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4aSC5. A motor differentiation model for liquid substitutions in children's speech

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Studies of lip-jaw coordination in children have shown a lack of motor differentiation between anatomically coupled articulators in young children's speech [Green & al. 2000, JSLHR 43: 239-255]. A model is described in which children contending with their developing motor systems generally strive to reduce the degrees of freedom of complex anatomical structures (e.g., the tongue). The claim is pursued that segmental substitutions (e.g., /w/ replacing /r/ or /l/) are the result of specific compensation strategies which aim to simplify the complexity of the articulatory task. The proposal that gestural simplification may dictate substitution strategies for liquid consonants has been suggested previously [Studdert-Kennedy & Goldstein 2003, Language Evolution, Oxford U. Pr. 235-254]. It is proposed here that gestural simplification may be achieved via one of two basic mechanisms: gestural omission and stiffening (and hence merger), and that these two mechanisms account for all of the commonly attested substitutions for English /r/ and /l/. Supporting data are presented from ultrasound studies of: postvocalic /r/ production of an 11-month-old female speaker of English, liquid production of a group of 3-5-year-old speakers of English, and liquid production and substitutions in the speech of adolescent speakers of English with speech and hearing disorders.

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A Motor Differentiation Model for Liquid Substitutions: English /r/ Variants in Normal and Disordered Acquisition

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INTRODUCTION

It has been shown that infants simplify arm reaching tasks by locking joints (Berthier & Keen 2006), thereby reducing kinematic degrees of freedom. Similar simplification can be seen in lip-jaw coordination in children's speech (Green & al. 2000). Both results suggest a developmental trajectory of increasing differentiation between anatomically coupled articulators in young children's motor behavior. Previous literature has described at least one case of failure to successfully differentiate between independently controllable parts of the tongue. Based on a case study of a child with APD whose production of /d/ involved constriction of the tongue against the entire palate (Gibbon & al. 1995), Gibbon (1999) defines lingual differentiation as the "ability of different tongue systems to function in a quasi-independent manner."

The goals of this paper are two-fold. The first is to describe a model in which children's developing speech motor systems strive to reduce the degrees of freedom of complex anatomical structures, specifically with regard to the tongue. The second is to show that common segmental substitutions (e.g., [w] for /r/ or /l/) can be described as being the result of specific strategies that aim to simplify lingual degrees of freedom.

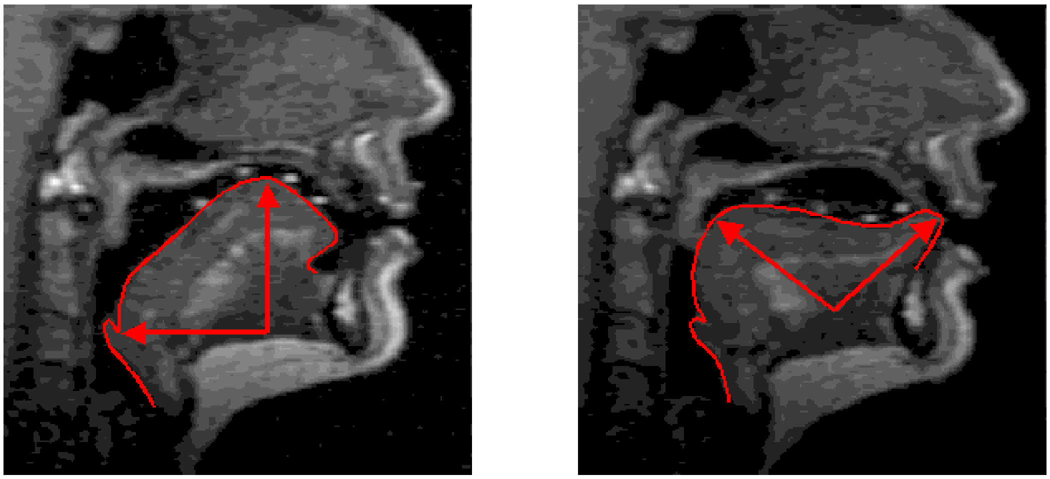
Liquids in Acquisition

English liquids /r/ and /l/ are typically later-acquired segments (Prather 1975, Locke 1983, Ingram 1989, Bernhardt & Stemberger 1998, etc.). In language development, substitutions often result, e.g.:

Common substitutions for /r/:
- Prevocalic: [w], [j]; e.g., *rabbit* [wæbɪt, jæbɪt])
- Postvocalic/syllabic: [ə], [ʊ], [i]; e.g., *ear* [iə] *car* [kaʊ, kai]

Common substitutions for /l/:
- Prevocalic: [w], [j], [d]; e.g., *lady* [weɪdi, jeɪdi, deɪdi])
- Postvocalic: [o], [ʊ]; e.g., *feel* [fio, fiʊ]

While many early-acquired sounds in English (e.g., /w/, /m/, /t/) require coordination of multiple independent articulatory events (or "gestures"), liquids are more 'lingually complex' than other sounds. In English, only /r/ and /l/ have two distinct lingual gestures, as shown in Figure 1 (Studdert-Kennedy & Goldstein 2003, McGowan 2004), with the possible exception of independent central and lateral margin control for some sibilant consonants (Stone & al. 1992), which are also acquired late. Data collection methods used to acquire MRI images are described in Whalen, Kang, Magen, Fulbright & Gore 1999 (subject CB).



(a) (b)

FIGURE 1. Midsagittal MRI cross-sections showing two lingual constrictions for a) /r/ and b) /l/

Proposal

In the current paper, it is proposed that: (1) speech development follows a trajectory of motor differentiation, and consequently, typically later acquisition of segments with multiple lingual constrictions, (2) the common substitutions described above result from reduction of lingual complexity, and (3) gestural simplification may be achieved via one of two basic mechanisms: gestural omission and gestural merger/averaging; these two mechanisms account for all of the commonly attested substitutions for English /r/ and /l/.

The model described here posits several principles that apply to speech development:

i. Complexity: Learning to differentiate anatomically coupled articulators (e.g., lip-jaw, tongue-tongue) is more difficult than learning to differentiate non-coupled articulators (e.g., lip-tongue, tongue-velum).

ii. Transparency: Many segments in a language are little affected by lack of oral motor differentiation (e.g., an undifferentiated lip & jaw does not prevent /p/ closure).

iii. Simplification: The entire tongue moves essentially as a single unit until differentiated, making only one constriction at a time (Note: if simplification is part of the underlying control structure, rather than simple lack of differentiation, it may be realized via mechanical stiffening; see below).

This model assumes that speakers are aware of the intended articulatory targets, although there may be confusion of acoustically close targets by some speakers, especially those with identifiable hearing impairment.

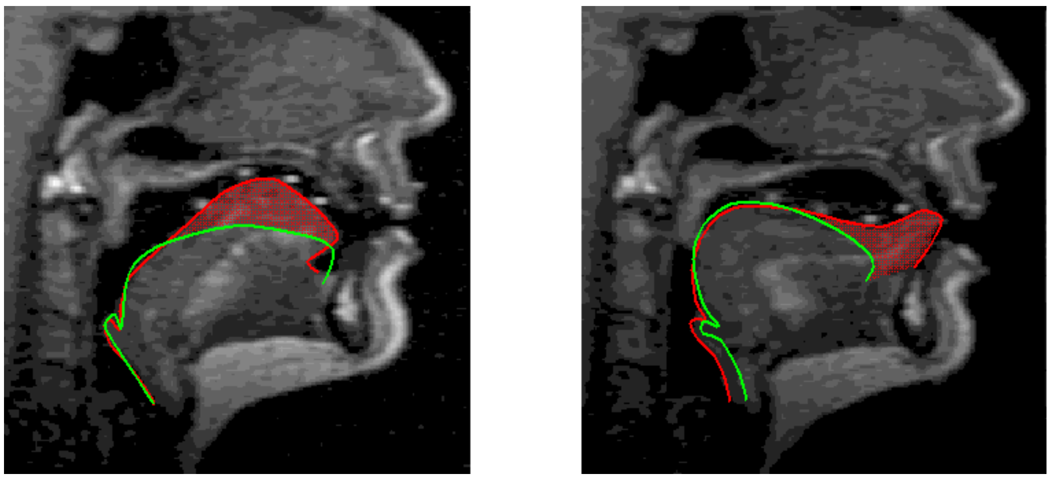
The proposed model implies a variety of predictions for different populations. First, young children and motor delayed speakers should employ substitutions that are lingually less "complex" than l/r; the same constraints should apply as well to other production tasks that may require lingual differentiation (e.g., consonant clusters). Second, the model proposes that the tongue does not "automatically" differentiate as part of general physical development, as in cases where there is insufficient perceptual input to require the development of lingual differentiation (e.g., hearing-impaired, L2 learners whose first language does not require English-like lingual differentiation for certain targets). Third, in L1 acquisition of languages other than English, we expect to see late acquisition of other lingually complex sounds and early acquisition of liquids that are lingually simplex.

SIMPLIFICATION STRATEGIES

The present proposal suggests that complex tongue shapes may be simplified by speakers in at least two ways: Gestural Omission and Stiffening. Both strategies are illustrated below (note that the examples in this subsection all show overlaid tongue tracings from different target sounds taken from normal adult speech).

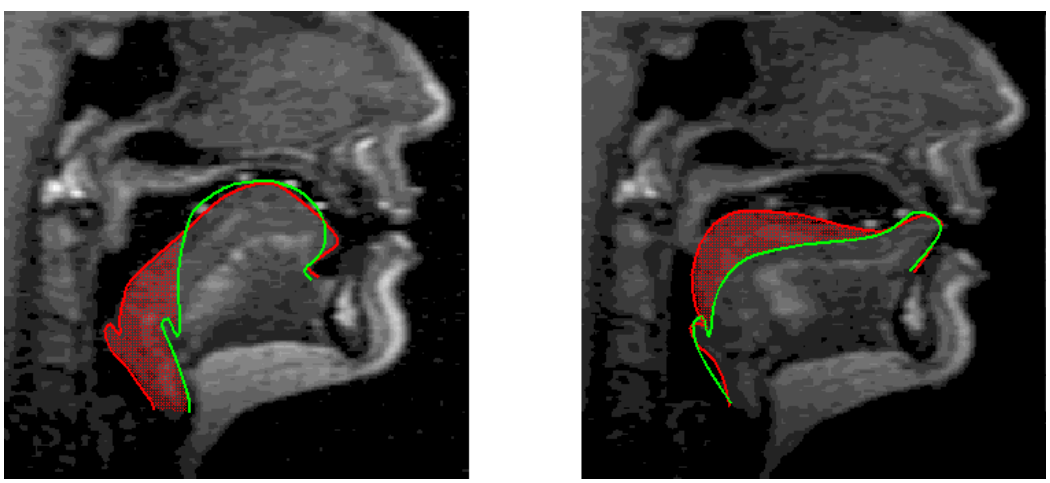
Gestural Omission

In gestural omission, one of the two expected gestures is absent, resulting in a single oral constriction. Figures 3 and 4 illustrate loss of anterior and posterior gestures, respectively.



(a) (b)

FIGURE 2. Midsagittal MRI cross-sections illustrating loss of the anterior gesture for a) /r/ (shown in red), resulting in a schwa-like tongue shape (actual schwa tracing overlaid in green), and for b) /l/ (shown in red), resulting in a high, back [w]-like tongue shape (actual [w] tracing overlaid in green).

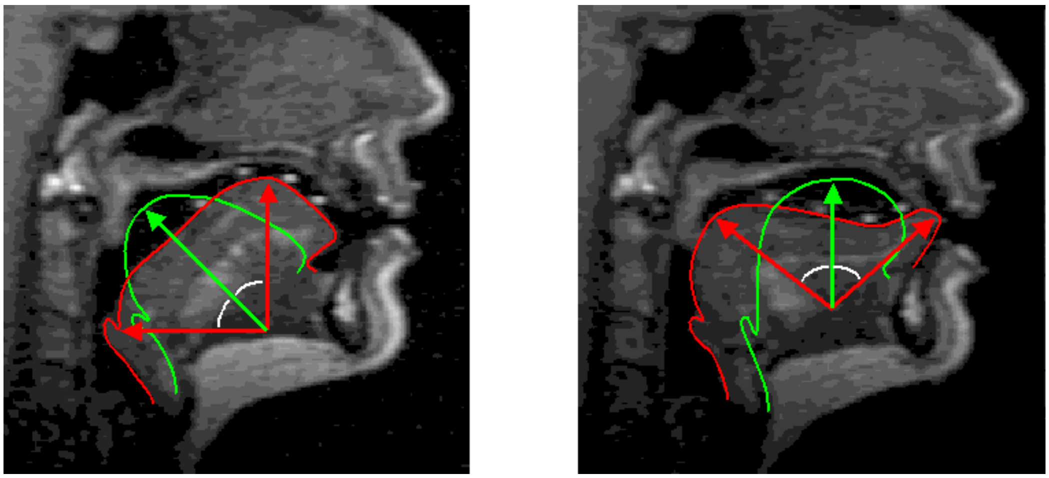


(a) (b)

FIGURE 3. Midsagittal MRI cross-sections illustrating loss of the posterior gesture for a) /r/ (shown in red), resulting in a /j/-like tongue shape (actual [j] tracing overlaid in green), and for b) /l/ (shown in red), resulting in a [d]-like tongue shape (actual [d] tracing overlaid in green).

Gestural Stiffening

In gestural stiffening, the tongue is treated as a single articulator (analogous to joint-locking in arm reaching tasks; Berthier & Keen 2006). This proposal assumes that, at least in some cases, speakers are aware of the intended targets, and merge the two tongue postures into a new third one, as illustrated in Figure 5. Computationally, this could be represented via a weighted averaging of targets. (It is acknowledged additionally that speakers with perceptual bases for their substitutions may produce a single constriction because their intended target has only one gesture.) Whether the actual mechanical stiffness of the tongue is greater in these cases can be tested electrophysiologically, but is beyond the scope of the present paper.



(a) (b)

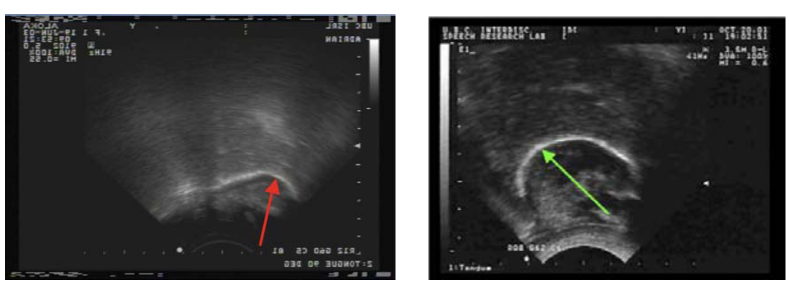
FIGURE 4. Midsagittal MRI cross-sections illustrating gestural stiffening for (a) /r/ (shown in red), resulting in a high, back [w]-like tongue target (actual [w] tracing overlaid in green), and for (b) /l/ (shown in red), resulting in a [j]-like tongue target (actual [j] tracing overlaid in green).

EXAMPLES

Examples of /r/ attempts by speakers from different populations are given below, showing substitutions exhibiting some of the above patterns.

L1 /r/ (Omission and Stiffening)

Example /r/ productions from two normally developing 4-year-old children are shown in Figure 6, illustrating both omission and stiffening. Methods used in collecting these images are described in Oh (2005).

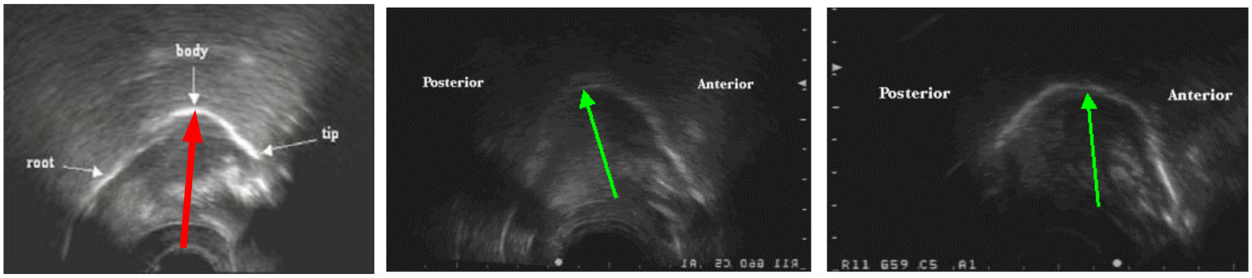


(a) (b)

FIGURE 5. Midsagittal ultrasound cross-sections of two four-year-old children's /r/ attempts showing gestural omission (posterior) (a) AD (4;4) and stiffening (b) LL (4;)

Delayed /r/ (Omission and Stiffening)

Example /r/ productions from three delayed adolescents are shown in Figure 6, illustrating both omission and stiffening.



(a) (b) (c)

FIGURE 6. Midsagittal ultrasound cross-sections showing /r/ attempts showing gestural omission (posterior) by (a) MB (13 yo with /r/-specific delay, possibly with early restricted frenulum; from Modha, Bernhardt, Church & Bacsfalvi in press) and stiffening by (b) VF (14 yo with /r/-specific delay) and (c) ML (12 yo with /r/-specific delay) [VF and ML images from Adler-Bock, Bernhardt, Gick & Bacsfalvi 2007]

Hearing-impaired /r/ (Stiffening)

As can be seen from the sample in Figure 7 below (images from study described in Bernhardt, Gick, Bacsfalvi & Ashdown 2003), all of the hearing-impaired adolescents used solitary gestures for /r/ more consistent with stiffening rather than omission of gestures (although whether there was stiffness in the tongue was not observable). For these speakers, the substitutions were a result of both an inability to perceive the intended target accurately, and to utilize instruction about the use of the anterior portion of the tongue (a mismatch between what they were hearing acoustically and what was asked of them articulatorily). After treatment with ultrasound as visual feedback, they were able to learn /r/, even without accurate acoustic information (see Bernhardt et al., 2003).

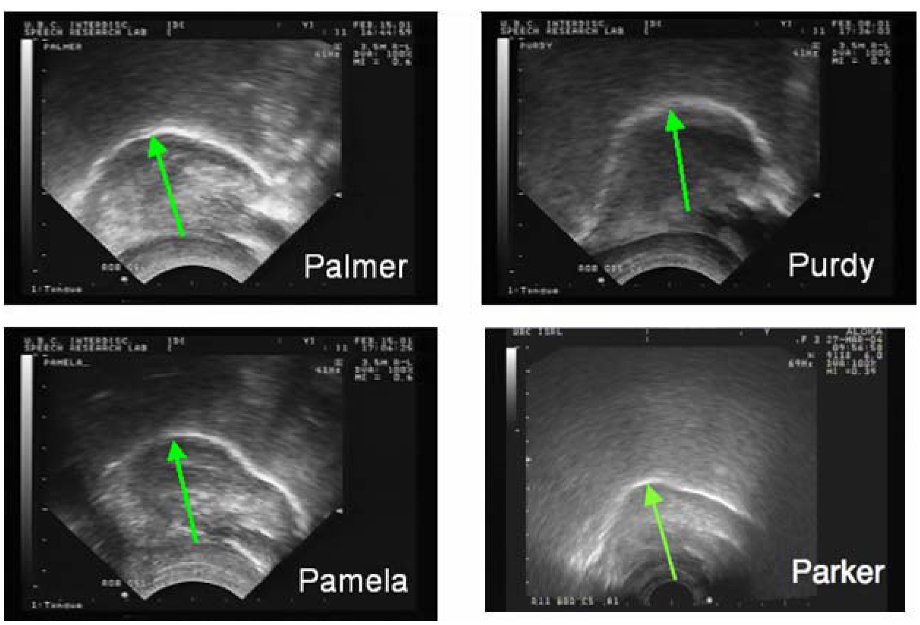


FIGURE 7. Midsagittal ultrasound cross-sections showing /r/ attempts by 4 hearing-impaired adolescents

Successful Early L1 /r/

Young children may avoid making multiple tongue constrictions for a variety of reasons. McGowan & al (2004: 881) suggest anatomical constraints for /r/: “Both a bulky tongue body and a small pharyngeal cavity would hinder young children’s ability to form both a palatal and pharyngeal constriction with the tongue,” while Menard & al. (2007) argue that children need to use substantially different articulations to produce adult-like acoustic results. A case study using ultrasound to image the tongue of a precocious 11-month-old female English speaker during postvocalic /r/ production (‘bear’) shows an adult-like overall tongue shape for postvocalic /r/ (‘bear’). We conclude that a control-based explanation is more plausible, with individual speakers reaching this developmental milestone at different times.

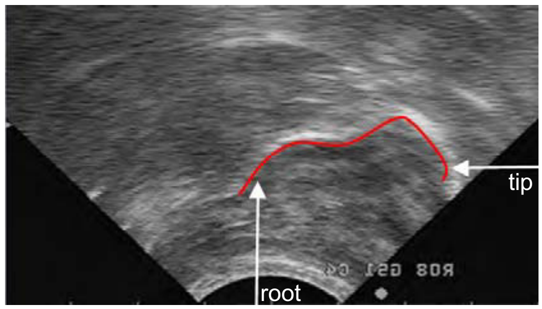


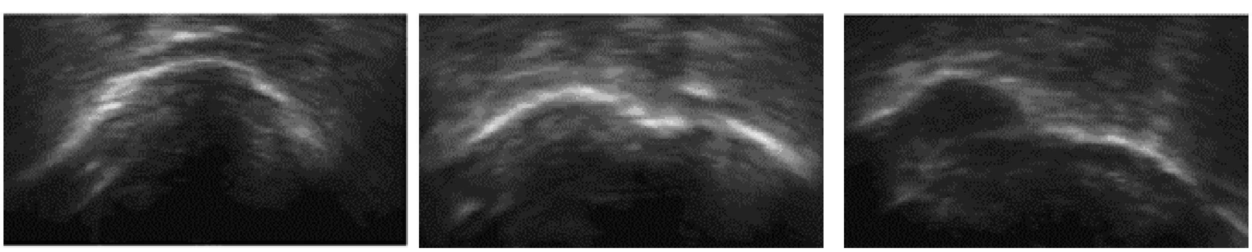
FIGURE 8. Midsagittal ultrasound cross-section of postvocalic /r/ produced by an 11-month-old female English speaker

QUANTIFICATION: A DIFFERENTIATION INDEX

While it is beyond the scope of this paper to discuss quantification of lingual complexity in detail, one simple method might describe the curvature of the tongue surface within a plane. For example, it is possible to fit a simple quartic polynomial to a digitized image of a tongue, from which it is simple to calculate the derivative, and thus give its mathematical curvature. A single index can then be given (for example on a scale from 1 to 10) where the lower end represents an undifferentiated (rounded) tongue shape and a higher value represents a highly differentiated tongue (one showing two clearly defined constrictions). An example of such an equation or “differentiation index” for the change in the curvature follows:

$$f'''' = \frac{24a}{s^3} ,$$

where a is a coefficient of the 4th power of the variable in the fit, and s is a scale factor which is being divided out (in the slowly varying derivative limit). This is scaled to a factor between one and ten. Examples of English /r/ attempts indexed using this method are shown in Figure 2. Note that the same approach could be applied to quantify differentiation based on midsagittal cross-sections of the tongue producing /l/, and coronal cross-sections of the tongue producing /s/. This quantification method will be developed in future work.



(a) (b) (c)

FIGURE 9. Midsagittal lingual ultrasound images of three different speakers’ /r/ attempts, increasing in differentiation: (a) rating of 4.4, (b) rating of 7.2, (c) rating of 8.1

DISCUSSION

Our examination of successful and unsuccessful /r/ attempts indicate that successful /r/ attempts correspond with more differentiated tongue shapes – even for extremely young speakers – and that unsuccessful /r/ corresponds with less differentiated shapes, with hearing-impaired speakers exclusively using the stiffening strategy. Findings from speaker AG support a motor control-based explanation.

The model proposed in this paper is consistent with cross-linguistic observations as well, whereby lingually complex sounds are acquired late, e.g.: Clicks (Herbert 1990), Arabic pharyngealized consonants (acquired around 3:6, while their non-pharyngealized counterparts are acquired around 2 years; Omar 1973, in Locke 1983), and Russian palatalized consonants (which exhibit a higher error rate than their non-palatalized counterparts in acquisition [Timm 1977, in Locke 1983]; interestingly, this pattern does not hold for /gʲ / and /kʲ/, which have the same complexity phonologically but require only a single lingual constriction).

CONCLUSIONS

In the model presented here, developing speech motor systems show reduction of the degrees of freedom of complex anatomical structures (specifically the tongue). Common segmental substitutions (e.g., [w] for /r/ or /l/) are described as being the result of simplifying lingual degrees of freedom. The model can account for patterns observed concerning lingually complex consonants in terms of common English substitutions, first language acquisition order, disordered speech, hearing impaired speech and cross-linguistic substitutions. Future work will include other lingually complex tasks, such as /s/ and consonant clusters, and more elaborated quantification techniques.

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