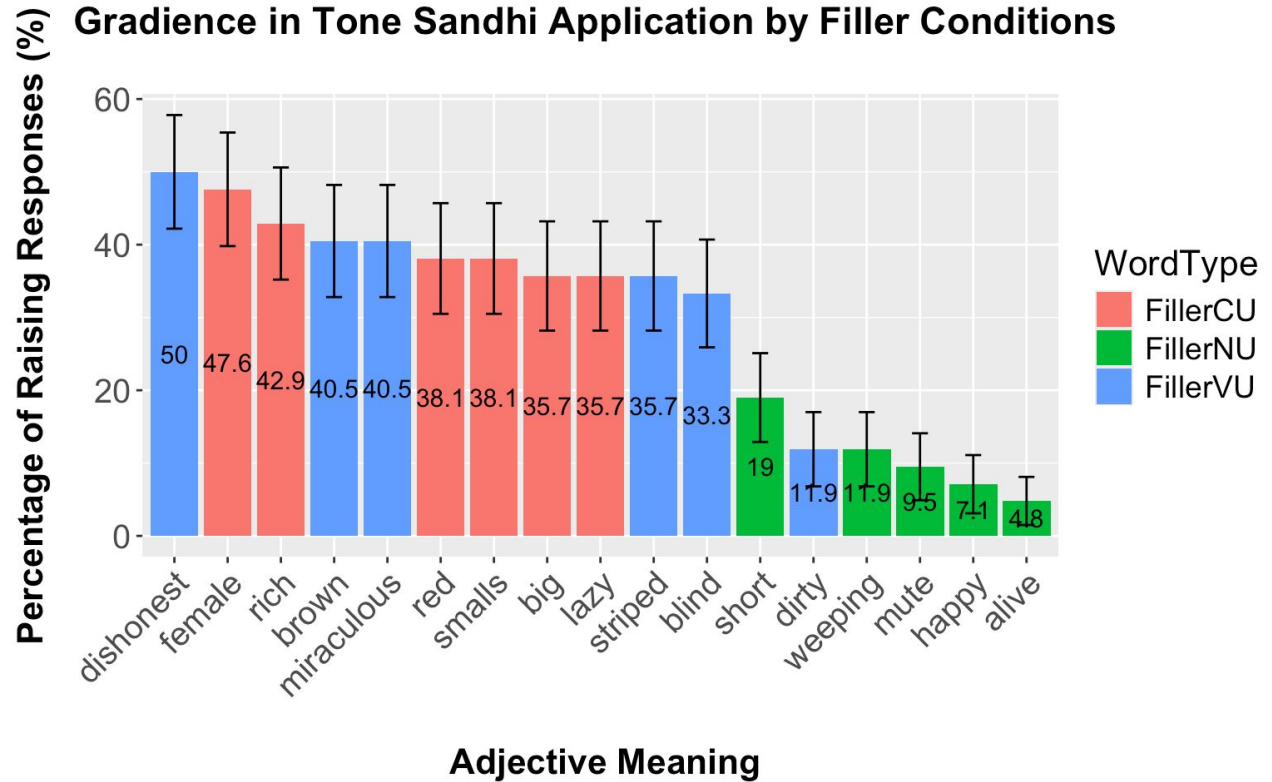
All real adjectives following Low tones (no non-Low tones) to reduce length of task

# Appendix: Real adjectives

Categorical (red) and variable (blue) undergoers elicited similarly high proportions of rising-tone responses.

Non-undergoers very rarely received rising tone responses.

**Participants' real-word responses track the lexical patterns**

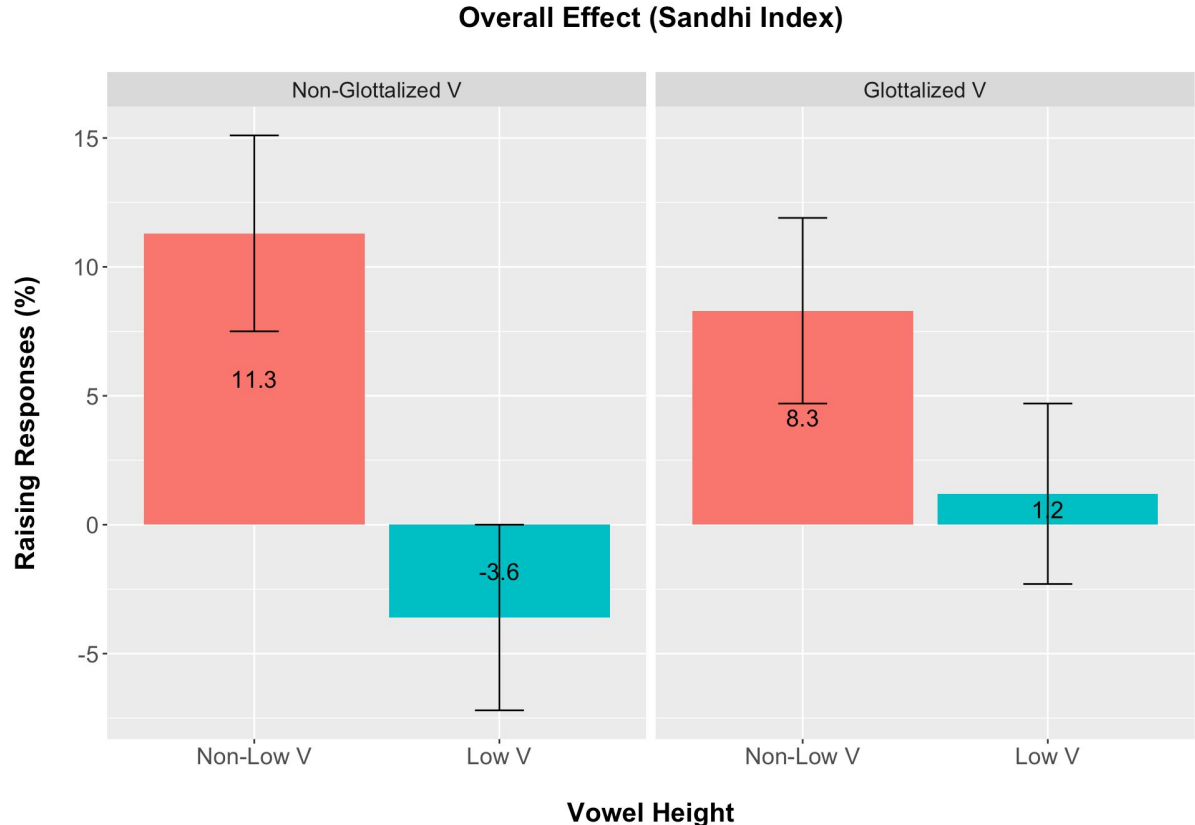


# Appendix: Sandhi index

Above 0 = positive effect  
of preceding tone

Overlapping with 0 = no  
effect of preceding tone

Takes into account  
likelihood of rising  
response in  
non-triggering context



**Glottalization** disfavored rising tone across the board.

Estimate = -0.60

95% CrI [-1.17, -0.02]

Suggests a universal **dispreference** for rising tones on glottalized vowels, regardless of preceding tone or vowel height

