Learning Derivationally Opaque Patterns in the Gestural Harmony Model

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Nzebi Height Harmony

(Guthrie 1968, Clements 1991, Parkinson 1996, Kirchner 1996, Smith 2020a)

- Partial height harmony: nonhigh undergoer vowels approach height of high trigger vowel, but do not necessarily reach it

- Nzebi (Bantu; Gabon) *yotization* (Guthrie 1968): in several verb tenses, roots followed by [i] and each nonhigh root vowel raised

- High-mid /e/ and /o/ raise to [i] and [u] in yotized roots

[betə]	[bit-i]	‘carry’
[bexə]	[bit-i]	‘foretell’
[βoːmə]	[βuːm-i]	‘breathe’
[kolənə]	[kulin-i]	‘go down’

Nzebi Height Harmony

(Guthrie 1968, Clements 1991, Parkinson 1996, Kirchner 1996, Smith 2020a)

- Low-mid /ɛ/ and /ɔ/ raise to [e] and [o] in yotized roots

[sɛbə]	[seb-i]	‘laugh’
[suɛmə]	[suem-i]	‘hide self’
[mɔnə]	[mon-i]	‘see’
[tɔːdə]	[toːd-i]	‘arrive’

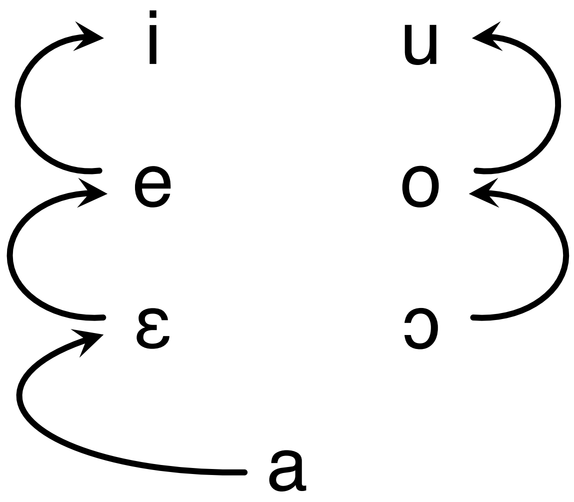
- Low /a/ raises to [e] in yotized roots

[salə]	[sɛl-i]	‘work’
[laxə]	[lɛx-i]	‘show’

Nzebi Height Harmony

(Guthrie 1968, Clements 1991, Parkinson 1996, Kirchner 1996, Smith 2020b)

Nzebi (Bantu; Gabon) raising harmony: In presence of trigger [i], each nonhigh root vowel raises one ‘step’ along a height scale



Simple Root	Yotized Root	Gloss
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[salə]	[sɛl-i]	‘work’

Chain Shifts as Derivational Opacity

- Underapplication opacity (McCarthy 1999; Baković 2007, 2011): phonological process appears not to have applied despite its structural description being met in a surface form

- Chain shifts are a type of underapplication opacity:

$$/X/ \rightarrow [Y] \qquad\qquad /Y/ \rightarrow [Z]$$

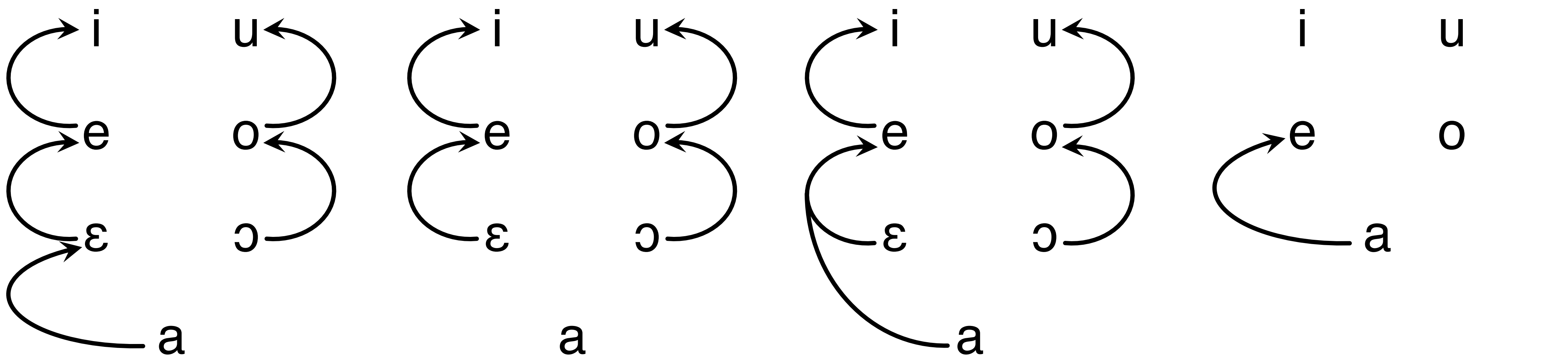
- Challenging for parallel-evaluating, output-driven Optimality Theory (Prince & Smolensky 1993/2004) and Harmonic Grammar (Legendre et al 1990; Smolensky & Legendre 2006):

If /Y/ → [Z], why not /X/ → Y → [Z]?

Chain-Shifting Height Harmony

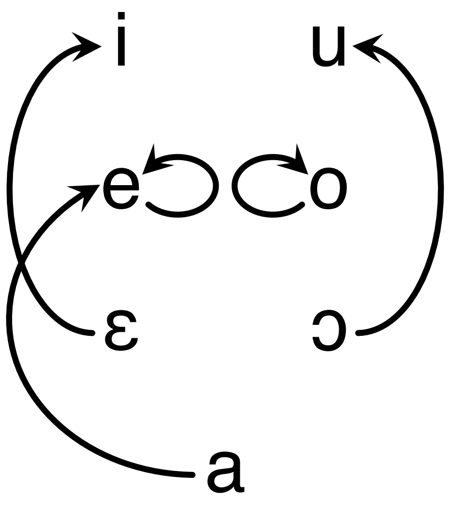
Chain-shifting vowel raising patterns in which vowels raise single step along height scale are well attested:

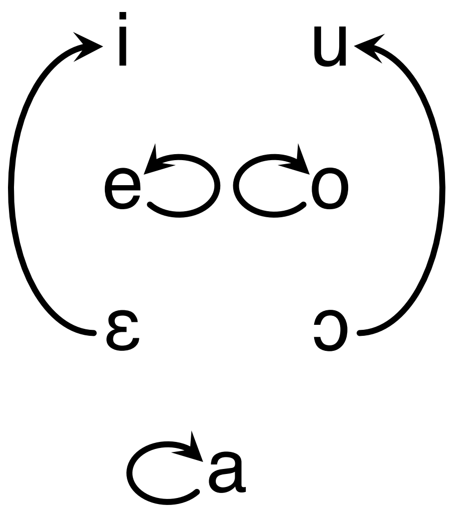
Nzebi Guthrie (1968)	Servigliano Italian (Nibert 1998)	Basaa (Schmidt 1996)	Basque (Hualde 1988)

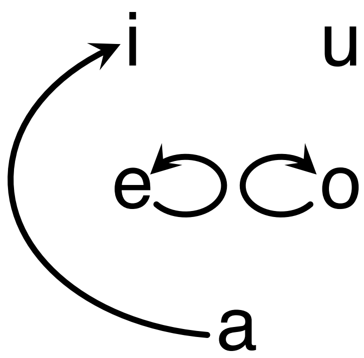


Unattested Saltatory Height Harmony

Two-step vowel raising patterns that ‘skip over’ a step in the height scale (i.e., saltation) are unattested (Parkinson 1996):







Saltation as Derivational Opacity

- Saltations are another type of underapplication opacity:

$$/X/ \rightarrow Y \rightarrow [Z] \qquad\qquad /Y/ \rightarrow [Y]$$

- Challenging for Optimality Theory and Harmonic Grammar:

$$\text{If } /X/ \rightarrow Y \rightarrow [Z]\text{, why not } /Y/ \rightarrow [Z]\text{?}$$

- Saltations are rare among phonological processes and apparently unattested in height harmony

The Big Questions

- Chain shifts and saltations cannot be generated in Optimality Theory or Harmonic Grammar using the faithfulness constraints of Correspondence Theory (McCarthy & Prince 1995), e.g. IDENT(F)-IO

> Can we formulate a phonological theory that generates derivationally opaque patterns?

- Chain-shifting and saltatory height harmony are both derivationally opaque, but only chain-shifting harmony is well-attested

> Can we formulate a phonological theory that predicts robust attestation of chain-shifting harmony and NOT saltatory harmony?

The Gestural Harmony Model

Gestural Harmony Model (Smith 2016, 2017ab, 2018, 2020ab):

- Subsegmental units of phonological representation are target-based gestures of Articulatory Phonology (Browman & Goldstein 1986, 1989)
- Vowel harmony is result of extension of trigger gesture to overlap gestures of other segments in a word
- Partial height harmony is result of blending between vowel gestures with different target articulatory states (heights)

Proposals: A Gestural Account of Derivationally Opaque Height Harmony

- Partial height harmony via blending in the Gestural Harmony Model generates attested chain-shifting raising and unattested saltatory raising

- Aspects of *learnability* of saltatory height harmony explain its lack of attestation

Learnability and Phonological Typology

- Patterns predicted by phonological framework are determined by setup of grammar, but also by how easy they are to learn (Pater & Moreton 2012; White 2013; Staubs 2014; Stanton 2016; Hughto 2020; O’Hara 2021)

- For a pattern to be robustly attested, it must be derivable within a phonological framework, but also easily learnable within that framework

The Gestural Gradual Learning Algorithm

- Gestural Gradual Learning Algorithm: error-driven, online learning algorithm used to model learning of phonological gestures' parameter settings

- Modeled the acquisition of gestural parameter settings that generate chain-shifting and saltatory height harmony

Gestural Harmony Model and Gestural Gradual Learning Algorithm correctly predict chain-shifting harmony to be more learnable/better attested

Examining the Alternatives: Featural Accounts of Derivationally Opaque Height Harmony

- Assuming non-standard faithfulness constraint definitions, both chain-shifting and saltatory patterns are derivable in Optimality Theory and Harmonic Grammar

- Modeled the acquisition of phonological grammars that derive derivationally opaque patterns in these frameworks using the Generational Stability Model (O'Hara 2021)

Featural frameworks that derive both chain-shifting and saltatory height harmonies incorrectly predict saltatory harmonies to be more learnable/better attested

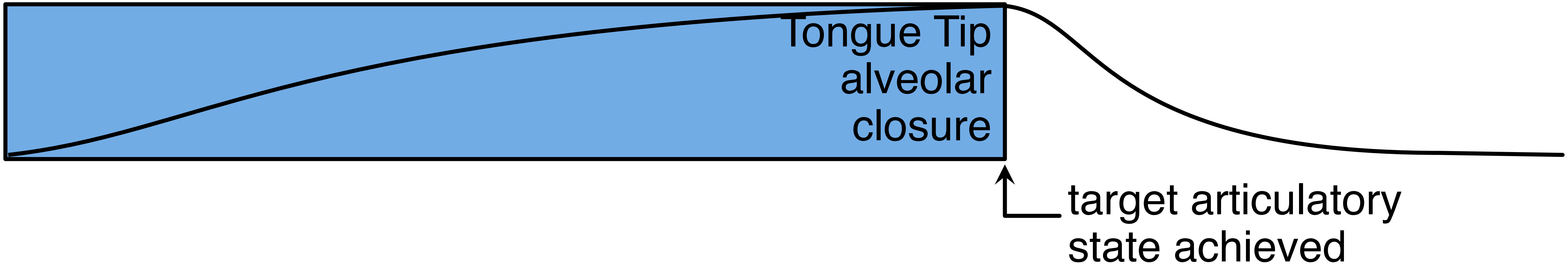
Roadmap

- Gestures as Phonological Units
- Gestural Harmony Model
- Gestural Analysis of Nzebi Chain-Shifting Height Harmony
- Gestural Gradual Learning Algorithm
- Generating and Learning Chain-Shifting and Saltatory Height Harmony in Featural Frameworks

Gestures as Phonological Units

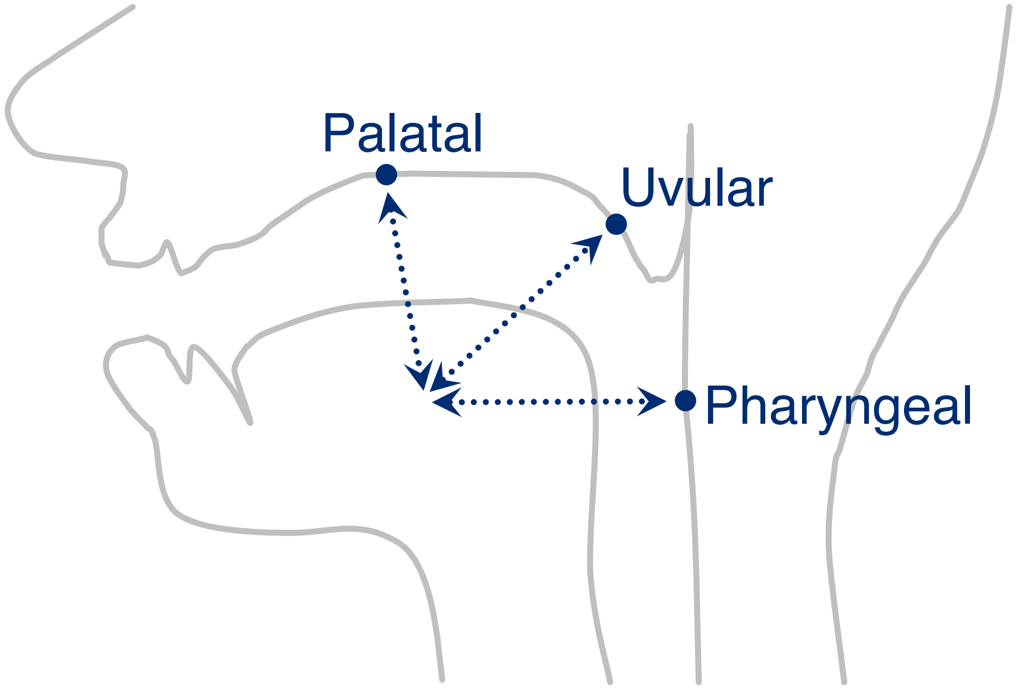
Gestures in Articulatory Phonology
(Browman & Goldstein 1986, 1989 et seq.)

- Gestures: dynamically-defined, goal-based units of phonological representation (Browman & Goldstein 1986, 1989)



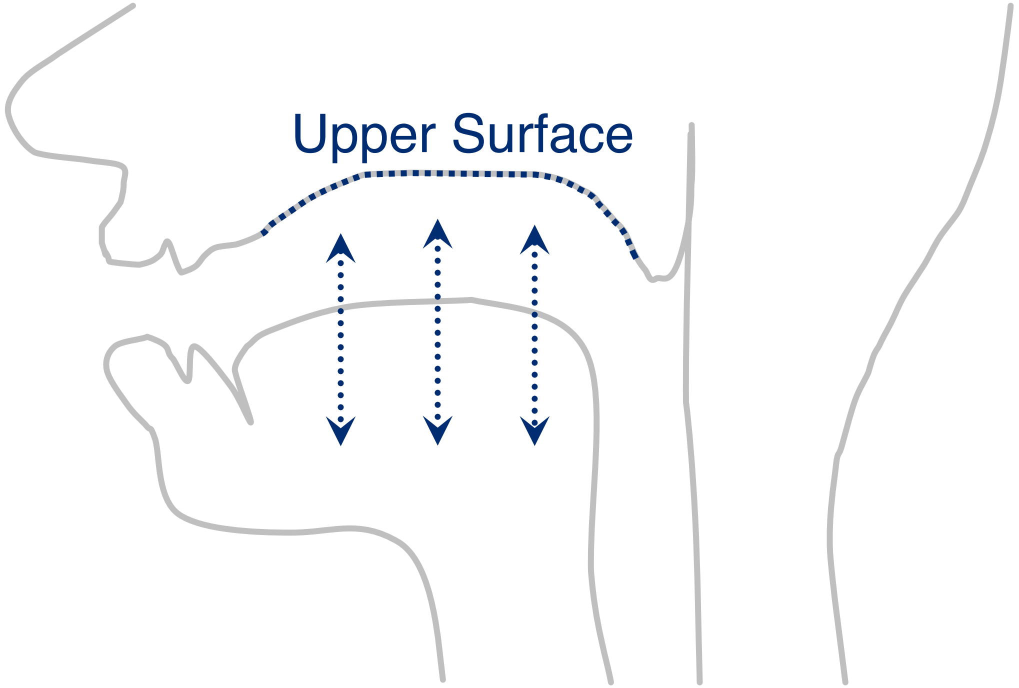
- Target articulatory state:
  - Constriction location
  - Constriction degree
- Blending strength (α): ability to command vocal tract articulators
- Ability to self-activate and self-deactivate (Smith 2016, 2017ab, 2018)

Constriction Location and Degree for Consonantal Gestures



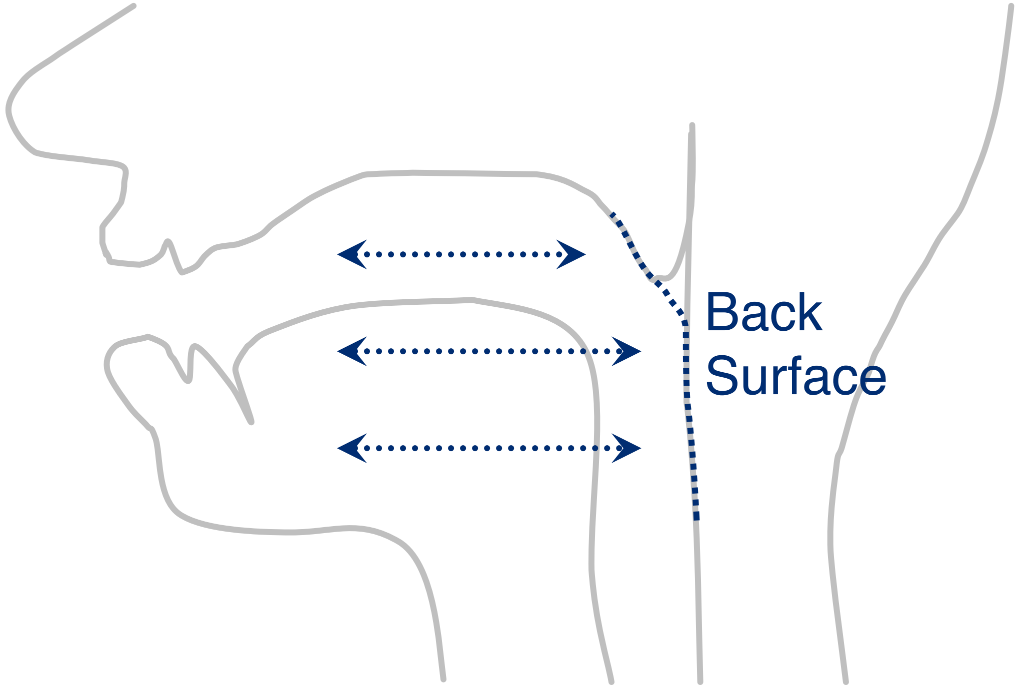
- Constriction location of gesture specifies target point along vocal tract surface
- Constriction degree of gesture specifies distance between active articulator and constriction location point

Constriction Location and Degree for Vowel Gestures
(Smith 2020a)



- Each vowel includes two tongue body gestures:
  - Constriction location ‘upper surface’
  - Constriction location ‘back surface’
- Constriction degree of upper surface gesture determines vowel height
- Constriction degree of back surface gesture determines vowel backness

Constriction Location and Degree for Vowel Gestures
(Smith 2020b)



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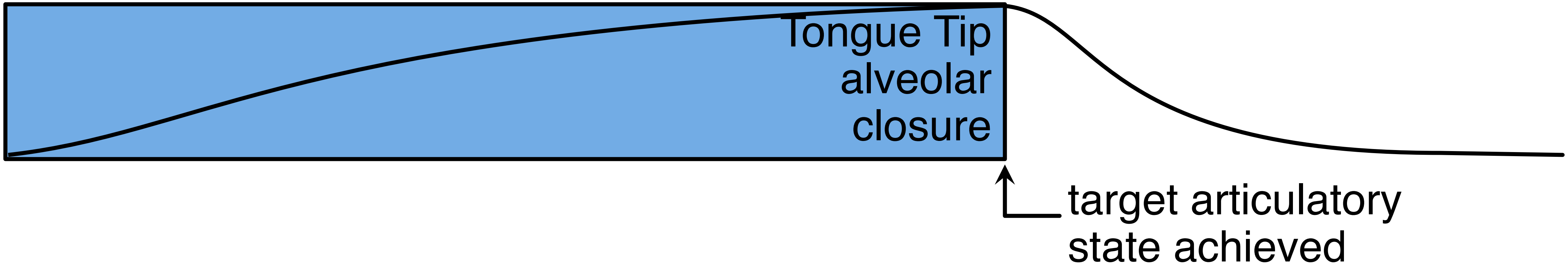
Gestures in Articulatory Phonology

(Browman & Goldstein 1986, 1989 et seq.)

- Gestures: dynamically-defined, goal-based units of phonological representation in Articulatory Phonology



- Target articulatory state:
  - Constriction location
  - Constriction degree
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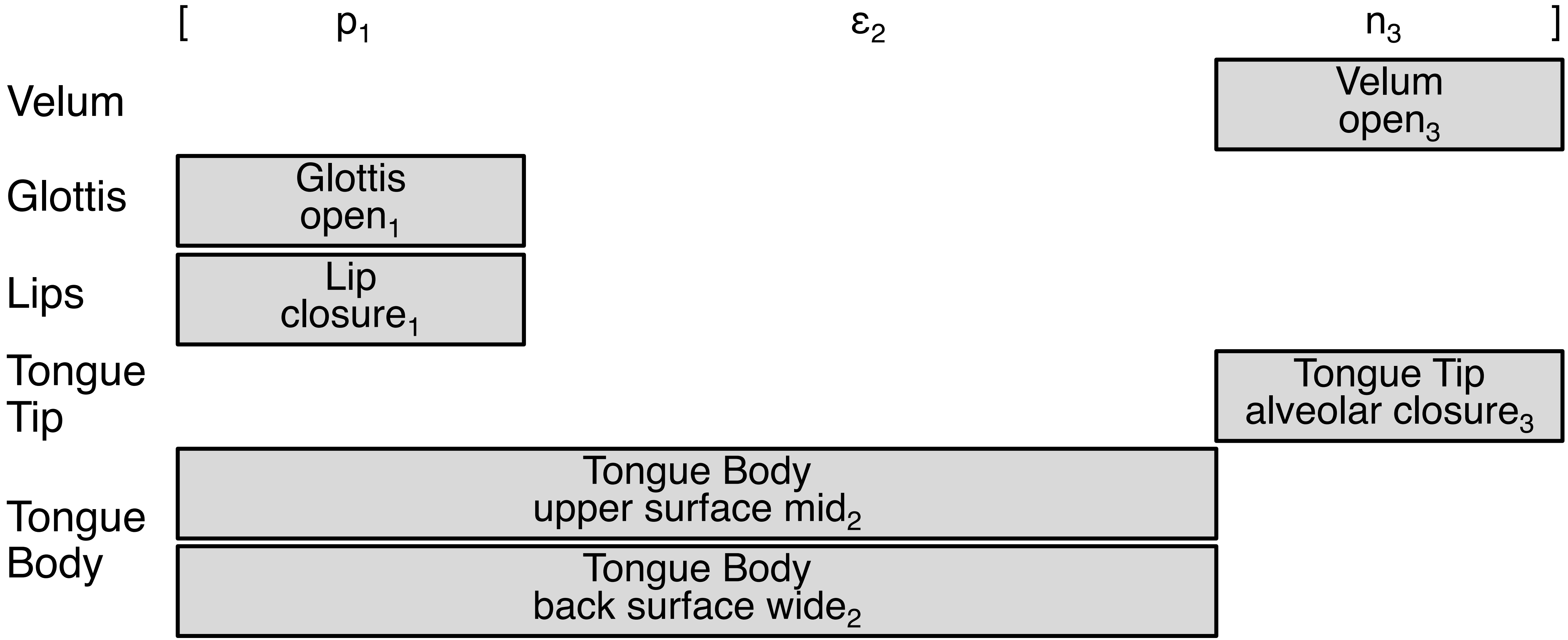
Representing Phonological Forms with Gestural Scores



subscript: segment-to-gesture correspondence

Gestural Blending Between Consonants and Vowels

[ɑ$_1$ g$_2$ ɑ$_3$]

Tongue Body velum closure$_2$

Tongue Body upper surface wide$_1$

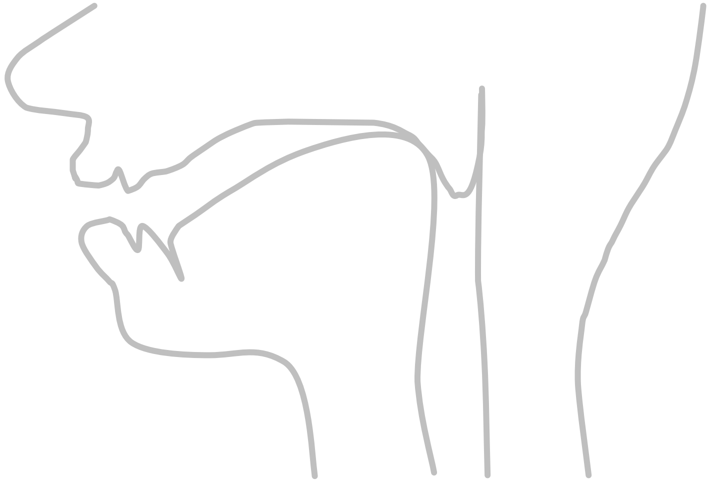
Tongue Body upper surface wide$_3$

Tongue Body back surface mid$_1$

Tongue Body back surface mid$_3$

Tongue body position for /ɑ/

Tongue body position for /g/



Gestural Strength and Blending

- Antagonistic gestures: gestures with conflicting target articulatory states

- Antagonism resolved by blending goal articulatory states of concurrently active gestures according to Task Dynamic Model of speech production (Saltzman & Munhall 1989, Fowler & Saltzman 1993)

$$\frac{\text{Target}_1 * \alpha_1 + \text{Target}_2 * \alpha_2}{\alpha_1 + \alpha_2} = \text{Blended Target}$$

Gestural Blending Between Consonants and Vowels

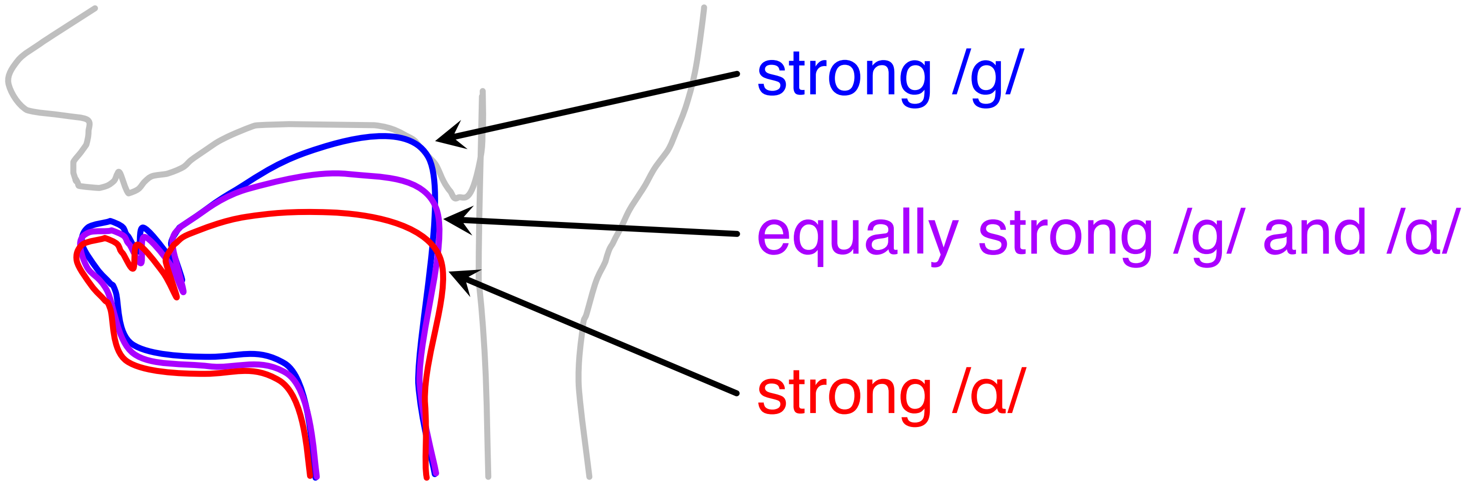
[ɑ g ɑ]

Tongue Body velum closure

Tongue Body upper surface wide | Tongue Body upper surface wide

Tongue Body back surface mid | Tongue Body back surface mid

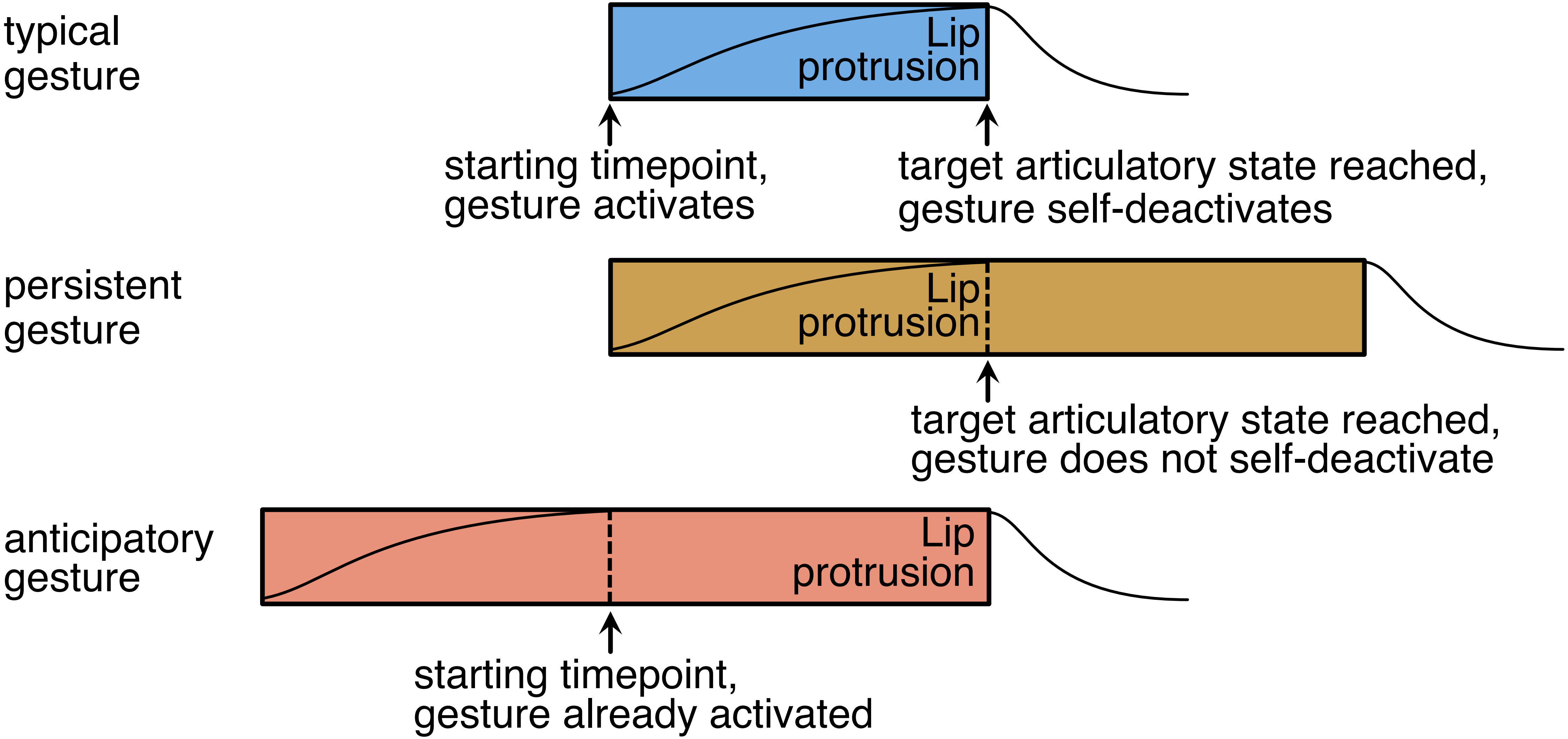
<u>Blended tongue body positions for /ɑ/ and /g/</u>



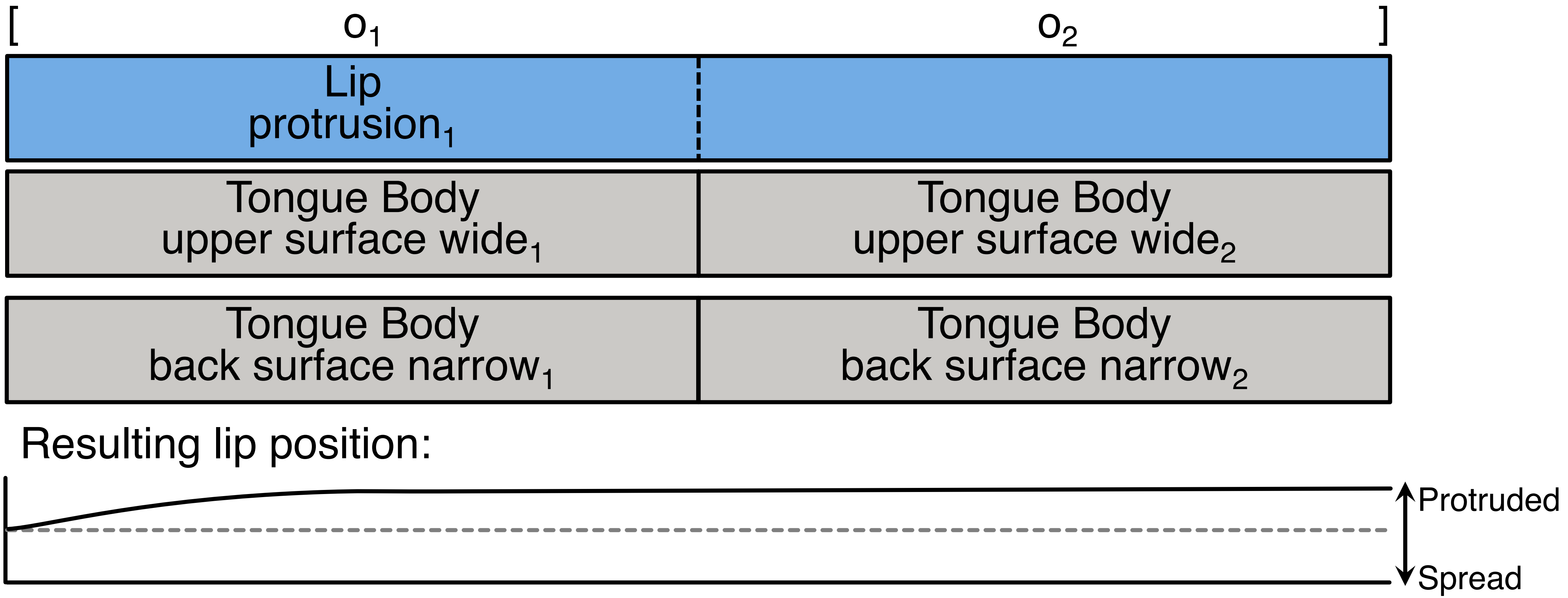
The Gestural Harmony Model

Gestural Activation and Deactivation

(Smith 2016, 2017ab, 2018)

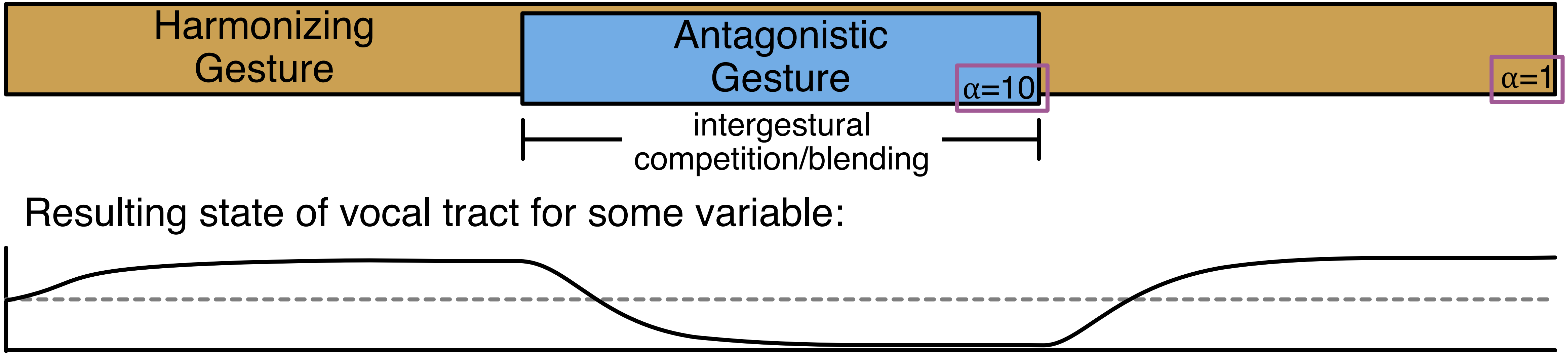


Example: Rounding Harmony

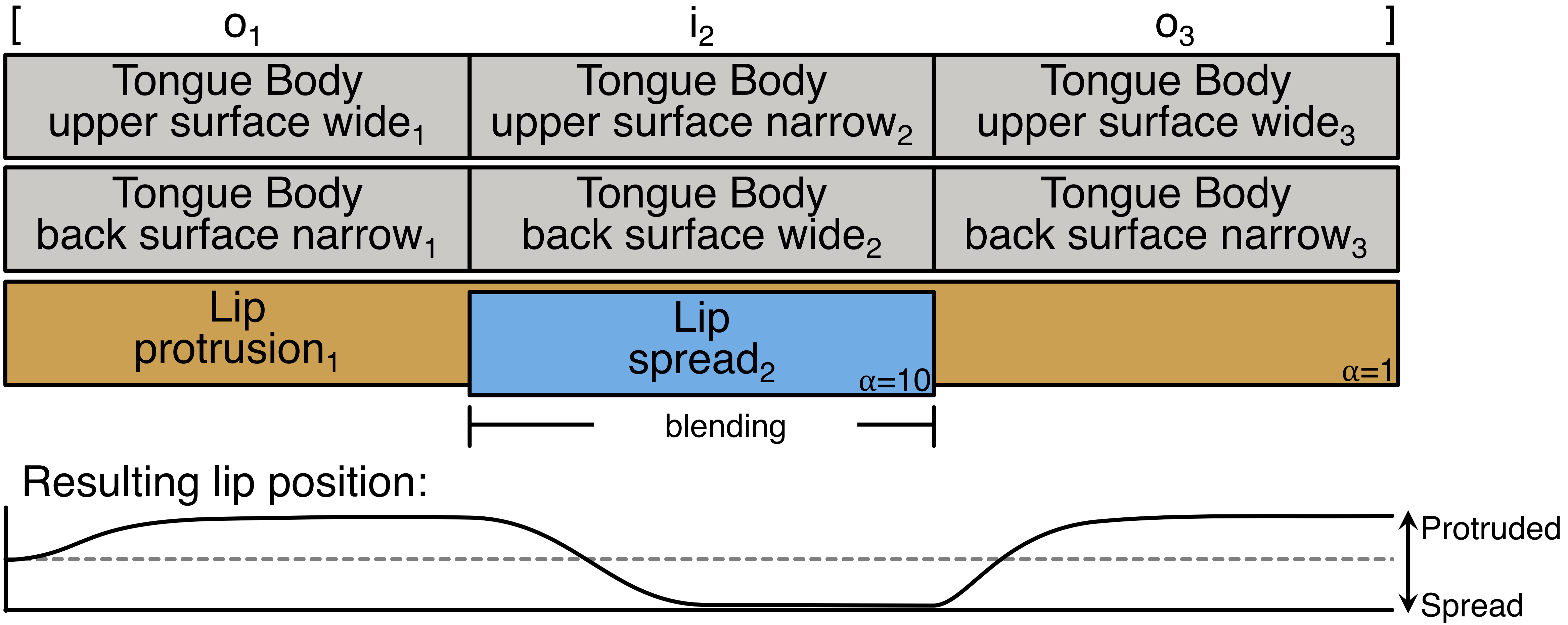


Transparency as Gestural Blending

- Transparency: competition between two concurrently active *antagonistic* gestures (Smith 2016, 2018)
- Gestural antagonism: two concurrently active gestures with opposing target articulatory states

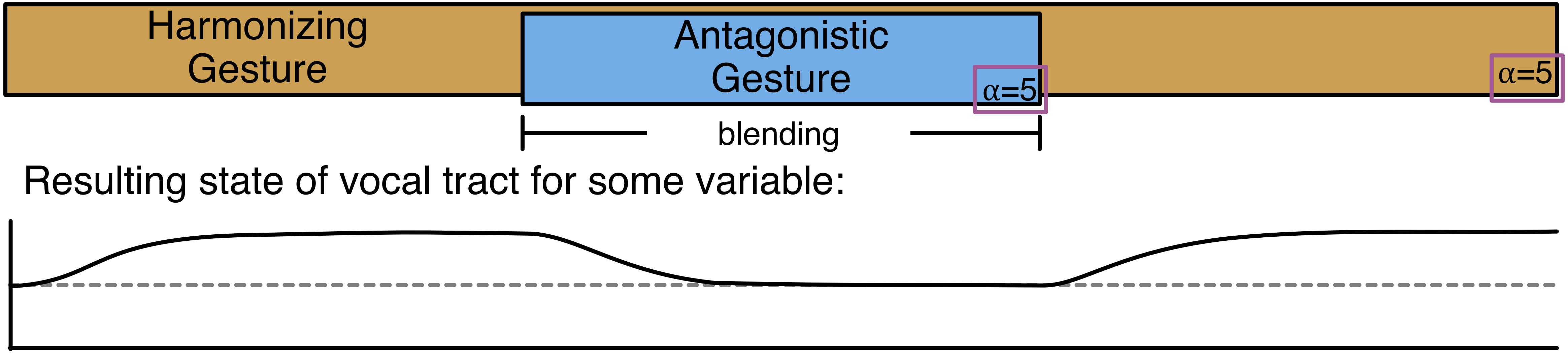


Example: Transparency in Rounding Harmony



Prediction: Partial Transparency via Gestural Blending

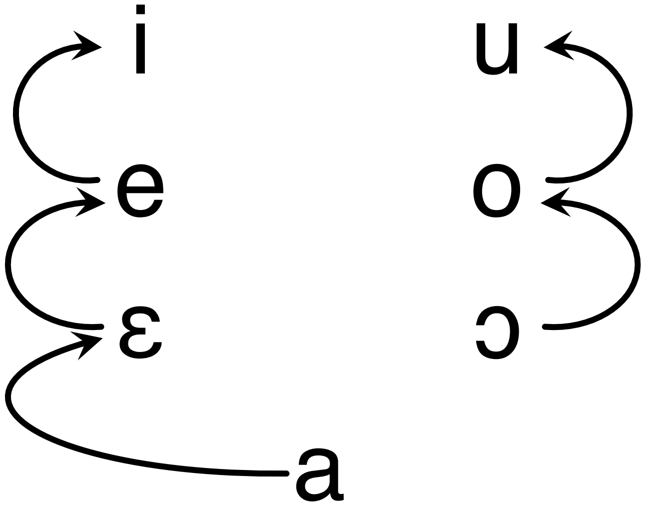
- Full transparency: overlapped gesture of transparent segment is much stronger than harmonizing gesture (e.g. 10-to-1)
- Identical or similar blending strengths of harmonizing gesture and overlapped gesture predicts partial transparency/partial undergoing of harmony



Chain-Shifting Height Harmony in Nzebi

Nzebi Chain-Shifting Height Harmony

(Guthrie 1968, Clements 1991, Parkinson 1996, Kirchner 1996; Smith 2020a)



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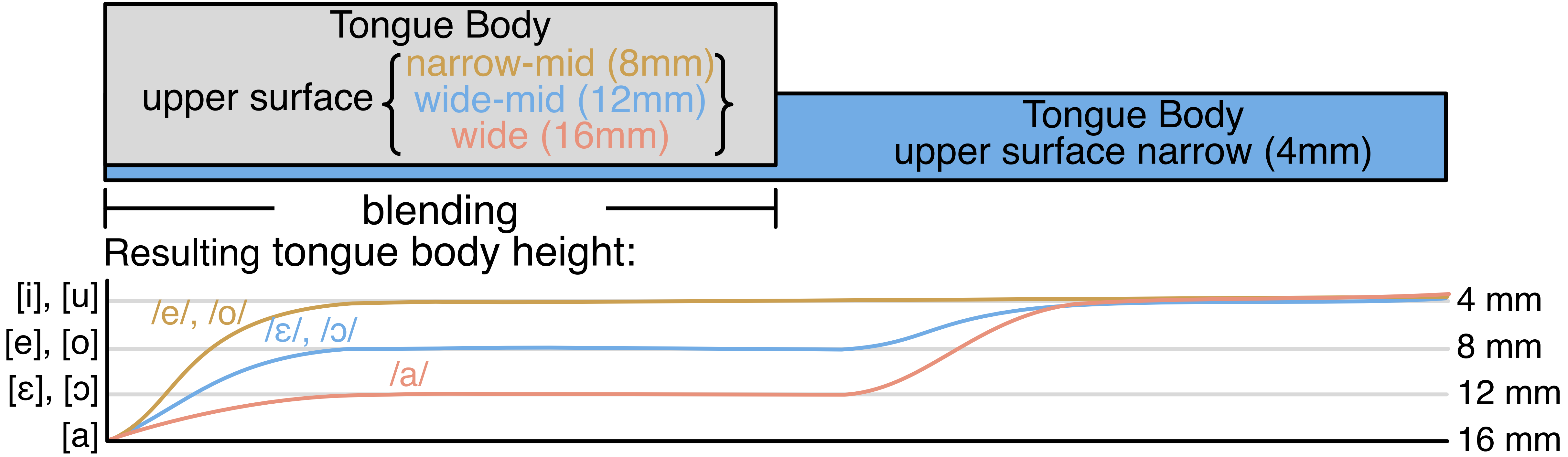
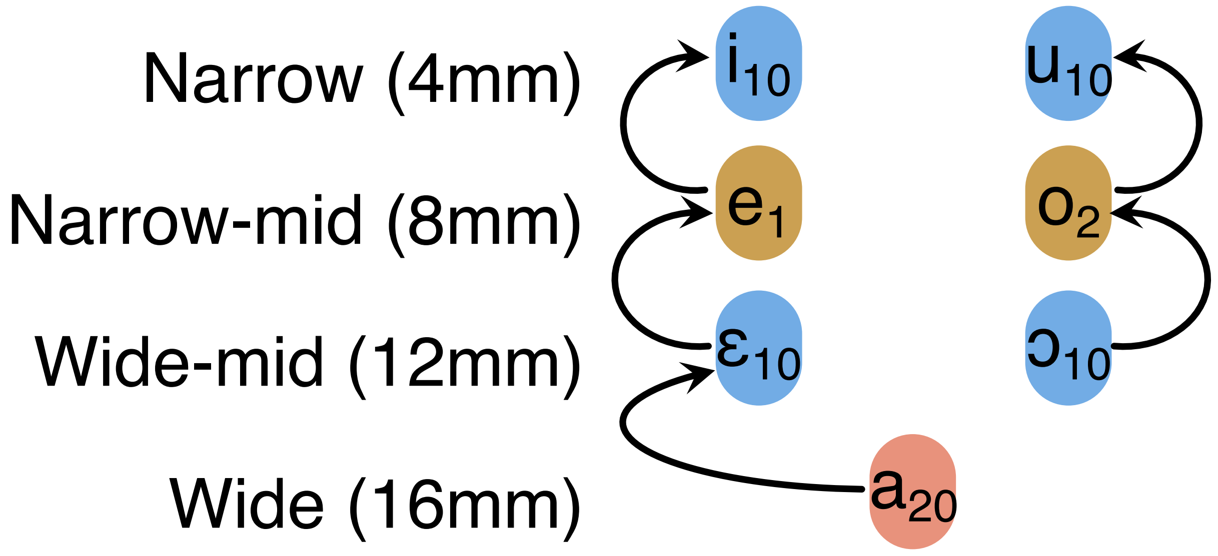
[mɔnə]	[mon-i]	‘see’
[salə]	[sɛl-i]	‘work’

A Gestural Analysis of Nzebi Height Harmony
(Smith 2020a)

- Vowel raising harmony due to overlap by anticipatory upper surface narrowing gesture of suffix high vowel /i/
- Vowels of different heights have antagonistic target states for upper surface constriction degree, resulting in gestural blending



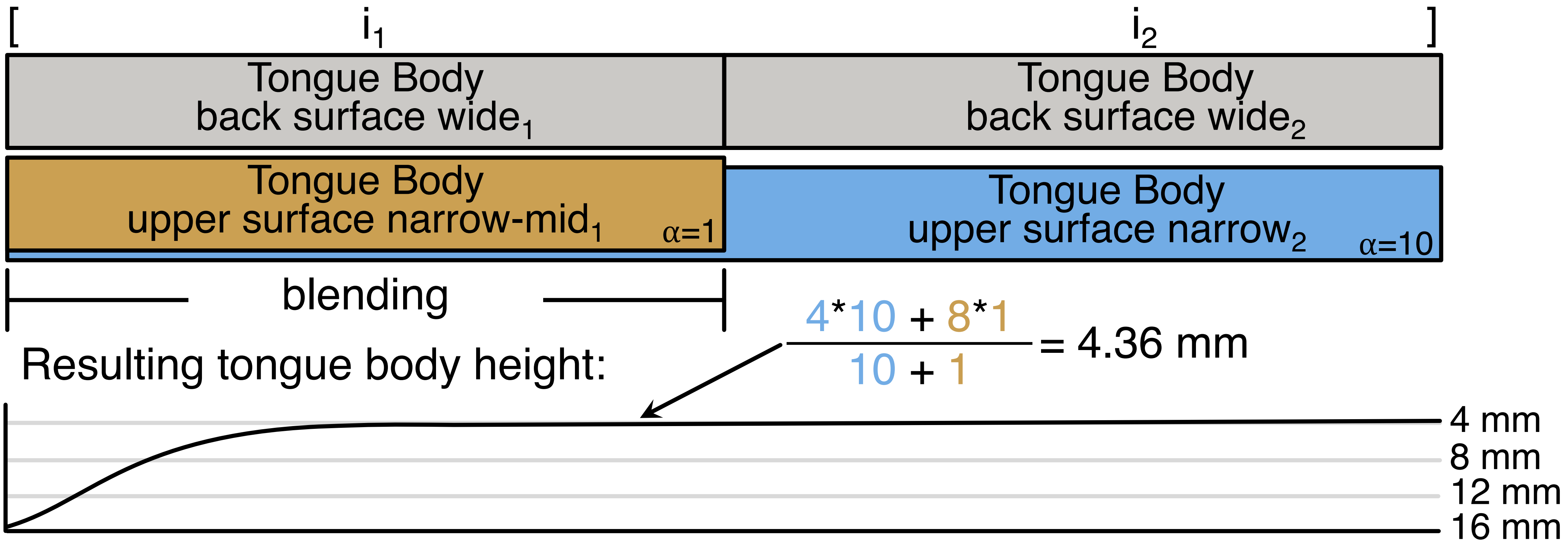
Nzebi Gestural Parameters



- Weak narrow-mid vowels /e/ and /o/ do not resist raising and surface as narrow
- Wide-mid vowels /ɛ/ and /ɔ/ surface as narrow-mid, partially resisting raising to narrow due to strength equal to trigger gesture
- Strong vowel /a/ surfaces as wide-mid, mostly resisting raising due to strength greater than trigger gesture

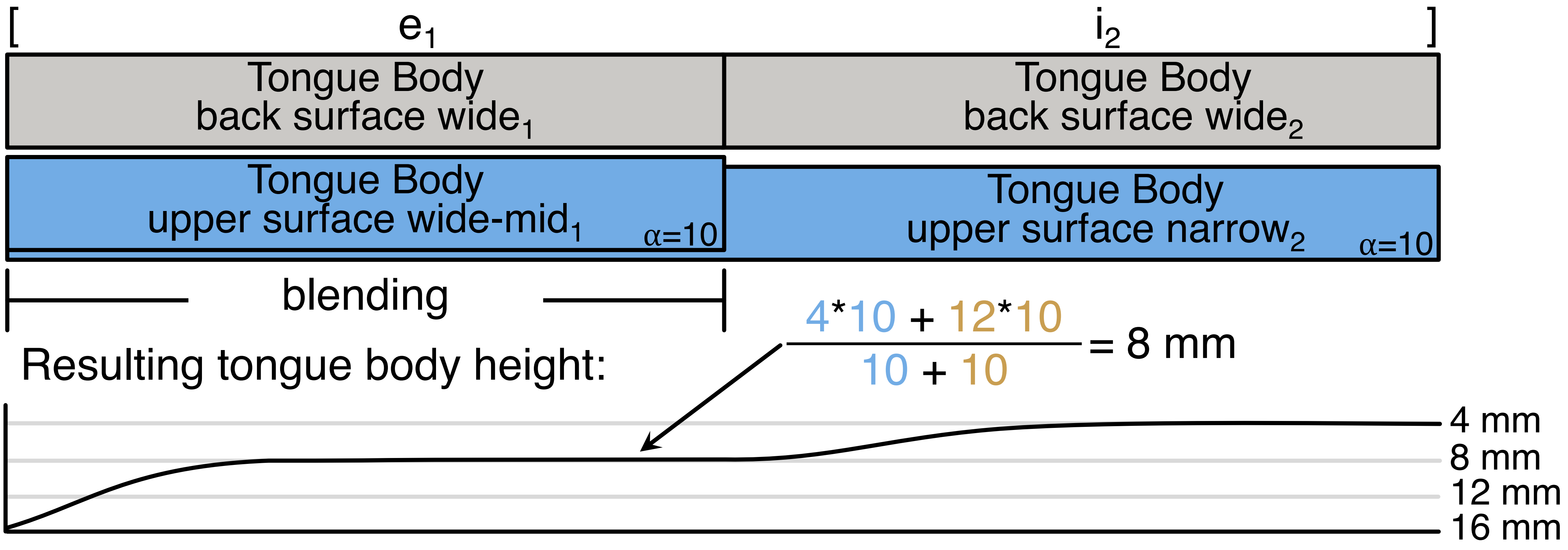
Nzebi Analysis: Narrow-Mid to High Raising

- Narrow-mid vowels /e/ and /o/ fully undergo harmony
- Relative gestural blending strengths favor target constriction degree (narrow upper surface constriction) of high vowels



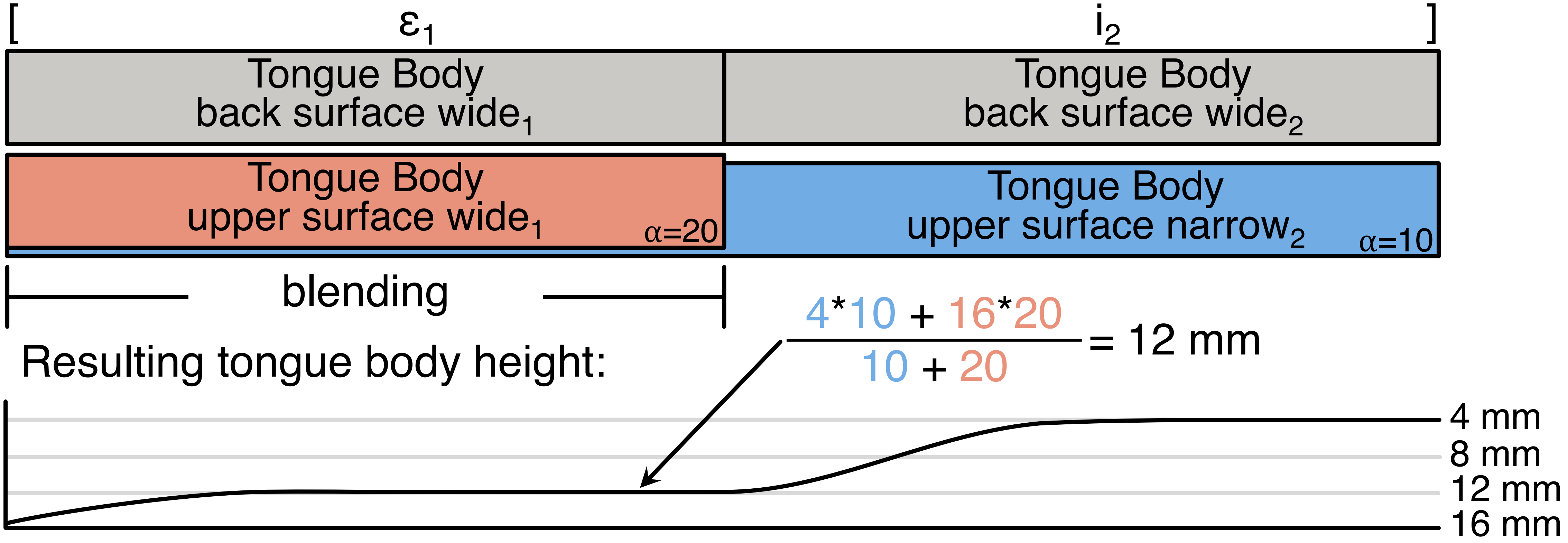
Nzebi Analysis: Wide-Mid to Narrow-Mid Raising

- Overlap between gestures of wide-mid vowels /ɛ/ and /ɔ/ and narrow /i/ produces narrow-mid [e] and [o]
- Intermediate blended articulatory state due to equal gestural strengths



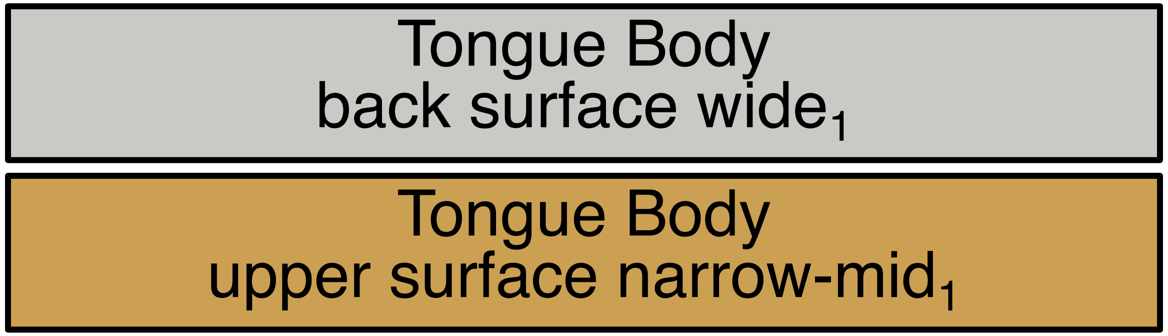
Nzebi Analysis: Wide to Wide-Mid Raising

- Overlap between gestures of wide vowel /a/ and narrow /i/ produces wide-mid vowel [ɛ]
- Blending strengths slightly favor target constriction degree of wide vowel

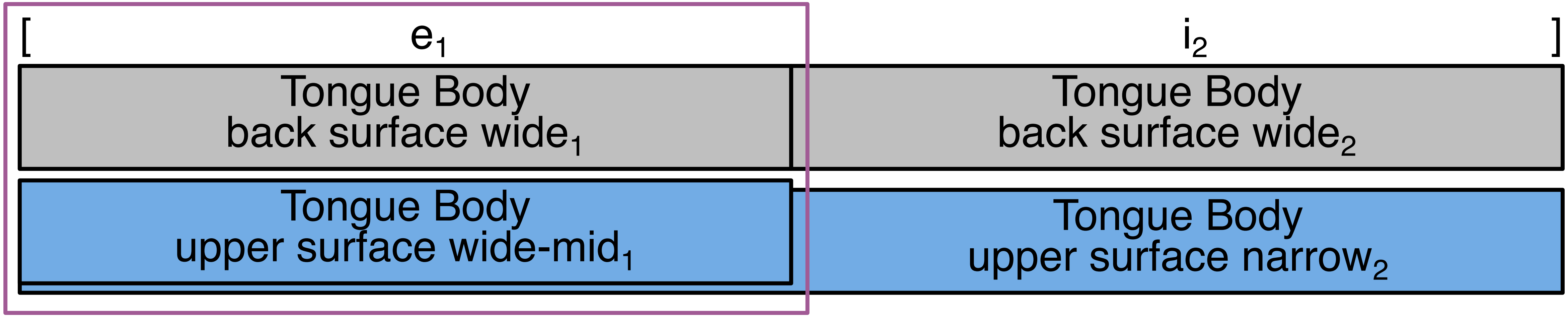


Modeling a Chain Shifting: Underlying and Derived Vowels

- Underlying mid-high vowel /e/:

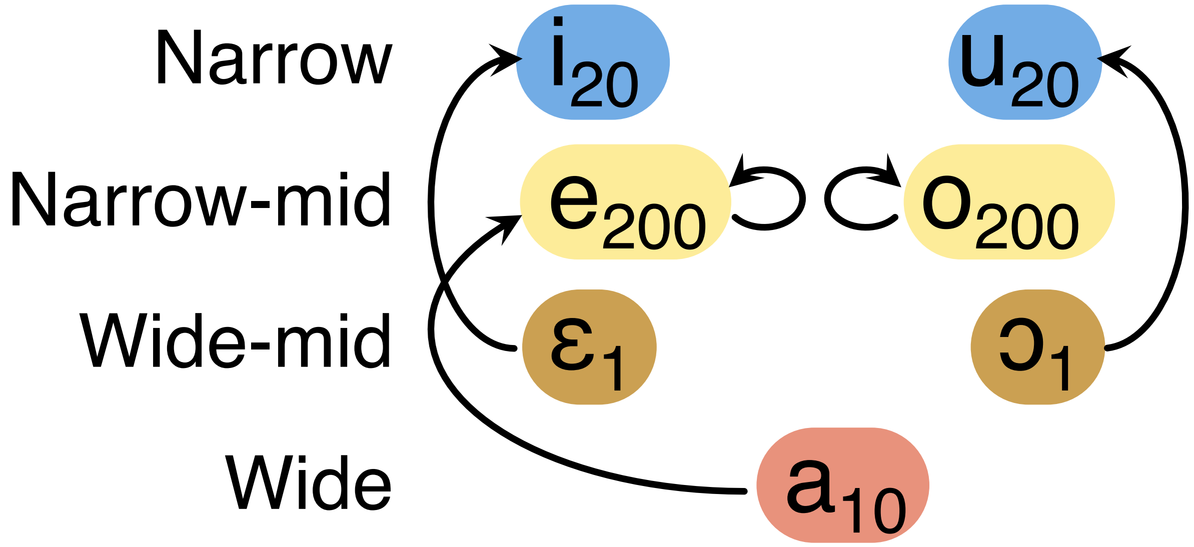


- Mid-high vowel [e] derived by blending $/\varepsilon/_1$ and $/i/_2$:



Gestural Blending for Saltatory Harmony?

With extreme enough strength values, saltatory height harmony can also be generated by the Gestural Harmony Model



Saltatory Height Harmony: Why Such Extreme Strengths?

Triggering full assimilation and resisting full assimilation depend on *overpowering* relationships between blended gestures:

- For assimilation of X to Y, Y's gestural strength must be exponentially higher than that of X (e.g., 10x)

- For Z to resist assimilation to Y, Z's gestural strength must be exponentially higher than that of Y

$$Z_{100} \mapsto Y_{10} \mapsto X_{1}$$

Saltatory Height Harmony: Why Such Extreme Strengths?

- Chain-shifting height harmony requires only one overpowering relation between vowels: high vowels overpower high-mid vowels to trigger full assimilation

/i/, /u/ ↦ /e/, /o/

- Saltatory height harmony requires two overpowering relations between vowels:
  - High-mid vowels overpower high vowels to fully resist raising
  - High vowels overpower low-mid vowels to trigger full assimilation

/e/, /o/ ↦ /i/, /u/ ↦ /ɛ/, /ɔ/

Simulating Learning with the Gestural Gradual Learning Algorithm

Learnability Affects Phonological Typology

- Learnability gradiently shapes typological frequency of phonological patterns (Hayes & Wilson 2008; Moreton & Pater 2012; Staubs 2016; Hughto 2019; O'Hara 2021)

- A pattern that is more difficult to learn is more likely to change across generations, becoming typologically underrepresented

  - Saltatory harmony requires much more data to be correctly learned than chain-shifting harmony
  - Saltatory harmony is far more likely to change across generations and disappear

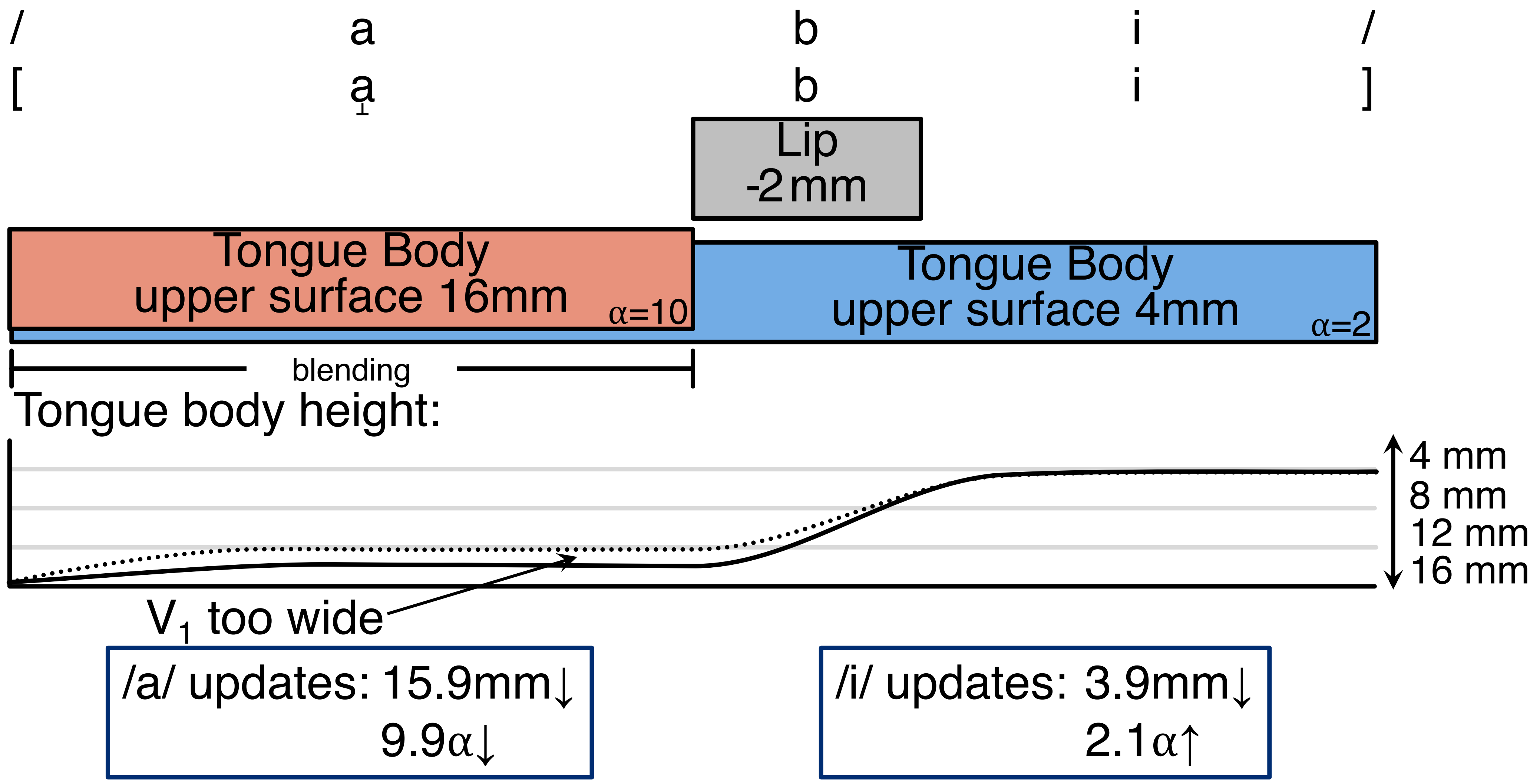
Gestural Gradual Learning Algorithm

- Error-driven, online learning algorithm used to model learning of phonological representations
- Learner is provided knowledge that high vowels trigger raising of preceding vowels via gestural overlap
- Task: set constriction degree targets and blending strengths for vowel and dorsal consonant gestures such that learner reproduces teacher's vowel raising pattern

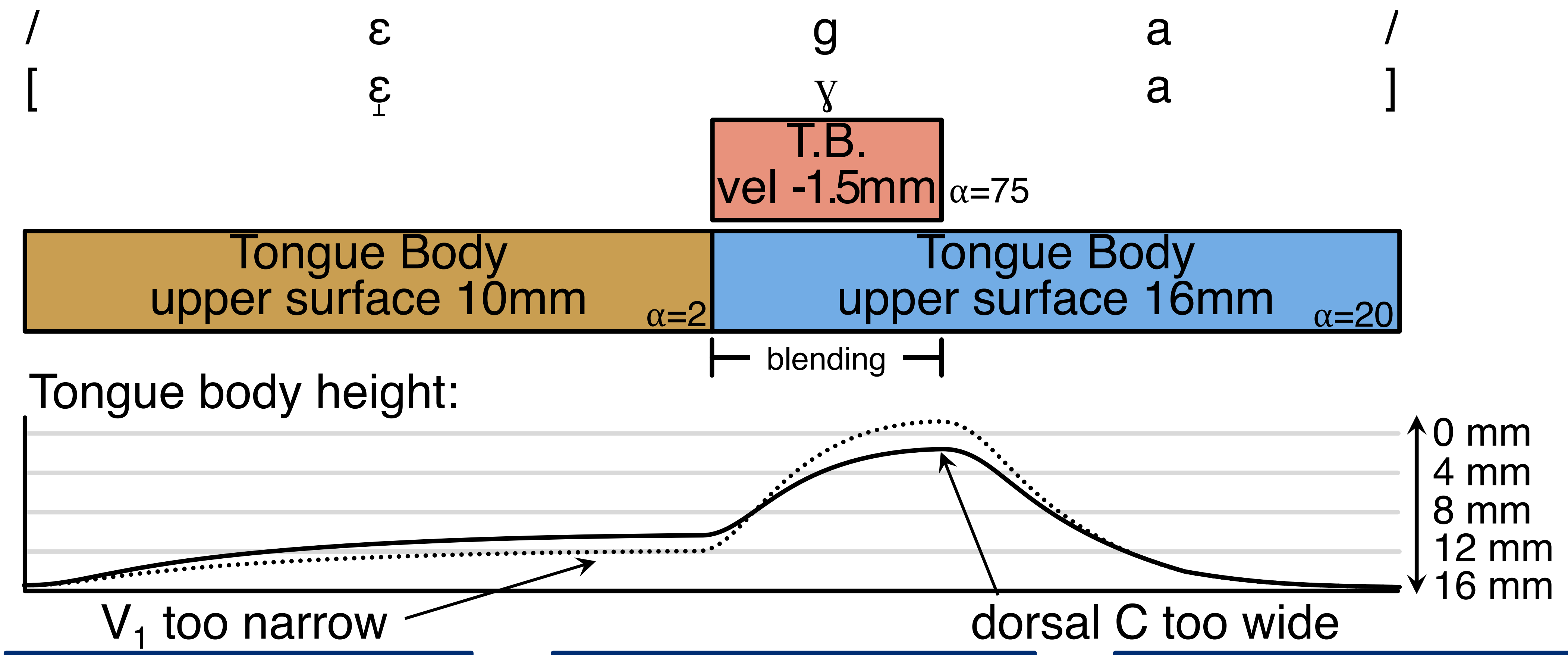
The Gestural Gradual Learning Algorithm

1. Initialize each gesture in learner's inventory with target constriction degree of 16 mm (i.e., all vowels start as [a]) and random blending strength (between 1 and 20)
2. On each training iteration, randomly generate $(V_1)CV_2$ sequence
3. Check for gestural blending:
   a. If V_2 is a trigger of harmony, it overlaps V_1, resulting in blending
   b. V_2 overlaps preceding C. If C is dorsal /g/, following V overlaps it, resulting in blending
4. If learner produces error (segment with constriction degree farther than 0.2 mm from teacher's production):
   a. Update constriction degree target of learner's tongue body gesture to produce a constriction degree that better matches teacher's output
   b. In cases of blending: update strength of learner's tongue body gestures to produce a constriction degree that better matches teacher's output

Sample Training Iteration #1



Sample Training Iteration #2



/ε/ update: 10.1mm↑

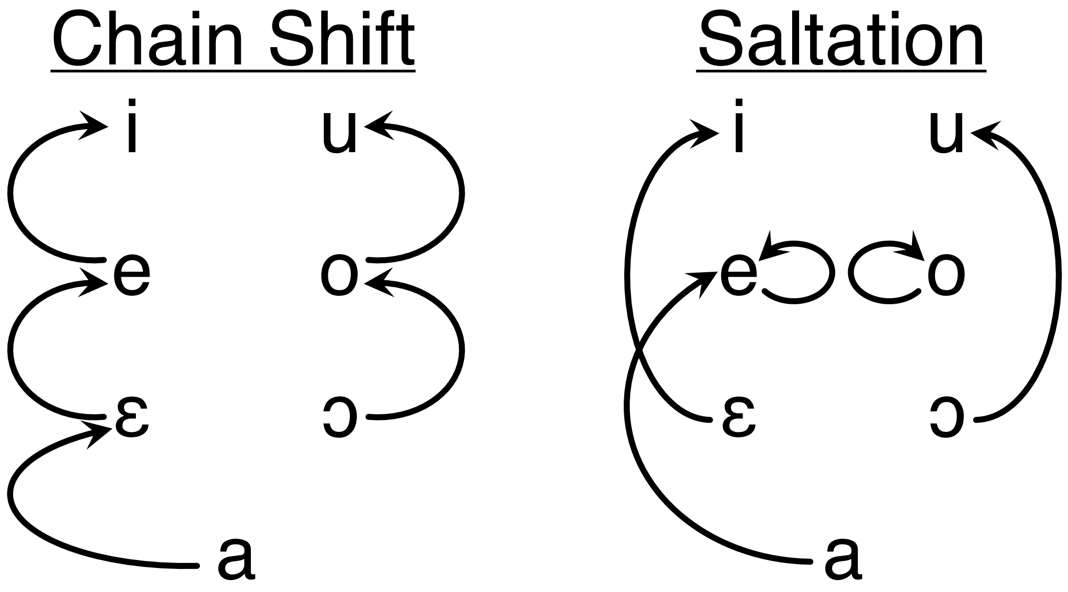
/g/ updates: -1.6mm↓
75.1α↑

/a/ updates: 15.9mm↓
19.9α↓

Our Models

- Patterns tested:
  - Four-height chain-shifting raising before high vowel trigger (Nzebi-like)
  - Four-height saltatory (two-step) raising before high vowel trigger (unattested)

- Ran 100 models of each type until convergence



Results: Learned Constriction Degrees and Blending Strengths for Chain-Shifting Harmony

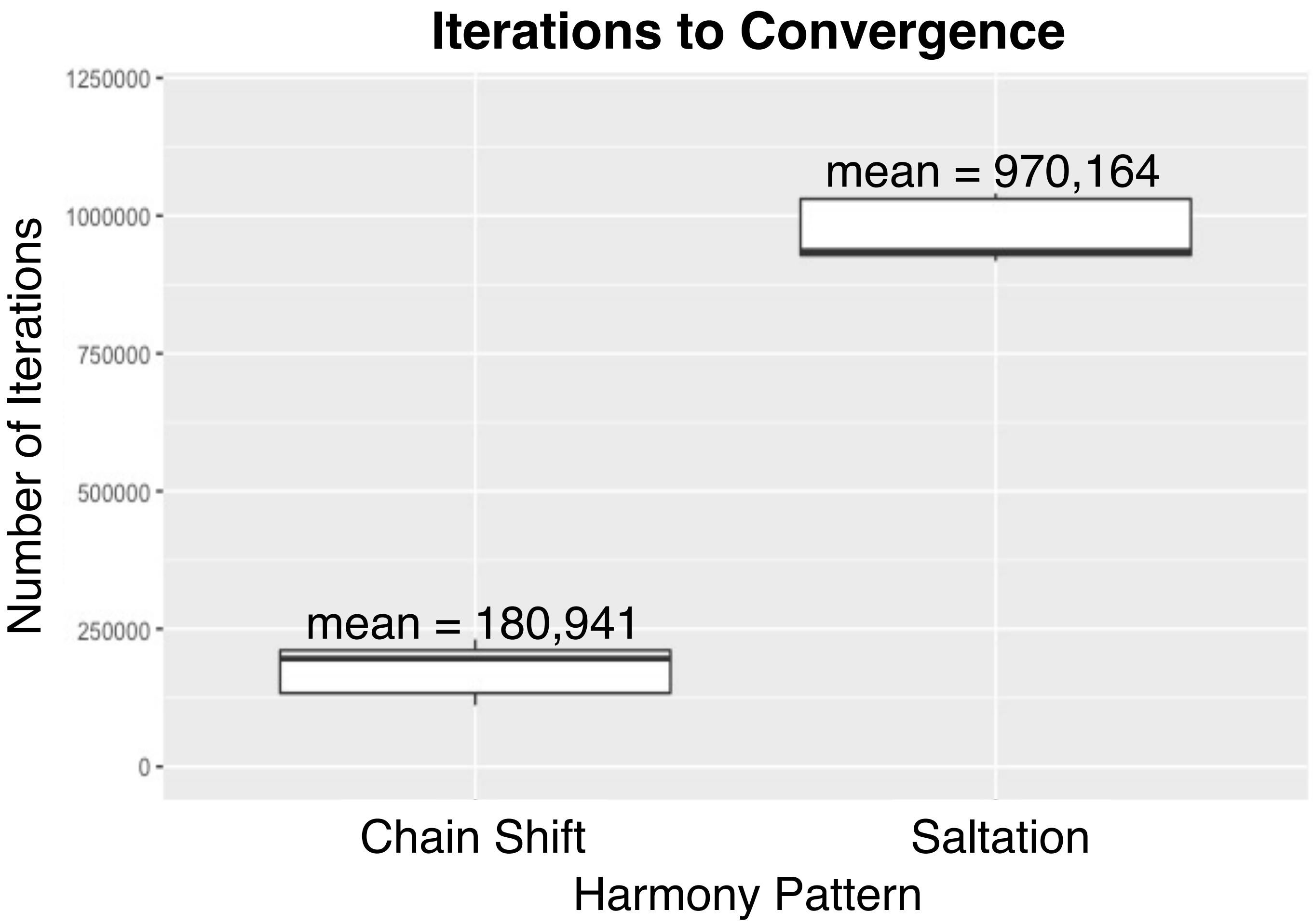
Segment	Blending Strength	Constriction Degree
/i/	11.44	3.84
/u/	11.49	3.84
/e/	1.02	7.80
/o/	1.03	7.80
/ɛ/	11.14	12.10
/ɔ/	11.14	12.10
/a/	22.20	16.10
/g/	379.64	-2.00

Results: Learned Constriction Degrees and Blending Strengths for Saltatory Harmony

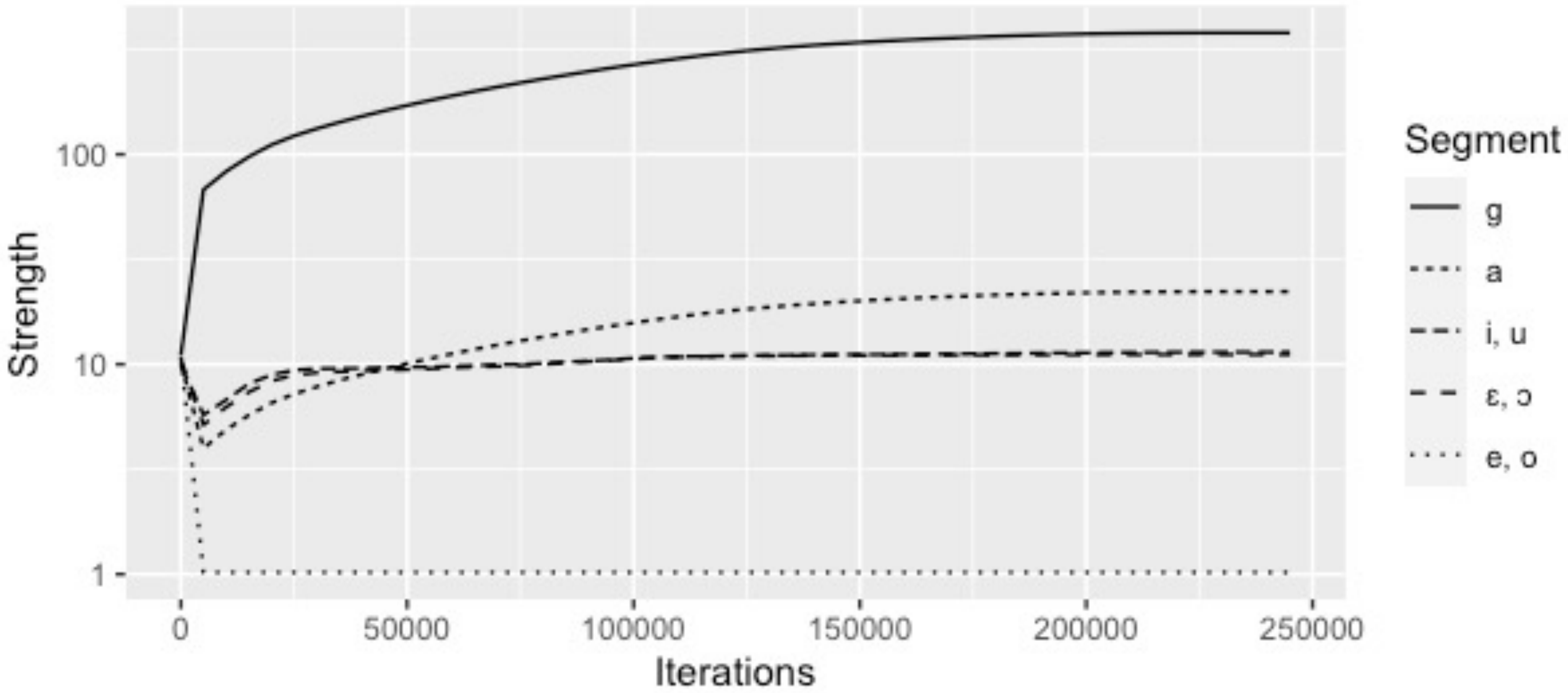
Segment	Blending Strength	Constriction Degree
/i/	26.39	3.90
/u/	26.39	3.90
/e/	343.47	8.10
/o/	343.47	8.10
/ɛ/	1.02	11.80
/ɔ/	1.02	11.80
/a/	12.76	16.08
/g/	3,125.85	-2.00

Results: Time to Model Convergence

- Chain-shifting height harmony models converged substantially faster than saltatory harmony models
- Saltation takes ~5.3 times as many iterations to learn
- Saltation is harder to learn, making it more likely to be mis-learned across generations and become less frequent typologically



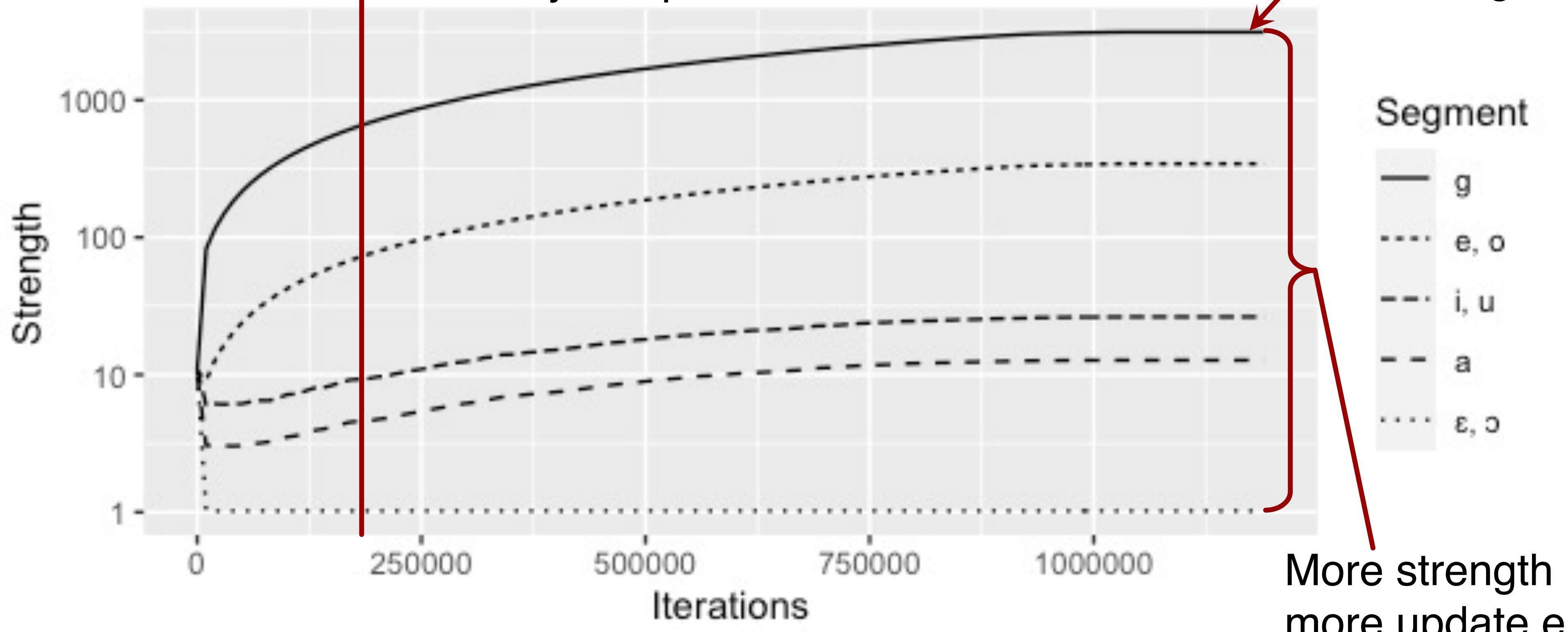
Learning Blending Strengths in Chain-Shifting Height Harmony



Learning Blending Strengths in Saltatory Height Harmony

Chain-shifting harmony learned by this point

More extreme strengths take longer to reach



More strength ratios → more update errors → more updates necessary

Saltation, Overpowering Relations, and Rate of Learning

<u>Chain Shift</u>

/g/

↧

/i/, /u/

↧

/e/, /o/

<u>Saltation</u>

/g/

↧

/e/, /o/

↧

/i/, /u/

↧

/ɛ/, /ɔ/

More overpowering relationships in a pattern

↓

More extreme strengths necessary

↓

More strength updates necessary during model training

Summary

- Gestural Harmony Model generates both chain-shifting and saltatory height harmony

- Learning models based on Gestural Gradual Learning Algorithm show that chain-shifting harmony is easier/faster to learn

- Learnability affects typology: patterns that are easier to learn (e.g. chain-shifting height harmony) are predicted to be more robustly attested crosslinguistically

Generating & Learning Chain-Shifting and Saltatory Height Harmony in Featural Frameworks

Chain Shifts and Saltations in Harmonic Grammar

- Chain shifts and saltations cannot be generated in Harmonic Grammar using the faithfulness constraints of Correspondence Theory (e.g., IDENT(F)-IO)

- Cumulative constraint interaction ('ganging') of faithfulness in Harmonic Grammar does not rule out multistep raising and cannot generate chain shifts (Albright et al. 2008; Farris-Trimble 2008)

- Ganging of markedness and faithfulness in Harmonic Grammar does not favor multistep raising and cannot generate saltations (White 2013; Hayes & White 2015; Smith to appear)

Chain Shifts in Harmonic Grammar with IDENT

(Albright et al. 2008; Farris-Trimble 2008)

Input: /e-i/	HARMONY(Height) w=3	IDENT(high) w=2	IDENT(ATR) w=2	ℋ
☞ a. [i-i]		-1		-2
b. [e-i]	-1			-3

Input: /ɛ-i/	HARMONY(Height) w=3	IDENT(high) w=2	IDENT(ATR) w=2	ℋ
☹ a. [i-i]		-1	-1	-4
b. [e-i]	-1		-1	-5
c. [ɛ-i]	-2			-6

Intended winner → b. [e-i]

Shared violation, no *asymmetric tradeoff* (Pater 2009)

Saltation in Harmonic Grammar with IDENT

(White 2013; Hayes & White 2015; Smith to appear)

Input: /e-i/	IDENT(high) w=5	HARMONY(Height) w=4	IDENT(ATR) w=2	$\mathcal{H}$
a. [i-i]	-1			-5
☞ b. [e-i]		-1		-4

Input: /ɛ-i/	IDENT(high) w=5	HARMONY(Height) w=4	IDENT(ATR) w=2	$\mathcal{H}$
a. [i-i]	-1		-1	-7
☹ b. [e-i]		-1	-1	-6
c. [ɛ-i]		-2		-8

Intended winner → a. [i-i]

Shared violation, no asymmetric tradeoff

Rethinking Faithfulness Constraints

(Tesar 2013; Magri 2018ab)

- Ability to generate underapplication opacity is characteristic of violation profiles of individual faithfulness constraints, not constraint interaction (Tesar 2013; Magri 2018ab)

- Violation profile of IDENT(F)-IO:

IDENT(/X/→Y→[Z]) = IDENT(/X/→[Y]) + IDENT(/Y/→[Z])

- IDENT violations incurred by less-faithful mapping are exactly those incurred by more-faithful component mappings

Rethinking Faithfulness Constraints

(Tesar 2013; Magri 2018ab)

- Chain shift requires constraint C that penalizes extra-unfaithful mapping *more* than its component more-faithful mappings:

$$C(/X/\rightarrow Y\rightarrow[Z]) > C(/X/\rightarrow[Y]) + C(/Y/\rightarrow[Z])$$

- Saltation requires constraint S that penalizes extra-faithful mapping *less* than its component more-faithful mappings:

$$S(/X/\rightarrow Y\rightarrow[Z]) < S(/X/\rightarrow[Y]) + S(/Y/\rightarrow[Z])$$

Rethinking Faithfulness Constraints

Alternative formulations of faithfulness fit violation profiles necessary to generate derivationally opaque chain shifts and saltations:

- Scalar and categorical faithfulness to scalar feature values (Gnanadesikan 1997)
- Distinct faithfulness constraints (*MAP(X,Y)) for all input-output mappings (Zuraw 2007; White 2013; Hayes & White 2015)

Feature Scales Theory
(Gnanadesikan 1997)

- Feature Scales Theory: specific feature values represented by position on feature scale

- Ternary vowel height scale:

  High = 1 Mid = 2 Low = 3

- Quaternary vowel height scale:

  High = 1 High-Mid = 2 Low-Mid = 3 Low = 4

Scalar and Categorical Faithfulness

(Gnanadesikan 1997)

Multiple versions of the featural faithfulness constraint IDENT:

- IDENT(X): Given an input segment A and its correspondent output segment B, then A and B must have values on scale X that are identical.
- IDENT-ADJACENT(X): Given an input segment A and its correspondent output segment B, then A and B must have values on scale X that are identical or adjacent.
- IDENT-PARTIAL(X): Given an input segment A and its correspondent output segment B, then A and B must have values on scale X that are identical, adjacent, or within-two.

Violation Profiles of Scalar and Categorical Faithfulness Constraints

Input: /a/	IDENT(Height)	IDENT-ADJ(Height)	IDENT-PART(Height)
a. [i]	*	*	*
b. [e]	*	*	
c. [ɛ]	*		
d. [a]			

IDENT(X) penalizes slightly unfaithful mappings just as much as very unfaithful mappings

IDENT-ADJ(X) and IDENT-PART(X) characterize mappings as 'faithful enough' or 'too unfaithful' rather than 'faithful' or 'unfaithful'

Generating a Chain Shift with Scalar Faithfulness

One-step raising does not violate IDENT-ADJ and IDENT-PART, but does better satisfy harmony-driving ASSIM constraints:

Input: /a-i/	IDENT-ADJ(Ht.) w=3	IDENT-PART(Ht.) w=2	ASSIM-PART(Ht.) w=2	ASSIM-ADJ(Ht.) w=2	ASSIM(Ht.) w=2	IDENT(Ht.) w=1	ℋ
a. [i-i]	-1	-1				-1	-6
b. [e-i]	-1				-1	-1	-6
☞ c. [ɛ-i]				-1	-1	-1	-5
d. [a-i]			-1	-1	-1		-6

Input: /ɛ-i/	IDENT-ADJ(Ht.) w=3	IDENT-PART(Ht.) w=2	ASSIM-PART(Ht.) w=2	ASSIM-ADJ(Ht.) w=2	ASSIM(Ht.) w=2	IDENT(Ht.) w=1	ℋ
a. [i-i]	-1					-1	-4
☞ b. [e-i]					-1	-1	-3
c. [ɛ-i]				-1	-1		-4

Generating Saltation with Categorical Faithfulness

IDENT(Height) penalizes all raising equally, motivating two-step raising to satisfy harmony-driving ASSIM constraints:

Input: /ɛ-i/	IDENT(Ht.) w=3	IDENT-PART(Ht.) w=3	ASSIM-ADJ(Ht.) w=3	ASSIM(Ht.) w=2	ASSIM-PART(Ht.) w=2	IDENT-ADJ(Ht.) w=1	$\mathcal{H}$
☞ a.[i-i]	-1					-1	-4
b.[e-i]	-1			-1			-5
c.[ɛ-i]			-1	-1			-5

Input: /e-i/	IDENT(Ht.) w=3	IDENT-PART(Ht.) w=3	ASSIM-ADJ(Ht.) w=3	ASSIM(Ht.) w=2	ASSIM-PART(Ht.) w=2	IDENT-ADJ(Ht.) w=1	$\mathcal{H}$
a.[i-i]	-1						-3
☞ b.[e-i]				-1			-2

Distinct Faithfulness

- *MAP constraints (Zuraw 2007; White 2013; Hayes & White 2015) assign distinct violation profiles to every input-output mapping

- *MAP(X,Y): Assign a violation when a segment that is a member of class X is in correspondence with a segment of class Y.

Generating a Chain Shift with Distinct Faithfulness

*MAP(a,i), *MAP(a,e), and *MAP(ɛ,i) penalize only multi-step raising:

Input: /a-i/	*MAP(a,i) w=6	*MAP(a,e) w=4	*MAP(ɛ,i) w=4	HARMONY(high) w=2	HARMONY(ATR) w=2	HARMONY(low) w=2	$\mathcal{H}$
a. [i-i]	-1						-6
b. [e-i]		-1		-1			-6
☞ c. [ɛ-i]				-1	-1		-4
d. [a-i]				-1	-1	-1	-6

Input: /ɛ-i/	*MAP(a,i) w=6	*MAP(a,e) w=4	*MAP(ɛ,i) w=4	HARMONY(high) w=2	HARMONY(ATR) w=2	HARMONY(low) w=2	$\mathcal{H}$
e. [i-i]			-1				-4
☞ f. [e-i]				-1			-2
g. [ɛ-i]				-1	-1		-4

Generating Saltation with Distinct Faithfulness

*MAP(e,i) penalizes only one-step raising from high-mid to high:

Input: /ɛ-i/	*MAP(e,i) w=2	HARMONY(high) w=1	HARMONY(ATR) w=1	*MAP(ɛ,e) w=1	*MAP(ɛ,i) w=1	$\mathcal{H}$
☞ a. [i-i]					-1	-1
b. [e-i]		-1		-1		-2
c. [ɛ-i]		-1	-1			-2

Input: /e-i/	*MAP(e,i) w=2	HARMONY(high) w=1	HARMONY(ATR) w=1	*MAP(ɛ,e) w=1	*MAP(ɛ,i) w=1	$\mathcal{H}$
c. [i-i]	-1					-2
☞ b. [e-i]		-1				-1

Constraint Weight Learning in Maximum Entropy Harmonic Grammar

- Error-driven learner of constraint weighting in Maximum Entropy Harmonic Grammar (Goldwater & Johnson 2003; Jäger 2007)

- Learning of constraint weights based on Perceptron update rule (Rosenblatt 1958; Boersma & Pater 2016)

- Time to convergence calculated by number of iterations until Maximum Entropy grammars assigned 90% probability to intended winning candidates in target grammar

Learning Simulation Setup

- Two sets of simulations based on constraint sets capable of generating chain shifts and saltations:
  - Scalar and categorical markedness and faithfulness from Feature Scales theory
  - Harmony-driving markedness constraints and distinct *MAP faithfulness constraints

- Greater initial weightings for *Map constraints penalizing more steps of raising

- Three initial constraint weighting conditions for distinct faithfulness constraint simulations
  - M > F: Harmony-driving markedness over *Map faithfulness
  - M ≈ F: Harmony-driving markedness equal to lowest-weighted *Map faithfulness
  - M < F: Harmony-driving markedness below *Map faithfulness

Learning Simulation Setup

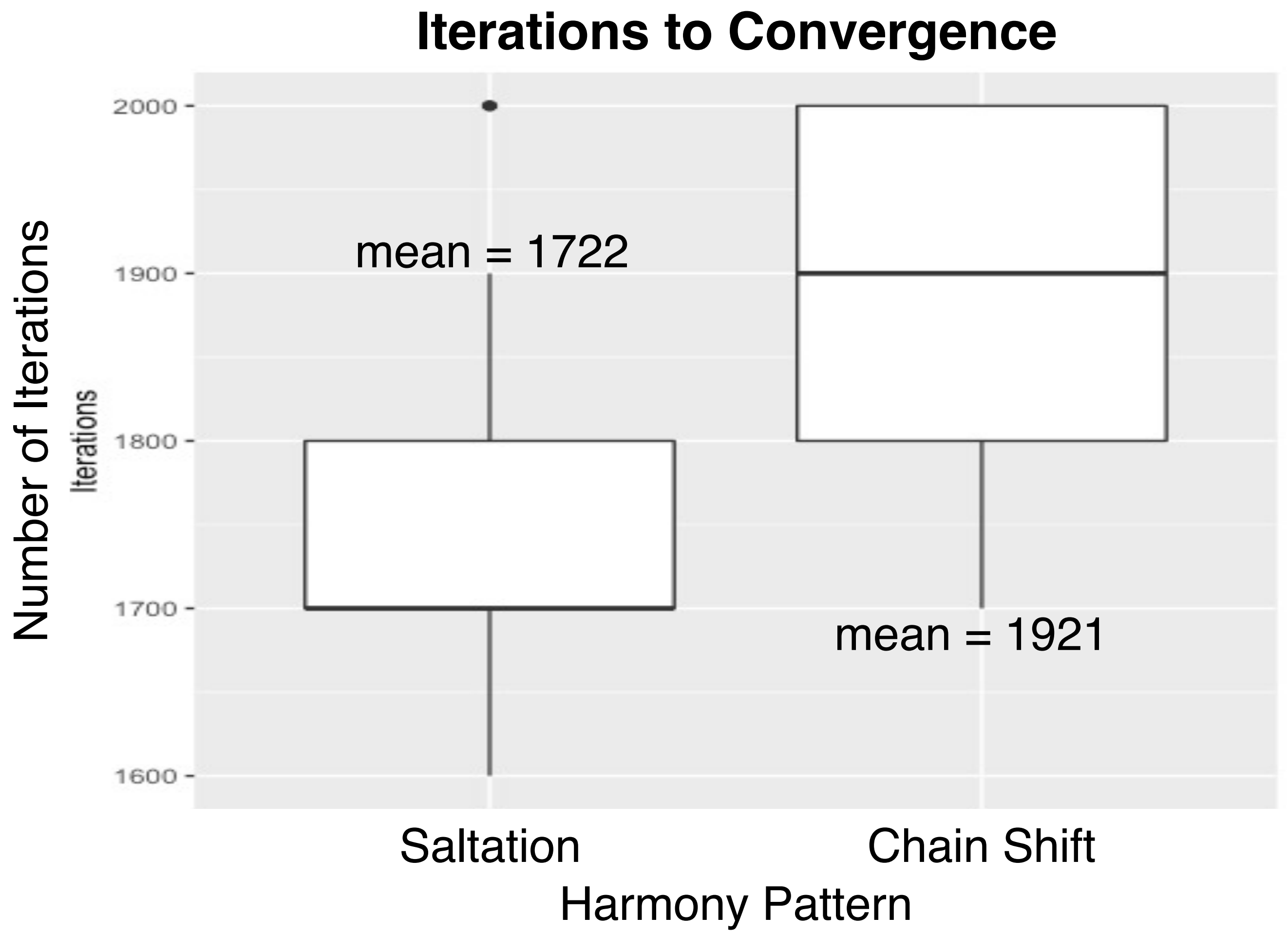
- 100 simulations per pattern type (chain-shifting versus saltatory) per constraint set (scalar/categorical versus distinct) per initial constraint weighting condition

- Various numbers of learning trials per generation, depending on overall pattern learnability in each model type
  - 2,200 learning trails per generation for scalar/categorical faithfulness
  - 3,600 learning trials per generation for distinct faithfulness models with M > F initial weighting condition
  - 2,000 learning trails per generation for other distinct faithfulness models

Scalar/Categorical Faithfulness Results: Time to Model Convergence

- Chain-shifting height harmony models converged more slowly than saltatory harmony models

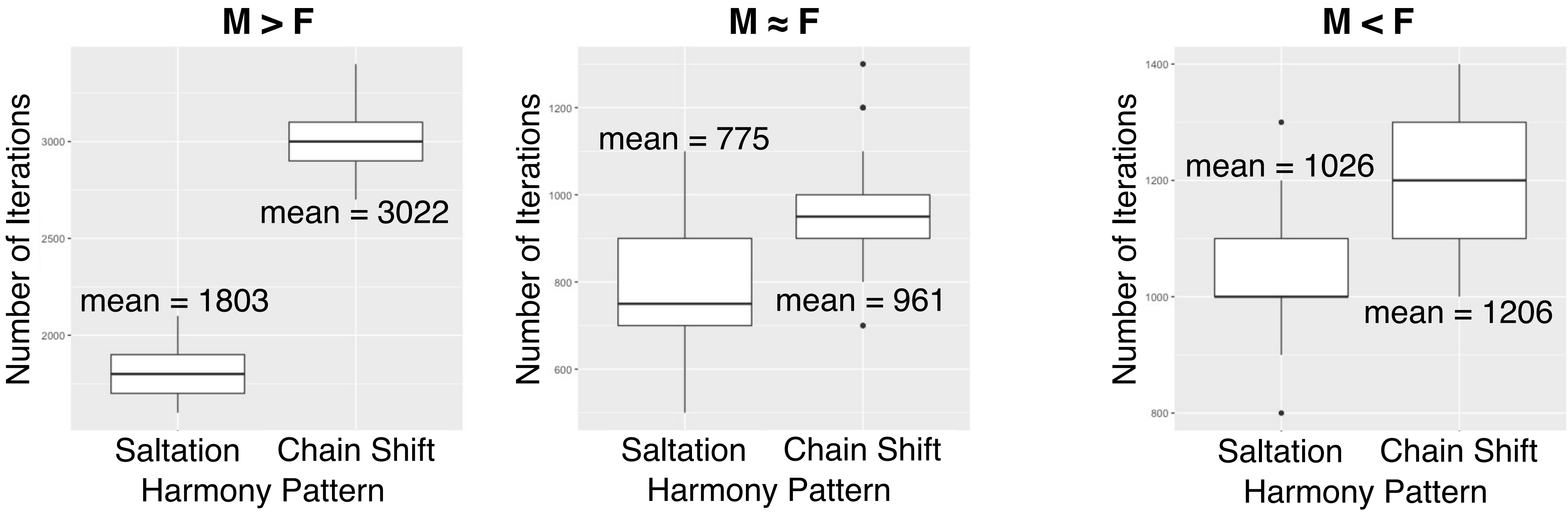
- Incorrectly predicts that chain-shifting height harmony should be harder to learn



Distinct Faithfulness Results: Time to Model Convergence

In all initial weighting conditions, chain-shifting height harmony models converged more slowly than saltatory harmony models

Iterations to Convergence



Generational Stability Model

(O'Hara 2021)

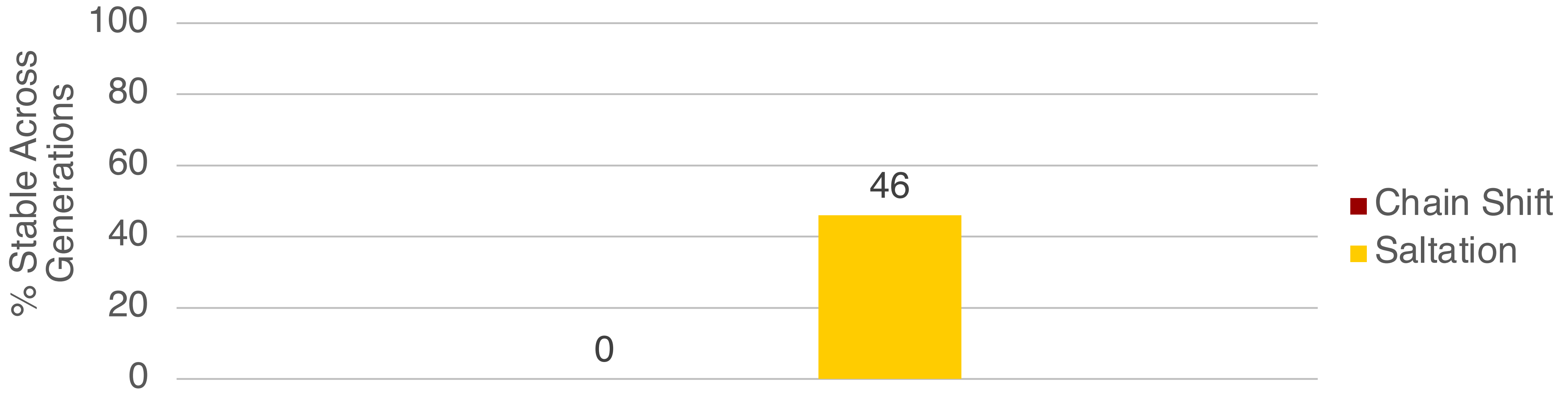
- Iterated learning model (Kirby & Hurford 2002; Staubs 2014; Hughto 2020):
  - Learner of a Maximum Entropy Harmonic Grammar trained by comparing its productions to its teacher's
  - Learner matures and becomes teacher for new learner of next generation
  - Imperfect learning at each generation leads to pattern changes across generations

- Models transmissibility of phonological patterns: greater cross-generational stability leads to more robust attestation

- Trained iterated versions of all models for twenty generations each

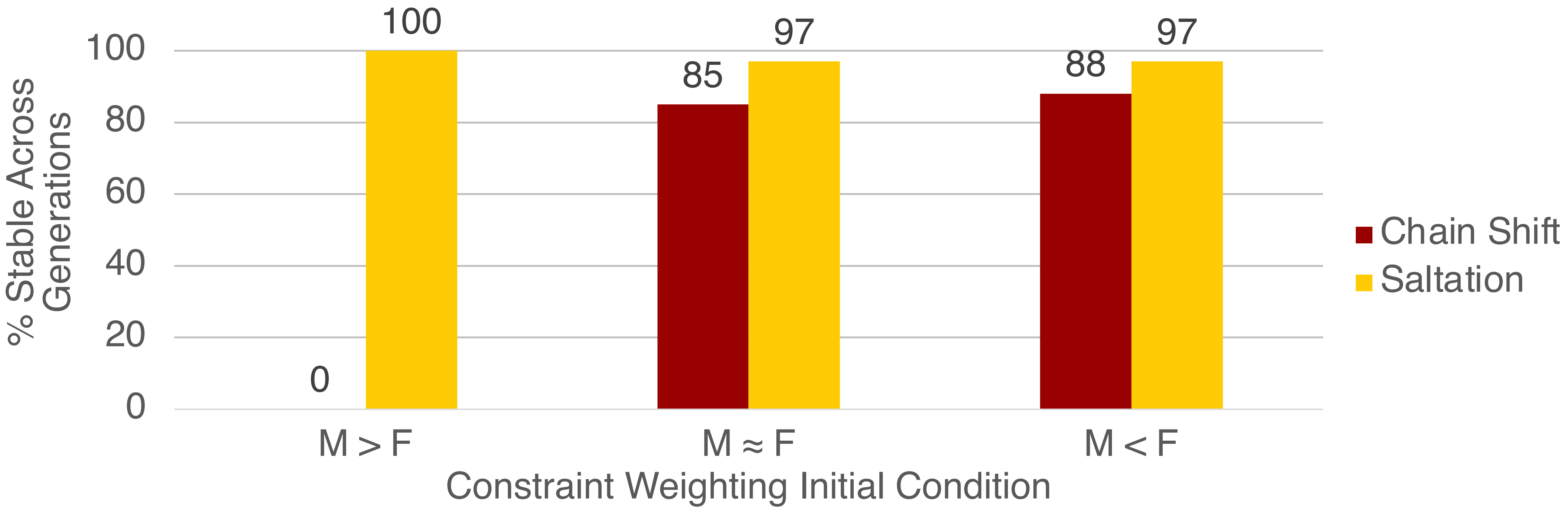
Results: Scalar and Categorical Faithfulness

Generational stability of patterns using scalar and categorical faithfulness constraints over feature scales:



Results: Distinct Faithfulness

Generational stability of patterns using distinct faithfulness constraints:



Summary

- Two feature-based approaches to generating underapplication opacity in Harmonic Grammar

- Both scalar/categorical faithfulness and distinct faithfulness incorrectly predict:
  - Saltatory height harmony is easier/faster to learn and more stably transmitted across generations
  - Saltatory height harmony should be more widely attested crosslinguistically than chain-shifting height harmony

Conclusion

Conclusion

- Gestural Harmony Model is sufficiently powerful to generate apparently derivationally opaque chain-shifting and saltatory height harmony patterns

- Featural frameworks that eschew Correspondence Theory-based faithfulness constraints also powerful enough to generate derivationally opaque chain shifts and saltations

- Results of learning simulations using Gestural Gradual Learning Algorithm correctly indicate a typological bias favoring attested chain-shifting harmony and against saltatory harmony

- Results of learning simulations in featural frameworks incorrectly indicate a bias favoring saltatory harmony and against chain-shifting harmony