FRICATION AND FORMANT FREQUENCIES IN THE MUNDABLI HIGH VOWELS

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ABSTRACT

Mundabli (Yemne-Kimbi, Cameroon) is reported to contrast two sets of high vowels: extra-high /i u/ and high /ɪ ʊ/, by way of frication intrinsic to /i u/. In this study, we assess the role of aperiodicity (zero crossing rate, ZCR) and formant frequencies (midpoint F1-F2) in these contrasts. Analysis of the dynamics of ZCR in the vowels of interest using generalized additive mixed models shows elevated aperiodic energy early in the duration of /i u/ compared to /ɪ ʊ/, modulated by onset consonant type. Small, inconsistent differences in F1 and F2 are observed, and /i/ tends to exhibit lower F2 than /ɪ/, suggesting that this contrast is not simply one of height. These findings contribute to our understanding of the fricative vowels and their development from plain high vowels; and add to the literature on vowel contrasts involving frication.

Keywords: frication, fricative vowels, zero crossing rate, formant analysis, Mundabli

1. INTRODUCTION

1.1. Mundabli vowels in context

Mundabli (ISO 639-3: boe; autonym [ɲɔ̄ ⁿdʒə̄n]) is a Yemne-Kimbi language spoken by 350-450 people from a single village on rugged terrain in the Lower Fungom area of northwestern Cameroon [30, 11]. Lower Fungom is notable for its linguistic-genetic diversity and intense multilingualism [11, 26], as well as the general degree of complexity of its languages' vowel systems [30, 11, 22, 24].

Mundabli is notable for exhibiting unusually close contrasts among its high vowels, which have been reported as cued entirely or in part by fricative noise. Voll [30, 39-41] describes the contrasts between the vowels /i, u/ and /ɪ, ʊ/ as extremely close in height, but quite reliably differing in frication: /i u/ are said to exhibit considerable fricative noise, and often cause delayed release, affrication, or trilling (in the case of /b/ > [bʙ]) of onset consonants (see Fig. 1). These extra-constricted vowels are also known to occur in neighboring languages of Lower Fungom such as Ajumbu, Fang, Koshin, and Mungbam [11, 22, 24]; the Grassfields area to the south [9, 27]; and languages in contact with both groups [3, 19].

1.2. Fricative vowels

Mundabli /i, u/ share some features with *fricative vowels*, vowels produced with an overlay of frication attributable to a coronal or labial constriction [3, 16]. Fricative vowels are mainly described for Chinese languages, where coronal fricative vowels are also known as apical vowels [17, 29]. Most often, fricative vowels have evident supralaryngeal frication for at least the first half of their duration [6, 21, 29]. They are also known to trigger affrication or trilling of preceding onset consonants [33, 10], not unlike the extra-constricted vowels found in Mundabli, and may also preferentially occur with affricate and fricative onsets [17, 10].

Unlike the /i-ɪ/ and /u-ʊ/ contrasts described for Mundabli, fricative and apical vowels tend to differ in formant frequencies from non-fricated high vowels. Fricative vowels in Chinese languages are known to have F1-F2 values similar to high central vowels, with lower F2 for coronal fricative/apical vowels compared to [i], and higher F2 for labial fricative vowels compared to [u] [21, 12, 29, 5]. These differences are generally thought to arise as enhancements to frication production, specifically the modification of tongue-palate contact to generate strident frication in coronal fricative vowels [21, 13, 8], or lowering or 'troughing' of the tongue during labial vowels [10, 28].

1.3. Research goals

Fricative vowels are generally thought to develop diachronically from phonologization of fricative noise occurring passively on very constricted high vowels [7, 13]. The Mundabli high vowels merit examination because they appear to contrast less robustly in terms of formant frequencies, and may thus represent a diachronic precursor to fricative vowels. As such, here we evaluate (1)

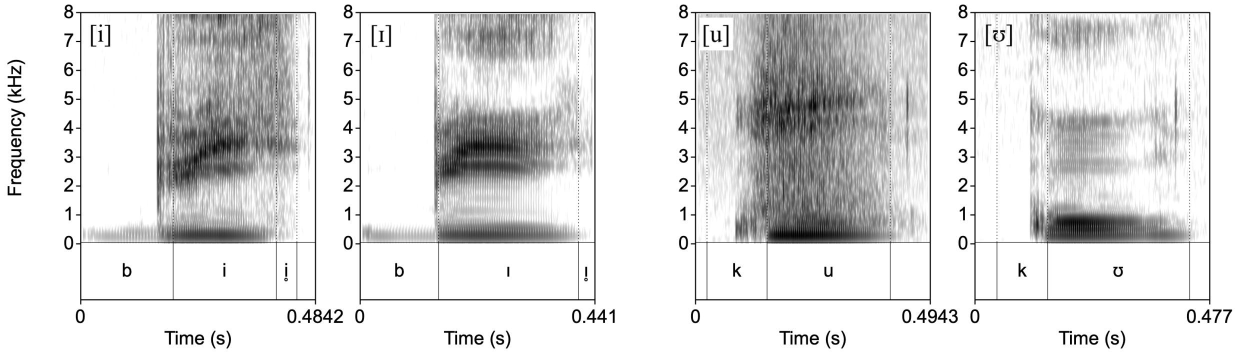

Figure 1: Sample tokens (speaker 1F) of /i ɪ u ʊ/: [bī̀] 'fish', [bí] 'go out-imp', [kū] 'rat-mole', [kʊ̄] 'bone'.

the contributions of frication noise and formant frequencies in the contrast between the pairs /i/-/ɪ/ and /u/-/ʊ/. We aim to identify (2) the time-dynamic pattern of frication in fricative vowels, and investigate (3) if the frication is modulated by consonants or by lexical tones. Using these data, we aim to answer the research question: are these pairs distinguishable by frication alone, or by a combination of frication and formant structure?

2. METHODOLOGY

2.1. Stimuli and data collection

The data set analyzed here was collected from four Mundabli speakers (2F, 2M) in Douala, Cameroon, in July 2022. Speakers were recorded in a quiet room using Shure SM10A head-mounted cardioid dynamic microphones and a Zoom H4n recorder (44.1 kHz sampling rate). From the resulting eight-hour corpus of elicited lexical items, we selected lexical items of the shape CV, where C is a non-nasal consonant and V is in /i ɪ u ʊ/. We excluded vowels occurring in pronouns, demonstratives, and in the first syllable of multisyllabic items (e.g. /kpʊ̰̋.kpóˤ/ 'woodpecker'; /dɪ̰̀.də̄m/ 'chest') since these appear to occur in prosodically weak positions. This yielded 1748 tokens in total (547 /u/, 498 /i/, 324 /ɪ/, 379 /ʊ/).

2.2. Data processing and analysis

Data were segmented in Praat v6.1.39 [2]. The first and second formants (F1, F2) were estimated at vowel midpoint. Praat's default settings for LPC formant estimation were used for the front vowels (ceiling 5.5 kHz, five formants estimated) for speakers 1F, 2F, and 2M; a lower 5 kHz ceiling was used for speaker 1M. For back vowels, the ceiling was lowered to preclude formant misidentification, and only two formants were estimated: a ceiling of 1.5 kHz was applied for speakers 1F, 2F, and 2M, and a ceiling of 1.4 kHz for speaker 1M. Tokens more than three standard deviations away from vowel-speaker means for F1 or F2 were removed (n=39). Measures were not normalized for speaker anatomical differences, due to the small portion of the vowel space analyzed (four of the 16 Mundabli monophthongs) and the similar height and (inferred) vocal tract length of three of the speakers (1M being roughly 0.3m taller than the others).

Formant measures were submitted to linear mixed-effects models in R v4.2.2 using *lme4* v1.1-31 [1], with *p*-values estimated using *lmerTest* v3.1-3 [15]. Separate F1 and F2 models were constructed for the front and back vowels. Models included fixed effects of vowel (/ʊ/ vs. /u/ or /ɪ/ vs. /i/), speaker, and their interaction, with random intercepts for onset and word. In front vowel models, onset was omitted as a random effect as it did not improve model fit. The less-constricted vowels /ɪ ʊ/ and speaker 1F are taken as reference levels. Post-hoc comparisons (Tukey's HSD tests) were carried out in R for F1 and F2 on estimated marginal means for each vowel pair within speaker using *emmeans* v1.8.5 [18].

To measure the timecourse of frication, we chose zero-crossing rate (ZCR) to measure the number of crossings of zero dB per second in the waveform, as in [25, 29]. To model the dynamics of ZCR, generalized additive mixed models (GAMMs) were constructed using *mgcv* v1.8-40 [32]. Separate models were constructed for comparison of the pairs /i/-/ɪ/ and /u/-/ʊ/. In the models, ZCR of the vowels was estimated over time, with factor smooths for speaker and onset. Tweedie distributions were used in the model, as ZCR follows a left skewed, long-tailed distribution. Results were visualized using

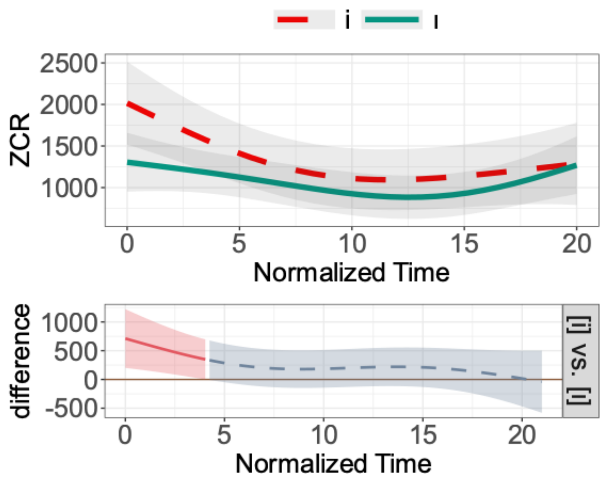

Figure 2: Top: GAMM fits for ZCR, /i/ and /ɪ/. Bottom: difference smooth; red indicates significant difference.

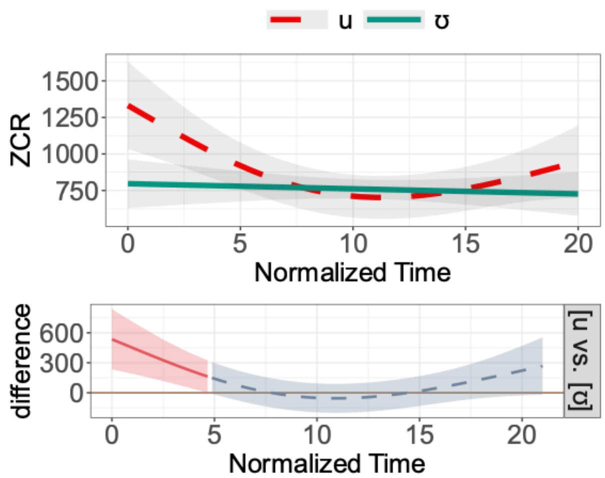

Figure 3: Top: GAMM fits for ZCR, /u/ and /ʊ/. Bottom: difference smooth; red indicates significant difference.

tidyverse v1.3.2 and *tidymv* v3.3.2 [31, 4].

3. RESULTS

3.1. Zero-crossing rate

The ZCR GAMM fits for /i, ɪ, u, ʊ/ are presented in Figs. 2–3. The /i/-/ɪ/ and /u/-/ʊ/ comparisons show clearly that more constricted /i u/ have significantly elevated ZCR at onset compared to /ɪ ʊ/. ZCR of /i u/ follows a high descending pattern, indicating that frication noise gradually attenuates over the timecourse of the vowel. After onset, neither vowel pair differs significantly in ZCR.

The level of ZCR in the vowel onset is substantially modulated by the type of onset consonant which precedes the vowel. Fricative and affricate onsets introduce visibly more frication into the following vowel, compared to plosives (Fig. 4). Because the models take by-onset variability into account, the significant differences in ZCR observed in Figs. 2-3 suggest that /i u/ contain somewhat more aperiodic energy than /ɪ ʊ/ even when occurring in "less favorable" contexts for producing frication.

3.2. Formant frequencies

Summary F1-F2 data are shown in Fig. 5. For the sake of brevity, we report only main effects of vowel and interactions of speaker and vowel, as the size of the acoustic contrast between the vowels for each speaker is mainly reflected in the interactions.

Moving first to the front vowel models, the main effect of the vowel /i/ on F1 reaches significance (β=-24.84, t=-3.84, p<0.0001), indicating that /i/ tends

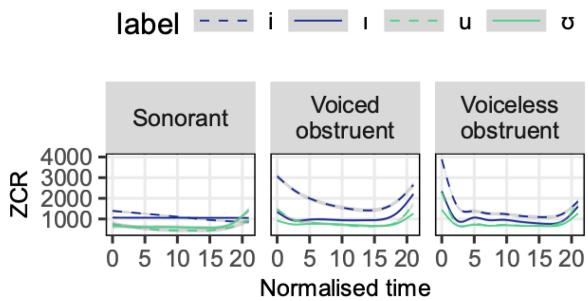

Figure 4: GAMM fits for ZCR by onset type and vowel.

to exhibit a lower F1 than /ɪ/. This tendency varies by speaker: speaker 2M's interaction with vowel reaches significance (β=27.271, t=4.253, p<0.0001), suggesting a slightly higher F1 for /i/ compared to /ɪ/. The main effect of /i/ on F2 fails to reach significance (β=-21.542, t=-0.95, p=0.35). However, speakers 2F and 2M exhibit significant interactions with vowel /i/ (2F: β=-56.95, t=-3.03, p=0.0026; 2M: β=-184.10, t=-8.78, p<0.0001), suggesting they exhibit a lowered F2 for /ɪ/ relative to /i/.

Turning to the back vowel models, the main effect of the vowel /u/ on F1 reaches significance (β=-81.64, t=-14.51, p<0.0001), indicating a tendency for /u/ to exhibit a lower F1 than /ʊ/. However, all interactions of speaker and vowel /u/ reach significance (1F: β=36.96, t=5.40; 1M: β=62.62, t=8.42; 2M: β=66.78, t=8.91; all p<0.0001): non-reference speakers exhibit a smaller F1 difference for the /u-ʊ/ pair. The main effect of the vowel /u/ on F2 is weakly significant (β=33.86, t=2.017, p=0.045),

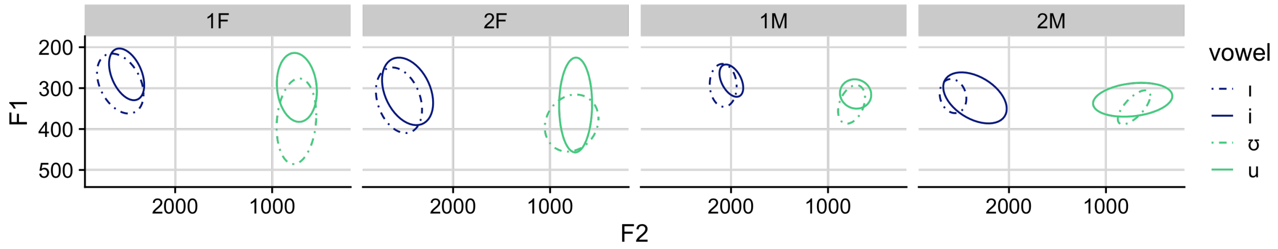

Figure 5: Confidence ellipses (95%) for F1 and F2 frequencies by vowel and speaker.

suggesting a slight tendency for /u/ to exhibit a higher F2 than /ʊ/. Again, however, interactions of speaker and the vowel /u/ reach significance for 1M (β=-100.33, t=-6.12, $p<0.0001$) and 2F (β=-44.67, t=-3.080, p=0.0021).

The above models suggest inter-speaker variation in implementation of the /i/-/ɪ/ and /u/-/ʊ/ contrasts in terms of formant frequencies. To investigate the degree to which speakers contrast each pair on each formant, we turn to by-speaker estimated marginal means (EMMs) for each vowel's F1 and F2. Differences for EMMs of front vowels (/ɪ/ minus /i/) and back vowels (/ʊ/ minus /u/) are shown in Table 1. F1 differs for both pairs in the predicted direction (i.e. /ɪ, ʊ/ have higher F1) for all speakers except for 2M. Unexpectedly, /i/ has lower estimated F2 compared to /ɪ/ for three speakers, with speaker 2M exhibiting a particularly large difference.

A. /ɪ/-/i/ difference

	F1 Est.	p	F2 Est.	p
1F	**24.84**	**<0.0001**	21.5	0.35
2F	**13.80**	**0.0472**	**78.5**	**0.0013**
1M	**18.58**	**0.0059**	**52.6**	**0.026**
2M	-2.43	0.7312	**205.6**	**<0.0001**

B. /ʊ/-/u/ difference

	F1 Est.	p	F2 Est.	p
1F	**81.6**	**<0.0001**	**-33.9**	**0.0477**
2F	**44.7**	**<0.0001**	10.8	0.5459
1M	**19.0**	**0.0034**	**66.5**	**0.0002**
2M	**14.9**	**0.0238**	-31.4	0.0776

Table 1: Difference in estimated marginal means for front vowels (/ɪ/ - /i/; A) and back vowels (/ʊ/ - /u/; B) by speaker. Significant differences in bold.

4. DISCUSSION

ZCR modeling reveals that both Mundabli vowel pairs /i/-/ɪ/ and /u/-/ʊ/ are distinguished by frication at vowel onset, modulated by onset consonant: more frication occurs following obstruents than sonorants. This overall difference in aperiodic energy and effect of onset consonant type have been reported for fricative vowels in Chinese [21, 8, 29], but not for Mundabli or other Lower Fungom or Grassfields languages with similar vowel contrasts.

The relationship between each vowel pair in terms of formant frequencies shows inter-speaker variation, and suggests a difference not reducible to height. While extra-high /i, u/ exhibit lower F1 than less-high /ɪ, ʊ/ as might be expected, F2 is generally lower for /i/ compared to /ɪ/, a reversal of the typical pattern. Speaker 2M lacks an F1 distinction for /i/-/ɪ/ and has an estimated F2 difference of more than 200 Hz for the same pair. This lowered F2 is typical of apical vowels in Chinese, due to fronting of the tongue-palate constriction [20]. Speaker 2M may exhibit a similar distinction for the /i/-/ɪ/ pair; whether this is idiosyncratic or typical of more Mundabli speakers is not yet clear.

Observed F1 and F2 differences are near each measure's just-noticeable difference [23, 14] and may not reliably cue the /i/-/ɪ/ or /u/-/ʊ/ contrasts. Frication may be more reliable, such that Mundabli (and languages with similar high vowel contrasts) may be on a hypothesized path for fricative vowel development in which tighter constrictions inadvertently produce frication[13, 7]. Increased airflow at obstruent release, as suggested by the Mundabli ZCR data, plausibly encourages the phonologization and enhancement of this frication.

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