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Ultrasound imaging and theories of tongue root phenomena in African languages

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1. INTRODUCTION

During the past decade, ultrasound (US) technology has played an important role in the development of phonetic and phonological theory, with much of the US research focussing on Indo-European languages. We explore the role of lingual ultrasound imaging in the documentation of African languages. We focus on three tongue root (TR) related phenomena: tongue-root harmony, click induced vowel retraction, and labial-velar fronting, and demonstrate how lingual US studies contribute to the development of theories of the phonetics / phonology interface.

In Dagbani, the phonologically dominant [+ATR] feature corresponds to an anterior position of the TR relative to the neutral position. Click data from Mangetti Dune !Xung, henceforth !Xung, show that TR retraction is part of the rarefaction gesture for two out of four clicks. We argue that phonetic TR retraction directly implies the presence of an [RTR] feature, which explains the patterning of clicks in the Back Vowel Constraint (BVC), a constraint ruling out the occurrence of [RTR] clicks with front vowels. We show that tongue dorsum (TD) / TR retraction captures the Dagbani restriction against labial-velars with front vowels. This raises the possibility that labial-velars may have the feature [RTR] which is lost in the front vowel context. The !Xung and Dagbani US data show that what might be considered inert articulatory movements may be linked to active or enhancing feature specifications. Ultrasound imaging, which allows us to clearly visualize the position of the TR in a non-invasive way, contributes to a theory of direct mapping of tongue root phenomena in African languages.

1.1. Phonetics-phonology mapping with tongue root

Theories of TR articulation and features often build on evidence from African languages, with recent work on clicks of crucial relevance. Here, we show that TR articulation is also important to our understanding of labial-velar consonants found in West African languages. We observe that much of the relevant evidence is based on studies that lack access to phonetic data. Some studies that have access to phonetic data, reject a direct mapping between phonetics and phonology while others recognize the importance of the phonetics-phonology mapping.

In studies of TR harmony, [ATR] (Stewart 1967) is often used as a feature with little insight into the precise phonetic properties of vowel pairs distinguished by this feature. Following articulatory studies such as Lindau (1979) and Tiede (1996), studies of African language vowel systems have assumed [ATR] to be the feature that distinguishes the vowel pairs i/ɪ, u/ʊ, e/ɛ, and o/ɔ.[1] It is not clear whether the position of the TR is the only distinction between vowels in each pair.

The same limitations exist in our understanding of clicks and labial-velars and the theories that build on them. Since Doke (1923), clicks have been assumed to be exotic sounds with two simultaneous articulations: a posterior velar articulation and an anterior articulation made with the lips, the tongue tip, or tongue blade. However, Miller-Ockhuizen (2003) proposed a phonological analysis whereby alveolar and lateral clicks are specified for an [RTR] feature, based on the phonological patterning of these clicks with uvulars. Miller, Namaseb & Iskarous (2007) and Miller et al. (2009) have shown, using ultrasound imaging, that alveolar clicks have a uvular posterior constriction, and they involve a TR retraction gesture, while palatal clicks, which pattern with dental clicks and plain coronal and velar consonants phonologically, do not involve TR retraction. Miller, Scott, Sands & Shah (2009) have shown that the lateral click in Mangetti Dune !Xung also involves TR retraction, and the dental click does not. Similarly, early works have assumed that a dorsal constriction was the farthest back constriction in labial-velars (Welmers 1950).

TR gestures in clicks and labial-velars went unnoticed. This oversight was in part due to the difficulty of investigating back articulations in the field. For example, researchers could not paint the TR to investigate the constriction location with palatography due to the gag reflex. Assumptions also influenced collection and interpretation of dynamic data. Maddieson's (1993) Electromagnetic Articulography (EMA) of labial-velars did not include a pellet on the TR which would have been possible. Traill (1985) did not analyze the motion of the TR that was visible in X-ray images.

Instrumental studies of TR harmony can be categorized into two types. There are studies arguing that phonological features are abstract, with no direct mapping between the feature [ATR] and the actual position of the TR (Hyman 1988; Salting 1998). Hyman’s view is based on an instrumental study of Ateso (Lindau & Ladefoged 1986) showing that the main articulatory difference between vowels distinguished by [ATR] is tongue height adjustment. In spite of this articulatory difference, vowels in Ateso are claimed to display a harmony pattern that is comparable to other Nilotic ATR systems. However, rather than disputing a direct phonetics-phonology mapping, the apparent exceptional mapping of Ateso vowels seems to question whether [ATR] is the correct feature for the pattern of lingual harmony observed in many languages. This is especially true in studies that claim a universally dominant [+ATR] feature (Baković 2000). Archangeli & Pulleyblank (1994) have shown that the dominant feature in the phonology of Wolof and Yoruba is [RTR]. Li (1996) argues that the dominant TR feature in the canonical vowel harmony pattern of Tungusic is [RTR], while Noske (2001) shows that both [ATR] and [RTR] are active in Turkana.

[1] Note that Lindau herself proposes a feature of pharyngeal expansion/retraction, not a feature restricted to tongue root advancement / retraction.

Other studies recognize that some level of direct mapping of detailed phonetic gestures onto phonological patterns exist. On tongue-root harmony, Parkinson (1996), Tiede (1996) and Gick et al. (2006) argue that [ATR] vowels have a unique TR gesture or pharyngeal cavity volume. This view is supported by X-ray, MRI and ultrasound studies. Experimental studies of clicks and labial-velars also show the inadequacy of earlier assumptions. Maddieson (1993) shows that Ewe labial-velars involve tongue-dorsum retraction. On clicks, recent articulatory studies (Miller, Namaseb & Iskarous 2007, Miller et al. 2009) have shown that the posterior constrictions in some clicks involve TR retraction. Miller (2009) proposes an analysis of the BVC that involves [RTR].

In this paper, we report results of three articulatory studies, which show that [+ATR] vowels, alveolar clicks and labial-velars all involve tongue-root gestures. Our investigations use lingual ultrasound imaging, which is particularly good for imaging the TR. We conclude that understanding the role of these articulatory gestures is crucial to understanding and evaluating phonological theories, and the mapping between phonetics and phonology.

2. EXPERIMENT 1: TONGUE ROOT POSITION IN [ATR] HARMONY

2.1. Introduction

There have been a number of studies of the TR since Stewart (1967) proposed [ATR] as the feature that distinguishes the Akan vowel pairs [i/ɪ, e/ɛ, o/ɔ, u/ʊ]. These include X-ray studies of Igbo (Ladefoged 1968) and Akan (Lindau 1979). Both studies report TR position as distinguishing the vowel pairs. [+ATR] vowels have a more anterior TR than [-ATR] vowels. Lindau (1979) shows that TR position combines with larynx height in Akan. [+ATR] vowels have a lowered larynx, while [-ATR] vowels have a raised larynx. Lindau suggests that the relevant distinction is pharyngeal volume, and she uses the feature [expanded].

Tiede investigates via MRI, whether Akan vowels in the two classes differ in the lateral dimension. His results show that compared to Class II vowels, Akan Class I vowels have greater TR advancement and lower larynx height in the sagittal dimension, and a larger pharyngeal airspace in the lateral dimension. Tiede also observes that the difference in lateral width is almost as large as that of the sagittal depth, which suggests that control in both dimensions is important in producing Akan vowel contrasts. But as Tiede notes, a major problem with MRI studies is having subjects sustain the gesture for vowels for a longer duration than in actual speech. This compromises the naturalness of the data obtained from MRI studies. US imaging is the least invasive and safest alternative that provides real time imaging of natural speech, although it does not measure pharyngeal volume.

Because there have been no tests on the articulatory basis for [+ATR] or [+RTR] dominance, the prediction that [+ATR] vowels are produced with a more anterior TR than [−ATR] vowels is the same whether a language has [+ATR] or [+RTR] as the dominant feature. We hypothesize that in a language with TR harmony, there is a direct mapping between the active harmonic feature and the position of the TR. The active harmonic feature should have an absolute articulatory correlate independent of the recessive feature. To test this, we compare the lingual gestures to the inter-speech posture (ISP) (Gick et al. 2004; Wilson 2006), the motionless position of the articulators during inter-utterance pauses. We predicts that for a language in which the TR position distinguishes [+ATR] and [-ATR] vowels, the active harmonic feature has a unique TR position compared to the ISP, while the recessive feature may not have a unique TR position. For Dagbani, which has a dominant [+ATR] feature, the TR of [+ATR] vowels is expected to be significantly anterior to the ISP; that of [−ATR] vowels could have the same TR position as the ISP, or they could be anterior or posterior to the ISP. The hypothesis builds on Hudu's (in prep.) study which shows that the TR of Dagbani [+ATR] vowels is consistently anterior to that of [−ATR] vowels, and that TR position is the most salient articulatory difference between them.

2.2. Methodology

Five native speakers of Dagbani residing in the Canadian cities of Mississauga, Victoria, and Ottawa participated in the study. In Mississauga and Victoria, a GE Logiq E portable US machine with an 8C-RS 5-8 MHz probe was used. In Ottawa, a Sonosite Titan High-resolution portable US machine with a C11 / 8-5 MHz probe was used. All recordings were done at a standard rate of 29.97 frames per second (which means a frame every 33 ms). The US probe imaged the entire mid-sagittal region, from the tongue-tip to the TR. US video was transmitted using a SVGA cable and recorded onto a computer using Adobe Premier Pro, via a Canopus Twinpac 100 audio-video mixer. All target vowels were located in roots mainly with an onset /t/ or /d/, and embedded in the carrier phrase, [bɔlɨmɨ __ tɨ ma]. 'Say __ for me'. The stimuli were mixed in a random order. The midpoints of the target vowels the ISP, the TR position when speakers completed one sentence and waited for the next stimulus, were extracted and measured using the image editing software ImageJ (Rasband 1997).

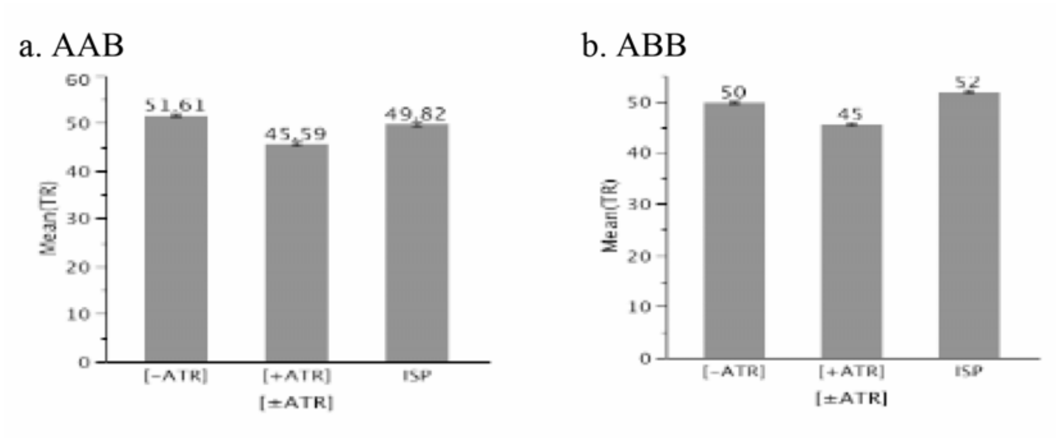
2.3. Results

The results of this experiment show that Class I vowels are significantly anterior to the ISP for all five speakers. For Class II vowels, four speakers had mean TR marginally anterior to the ISP, one speaker had a TR posterior to the ISP. Bar charts for two speakers are shown in Figure 1.

2.4. Discussion

The results are consistent with the hypothesis that in a language with ATR vowel harmony, the dominant feature has a unique TR position compared to the neutral TR position. In Dagbani, only the [+ATR] vowels display consistently anterior TR postures relative to the ISP when results for all speakers are considered. [-ATR] vowels display more variable TR postures. In a system with a direct mapping between articulatory gestures and phonological features, these results are exactly what we expect for a language with a phonologically dominant [+ATR] feature.

Figure 1
Mean TR values (in mm) for [−ATR], [+ATR] and ISP for speaker AAB and ABB



3. EXPERIMENT 2: TONGUE ROOT POSITION IN CLICKS

3.1. Introduction

Since Doke (1923), the posterior of the two constrictions in all click types was thought to be velar. Thus all clicks were specified for the feature [back] (Traill 1985; Sagey 1990). Traill described a co-occurrence constraint, the Back Vowel Constraint (BVC), between velar consonants, central [!] and lateral [ǁ] alveolar clicks with front vowels in !Xõó. He proposed rule ordering to account for the presence of front vowels following dental [|] and palatal [ǂ] clicks, a proposal that was developed by Sagey (1990). In these analyses, all clicks retract the vowel /i/ to [a] via the BVC, and a second rule, called Dental Assimilation, fronts [a] at an intermediate level of representation to [i] when found between [|] and [ǂ] and following [i]. This analysis was based on the phonetic analysis of orthographic 'x' as velar. Since /i/ following 'x' surfaces as [əi], it was assumed that velars pattern with the alveolar clicks, blocked from occurring with [i].

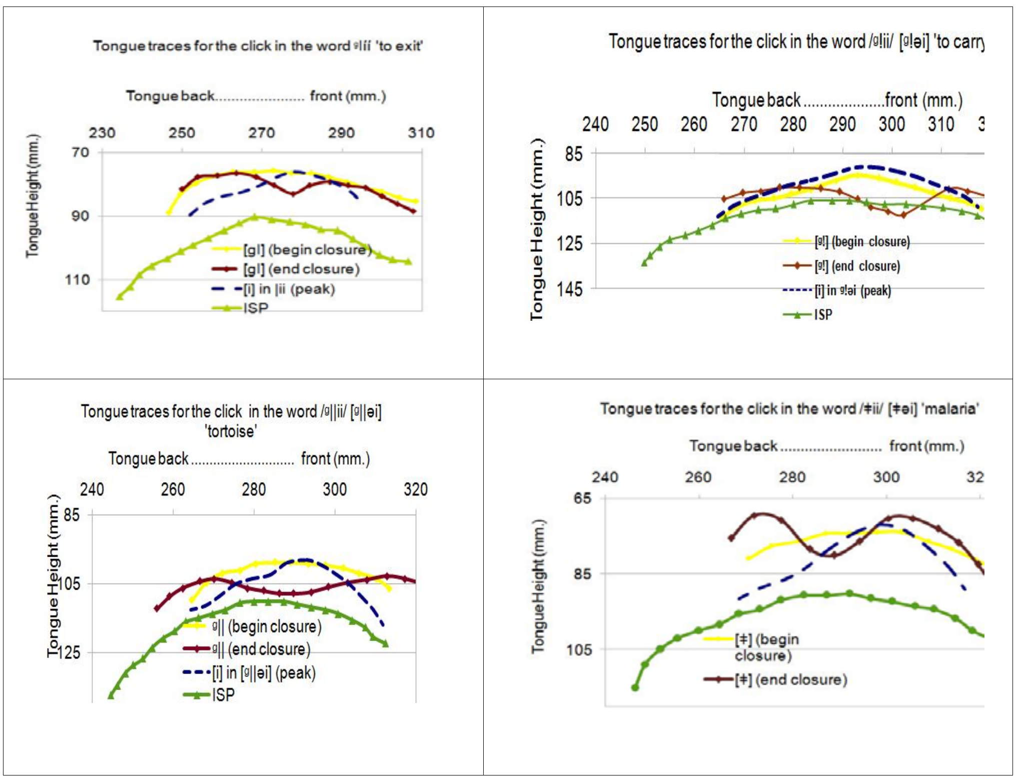
Miller-Ockhuizen (2003) showed that 'x' in Ju|'hoansi is uvular, and represents it as [χ], and that [k] and [χ] pattern differently in Ju|'hoansi. [k] co-occurs with [i], while [χ] and [kχ'] co-occur with [əi]. Miller-Ockhuizen (2003) proposed that [!] and [ǁ] should be specified for [RTR], based on their patterning with uvular and uvularized consonants, and proposed an analysis in terms of the BVC, which targets only consonants with an [RTR] feature. Miller, Namaseb & Iskarous (2007) and Miller et al. (2009) showed, using US imaging, that [!] in Khoekhoe and N|uu involve TR retraction, while [ǂ] in these languages does not. Miller, Scott, Sands and Shah (2009) have shown that the alveolar click in !Xung involves TR retraction, while [|] and [ǂ] involve TR raising. [ǁ] has an intermediate TR posture. In this paper, we compare all four clicks in !Xung to the ISP, to test the hypothesis that [RTR] is the active feature. We hypothesize that the TR in [!, ǁ] will be posterior to the TR in ISP, while the TR in [|, ǂ] may not differ from ISP.

3.2. Methodology

We used the Corrected High-speed Anchored Ultrasound with Software Alignment (CHAUSA) method (Miller 2008; Miller and Finch 2009) and the GE Logiq E US machine to minimize variability in the release gestures traced. An Ultrasound Stabilization headset (Articulate Instruments 2009) was used to anchor the probe to the head and head movement correction was undertaken using Palatoglossatron (Mielke et al. 2005). Data from 2 male and 2 female speakers were collected for all four clicks in four vowel contexts in the frame sentence [Mà o kx'úí___ , kà djàlà] 'I say ____, (and) it is good.' Only the data from male speaker Jenggu Rooi Fransisko are presented here. The data are from a single token of each word collected in the /i/ context. A quantitative study of 15 repetitions of each click is in progress (Miller and Scott in prep).

Figure 2

Tongue traces of (a) the dental click in the word ᶢ|íí 'to exit', (b) the central alveolar click in the word ᶢ!ə́í 'to carry on shoulder', (c) the lateral alveolar click in the word ᶢǁəì 'tortoise', and (d) the palatal click in the word ǂı̃̀ı̃̀ɦ 'malaria'



3.3. Results

Figure 2 provides US traces of the tongue at the beginning of the click closure (begin closure), the last frame before the posterior click release (end closure), the peak palatal gesture in the [i] vowel, and the ISP, for all four clicks in !Xung. The temporal location of the target [i] gesture differs for the different click types, occurring earlier in the [i] allophone that occurs after [|] and [ǂ], and later in the [əi] allophone. The TR position during the release of all of the clicks is behind that of the TR position found in ISP. However, in the dental [|] and palatal [ǂ] clicks, the TR position is also raised, a gesture distinct from advancement. It is only in [!] and [‖] clicks that the TR is retracted into the lower pharyngeal region.

3.4. Discussion

The uniquely retracted TR for the alveolar clicks (with no raising) is consistent with our hypothesis that the TR position of the alveolar clicks plays a role in the lowering and retraction of the following vowel. We propose that only TR retraction into the pharyngeal region results in an active [RTR] feature observed in click induced vowel lowering and retraction.

4. EXPERIMENT 3: TONGUE ROOT POSITION IN LABIAL-VELARS

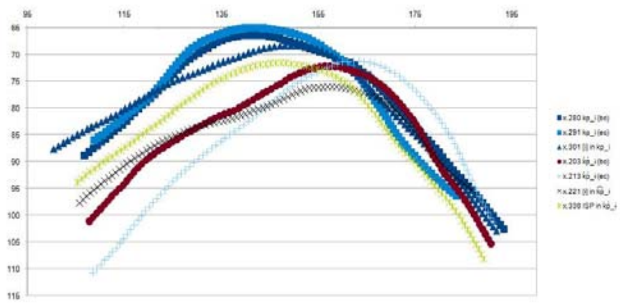
4.1. Introduction

Labial-velars are complex segments with labial and velar constrictions (Welmers 1950; Ladefoged 1968). Dynamic studies of labial-velars were undertaken by Maddieson (1993) and Connell (1994). Maddieson collected EMA data from one speaker of Ewe. He placed five sensor coils on the speaker, with the coil the farthest back placed on the tongue dorsum. The study showed that there was a degree of tongue retraction during the release of labial-velars, which differed from the tongue fronting gesture that occurred during the release of the plain velar [k], particularly before high front vowels. Ladefoged (1968) found two loci associated with spectrograms of labial-velars in Yoruba, and Connell (1994: 455) found split F2 transitions in Ibibio labial-velars. Connell hypothesized that the 'secondary, weaker and negative, offset, reflects some movement posterior to, or associated with, the velar closure – that it may conceivably reflect a lowering of F2 that could be associated with an early retraction of the tongue dorsum.' Since the electropalatographic study used by Connell (1994) could not image the posterior edge of the dorsal constriction, any TR dynamics involved would not have been visible. We investigate the articulation of Dagbani labial-velars, which become labial-coronals before front vowels (Ladefoged 1968), using high-speed US. Based on the results of the Dagbani ATR study, we hypothesize that in addition to TD retraction, the TR will be retracted during the release of the constriction in labial-velars in the [ɨ] context, compared with the [i] context.

4.2. Methodology

We used the CHAUSA method, and the GE Logiq E US machine. We used head stabilization, rather than head movement correction used in the click study. The sentences *n dáá kpíl já 'I put it in my mouth'* and *n dáá kp□́r□□ já 'I instigated'* were recorded twelve times each (4 repetitions each in 3 takes). The tongue edge was traced using Edgetrak software (Li et al. 2005) from the beginning of the labial-velar closure, to the end of the closure, producing about 10 traces per consonant. The midpoint of the vowel and the ISP were also traced. We collected data from 5 adult speakers of Dagbani in Toronto, Canada. Results are reported here for one male speaker. A larger quantitative study is in progress.

Figure 3
/kp/ in [+ATR] and [-ATR] high front vowel contexts



4.3. Results
Figure 3 provides two traces of the tongue during the labial-velar consonant in [i] and [ɨ] contexts. Traces at the beginning and end of the closure, midpoint of the following vowel, and ISP are shown. The lingual constriction is fronted in the [tp] allophone of /kp/. The TR at the end of closure is the same as in ISP, suggesting that TR advancement is not active. When we compare the TD and root in the [kp] allophone that occurs in the [ɨ] context, we see that the TR is farther back at the release of [kp] than in ISP.

4.4. Discussion
These results suggest that TD / TR retraction may be active in the phonology of Dagbani labial-velars. Just as TR advancement from ISP implies [ATR] for vowels, TR retraction from ISP suggests a retraction feature for labial-velars. This loss of TD / TR constriction before front vowels is not surprising. Given that vowel fronting enhances TR advancement and impedes retraction (Archangeli & Pulleyblank 1994), maintaining the constriction could affect the front articulation and [+ATR] feature for [i] and [e]. This does not happen because Dagbani has a dominant [+ATR] feature in its vowel harmony. Ongoing phonetic and phonological studies will show if [RTR] is active in Dagbani labial-velars.

5. CONCLUSION

We have discussed three lingual US studies investigating the TR in two African languages. Experiment 1 shows that the TR of Dagbani [+ATR] vowels advance from the ISP, while [-ATR] vowels are less predictable. In the other two experiments, conflicts between the articulatory positions of adjacent segments are resolved in ways that preserves the active / dominant features in the language. In !Xung, [i] lowering and retraction is induced by [RTR] clicks. Such a measure is blocked in Dagbani labial-velars, because the [+ATR] vowel feature is active in the language. The loss of the TD / TR constriction of the labial-velar ensures that the [+ATR] feature of the front vowel is maintained. We have argued that these results support a direct mapping between the TR position and [ATR] and [RTR] for vowels and clicks and suggest a possible mapping between a TD / TR constriction and a dorsal / [RTR] feature of labial-velars. US imaging has been crucial in providing more details on the articulatory properties of complex segments that were not known in early studies. Given its portability, non-invasiveness and safety, US promises to be one of the best tools in language documentation understanding of theories of phonetics and phonology.

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