Dorsal Harmony in Squliq Atayal: An Acoustic and Ultrasound study

Ching-Hung Lai and Chenhao Chiu
National Taiwan University

1 Introduction

Consonant harmony refers to an effect of one consonant assimilating to another consonant while these two consonants are separated by a string of segments (Hansson, 2001). As for the dorsal harmony (or dorsal consonant harmony), it refers to the harmonious effect on dorsal consonants. Dorsal harmony has been reported as a diachronic sound change in Atayal language family; Proto-Atayal /*k/ became /q/ in descendant Atayal dialects, such as Squliq, Skikun, and Matu'uwal, when followed by a uvular /q/ or a pharyngeal /ħ/ (Li, 1980; Goderich, 2020). However, it is still unknown whether dorsal harmony is also observed in those Atayal dialects as a morpho-phonological process in a synchronic pattern since the observed dorsal harmony as a contemporary morpho-phonological process in Atayalic languages is solely from impressionistic transcription (Lee, 2009). In the present study, we examined dorsal harmony in Squliq Atayal, a vulnerable language spoken by less than 10,000 people (Moseley, 2010). In this study, we applied ultrasound to capture the whole tongue surface in the midsagittal plane. We also tried to explain dorsal harmony with acoustic analyses to complement the phonological accounts proposed by Lee (2009).

Squliq Atayal has 19 consonants and 5 vowels[1](/a, i, u, e, o/) with a marginal lenited vowel (/ə/) in its sound inventory (Li, 1980, 1981). The maximum syllable structure is CGVG (e.g., /qwaw/ 'wine') (Li, 1980). For multisyllabic words, all the vowels preceding the penultimate syllable will lenite into a schwa, except for the infix /-in-/. Besides, since consonant clusters are forbidden in Squliq Atayal, the marginal vowel schwa will be inserted to conform to the phonotactics when morphological processes, such as affixation (Huang & Wu, 2016) and reduplication (Lin, 2015), occur.

Squliq Atayal has two dorsal consonants, uvular /q/ and pharyngeal /ħ/[2]. These two consonants provided the environment for dorsal harmony. Table 1 showed the reconstructed Proto-Atayal and six major dialects of Atayal from Goderich (2020). Examples 1.-3. in Table 1 showed that Proto-Atayal /*k/ became /q/ when followed by a uvular /q/. Such a change only occurred in three dialects: Matu'uwal, Skikun, and Squliq. Note that /*k/ did not become /q/ for the words /*kVbVhniq/ and /*kisəliq/ in Matu'uwal, suggesting that the harmony effect might be weak in this dialect. Proto-Atayal /*k/ also became /q/ when followed by a pharyngeal /ħ/, as seen in examples 4.-6. This type of change only happened in Skikun and Squliq, but not applied to all the words (e.g. *k* in **kVbəhul* 'hundred' did not become *q* in all the dialects of Atayal.). Examples 7.-9. showed that Proto-Atayal /*k/ became /q/ without any following dorsal consonant. Such phenomenon is only seen in Skikun and Squliq. In sum, dorsal harmony bears a strong effect in Squliq, Skikun, and Matu'uwal.

Truku Seediq, one of the sister languages to Atayal, was reported to employ dorsal harmony as a (morpho-)phonological process in addition to diachronic sound change (Lee, 2009). Table 2 showed the transcription from Lee (2009). The prefix /m-k-/ 'from' was affixed to nouns with /q/ (1. and 2.) and without /q/ (3. and 4.). As revealed, the change from /k/ to [q] occurs when followed by a /q/.

Since dorsal harmony is observed as a historical sound change in the Atayal family and also in Seediq as a morpho-phonological process, it would be of great interest to examine whether dorsal harmony is also in effect in contemporary Atayal as a morpho-phonological process. Besides, during the fieldwork, it was challenging to identify the dorsal stop (either [k] or [q]) when followed by a /q/. With these in mind, in

[1] From historical viewpoint, /e/ is derived from /*aj/ and /o/ is derived from /*aw/ (Li, 1980). Thus, one may argue there are only 3 vowels in all Atayal dialects.
[2] It is written as h in the writing system.

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	Proto-Atayal	Gloss	Matu'uwal	Skikun	Squliq	Plngawan	Klesan	S'uli
1.	*kVbVhəniq	'bird'	kabahniq	**q**əbəhəniq	**q**əbəhəniq	kabahniʔ	–	kabahni
2.	*kisəliq	'to love'	kisliq	**q**əsəliq	**q**əsəliq	kisliʔ	kəsəli	–
3.	*kaniq	'to eat (AV, imp)'	**q**aniq	**q**aniq	**q**aniq	kaniʔ	kani	kani
4.	*kVtəhuɹ	'fat, thick'	kithuw	**q**ətəhuy	**q**ətəhuy	hatuhuɹ	təhuy	kətəhuy
5.	*kumayhuɹ	'to dig (AV)'	kumayhuw	kəmihuy	**q**əmihuy	kumehuɹ	–	–
6.	*kVbəhul	'hundred'	kabhul	kəbəhul	kəbəhul	kabhul	kəbəhun	kəbəhun
7.	*kani	'this thing'	–	**q**ani	**q**ani	kani	kwani	–
8.	*kaca	'that thing'	–	**q**aca	**q**asa	kaca	kyaca	–
9.	*kuwalit	'eagle'	kuwaliʔ	kwaliʔ	**q**waliʔ	–	kwalit	kwalit

Table 1: Dorsal harmony in Atayal dialects as a historical sound change. Data were adopted from Goderich (2020). The harmonious effect was shown in bold font. Example 1.-3. exhibited dorsal harmony induced by the uvular stop /q/. Example 4.-6. demonstrated dorsal harmony caused by the pharyngeal fricative /ħ/. Example 7.-9. showed that /k/ turned into /q/ in some words even though there was so such an environment for dorsal harmony. (h is realized as [ħ] in Matu'uwal, Skikun, Squliq, Klesan, and S'uli, but realized as [h] in Plngawan.)

	Phonemic	Phonetic	Gloss
1.	/m-k-quɣan/	[mə**q**əqóɣan]	'from Qowgan village'
2.	/m-k-dɣijaq/	[mə**q**ədəɣíjaq]	'from the mountains'
3.	/m-k-tkidiɣ/	[məkətəkíɟiɣ]	'from Tkijig village'
4.	/m-k-bsəŋan/	[məkəbəsə́ŋan]	'from Bsngan village'

Table 2: Dorsal harmony in Truku Seediq as a morpho-phonological process. Data were adopted from Lee (2009). The harmonious effect was shown in bold font. Example 1. and 2. exhibited dorsal harmony of the uvular stop /q/ where the prefix /m-k-/ turned into [m-q-], while Example 3. and 4. showed that the /k/ in prefix /m-k-/ remained as [k] when there was no environment for dorsal harmony. (The acute accent indicated the vowel was stressed.)

the present study, we applied articulatory and acoustic analyses to uncover whether and dorsal harmony is manifested in Squliq Atayal.

2 Methodology

2.1 *Participant* Due to the pandemic, only one female and one male participants were recruited in the production experiment. The female speaker is 52 years old from the Mkmatuy village in Jianshi Township, Hsinchu County, Taiwan. She is a native speaker of Squliq Atayal and works as an Atayal teacher. The male speaker is 75 years old priest, also from the Mkmatuy village. He is a native speaker of both Squliq and Ci'uli Atayal. Both informants speak fluent Mandarin and the elicitation was conducted mainly through Mandarin.

2.2 *Equipment* The ultrasound data was obtained from an ultrasound machine (CGM OPUS5100) with a transvaginal probe (CLA 651). An ultrasound stabilization headset from Articulate Instrument (2008) was applied to obtain stable and consistent images from the participants. Ultrasound videos were recorded using the ExtremeCap U3, a USB 3.0-powered capture card. The frame rate was set at 40fps with 6.5 MHz scanning frequency and 4-8.3 MHZ reception frequency. The acoustic data were recorded from an Audio-Technica cardioid condenser microphone (AT2035) via USBPre 2 Portable High-Resolution Audio Interface for the female speaker, and from Zoom H4n Pro for the male speaker. The microphone was placed 20 cm from the speakers' mouth and the sampling rate was 44,100 Hz.

To examine the audio-video alignment of the ultrasound videos, we used plosive sounds for their rapid tongue movement and clear release burst. The tongue release time obtained from ELAN 6.0 (Borovanský et al., 1998) and the burst onset obtained from Praat 2.0 (Boersma & Van Heuven, 2001) were temporarily aligned. The misalignment was less than 25 ms (1/40fps).

2.3 *Material and procedure* The data were collected from an elicitation scenario. The experimenters prepared a word/sentence list with their research interests. Due to the COVID-19 restriction, the data from the female speaker were collected in April, 2021. and the data from the male speaker were collected in August, 2021. The data from the first speaker was first analyzed during the lock-down. Materials that would induce potential confounds are removed from the stimuli for the second informant. As such, the stimuli from the female and the male speakers were slightly different but comparable.

For the first speaker (henceforth, P01), the successfully elicited words were shown in Table 3, including five conditions: Baseline [k] (without any following post-velar consonant, e.g., *ktu'* /kətuʔ/ 'belly'), Baseline [q] (e.g., *qmisan* /qəmisan/ 'winter'), Short distance [k] (/kəq-/ sequence, e.g., *kqtux* /kəqətux/ 'salty'), Long distance [k] (/kəCVq-/ sequence, where C is not a post-velar consonant, e.g., *kgiqas* /kəɣiqas/ 'new'), and Cross-boundary [k] (/qu#kə-#qani/ sequence, e.g., qu kneril qasa /qu#kəneril#qasa/ 'that woman'). Since diachronically /*k...q/ sequence has all become /q...q/ in Squliq Atayal (e.g., Proto-Atayal /*kisəliq/ > Squliq /qəsəliq/), prefix *k-* /k-/ is used to create the word-internal conditions. The prefix *k-* is restricted to the negation of stative verbs (see *kqtux* in (1) and *kqthuy* in (2)), as mentioned in Huang & Wu (2016) and found also in Seediq (Tsukida (2005) cited in Lee (2009)). Therefore, each word is embedded in a negation sentence to create a natural environment. Besides, a schwa will be inserted to avoid consonant clusters. Thus, only the vowel /ə/ is available for short and long distance conditions. For the baseline and cross-boundary conditions, the same vowel was chosen to avoid any coarticulatory effect. The informant was asked to produce at least five consecutive tokens for each sentence with a normal speech rate. There were at least two words for each condition, except for Long distance [k]. After the data collection, we found that the schwa between /k/ and /j/ in the word *k_yaqih* /kəjaqiħ/ was almost inaudible and the tongue shape of /k/ is influenced by the glide /j/. Thus, this word was removed from the analysis, leaving only one word in Long distance [k] condition. In total, 93 tokens were included in the statistic model.

Condition	Word 1	Word 2	Token
Baseline [k]	*ktu'* /kətuʔ/ 'belly'	*kmukan* /kəmukan/ 'Hokkien'	12
Baseline [q]	*qbsuzyan* /qəβəsuzjan/ 'elder siblings'	*qmisan* /qəmisan/ 'winter'	31
Short distance [k]	*kqtux* /kəqətux/ 'salty'	*kqthuy* /kəqətəhuj/ 'thick'	28
Long distance [k]	*kgiqas* /kəɣiqas/ 'new'	*k_yaqih* /kəjaqiħ/ 'bad'	7
Cross-boundary [k]	*qu kneril qasa* /qu kəneril qasa/ 'that woman'	*qu kmukan qasa* /qu kəmukan qasa/ 'that Hokkien'	15

Table 3: Stimuli for the first participant (P01).

(1) ini' kqtux qu knalay=nya'.
/iniʔ kəqətux qu kinalaj=nja/
NEG salty NOM made=3PL.SG.GEN
'The thing he made is not salty.'

(2) ini' kqthuy na' qu qhuniq qani.
/iniʔ kəqətəhuj naʔ qu qəhuniʁq qani/
NEG thick still NOM tree this
'This tree is not thick enough.'

For the second speaker (henceforth, P02), the stimuli were presented in Table 4. Compared with the stimuli for P01, we added one more word for each condition. Besides, we replaced the Baseline [k] condition with Baseline [k-], i.e., the baseline condition for /k/ phoneme was from the inflectional morpheme /k-/ instead of lexical /k/. As for the cross-boundary conditions, we separated the sequential relationship between /k/ and /q/. That is, we created environments for /k/ only preceded by /q/ (e.g., *qu*[3] *kneril* /qu#kəneril/ 'female') or followed by /q/ (e.g., *kneril qu* /kəneril#qu/ 'female'). During the experiment, we first made the informant familiarize the sentences and made sure the sentences are congruent. Then, the stimuli were randomized and presented in written Squliq Atayal via PowerPoint. There were ten repetitions for each word. However, the /k/ in some words, especially those in Short distance [k] condition, tend to be omitted. Thus, tokens without the inflectional morpheme /k-/ were removed. 151 tokens were included in the final statistic model.

Condition	Word 1	Word 2	Word 3	Token
Baseline [k-]	*kngta'* /kəŋətaʔ/ 'fainted'	*knbu'* /kənəβuʔ/ 'sick'	*km'abi'* /kəməʔaβʔ/ 'sleepy'	20
Baseline [q]	*qbsuzyan* /qəβəsuzjan/ 'elder siblings'	*qmisan* /qəmisan/ 'winter'	*qnxan* /qənəxan/ 'life'	27
Short dist. [k]	*kqtux* /kəqətux/ 'salty'	*kqruzyux* /kəqəruʑjux/ 'long'	*kqmupang* /kəqəmupaŋ/ 'bitter'	22
Long dist. [k]	*kgiqas* /kəɣiqas/ 'new'	*kbuqax* /kəβuqax/ 'corrode'	*kplqwi'* /kəpələqwiʔ/ 'become white'	29
Cross bound. [k]-[q]	*kneril qu** /kəneril qu/ 'woman'	*kmukan qu* /kəmukan qu/ 'Hokkien'	*Ksyatun qu* /kəɕjatun qu/ 'Ksyatun'	30
Cross bound. [q]-[k]	*qu kneril* /qu kəneril/ 'woman'	*qu kmukan* /qu kəmukan/ 'Hokkien'	*qu Ksyatun* /qu kəɕjatun/ 'Ksyatun'	28

Table 4: Stimuli for P02.

2.4 *Data analysis* The recordings were labeled in Praat by the first author. For the ultrasound image analyses, onset of the burst onsets from the target consonants (mainly [k]; it will be specified when it is /q/) and the midpoints of the schwa following the target consonants were labeled from a point tier in Praat. Customized R (R Core Team, 2020) and MatLab (MATLAB, 2020) scripts were used to extract target frames. Then, we performed several analyses to examine if dorsal harmony exists in Squliq Atayal. First, with the obtained images, the region of interest (ROI) was defined as a rectangle that covered the tongue surfaces across all the target consonants. To increase the signal-to-noise ratio of the images, the images were then filtered by following the methods used in Carignan (2014) and Mielke et al. (2017): Anisotropic diffusion speckle filter (Aja-Fernández & Alberola-López, 2006) for reducing the noise while preserving the edge, median filter for reducing local noise, Gaussian filter for reducing global noise, Laplacian filter for increasing the contrast, and bicubic interpolation for reducing the pixel numbers. All filtered images were put into Python (Van Rossum & Drake Jr, 1995) for principal component analysis (PCA) using *sklearn* package. Principal components that can explain 80% of variance were adopted to reconstruct the images and the PC values of each token were submitted to Linear Discriminant Analysis (LDA). We assigned baseline conditions to construct an LDA model, using the *MASS* package in R. To make sure the good performance of LDA model, we used hold-out method for cross-validation. Finally, we applied the LDA model to predict the rest of conditions and obtain the LD values. The LD values were normalized to numbers between 0 and 1, with 0 set to be Baseline [k] and 1 to be Baseline [q]. By doing so, we can visualize the similarities of tongue contours using density plots (see Strycharczuk & Sebregts (2018) and Faytak et al. (2020) for a similar approach).

[3] *qu* is the nominative marker in Squliq Atayal so it does not change the lexical meaning of kneril.

Second, in addition to PCA-LDA, we also traced tongue contours using GetContours (Tiede & Whalen, 2015) from the onset of target consonants and midpoint of the vowel following the target consonants. Tongue contours were then fitted through generalized additive mixed models (GAMMs) (Wieling, 2018), using *mgcv* and *itsadug* packages, and visualized through *plotly* package in R.

Many studies have shown different methods to compare plosives with different places of articulation, such as formant transitions (Liberman et al., 1954) and locus equations (Sussman et al., 1991); however, these studies focused on places of articulation quite distant from one another, i.e., bilabial, alveolar, and velar. In this study, we tried to differentiate the velar plosive /k/ from the uvular plosive /q/. The existing analyses may not be suitable for the purpose of the current study. To distinguish a velar /k/ from a uvular /q/, Denzer-King (2013) reported that the difference between F3 and F2 onsets of the following vowel (henceforth, Fdiff) serves as a reliable acoustic measurement, with a higher Fdiff in /q/.

For the acoustic analyses in the present study, F2 and F3 for the vowels following the target consonants were extracted using a customized Praat Script, with the following settings: Maximum formant was 5500 Hz for female speakers, the number of formants was 5, window length was 0.025, and pre-emphasis was 50 dB. Then, formants were visually inspected and removed if wrongly traced. A total of 15 tokens (16.1%) from P01 were dropped. Only the acoustics from P01 was analyzed since the data from P02 were largely contaminated by the rain in background and hence removed from the analyses.

3 Results

3.1 *Generalized additive mixed models (GAMMs)* To examine the effect of dorsal harmony, first we compared the tongue shapes of /q/ change in different conditions. Figure 1 showed the fitted tongue contours of Baseline [q] (e.g., /q/ in *qmisan* /qəmisan/ 'winter') and the /q/ in Short distance [k] conditions (e.g. /q/ in *kqtux* /kəqətux/ 'salty'). Tongue tip is to the right of the figure. The radius values are expressed as pixel values. There is no statistical differences between the two tongue contours (i.e. no shaded areas in the figure), indicating that tongue posture of /q/ is maintained in Short distance [k], as in Baseline [q].

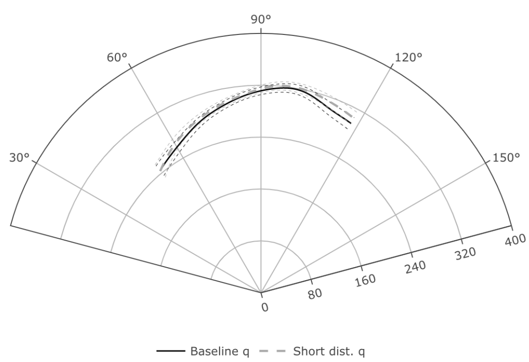
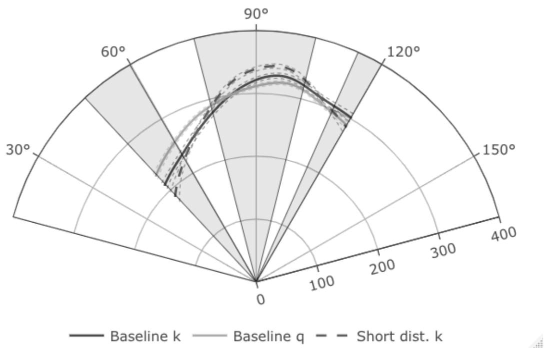


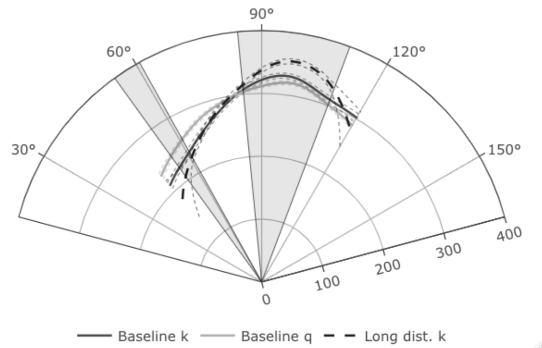
Figure 1: GAMMs fitted tongue contours (from consonant onset) of /q/ in Baseline [q] and Short distance [k] condition. Tongue tip locates on the right-hand side. The radius values are expressed as pixel values. Shaded areas indicate statistical differences between Baseline [q] and Short distance [k] (there is no shaded areas in this figure; thus, no statistical differences was found between the phoneme /q/ in Baseline [q] and Short distance [k] conditions.).

In terms of the tongue gestures of [k], fitted tongue contours from the onset of target consonants were shown in Figures 2 (P01) and 3 (P02). Shaded areas indicate statistical differences between the variant [k] and Baseline [k]. From both figures, Baseline [k] has a raised tongue body and Baseline [q] has a retracted tongue root. As revealed in Figure 2, the tongue contours of variant [k] have deviated from the Baseline [k], though not entirely conformed to the Baseline [q] contour. It is also noted that for P01 (Figure 2), all [k] variants showed similar tongue contours, with the tongue root advanced, tongue body raised and tongue tip lowered. In contrast, for P02 (Figure 3), Short distance [k] and Cross-boundary [q]-[k] have more retracted tongue roots, which is more similar to that in Baseline [q]. Different from Baseline [q] , the tongue bodies in these two conditions are raised as observed in Baseline [k], suggesting that the tongue postures in Short distance [k] and Cross-boundary [q]-[k] may still preserve some properties of /k/. On the other hand, Long distance

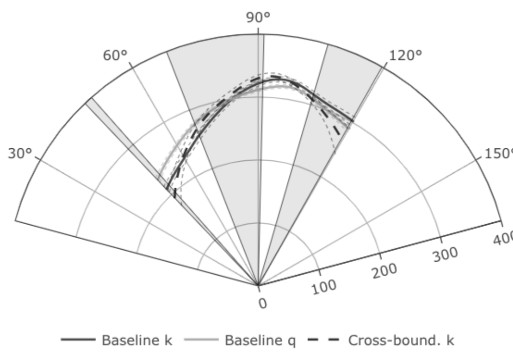
[k] and Cross-boundary [k]-[q] only have raised tongue bodies, but no obvious tongue root retraction.



(a) Short distance k



(b) Long distance k

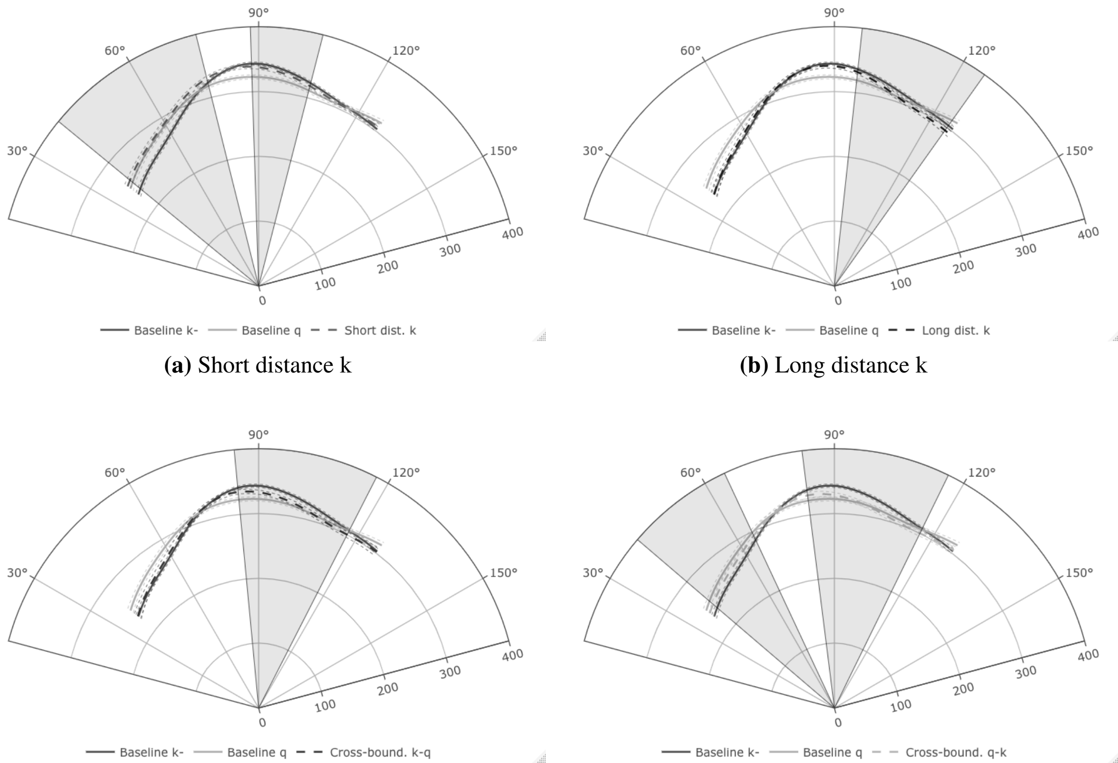


(c) Cross-boundary k

Figure 2: GAMMs fitted tongue contours (from consonant onset) of variant [k], Baseline [k] and [q] for P01 in the context of (a) short distance, (b) long distance, and (c) cross-boundary. Tongue tip locates on the right-hand side. The radius values are expressed as pixel values. Shaded areas indicate statistical differences between the variats of [k] and Baseline [k].

Apart from target consonants, the tongue contours from midpoints of the vowels following the target consonants were also fitted through GAMMs (see Figure 4). As Hansson (2001) mentioned that in consonant harmony, the intervening segments between two consonants are not affected perceptually but phonetically. Thus, Baseline [k] and Short distance [k] were chosen to see if the vowel segment between dorsal consonants is affected. The tongue tip difference shown in Figure 4 may also be attributed to the limitation of ultrasound image. It is obvious that the vowel midpoint in Short distance [k] (e.g., the first /ə/ in *kqtux* /kəqətux/) has a more raised tongue body and retracted tongue root compared to that in Baseline [k] (e.g., /ə/ in *ktu'* /kətuʔ/).

3.2 *Principle component analysis and linear discriminant analysis (PCA-LDA)* Figure 5 show LDA results from the model constructed by the onset of target consonants from Baseline [k] and Baseline [q]. The cross-validated error rate was 9.3% and 56.2% for P01 and P02, respectively. For P01 (Figure 5), it is clear that Baseline [k] and q locate at two sides while variant [k] locates between the two, with obscure bimodal distribution but no any obvious peak. This indicates that the variants of [k] are neither like Baseline [q] nor like Baseline [k]. Instead, they might be combinations of /k/ and /q/. As for P02, the cross-validated error rates quite high (56.2%), which suggests that the LDA model cannot successfully distinguish the baseline conditions. Thus, the LDA results from P02 shall not be further interpreted unless a lower cross-validated error rate is obtained.



(a) Short distance k **(b)** Long distance k

(c) Cross-boundary k-q **(d)** Cross-boundary q-k

Figure 3: GAMMs fitted tongue contours (from consonant onset) of variant [k], Baseline [k] and [q] for P02 in the context of (a) short distance, (b) long distance, (c) cross-boundary k-q, and (d) cross-boundary q-k. Tongue tip locates on the right-hand side. The radius values are expressed as pixel values. Shaded areas indicate statistical differences between the variats of [k] and Baseline [k].

3.3 *Acoustic results* The Fdiff (onset F3 - F2) results from P01 were shown in Figure 6 (the data from P02 was influenced by the rain in background). One-way ANOVA shows an effect for different conditions ($F(4, 73) = 13.5$, $p < .001$). The significance from post-hoc Tukey's tests is indicated by asterisks in the figure. The post-hoc results are in agreement with Denzer-King (2013): Baseline [q] has a higher Fdiff than Baseline [k] ($p < .001$). Short and Long distance [k] are significantly different from Baseline [q] ($p < .001$ for both) but not significantly different from Baseline [k] ($p = .537$ and $p = .898$, respectively). On the other hand, Cross-boundary [k] is significantly different from Baseline [k] ($p = .037$) but not from Baseline [q] ($p = .275$).

4 Discussion

The current study applied ultrasound and acoustic measurements to investigate dorsal harmony in Squliq Atayal. The results revealed that variants of [k] showed different tongue postures and acoustic properties from Baseline k. We also applied several methods (i.e. GAMMs, PCA-LDA, and acoustic analyses) to show that the direction of harmony from velar to uvular (/k/ → [q]) has an articulatory grounding, which will be discussed below.

The GAMM results show that the tongue contours of variant [k] are different from Baseline [k] (Figures 2 and 3), which may be contributed to the high coarticulatory aggressiveness of uvular /q/. Coarticulatory aggressiveness refers to the ability to exert coarticulatory effects on neighboring segments. Recasens & Rodríguez (2016) found that coarticulatory aggressiveness is highly positively correlated with coarticulatory resistance, which refers to the ability to resist coarticulatory effects from adjacent segments. From the GAMM results, it was observed that [k] in variant [k] is different from [k] in Baseline [k] (Figure 2), and that [q] in

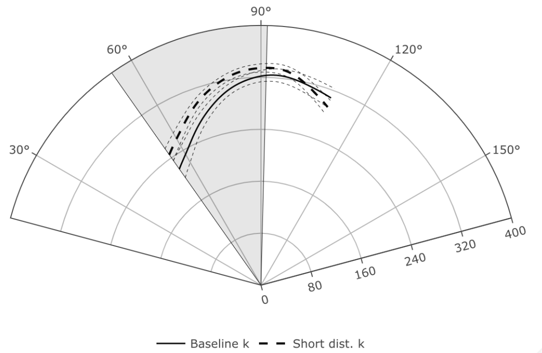


Figure 4: GAMMs fitted tongue contours (from vowel midpoint) of /ə/ in Baseline [q] and Short distance [k] condition (the schwa immediately follows the onset consonant). Tongue tip locates on the right-hand side. The radius values are expressed as pixel values. Shaded areas indicate statistical differences between Baseline [q] and Short distance [k] conditions.

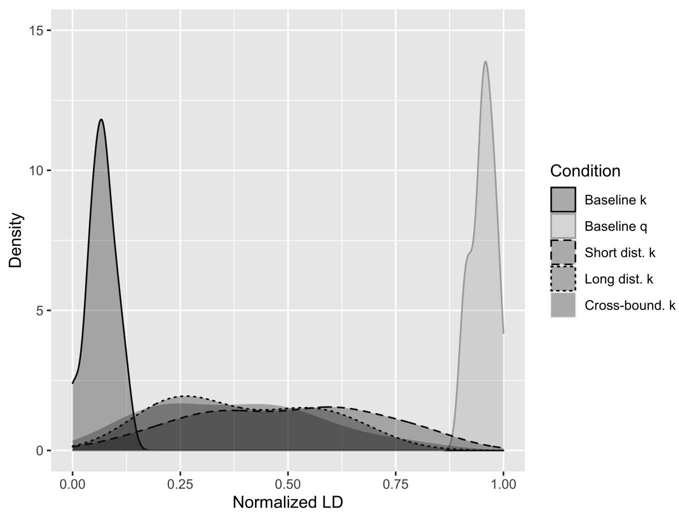


Figure 5: LDA results of variant [k] predicted by the model constructed by Baseline [k] and [q] from P01. The LD values were normalized to 0 and 1, representing Baseline [k] and Baseline [q], respectively. Thus, the LD values close to 1 means that the tongue shape is more similar to Baseline [q], and vise versa.

Baseline [q] is not significantly different from [q] in Short distance [k] (Figure 1). This may suggest that /q/ have higher coarticulatory resistance than /k/. In turn, the high coarticulatory aggressiveness of /q/ may exert an coarticulatory effect on the neighboring /k/ sounds. Therefore, tongue contours from variant [k] are different from that in Baseline [k].

It is also observed that variant tongue contours of [k] have similar tongue gestures in Figure 2. The LDA results also support this interpretation given that LD values from variant [k] have comparable distributions (Figure 5). In the framework of neuromuscular modules (NMM), the uvular /q/ is associated with the physiological states of tongue raising and retraction (Moisik et al., 2021). In the scenario of dorsal harmony, the physiological states of /q/ may also be associated with /k/, resulting in the tongue contours deviated from Baseline [k]. It is noted that similar tongue gestures were observed for the variant [k] in all three contexts. Such comparable tongue gestures may be accounted for by similar quantal combinations of intrinsic tongue muscle activation. This account would call for future studies.

Proto-Atayal /*k/ can become /q/ even when there is no such environment for dorsal harmony (e.g., Proto-Atayal /*kani/ > Squliq /qani/). Our GAMM results provided a possible explanation for such a phenomenon.In Cross-boundary [k] (Figure 2c) and Cross-boundary [q]-[k] (Figure 3d), the word itself does not have a post-velar consonant but is surrounded or close to /q/. The tongue shape from Cross-boundary

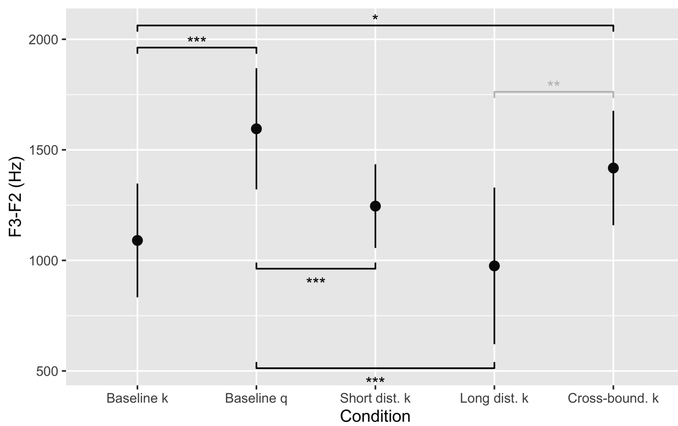


Figure 6: The Fdiff (onset F3 - F2) results from P01. The dot indicated the mean values of Fdiff, and the bar showed the standard diviation of Fdiff. The pairs with significant differences using post-hoc Tukey test were marked in the Figure with asterisks.

[k] in P01 is similar to Short and Long distance [k] and the tongue shape from Cross-boundary [q]-[k] in P02 is similar to Baseline [q], suggesting that dorsal harmony may exert across word boundaries. Such cross-boundary effect may serve as an explanation to account for /*k/ becomes /q/ when there is no such environment.

The acoustic results did not seem to match with our GAMM results. If we only measured the acoustic signals, we might conclude that dorsal harmony only occurs in Cross-boundary [k] condition from P01. However, the GAMM results from the same participant (P01) showed that all the variants of [k] exhibit the effect of dorsal harmony. Considering 2 and 6, for variant [k], the more anterior the constriction, the lower the Fdiff. However, the locations of the maximum constriction between Baseline [k] and Baseline [q] do not differ whereas their Fdiffs instead yield a significant difference. The discrepancy between the acoustic and articulatory results suggests that there might be other factors determining the Fdiff and its relationship with articulatory gestures would require further investigation.

To explain why the direction of dorsal harmony is /k/ → [q], Lee (2009) proposed the feature hierarchy in Truku Seediq (see Figure 7). When the consonant harmony occurs, the more dominant feature would exert its force on the less dominant feature and make them identical. In Lee's proposal, [pharyngeal] has a higher ranking than [dorsal]. Since /q/ and /k/ share [+dorsal] feature and they are only contrastive in [pharyngeal] feature, the dominant feature [+pharyngeal] from /q/ would make [-pharyngeal] /k/ become /q/. However, Lee's proposal only considered plosive inventory. Dorsal harmony was also triggered by pharyngeal /ħ/. If we consider the whole consonant inventory, it is unlikely that [fricative] has a lower ranking than [pharyngeal]. Moreover, in all the attested languages with dorsal harmony, none of them exert the opposite direction (i.e., /q/ → [k]) (Hansson, 2001). Thus, it is reasonable to assume dorsal harmony has physiological grounding. In the current study, we proposed that it is the high coarticulatory aggressiveness of /q/ that makes /k/ become /q/. The GAMM results showed that the inserted schwa between k and q is highly coarticulated with /q/ (Figure 4), which supports the idea of coarticulatory aggressiveness. In this vein, pharyngeal /ħ/ can also be the trigger of dorsal harmony because of its high coarticulatory aggressiveness. The data from our informant showed that phonemic /iq/ is realized as [iɑq], /iħ/ as [iħ], and /ik/ as [ik]. This might serve as evidence in support of the ranking of coarticulatory resistance: /q/ > /ħ/ > /k/, which might be able to explain why there is no /k...q/ sequence but there are some /k...ħ/ sequence in Squliq Atayal. Future study is required to see the coarticulatory aggressiveness of /ħ/.

Lee (2009) showed that there are only very few examples with /q...k/ sequence and */k...q/ is not allowed in Atayal. Consequently, she proposed that dorsal harmony has right-to-left fixed directionality in Atayalic languages. However, from our data, Short distance [k] (Figure 3a) and Cross boundary q-k (Figure 3d) showed dorsal harmony in right-to-left and left-to-right directionality, respectively. The GAMM results from P02 (Figure 3) may suggest that the dorsal harmony in Squliq Atayal may not have a fixed directionality since we also see the harmony effect in Cross-boundary [q]-[k] condition (left-to-right), as opposed to Lee's claim

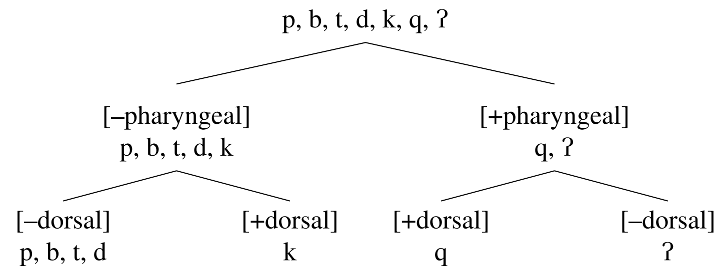


Figure 7: Feature ranking of in Truku Seediq plosive inventory proposed by Lee (2009). In the case of dorsal harmony, both /k/ and /q/ are [+dorsal]. The [+pharyngeal] of /q/ would make /k/ ([-pharyngeal]) become /q/.

that dorsal harmony has right-to-left directionality in Atayalic languages. The operation of dorsal harmony might be bi-directional.

It is noted that our results collected from two native speakers are not without any variations. The different results from P01 and P02 may be attributed to several factors. First, they are in different generations (P01: 52 years old; P02: 75 years old). It requires more data to see whether dorsal harmony has different patterns in different generations. Second, the data were collected in different procedures. For P01, she was asked to translate the Mandarin sentence into Squliq and no word forms in Squliq Atayal was presented to her. As for P02, he was asked to translate the Mandarin first, and then, the stimuli were presented in word form in Squliq Atayal. As such, this informant may have intended to produce the phonemes as close as the Romanized word forms. For Long distance [k] and Cross-boundary [k]-[q], the informant might have produced /k/ as it is and refrained it from the coarticulatory effects exerted from the far away /q/. Last but not least, P02 speaks both Squliq and Ci'uli Atayal. As we can see in Table 1, many dialects of Atayal have lost the /*q/ phoneme, and Ci'uli is one of them. It is not clear if the different pattern of dorsal harmony can be accounted for by the influence from the Ci'uli dialect. More data would be required to test the factors mentioned above.

The ultrasound and acoustic measurement only provide phonetic evidence on how different the variants of [k] are. How these variants of [k] may be perceived by native speakers of Squliq Atayal remains unanswered. Future studies on perception would be required to make a solid claim of synchronic dorsal harmony in Squliq Atayal.

5 Conclusion

The current study provided supportive evidence for dorsal harmony in Squliq Atayal that the tongue contours of all variant [k] have deviated from the Baseline k. Besides, we proposed that high coarticulatory aggressiveness serves as the driving force of the observed dorsal harmony. Such an account has a physiological grounding and holds for all attested languages with dorsal harmony. Future studies would be required to examine how native speakers of Squliq Atayal perceive those variants of [k].

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