

Context effects on the acoustic realization of stops and affricates in Northern Pwo Karen

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Studies have shown that the voice onset time (VOT) of alveolo-palatal affricates is the longest, followed by velars, dental/alveolars, and bilabials. In a reciprocal pattern, closure duration is the longest for bilabials, followed by dental/alveolars, and then velars. Longer VOT is also associated with high and front vowels and tones with rising components. Moreover, the VOT of voiceless unaspirated stops is reported to be longer and closure duration shorter in nasal words. Finally, the voiceless interval has been described as constant in some languages and inconstant in others. Given the evidence of previous research, this study investigates the effects of place, nasality, tone, and vowel quality on the VOT, closure duration, and voiceless interval of the voiced and voiceless obstruents of Northern Pwo Karen (N. Pwo), a language of Thailand. N. Pwo (ISO 639-3 *pwv*) is a ‘true voicing’ language with a three-way distinction in stops, voiceless aspirated and unaspirated affricates, oral and nasal vowels, and six tones (four modal tones and two glottalized tones). In N. Pwo, the place effects on VOT and closure duration pattern reciprocally. Whereas, both VOT and the voiceless interval are longer before oral vowels compared to nasal vowels. VOT is longest before the mid tone, which has a slight rise, while it is the shortest before the falling-glottalized tone. This pattern is reversed for the closure duration of aspirates and voiced stops. Finally, VOT, closure duration, and the voiceless interval are the longest before high and front vowels.

1 Introduction

Abramson & Whalen (2017: 84) claim that after 50 years, voice onset time (VOT) ‘has proven to be a robust measure of the acoustic realization of the consonantal voicing distinctions in most languages’. Affricates can also be distinguished from stops using VOT (Abramson 1989, 1995). Moreover, VOT has been shown to be affected by place and vowel quality. In general, VOT is significantly longer for affricates, followed by velars, dentals or alveolars, and bilabials (Abramson 1995, Cho & Ladefoged 1999). VOT is also significantly longer before high vowels, while vowel advancement effects on VOT are mixed (Nearey & Rochet 1994, Morris, McCrea & Herring 2008).

Recently, tone has been shown to affect the VOT of voiceless unaspirated and aspirated stops in Chinese language varieties. For Mandarin (ISO 639-3 *cmn*) voiceless unaspirated stops, VOT was significantly longer before the high and falling-rising tones in contrast to the rising tone, while for aspirated stops, VOT was significantly longer before the falling-rising tone compared to the falling tone (Chen, Peng & Chao 2009). In Hakka (ISO 639-3 *hak*), another Chinese variety, the shortest VOT was associated with the two stopped-syllable tones (Chen et al. 2009).

The effect of place and nasality on VOT, closure duration, and the voiceless interval has been studied in two nasal harmony languages: Paraguayan Guaraní (ISO 639-3 *gug*), a member of the Tupí family (Walker 1999), and Desano (ISO 639-3 *des*), a Tukanoan language (Silva 2008). Both researchers found that the mean VOT of intervocalic voiceless stops is significantly longer and closure duration is significantly shorter in nasal words. However, their results differ regarding the voiceless interval. Walker (1999) found no significant difference in the mean length of the voiceless interval of nasal and oral words, while Silva (2008) found that the voiceless interval is significantly longer in oral words compared to nasal words.

While the laryngeal timing of obstruents has been investigated in a wide variety of languages, investigations of the laryngeal timing of the obstruents of Karenic languages is limited. Except for the investigations of Kayan plosives, vowels, and tones with six speakers (Luangthongkum 2010) and Sgaw Karen tone perception with four speakers (Brunelle & Finkeldey 2011), all other acoustic studies of Karenic languages have reported on the speech of a single speaker (Abramson 1995, Sun 2016). Furthermore, Abramson (1995) is the only study that has investigated VOT in a Pwo Karen language variety.

Given the state of research on Karenic languages and context effects on VOT, closure duration, and the voiceless interval, the main purpose of this study is to provide a first description of some of the acoustic aspects of Northern Pwo Karen (N. Pwo) stops and affricates. N. Pwo (ISO 639-3 *pww*) is an under-documented Karenic language with a three-way stop distinction (voiceless unaspirated, voiceless aspirated, and voiced) and a two-way affricate distinction (voiceless unaspirated and voiceless aspirated). The phoneme inventory includes both oral and nasal vowels, as well as six tones: four modal tones and two glottalized tones. A secondary purpose of this study is to investigate the effects of place, nasality, tone, and vowel quality on the VOT, closure duration, and voiceless interval of obstruents in one language.

In the rest of the paper, we consider studies of context effects on VOT, closure duration, and the voiceless interval (Section 2). We then describe the methodology of the current study, including the N. Pwo syllable shapes and phoneme inventory, participants, materials, procedure, and measurements (Section 3). Then, the results of the acoustic analysis are presented (Section 4), followed by discussion (Section 5) and the conclusion (Section 6).

2 Previous work on VOT, closure duration, and the voiceless interval

In this overview of previous studies of context effects on VOT, closure duration, and the voiceless interval, place effects are considered first (Section 2.1). Then, vowel quality effects on VOT are detailed (Section 2.2), followed by nasality effects on VOT, closure duration, and the voiceless interval (Section 2.3), and then tonal effects on VOT (Section 2.4). The section ends with the questions and predictions considered in this paper (Section 2.5).

2.1 Place effects on VOT, closure duration, and the voiceless interval

Place effects on VOT have received more attention than vowel quality, nasality, or tone effects. One common finding is that velar or uvular stops are associated with the longest VOT, while bilabial stops are associated with the shortest VOT (Cho & Ladefoged 1999: 218). When the two alveolo-palatal affricates, /tʃ/ and /tʃ^h/, are included in a study of VOT, the affricates show the longest VOT, followed by the velar, and then dental stops, while the

bilabial stops exhibit the shortest VOT (Abramson 1989, 1995). Often, however, a difference in VOT between labial and dental or alveolar stops is not found (e.g. Abramson & Lisker 1972, Cho & Ladefoged 1999).

Cho & Ladefoged (1999: 213) suggest possible explanations for place effects on VOT. For unaspirated stops, the differences in VOT could be due to the size of the supralaryngeal cavity behind the constriction. For example, the size of the cavity is smaller for /k/ causing greater pressure that takes longer to fall, so VOT is longer. Conversely, the volume of the cavity in front of the constriction is larger, so the pressure takes longer to fall, again resulting in longer VOT for stops produced further back in the mouth. Slower movement of the back of the tongue could also result in longer VOT compared to the quicker movement of the tip of the tongue or lower lip. Finally, the extent of the contact area of the articulators could affect the length of VOT. A smaller contact area would contribute to shorter VOT, while a greater contact area would contribute to longer VOT. For voiceless aspirated stops, they suggest that intraoral pressure drops more slowly for /k^h/ than for /t^h/ or /p^h/. This results in a slower reduction of the glottal opening after the release of the aspirated stop, which results in longer VOT further back in the mouth. They also mention the reciprocal timing relationship between closure duration and VOT in the belief that the duration of the vocal fold opening is fixed. However, Docherty (1992) has shown that the duration of the voiceless interval is not necessarily of fixed length, in contrast to Weismer (1980).

Until 2010, the only acoustic study of a Karenic language was Abramson (1995), which was a study of the laryngeal timing of the obstruents of one Pwo Karen speaker from Paa Sangngaam village in Chiang Rai province, Thailand, and a Sgaw Karen (ISO 639-3 ksw) speaker from Taunggyi, Southern Shan State, Myanmar. Both language varieties are mutually unintelligible with N. Pwo. In this study, the Pwo Karen obstruents included bilabial, alveolar, and velar voiceless aspirated and unaspirated stops, voiceless alveolo-palatal aspirated and unaspirated affricates, and bilabial and alveolar voiced stops. The Sgaw Karen obstruents included the same stops, along with voiceless aspirated and unaspirated sibilants. Abramson's results show a separation between voiceless aspirated and unaspirated obstruents, as well as voiced stops, at each place of articulation for both languages. Concerning the inclusion of the affricates in this study, Abramson (1995: 159–161) comments that their inclusion is justified, with the proviso that the voicing lag from the release of the affricate to the glottal pulsing of the vowel is composed of frication, not the aspiration that is characteristic of the voiceless aspirated stops. Furthermore, the aspirated affricate evidences a longer period of frication as opposed to the unaspirated affricate.

Since 2010, the Karen Linguistics Project of Chulalongkorn University, Bangkok, Thailand, has produced several studies on phonetic aspects of Karenic languages. A study of four female and two male speakers of Kayan (ISO 639-3 pdu), which is distantly related to N. Pwo, found that the VOT differences between labial and alveolar plosives were not statistically significant, while VOT differences between the labial and alveolar plosives compared to the velar plosive were statistically significant (Luangthongkum 2010).

Concerning place effects on closure duration, Weismer (1980), in a study of English obstruents, reported that when VOT is longer, closure duration is shorter and vice versa. Therefore, one would expect labials to have the longest closure duration, followed by dentals, velars, and then alveolo-palatals, which is the opposite of the pattern expected for VOT. However, Yao (2007) reports wide speaker variation for both the VOT and closure duration of English word-initial voiceless aspirated stops, which are not utterance-initial, in the Buckeye corpus (Pitt et al. 2005). The results show that the average closure duration of /p/ was significantly longer than /t/ and /k/ for all speakers. Also, the average closure duration of /k/ was greater than the average closure duration of /t/. Furthermore, the difference in closure duration between /t/ and /k/ was much less significant. Finally, the variability in closure duration was 'most sensitive' to the target stop and the preceding environment, while VOT was the most sensitive to speaker, speaking rate, the following phone, and word frequency (Yao

2007: 220). Thus, closure duration and VOT are not necessarily in a reciprocal relationship across all stops. They are sensitive to both linguistic context and non-linguistic variables.

As for the voiceless interval, we found two definitions in the literature. Weismer (1980: 429) stated that ‘the voiceless interval for voiceless stops will generally include the duration of the closure plus the voice-onset time’. Yao (2007) also reports on total duration (closure duration + VOT) in his corpus study of English. In contrast, other researchers define the voiceless interval as closure duration + voice onset time – the offset voicing or VOICING BLEED (Davidson 2016) of the preceding vowel (Suomi 1980, Docherty 1992, Walker 1999, Silva 2008). For this study, we use the second definition of the voiceless interval.

Weismer (1980) reported that the mean duration of the voiceless interval of intervocalic voiceless stops and fricatives was constant, regardless of either the place or manner of articulation. Suomi (1980), who studied voicing in English and Finnish stops, also concluded that the voiceless interval is constant regardless of place of articulation. However, Docherty (1992) determined that the voiceless interval is not constant based on his study of the timing of British English obstruents. He also noted that both Weismer (1980) and Suomi (1980) concluded that the voiceless interval is constant based on mean voiceless interval measurements, without considering the variation across speakers, as evidenced by the wide standard deviations.

2.2 Vowel quality effects on VOT

After place, vowel quality is the next most studied VOT context effect. Significantly longer VOT preceding high vowels has been observed in English and French (Nearey & Rochet 1994, Morris et al. 2008), as well as Mandarin Chinese (Rochet & Fei 1991, Chao & Chen 2008). Results for vowel advancement are not as straightforward. For Mandarin Chinese, Rochet & Fei (1991) found that VOT was significantly longer for /p/ when followed by /u/, while VOT was the longest for /t/ before /i/. In contrast, Chen, Chao & Peng (2007) reported that front vs. back vowels do not significantly affect the VOT of Mandarin voiceless aspirated and unaspirated stops. Concerning voiced stops, Nearey & Rochet (1994) did not find any significant vowel context effects on the VOT of French voiced stops.

2.3 Nasality effects on VOT, closure duration, and the voiceless interval

Walker (1999) investigated VOT, closure duration, and the voiceless interval of intervocalic voiceless unaspirated stops in nasal and oral words in Paraguayan Guaraní, which is known for its nasal harmony. Then, Silva (2008) repeated Walker’s study with Desano, which also exhibits nasal harmony. In these two languages, nasal harmony affects both vowels and voiced obstruents. In contrast, voiceless obstruents do not nasalize, although they do not block the spreading of nasality. In Walker’s study, longer VOT and shorter closure duration were associated with voiceless stops in nasal words as opposed to oral words. Furthermore, in an interaction with place of articulation, VOT was significantly longer for both /p/ and /t/ in nasal words as opposed to oral words. For /k/, however, average VOT in nasal and oral words was not significantly different.

For closure duration, both Walker (1999) and Silva (2008) found that the closure duration of /p/ and /t/ was longer for oral words as opposed to nasal words, while the closure duration for /k/ in nasal and oral contexts was not significantly different. Walker (1999: 78) suggests that the reason for the lack of a difference in velar closure duration in relation to VOT in nasal and oral contexts is because ‘aspects of the timing with velars are highly fixed in comparison to other stops’. These results indicate that closure duration can also be affected by place and nasality.

Concerning the voiceless interval, Walker (1999) found that the average length of the voiceless interval was not significantly different in nasal vs. oral contexts for /p/ and /t/. However, she found that the length of the voiceless interval for /k/ is significantly longer in

oral contexts. For Desano, Silva (2008) reports a smaller difference in the voiceless interval for /p/ between nasal and oral contexts, while the difference in the voiceless interval for /t/ and /k/ is larger between nasal and oral contexts. Therefore, he concludes that the length of the voiceless interval is not constant. These studies show that the voiceless interval can be affected by both place and nasality. Therefore, if the voiceless interval can be affected by place and nasality, it may be affected by other context effects, such as tone and vowel quality.

2.4 Tonal effects on VOT

Liu et al. (2008) found that the VOT of Mandarin Chinese voiceless aspirated stops preceding Tone 2 (35) and Tone 3 (214) was significantly longer than the VOT preceding Tone 4 (51). The reason for this is that ‘the longer VOT values in the MR [mid-rising] and FR [falling-rising] tones may be related to the fact that both tones have a rising component in their pitch contours. . . The anticipated increase of tension in the voicing source and pitch may have delayed the onset of vibration of the vibratory structure’ (Liu et al. 2008: 215).

Chen et al. (2009) reported the same results for Mandarin aspirated stops. However, when they excluded the non-words in the data, they found that the VOT of voiceless aspirated stops was significantly longer preceding Tone 3 (214) compared to Tone 4 (51). The VOT of unaspirated stops was significantly longer preceding Tone 1 (55) and Tone 3 (214) compared to Tone 2 (35).

When Chen et al. (2009) examined the effect of tone on the voiceless stops in real words of Hakka (ISO 639-3 hak), another Chinese variety, they found that the VOT of both aspirated and unaspirated stops was significantly longer before Tone 1 (24) and Tone 5 (11). In addition, the VOT of unaspirated stops was significantly shorter before Tone 8 (55), while the VOT of aspirated stops was significantly shorter before Tone 4 (32) and Tone 8 (55). Both Tone 4 and Tone 8 only occur in stopped syllables, which are characterized as ‘short, rapid and ended by a stop’ (Chen et al. 2009: 557).

In Asian languages, tones are complexes of pitch, voice quality, and duration (Andruski & Ratliff 2000, Brunelle 2009). For example, Brunelle & Finkeldey (2011: 375) describe Sgaw Karen Tone 4 as a glottalized tone that is distinguished by shorter duration and glottalized voice quality. The Vietnamese (ISO 639-3 vie) B2 tone is described as shorter than other tones and ending on a glottal stop (Brunelle 2009: 80). Furthermore, the realization of a glottalized tone can range ‘from a strong laryngealization to a full glottal stop’ (Brunelle 2009: 80). In addition, stop-final syllables, including syllables with a glottal stop coda, are treated the same. Duanmu (1994: 78) observes that

in Asian tone languages stopped syllables (i.e. those whose coda is [ʔ] or a glottalized [p], [t], or [k]) do have different pitch contours from unstopped syllables; usually, the pitch contour is shorter on a stopped syllable than on unstopped syllables. As a result, tones on stopped syllables are usually listed separately in traditional descriptions.

However, shorter tone duration does not necessarily correlate with shorter VOT. Sun (2016) provides a preliminary investigation of the interaction between breathiness and the voiceless aspirated and unaspirated stops of one Sgaw Karen speaker. Sgaw Karen has a modal mid tone, two breathy tones (breathy high and breathy low), and two glottalized tones (high glottalized and low glottalized). The mid tone duration is the longest, followed by the breathy tones. The two glottalized tones are the shortest. In addition, aspirated stops do not co-occur with the low breathy tone at all, while real words with an aspirated stop and a high breathy tone are rare and only occur with /p^h/ and /t^h/. The average VOT of /p^h/- and /t^h/-initial syllables is the longest before the mid (112–121 ms) and glottalized tones (115–130 ms), while the shortest VOT occurs before the high breathy tone (85–98 ms). For /p/ and /t/, VOT is somewhat longer before the glottalized tones (8–10 ms) compared to the mid tone (6–9 ms), while the shortest VOT occurs before the breathy tones (2–5 ms). These results

show that neither tone duration nor the presence of aspiration with a breathy tone predict shorter VOT. As Liu et al. (2008) suggest, the greater articulatory effort required to produce particular tones could result in longer VOT. Less articulatory effort is required to produce breathy phonation (Marasek 1997, Gick, Wilson & Derrick 2013), which could contribute to shorter VOT before the Sgaw Karen breathy tones.

To summarize, for voiceless aspirated stops, longer VOT tends to be associated with modal tones with rising components and low tones, while shorter VOT is associated with falling and stopped-syllable tones, although stops that occur before breathy tones can exhibit even shorter VOT. For voiceless unaspirated stops, results are mixed. In Mandarin, the longest VOT occurs preceding Tone 1 (55) and Tone 3 (214), while the shortest VOT occurs preceding Tone 2 (35). In Hakka, the longest VOT occurs preceding both the rising and low tones and the shortest VOT occurs preceding Tone 8, one of the stopped-syllable tones.

2.5 Questions and predictions

Given the results of previous research, this study seeks to answer three questions:

Question 1: *How is the VOT of stops and affricates affected by vowel quality, tone, and nasality in a language with a three-way distinction in stops, such as N. Pwo?*

First, studies on the effect of vowel quality on VOT seem to have been limited to languages with a two-way stop distinction. Second, tone has been shown to affect the VOT of voiceless unaspirated and aspirated stops in Chinese language varieties and in Sgaw Karen. However, the effect of tone on the VOT of voiced stops is yet to be investigated. N. Pwo is a ‘true voicing’ tonal language, which makes it an ideal candidate for investigating tonal effects on voiced stop VOT. Third, the effect of following nasal vowels on VOT has not been investigated in any language, so this is one gap that this study aims to fill.

Question 2: *Are VOT and closure duration in a reciprocal relationship when affected by vowel quality, a post-obstruent nasalized vowel, or tone?*

It has been claimed that VOT and closure duration are in a reciprocal relationship with each other. For place, when VOT is shorter, closure duration is longer and vice versa (Weismer 1980). Both Walker (1999) and Silva (2008) have shown that this reciprocity is maintained in nasal and oral words in a nasal harmony language. However, it is not known whether this reciprocal relationship between VOT and closure duration holds for tone, nasalized vowels, or vowel quality effects.

Question 3: *Is the voiceless interval affected by place, vowel quality, nasality, and tone in a three-way stop language, such as N. Pwo?*

Reports of the constant length of the voiceless interval by place and nasality have been mixed. Furthermore, it is not known whether vowel quality, nasalized vowels, and tone have any effect on the voiceless interval.

Based on the results of previous studies, we expect contextual effects on VOT that differ by type (voiceless aspirated, voiceless unaspirated, or voiced). For place effects, we predict that VOT will be the longest for the alveolo-palatals (affricates), followed by the velars, and then the dentals and bilabials. It is also possible that the difference in the VOT of dentals and bilabials will not be significant. Since N. Pwo has modal and glottalized tones, we predict that VOT will be the longest preceding the mid and high tones, which both rise slightly, as well as the low tone, while VOT will be the shortest before the falling and glottalized tones. VOT will also be the longest before high vowels. Moreover, the VOT of alveolo-palatal aspirated and unaspirated obstruents before front vowels will be the longest, while the VOT of the bilabial plosives before front vowels will be the shortest. Finally, no vowel context effects are predicted for voiced stops.

As for the reciprocal relationship between VOT and closure duration that has been observed in other languages, we expect that closure duration will be the longest for bilabials, followed by the dentals, velars, and then affricates. As for a nasality effect, it is not possible to make a prediction since N. Pwo has nasalized vowels, not nasal words that come about through nasal harmony. It is also not possible to predict the effects of vowel quality and tone on closure duration, due to the lack of previous work. Finally, we expect context effects on the voiceless interval, although it is not possible to predict what effects there might be based on previous work.

3 Methods

For this study of the effects of place, vowel quality, tone, and nasality on VOT, closure duration, and the voiceless interval, meaningful N. Pwo words were recorded in a carrier phrase that placed the target stop or affricate in a word-initial, intervocalic position. Information about the relevant phonological inventory of N. Pwo is detailed in Section 3.1, followed by the speech materials in Section 3.2, the participants in Section 3.3, the recording procedure in Section 3.4, and the acoustic measurements in Section 3.5.

3.1 Northern Pwo Karen

N. Pwo is an isolating language with major and minor syllables. Major syllables (C(C)V^T) are stressed and make use of the full inventory of consonants, vowels, and tone. In contrast, minor syllables (Cə) are reduced and never occur alone or word-finally. They have a limited single initial consonant inventory and unstressed /ə/ as the only vowel, with no tone. See Pittayaporn (2015) for an examination of this areal phenomenon of Mainland Southeast Asian languages.

The N. Pwo stop and affricate inventory (Table 1) includes voiceless unaspirated, voiceless aspirated, and voiced stops, along with voiceless unaspirated and aspirated alveolo-palatal (laminal post-alveolar) affricates (Cooke, Hudspith & Morris 1976, Phillips 2009).

Table 1 Northern Pwo Karen stops and affricates.

	Bilabial	Dental	Alveolo-palatal	Velar
Voiceless unaspirated	p	t	tʃ	k
Voiceless aspirated	p ^h	t ^h	tʃ ^h	k ^h
Voiced	b	d		

The vowel inventory (Table 2) includes both monophthongs and diphthongs consisting of a low /ɐ/ with high /i ī u/ offglides. Monophthongs can be either oral or nasal while diphthongs are only oral. Length is not contrastive.

Table 2 Northern Pwo Karen vowels.

	Front	Central	Back	Diphthongs
Close	ī ī̃	ī̃ ī̃̃	ū ū̃	
Close-mid	ē ē̃	ə̄ ə̄̃	ō ō̃	
Open-mid	ɛ	ɐ̄ ɐ̄̃	ɔ̄ ɔ̄̃	ɛī ɛī̃ ɐu

Finally, N. Pwo has six tones (Table 3): four modal tones, High (H), Mid (M), Low (L), Falling (F), and two glottalized tones, Mid-glottalized (MQ) and Falling-glottalized (FQ) that end in laryngealization or a glottal stop. The tones are characterized using the Chao (1967)

tone numbers, which provide an approximation of the contour patterns of lexical tones in a five-level system.

Table 3 Northern Pwo Karen tones.

Tone name	IPA	Chao tone numbers
High (H)	/é/	45
Mid (M)	/ē/	33
Low (L)	/è/	21
Falling (F)	/ê/	41
Mid-glottalized (MQ)	/éʔ/	33 ^ʔ
Falling-glottalized (FQ)	/êʔ/	32 ^ʔ

1 = Low, 2 = Half-Low, 3 = Middle, 4 = Half-High, 5 = High

3.2 Materials

A list was created of all the possible major CV syllables occurring with the ten oral obstruents /p p^h b t t^h d tɕ tɕ^h k k^h/, seven oral vowels /i e ε ɐ u o ɔ/ and six nasal vowels /ĩ ẽ ẽ̃ ã õ ã̃/, along with the six tones (high, mid, low, falling, mid-glottalized and falling-glottalized). In this list, the phonemic diphthongs were excluded, as well as the high and mid central vowels due to their rarity. Also, the N. Pwo vowel inventory does not include a nasalized /ẽ̃/ in opposition to the oral /ε/ (see Table 2).

When this list of 840 possible major syllables was tested with a N. Pwo speaker, only 289 meaningful words were found in which the target stops and affricates occur in the initial major syllable of a mono- or polysyllabic word (see Appendix A). Phonotactically, nasalized vowels never co-occur with the glottalized tones. Also, in the elicitation list, no voiced stops and no tokens of /i/ and /u/ occur with the mid-glottalized tone, no tokens of /e/ and /o/ occur with the falling-glottalized tone, and no tokens of /ɔ/ occur with the high, mid, and falling tones. The distribution of place, vowel, and tone combinations in the data set is tabulated in Appendix B.

3.3 Participants

Twelve participants, six men and six women, were recruited by an assistant, who is a speaker of N. Pwo and a leader in the N. Pwo Karen community in Chiang Mai, Thailand. Participants' ages ranged from 17–37 years. Eleven participants were born and grew up in southern Mae Hong Son province, while one participant came from southern Chiang Mai province.

All participants were multilingual speakers of at least N. Pwo and Standard Thai, as well as Northern Thai, a lingua franca in northern Thailand. Some were also fluent in Sgaw Karen, a related Karenic language, and some were familiar with English. Most of the participants were either in university or vocational school, or they had already graduated. The single exception was one speaker with a Grade 9 education. All the participants were readers of Standard Thai and all but three of them were proficient readers of the N. Pwo writing system, which uses an adapted Thai script. These three participants transliterated problem words using Thai spelling to help them read the words correctly.

3.4 Procedure

Recordings were carried out in a quiet room at Payap University, Chiang Mai, Thailand, with a Marantz PMD661 digital recorder and either a Shure WH20 head-mounted or a Shure SM57 microphone. The data collection was conducted by the N. Pwo assistant who gave instructions in a mix of Standard Thai and N. Pwo, although communications eventually

became N. Pwo exclusively. Participants had the opportunity to practice reading through the list prior to recording, and reading practice also occurred during the recording, as necessary. The N. Pwo assistant checked for misreadings, while the first author ran the recording equipment, checked for hesitations, and collated the list of words to be reread.

Participants were asked to read the word list at a normal speaking rate, in 200-item blocks. The words were read in the carrier phrase *nə = nə̀tɕé _____ tɕʰi = ê* Did you hear _____? (Lit.: “You hear _____ QUES”). Each word was repeated twice, in a randomized list of 578 items, by 12 speakers (578 x 12), for a total of 6,936 tokens. Any reading mistakes were noted, and speakers were asked to reread items at the end of the recording session. Reading mistakes were most often due to hesitations or the mispronunciation of tone. Generally, recording took about 45 minutes to an hour per participant. For participants who were not literate in N. Pwo, the recording time was longer, as they took more time to practice and reread mispronounced words.

3.5 Measurements

Several measurements related to the target stop in each token were marked using Praat (Boersma & Weenink 2012). For the voiceless obstruents, voiced closure (VDCLO) was measured from the last visible instance of the F2 and/or F3 formants to the end of the voicing bleed, which was determined based on a change in the pattern of the waveform and the end of voicing in the spectrogram. Voiceless closure (VLCLO) was measured from the end of the voicing bleed of the preceding vowel to the burst release of the target obstruent. VOT (REL) was measured from the burst release to the onset of voicing of the following vowel. The vowel onset was marked when the pattern of the waveform changed and the striations in the spectrogram became darker. In cases of multiple burst releases, VOT was measured from the first burst release. Figure 1 illustrates the measurement of the syllable *tɕʰē*. For the purposes of this study, VOT is labelled REL, closure duration is voiced closure (VDCLO) + voiceless closure (VLCLO), and the voiceless interval is voiceless closure (VLCLO) + VOT (REL).

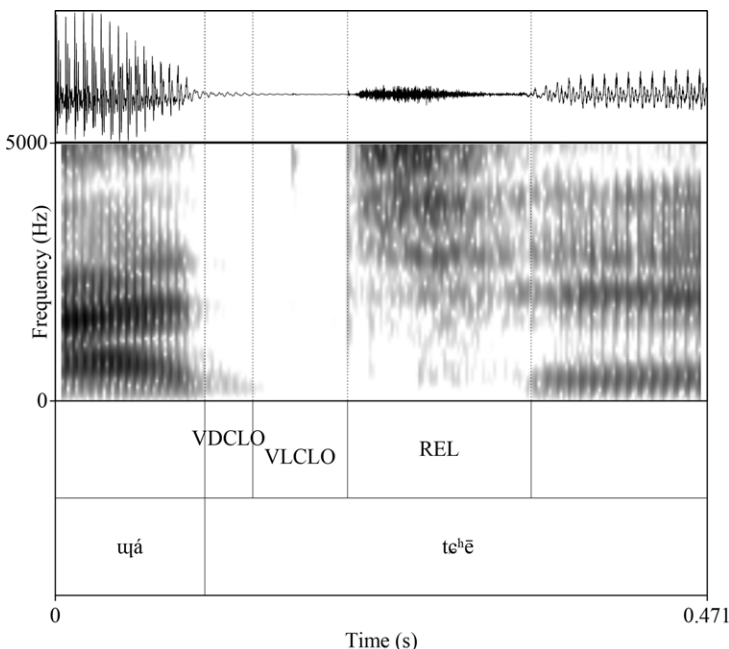


Figure 1 Waveform and spectrogram of /tɕʰē/ (VDCLO – voiced closure, VLCLO – voiceless closure, REL – release).

N. Pwo voiced stops are voiced for more than 50% of the closure, which makes N. Pwo a ‘true voicing’ language (Davidson 2016, Abramson & Whalen 2017). Voiced closure (VDCL) or negative VOT was measured from the last visible instance of the F2 and/or F3 formants of the preceding vowel to the onset of voicing in the following vowel (Lisker & Abramson 1964, Klatt 1975). Figure 2 illustrates the measurement of the syllable $d\hat{e}$.

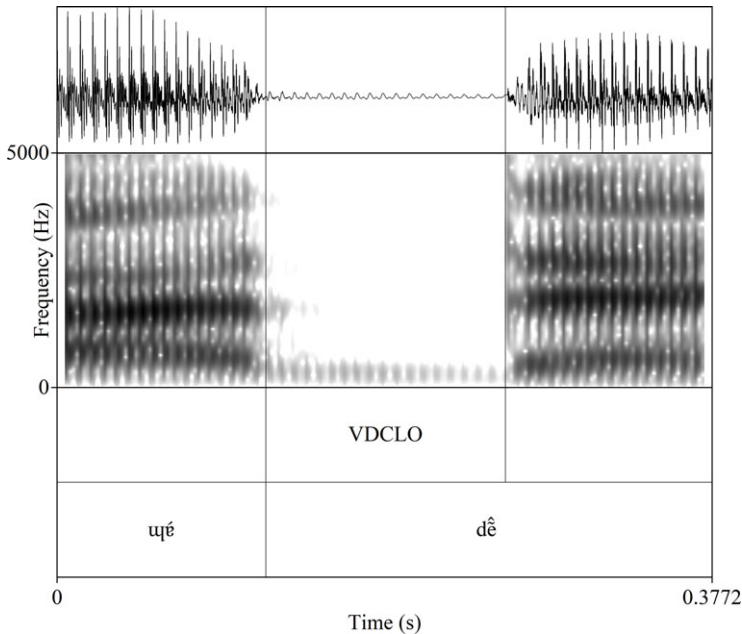


Figure 2 Waveform and spectrogram of the voiced closure (VDCL) of $/d\hat{e}/$.

4 Results

Nine tokens were removed due to mispronunciations, and a further forty-two tokens were removed due to hesitations. This left 6,885 tokens for the analysis. Most of the hesitations were produced by three of the six female speakers and three of the six male speakers, while most of the mispronunciations were produced by five of the twelve speakers. Even so, the data set included at least one iteration of every word by every participant.

These data were analysed using linear mixed effects regression in *R* (R Core Team 2019), with the *lme4* package (Bates et al. 2019). The package *lmerTest* (Kuznetsova et al. 2019) was used to produce degrees of freedom and *p*-values using the Satterthwaite approximation. However, we note that Bates et al. (2015: 34) indicate that any method for approximating degrees of freedom for linear mixed-effects regression is ‘at best *ad hoc*’.

In addition to random effects for speaker and word, all possible random slopes with speaker were tested and included in the final model if they improved model fit and did not cause convergence issues. All the dependent variables, VOT, closure duration, and the voiceless interval, had slightly skewed distributions and the distribution for the unaspirated VOT had a multimodal distribution likely related to place of articulation. We transformed all the dependent variables using a base-10 logarithm, which better approximated a normal distribution and maintained consistency across all the models. Furthermore, since the differences

were so large between the voiceless aspirated, voiceless unaspirated, and voiced obstruents, we analysed the different types separately after modelling an overall effect.

The factors tested were: Type (aspirated, unaspirated, voiced), Place of Articulation (bilabial, dental, alveolo-palatal, velar), Nasality (oral, nasal), Tone (high, mid, low, falling, mid-glottalized, falling-glottalized), Vowel Height (high /i ɨ u ʉ/, non-high /e ɛ ɐ ɐ̃ o ɔ̃/), and Vowel Advancement (front /i ɨ e ɛ/, back /ɐ̃ u ʉ o ɔ̃/). The Syllable variable registered the number of syllables in a word (one syllable, two syllables, three syllables). A backward stepwise model-fitting procedure was used in which non-significant effects were excluded from the model. The testing of context effect interactions was limited to interactions with place of articulation. None of the factors were fully crossed since data was not available in many cases due to the phonotactics of the language and the lack of meaningful words for all logical combinations of obstruents, vowels, and tones. The combinations of obstruents, vowels, and tones in the data set are shown in Appendix B. Place interactions were included in the final model if they were significant and did not cause convergence issues. In the results to follow, the analysis of voice onset time is reported first (Section 4.1), followed by closure duration (Section 4.2), and then the voiceless interval (Section 4.3).

4.1 Voice onset time

A first linear mixed effects model of the entire dataset – with speaker and word random effects, a vowel advancement random slope with speaker, and no interactions – shows a large effect of Type. In Figure 3, the unaspirated obstruents exhibit the shortest VOT followed by the aspirated obstruents, which are significantly longer ($p < .001$). Voiced stops evidence negative VOT. Since the difference in VOT by type was so large, a separate analysis was carried out for the voiceless aspirated and unaspirated tokens to better explore context effects.

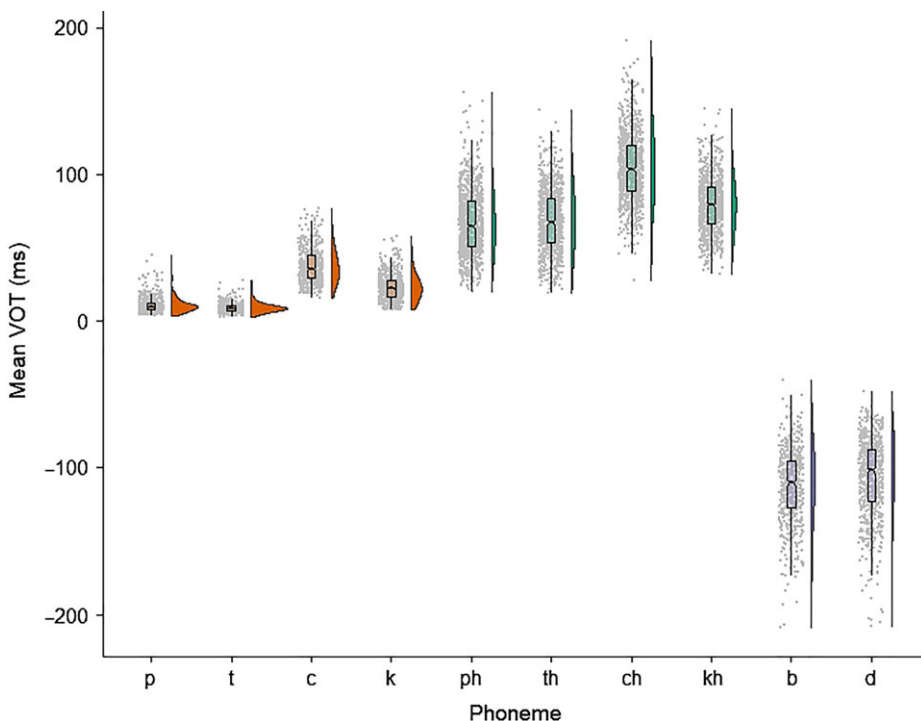


Figure 3 (Colour online) Raincloud plot of mean VOT by phoneme and type (unaspirated obstruents in orange, aspirated obstruents in green, and voiced stops in lavender).

Since negative VOT is equivalent to closure duration, the voiced stop results are reported under closure duration in Section 4.2. Aspirated obstruent results are reported first (Section 4.1.1), followed by the unaspirated obstruents (Section 4.1.2). The section ends with a summary of the VOT results (Section 4.1.3).

4.1.1 Aspirated obstruents

A linear mixed effects regression model of the aspirated tokens, which included speaker and word random effects, showed significant main effects of place, nasality, tone, vowel height, and vowel advancement, along with a significant interaction of place and vowel advancement (Table 4). The model also included a nasality random slope with speaker. The model intercept is Syllables: 1s, Place: Bilabial, Nasality: Nasal, Tone: Falling-glottalized, Vowel Height: Non-High, and Vowel Advancement: Back.

Table 4 VOT for aspirated tokens; $N = 3536$.

Fixed effects	Estimate	Std. Error	df	<i>t</i> -value	Pr (> <i>t</i>)
(Intercept)	4.081	0.060	16.211	68.163	< .001 ***
Syllables:2s	-0.135	0.020	124.005	-6.743	< .001 ***
Syllables:3s	-0.247	0.048	123.775	-5.191	< .001 ***
Place: Dental	-0.026	0.021	123.938	-1.270	.206
Place: Velar	0.138	0.020	124.596	6.726	< .001 ***
Place: Alveolo-Palatal	0.368	0.020	124.745	18.511	< .001 ***
Nasality: Oral	0.092	0.017	25.246	5.486	< .001 ***
Tone: High	0.087	0.022	123.853	3.992	< .001 ***
Tone: Mid	0.140	0.023	124.084	6.086	< .001 ***
Tone: Low	0.105	0.023	124.091	4.586	< .001 ***
Tone: Falling	0.031	0.024	124.995	1.283	.202
Tone: Mid-glottalized	0.061	0.027	124.047	2.277	.025 *
Vowel Height: High	0.036	0.012	124.300	3.027	.003 **
Vowel Advancement: Front	-0.150	0.022	124.607	-6.858	< .001 ***
Place: Dental × Vadv: Front	0.111	0.030	125.335	3.642	< .001 ***
Place: Velar × Vadv: Front	0.153	0.032	124.656	4.862	< .001 ***
Place: Alveolo-Palatal × Vadv: Front	0.222	0.030	124.613	7.384	< .001 ***

Vadv = Vowel advancement. Significance codes: *** $p < .001$, ** $p < .01$, * $p < .05$

For place, the reported and relevelled models show that VOT is significantly longer for the alveolo-palatal aspirate, followed by the velar aspirate, and then the dental and bilabial aspirates. The difference in VOT between the dental and bilabial aspirates is not significant. VOT preceding oral vowels is significantly longer than VOT preceding nasal vowels. For tone, after releveling to investigate all possible comparisons, we found that the longest VOT occurs preceding the mid tone, while the shortest VOT occurs preceding the falling-glottalized tone. VOT preceding the remaining tones falls between these two extremes in stepwise fashion, starting with the low tone. Thus, VOT preceding the low tone is significantly less than VOT preceding the mid tone, but not significantly different from VOT preceding the high tone. VOT preceding the high tone is also not significantly different from VOT preceding either the low tone or the mid-glottalized tone, and so on. VOT is significantly longer preceding high vowels as opposed to non-high vowels. Finally, an interaction between place and vowel advancement shows that VOT is significantly longer for the alveolo-palatal aspirate preceding front vowels compared to the velar and dental aspirates. The bilabial aspirate evidences the shortest VOT before front vowels.

4.1.2 Unaspirated obstruents

The unaspirated tokens show significant main effects of place, tone, and vowel height, along with significant place and nasality and place and vowel height interactions (Table 5). The model includes a nasality random slope with speaker. Finally, the model intercept is Place: Bilabial, Nasality: Nasal, Tone: Falling-glottalized, and Vowel Height: Non-High.

Table 5 VOT for unaspirated tokens; $N = 2133$.

Fixed effects	Estimate	Std. Error	df	t-value	Pr (> t)
(Intercept)	2.232	0.077	36.449	28.853	< .001 ***
Place: Dental	-0.226	0.067	74.070	-3.387	< .005 ***
Place: Velar	0.596	0.052	71.932	11.423	< .001 ***
Place: Alveolo-Palatal	1.127	0.064	73.585	17.647	.001 **
Nasality: Oral	-0.078	0.054	72.669	-1.450	.151
Tone: High	0.064	0.050	72.798	1.277	.206
Tone: Mid	0.122	0.043	73.131	2.818	.006 **
Tone: Low	0.144	0.060	72.327	2.531	.014 *
Tone: Falling	0.061	0.043	73.377	1.425	.158
Tone: Mid-glottalized	0.019	0.057	73.095	0.338	.736
Vowel Height: High	0.236	0.061	72.087	3.896	< .001 ***
Place: Dental × Nasality: Oral	0.154	0.080	73.104	1.931	.057 .
Place: Velar × Nasality: Oral	0.267	0.067	72.097	3.981	< .001 ***
Place: Alveolo-Palatal × Nasality: Oral	0.248	0.074	72.881	3.342	.001 **
Place: Dental × Vheight: High	-0.107	0.084	72.173	-1.275	.206
Place: Velar × Vheight: High	-0.056	0.077	72.278	-0.734	.465
Place: Alveolo-Palatal × Vheight: High	-0.196	0.081	72.200	-2.429	.018 *

Vheight = Vowel height. Significance codes: *** $p < .001$, ** $p < .01$, * $p < .05$, . $p < .1$

The place of articulation results, which included releveling, indicate a significant difference in VOT at each place of articulation across all comparisons in the expected directions. Interestingly, the VOT of the dental non-aspirate is significantly shorter than the VOT of the bilabial non-aspirate. For nasality, VOT is significantly longer before oral vowels for the alveolo-palatal and velar non-aspirates compared to the bilabial non-aspirate. The VOT of the dental non-aspirate is not significantly different from the other three places of articulation before oral vowels. Considering tone, VOT preceding a mid or low tone is significantly longer than VOT preceding the falling glottalized tone. VOT preceding the high, falling, and mid-glottalized tones is not significantly different in comparison to the mid, low, and falling-glottalized tones. Before high vowels, the VOT of the bilabial non-aspirate is significantly longer compared to the alveolo-palatal non-aspirate. In addition, the VOT of the dental and velar non-aspirates before high vowels is not significantly different from either the bilabial or the alveolo-palatal non-aspirates.

4.1.3 Summary of VOT results

To summarize, the effects of place, nasality, tone, and vowel quality are specific to whether the voiceless obstruent is aspirated or unaspirated. As shown in Table 6, VOT is the longest for the alveolo-palatals, while it is the shortest for the bilabials and/or the dentals. There is no significant difference in VOT between the dental and bilabial aspirates, while the short lag VOT of the bilabial non-aspirate is significantly longer than the VOT of the dental non-aspirate. VOT is significantly longer before oral vowels for the aspirates. In an interaction between

Table 6 Summary of VOT effects (longest to shortest VOT).

VOT Effects	Aspirated (long lag)	Unaspirated (short lag)
Place	$t_c^h > k^h > p^h/t^h$	$t_c > k > p > t$
Nasality	Oral > Nasal	Oral t_c/k (t) p
Tone	M > L = H = MQ = F = FQ	M/L (H, F, MQ) FQ
Vowel Height	High > Non-High	High p (t, k) t_c
Vowel Advancement	Front $t_c^h > k^h/t^h > p^h$	None

Note: Slashes between items (e.g. p^h/t^h) indicate no significant difference in VOT. An equals sign indicates no significant difference between contiguous items. Configurations like M/L (H, F, MQ) FQ indicate that while VOT is significantly different between M/L and FQ, it is not significantly different between H, F, and MQ and M/L or FQ.

place and nasality, VOT is significantly longer for the alveolo-palatal and velar unaspirated obstruents preceding oral vowels in comparison to the bilabial non-aspirate. The dental non-aspirate does not differ significantly from the other places of articulation before oral vowels.

Concerning tone, the VOT of the voiceless aspirated and unaspirated obstruents is consistently the longest preceding the mid tone and the shortest preceding the falling-glottalized tone. Considering vowel height, the longest VOT occurs before high vowels for both aspirated and unaspirated obstruents, although in an interaction between place and vowel height, VOT is significantly longer for the bilabial non-aspirate before high vowels in contrast to the alveolo-palatal non-aspirate. Finally, VOT is significantly longer for the alveolo-palatal aspirate compared to the bilabial aspirate before front vowels, with the velar and dental aspirates patterning together.

4.2 Closure duration

For the investigation of context effects on closure duration, the voiced plosives were included in the analysis since closure duration and negative VOT are the same (Abramson & Whalen 2017). Although a mixed effects model for all the data failed to converge, comparison of mean closure duration by place of articulation showed a substantial effect of Type. Figure 4 shows that the mean closure duration of aspirated stops (76 ms) is shorter than the mean closure duration of the voiced stops (109 ms), which is shorter than the unaspirated stops (119 ms). Therefore, as with VOT, we separated tokens by type to better examine context effects.

Voiceless aspirated obstruents are covered first (Section 4.2.1), followed by voiceless unaspirated obstruents (Section 4.2.2), and then voiced stops (Section 4.2.3). The section ends with a summary of the closure duration results (Section 4.2.4).

4.2.1 Voiceless aspirated obstruents

A linear mixed effects model with the voiceless aspirated tokens shows main effects of place, tone, vowel height, and vowel advancement, with no significant place interactions. The model includes a vowel advancement random slope with speaker (Table 7). The model intercept is Syllables: 1s, Place: Bilabial, Tone: Falling-glottalized, Vowel Height: Non-High, and Vowel Advancement: Back.

The final and relevelled models indicate that the closure duration of the bilabial aspirate is significantly longer than the alveolo-palatal aspirate, which evidences the shortest closure duration. The difference in closure duration between the dental and velar aspirates is not significant. Thus, significant differences in closure duration occur between the bilabial, dental/velar, and alveolo-palatal places of articulation. For tone, closure duration is significantly longer before the mid-glottalized and falling-glottalized tones, while closure duration is significantly shorter preceding the mid and high tones. The difference in closure duration

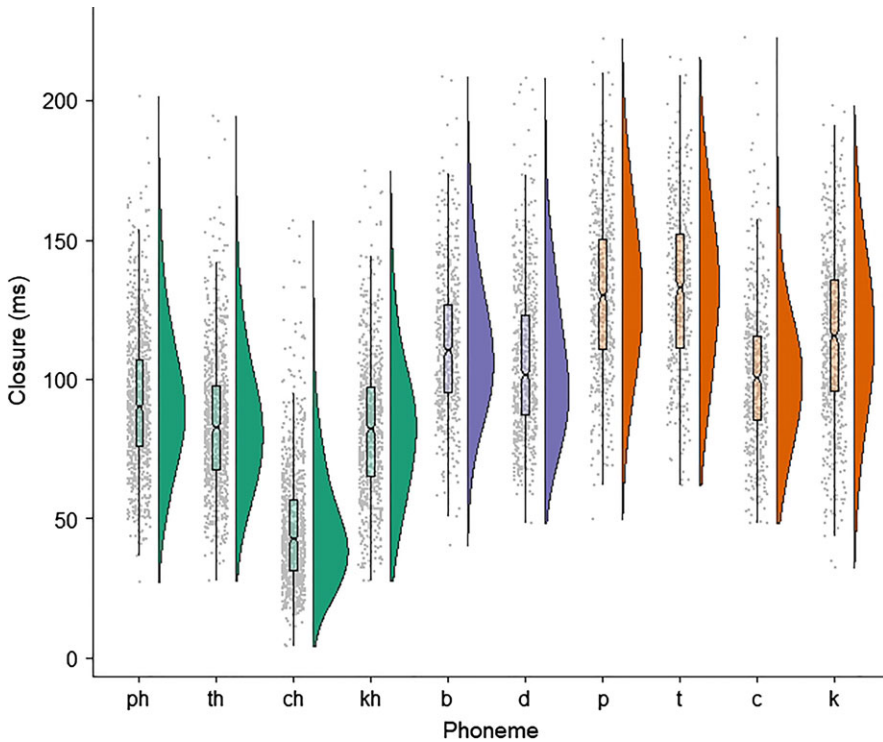


Figure 4 (Colour online) Raincloud plot of mean closure duration by phoneme and type (aspirated obstruents in green, voiced stops in lavender, and unaspirated obstruents in orange).

Table 7 Closure duration for aspirated tokens; $N = 3536$.

Fixed effects	Estimate	Std. Error	df	<i>t</i> -value	Pr (> <i>t</i>)
(Intercept)	4.508	0.061	14.966	73.782	< .001 ***
Syllables: 2s	-0.190	0.022	132.844	-8.649	< .001 ***
Syllables: 3s	-0.119	0.052	132.557	-2.270	.025 *
Place: Dental	-0.102	0.017	133.897	-6.069	< .001 ***
Place: Velar	-0.103	0.017	133.665	-5.984	< .001 ***
Place: Alveolo-Palatal	-0.748	0.017	133.481	-44.960	< .001 ***
Tone: High	-0.078	0.023	132.568	-3.324	.001 **
Tone: Mid	-0.091	0.024	132.709	-3.738	< .001 ***
Tone: Low	-0.054	0.024	132.827	-2.269	.025 *
Tone: Falling	-0.033	0.026	133.799	-1.287	.200
Tone: Mid-glottalized	0.017	0.030	132.985	0.560	.576
Vowel Height: High	0.088	0.013	133.322	6.721	< .001 ***
Vowel Advancement: Front	0.054	0.018	16.453	2.949	.009 **

Significance codes: *** $p < .001$, ** $p < .01$, * $p < .05$

between the mid-glottalized, falling-glottalized, and falling tones is not significant. In addition, the difference in closure duration between the falling and low tones is not significant, nor is the difference in closure duration between the low, mid, and high tones. Considering vowel quality, closure duration is significantly longer preceding both high and front vowels.

4.2.2 Voiceless unaspirated obstruents

For the voiceless unaspirated obstruents, closure duration shows significant main effects of place and vowel advancement, with significant interactions between place and vowel height and place and vowel advancement. A vowel advancement random slope with speaker is also included in the model (Table 8). The model intercept is Syllables: 1s, Place: Bilabial, Vowel Height: Non-High, and Vowel Advancement: Back.

Table 8 Closure duration for unaspirated tokens; $N = 2133$.

Fixed effects	Estimate	Std. Error	df	<i>t</i> -value	Pr (> <i>t</i>)
(Intercept)	4.866	0.050	12.706	97.070	< .001 ***
Syllables: 2s	-0.211	0.016	75.220	-12.888	< .001 ***
Syllables: 3s	-0.206	0.034	74.535	-6.021	< .001 ***
Place: Dental	-0.009	0.021	75.599	-0.417	.678
Place: Velar	-0.124	0.018	75.789	-6.757	< .001 ***
Place: Alveolo-Palatal	-0.308	0.020	75.278	-15.684	< .001 ***
Vowel Height: High	-0.012	0.024	75.724	-0.490	.626
Vowel Advancement = Front	0.100	0.021	57.483	4.695	< .001 ***
Place: Dental × Vheight: High	0.086	0.034	76.003	2.528	.014 *
Place: Velar × Vheight: High	0.004	0.030	75.780	0.145	.885
Place: Alveolo-Palatal × Vheight: High	0.104	0.031	75.600	3.311	.001 **
Place: Dental × Vadv: Front	-0.064	0.030	75.621	-2.112	.038 *
Place: Velar × Vadv: Front	-0.082	0.027	75.602	-3.005	.004 **
Place: Alveolo-Palatal × Vadv: Front	-0.084	0.029	75.907	-2.943	.004 **

Vheight = Vowel height, Vadv = Vowel advancement. Significance codes: *** $p < .001$, ** $p < .01$, * $p < .05$

The combination of the reported and revealed models shows that closure duration is the longest for the bilabial and dental stops, with no significant difference between them. The velar unaspirated stop evidences the next longest closure duration, followed by the voiceless unaspirated affricate. In an interaction with place, closure duration is also significantly longer for the dental and alveolo-palatal non-aspirates before high vowels as opposed to the bilabial and velar non-aspirates. Finally, closure duration for the bilabial non-aspirate before front vowels is significantly longer compared to the dental, velar, and alveolo-palatal non-aspirates.

4.2.3 Voiced stops

The negative VOT or voiced closure of the voiced plosives /b/ and /d/ shows significant main effects of place, tone, vowel height, and vowel advancement, with no significant effects of nasality and no significant place interactions (Table 9). The model includes a vowel height random slope with speaker. The model intercept is Syllables: 1s, Place: Bilabial, Tone: Falling-glottalized, Vowel Height: Non-High, and Vowel Advancement: Back.

The voiced closure of the bilabials is significantly longer than the voiced closure of the dentals. For tone, voiced closure is significantly longer before a falling-glottalized tone, compared to the high, mid, or falling tones. No significant difference in voiced closure occurs with the low tone. Note that the dataset does not include any tokens of voiced stops with the mid-glottalized tone. Voiced closure is also significantly longer preceding both high and front vowels.

4.2.4 Summary of closure duration results

To summarize, closure duration for the voiceless aspirated, voiceless unaspirated, and voiced tokens shows effects of place, tone, vowel height, and vowel advancement, but not nasality –

Table 9 Closure duration for voiced tokens; $N = 1216$.

Fixed effects	Estimate	Std. Error	df	<i>t</i> -value	Pr (> <i>t</i>)
(Intercept)	4.723	0.048	13.244	99.215	< .001 ***
Syllables: 2s	-0.256	0.026	49.751	-10.004	< .001 ***
Syllables: 3s	-0.256	0.042	42.201	-6.140	< .001 ***
Place: Dental	-0.084	0.011	42.670	-7.370	.046 *
Tone: High	-0.063	0.031	43.631	-2.034	.048 *
Tone: Mid	-0.038	0.017	47.654	-2.213	.032 *
Tone: Low	0.000	0.022	46.791	-0.013	.990
Tone: Falling	-0.035	0.017	46.624	-2.048	.046 *
Vowel Height: High	0.077	0.016	13.931	4.976	< .001 ***
Vowel Advancement: Front	0.025	0.011	44.680	2.161	.036 *

Significance codes: *** $p < .001$, ** $p < .01$, * $p < .05$

see Table 10. In this table, the bilabial aspirate, the bilabial and dental non-aspirates, and the bilabial voiced stop evidence the longest closure duration, while the alveolo-palatal affricates and the dental voiced stop show the shortest closure duration. In addition, the closure duration of the dental and velar aspirates and the velar non-aspirate is significantly different compared to the bilabial or alveolo-palatal places of articulation. Significant tonal effects on closure duration are limited to the aspirates and the voiced stops. The longest closure duration precedes the mid-glottalized and falling-glottalized tones for the aspirates and the falling-glottalized tone for the voiced stops. The shortest closure duration precedes the mid and high tones for the aspirates and the high, mid, and falling tones for the voiced stops. For vowel height, the longest closure duration precedes high vowels for the aspirates and the voiced stops, while closure duration is significantly longer for the dental and alveolo-palatal non-aspirates before high vowels in opposition to the bilabial and velar non-aspirates. Finally, the longest closure duration for the aspirates and the voiced stops occurs preceding front vowels. In addition, closure duration is significantly longer for the bilabial non-aspirate before front vowels in opposition to the dental, velar, and alveolo-palatal non-aspirates.

Table 10 Summary of significant closure duration effects (longest to shortest closure duration).

Closure duration effects	Aspirated	Unaspirated	Voiced
Place	$p^h > t^h/k^h > t\zeta^h$	$p/t > k > t\zeta$	$b > d$
Nasality	None	None	None
Tone	MQ/FQ (F) (L) M/H	None	FQ (L) H/M/F
Vowel Height	High > Non-High	High $t/t\zeta > p/k$	High > Non-High
Vowel Advancement	Front > Back	Front $p > t/k/t\zeta$	Front > Back

Note: Slashes between items (e.g. t^h/k^h) indicate no significant difference in closure duration. Configurations like MQ/FQ (F) (L) M/H indicate that while closure duration is significantly different between MQ/FQ and M/H, it is not significantly different between F and MQ/FQ, (F) and (L), and (L) and M/H.

4.3 The voiceless interval

A voiceless interval mixed effects model for all the data, which included type and vowel advancement random slopes with speaker, shows an effect of Type. As shown in Figure 5, the aspirated tokens exhibit longer voiceless intervals compared to the unaspirated tokens ($p < .001$). As a result, we analyse context effects of the aspirated and unaspirated voiceless interval separately.

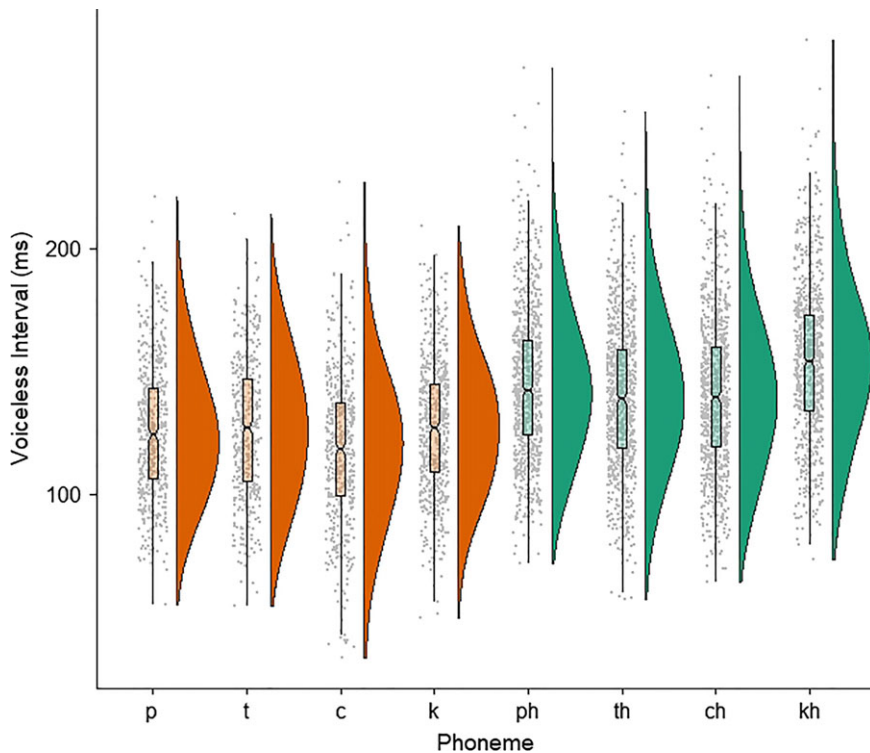


Figure 5 (Colour online) Raincloud plot of mean voiceless interval by phoneme and type (unaspirated obstruents in orange and aspirated obstruents in green).

The results for voiceless aspirated obstruents are presented first (Section 4.3.1), followed by the voiceless unaspirated obstruents (Section 4.3.2). The section ends with a summary of the voiceless interval results (Section 4.3.3).

4.3.1 Voiceless aspirated obstruents

The analysis of the voiceless interval of aspirates shows main effects of place, nasality, vowel height, and vowel advancement, with a significant place and vowel advancement interaction (Table 11). The model includes nasality and vowel height random slopes with speaker. The model intercept is Syllables: 1s, Place: Bilabial, Nasality: Nasal, Vowel Height: Non-High, and Vowel Advancement: Back.

The reported and relevelled models indicate that the voiceless interval of the velar aspirates is the longest, followed by the bilabial aspirate. The dental and alveolo-palatal aspirates evidence the shortest voiceless interval with no significant difference. The voiceless interval is significantly longer preceding oral as opposed to nasal vowels. It is also significantly longer preceding high vowels. Finally, in an interaction between place and vowel advancement, the voiceless interval of the alveolo-palatal aspirate is significantly longer preceding front vowels compared to the bilabial, dental, and velar aspirates.

4.3.2 Unaspirated obstruents

The analysis of the voiceless interval of voiceless unaspirated obstruents shows significant main effects of place, nasality, and vowel advancement, with a significant place and vowel height interaction (Table 12). No random slopes are included in the model. The model

Table 11 The voiceless interval for aspirates; $N = 3536$.

Fixed effects	Estimate	Std. Error	df	<i>t</i> -value	Pr (> <i>t</i>)
(Intercept)	4.936	0.046	11.620	108.178	< .001 ***
Syllables: 2s	-0.151	0.011	135.691	-13.918	< .001 ***
Syllables: 3s	-0.189	0.026	135.584	-7.197	< .001 ***
Place: Dental	-0.060	0.011	135.871	-5.205	< .001 ***
Place: Velar	0.060	0.011	137.081	5.315	< .001 ***
Place: Alveolo-Palatal	-0.081	0.011	136.954	-7.324	< .001 ***
Nasality: Oral	0.048	0.011	13.518	4.554	< .001 ***
Vowel Height: High	0.051	0.010	13.401	5.200	< .001 ***
Vowel Advancement: Front	-0.026	0.012	136.337	-2.145	.034 *
Place: Dental × Vadv: Front	0.034	0.017	136.820	2.015	.046 *
Place: Velar × Vadv: Front	0.031	0.017	136.774	1.781	.077 .
Place: Alveolo-Palatal × Vadv: Front	0.094	0.017	136.496	5.650	< .001 ***

Vadv = Vowel advancement. Significance codes: *** $p < .001$, ** $p < .01$, * $p < .05$, . $p < .1$

Table 12 The voiceless interval for non-aspirates; $N = 2133$.

Fixed effects	Estimate	Std. Error	df	<i>t</i> -value	Pr (> <i>t</i>)
(Intercept)	4.829	0.044	12.350	110.909	< .001 ***
Syllables: 2s	-0.200	0.014	77.128	-14.546	< .001 ***
Syllables: 3s	-0.209	0.029	76.101	-7.293	< .001 ***
Place: Dental	-0.031	0.015	77.061	-2.043	.045 *
Place: Velar	-0.006	0.013	77.539	-0.468	.641
Place: Alveolo-Palatal	-0.147	0.014	77.592	-10.186	< .001 ***
Nasality: Oral	0.024	0.010	77.395	2.461	.016 *
Vowel Height: High	0.007	0.020	77.740	0.351	.727
Vowel Advancement: Front	0.047	0.010	77.911	4.766	< .001 ***
Place: Dental × Vheight: High	0.055	0.029	78.209	1.912	.060 .
Place: Velar × Vheight: High	0.011	0.026	77.777	0.430	.668
Place: Alveolo-Palatal × Vheight: High	0.062	0.027	77.570	2.303	.024 *

Vheight = Vowel height. Significance codes: *** $p < .001$, ** $p < .01$, * $p < .05$, . $p < .1$

intercept is Syllables: 1s, Place: Bilabial, Nasality: Nasal, Vowel Height: Non-High, and Vowel Advancement: Back.

The final and relevelled models indicate that the voiceless interval of the bilabial non-aspirate is the longest and the alveolo-palatal non-aspirate voiceless interval is the shortest. The difference in the voiceless interval is not significant between the bilabial and velar non-aspirates and the velar and dental non-aspirates. Before high vowels, the voiceless interval is significantly longer for the alveolo-palatal non-aspirate, while it is significantly shorter for the bilabial and velar non-aspirates. Moreover, the voiceless interval of the dental non-aspirate before a high vowel is not significantly different from either the alveolo-palatal non-aspirate or the bilabial and velar non-aspirates. Finally, the voiceless interval of non-aspirates is significantly longer before front vowels.

4.3.3 Summary of voiceless interval results

In sum, as with both VOT and closure duration, the effects of place, nasality, and vowel quality on the voiceless interval are unique to each type. The significant differences in the length of the voiceless interval by context are detailed in Table 13.

Table 13 Summary of voiceless interval effects (longest to shortest voiceless interval).

Voiceless interval effects	Aspirated	Unaspirated
Place	$k^h > p^h > t^h/t\zeta^h$	$p(k) > t > t\zeta$
Nasality	Oral > Nasal	Oral > Nasal
Tone	None	None
Vowel Height	High > Non-High	High $t\zeta$ (t) p/k
Vowel Advancement	Front $t\zeta^h > p^h/t^h/k^h$	Front > Back

Note: Slashes between items (e.g. $p^h/t^h/k^h$) indicate no significant difference in voiceless interval duration. Configurations like $p(k) > t > t\zeta$ indicate that while the voiceless interval between p , t , and $t\zeta$ is significantly different, it is not significantly different between p and (k) and (k) and t .

Comparing place effects on the voiceless interval of the aspirates, the velar aspirate is the longest, followed by the bilabial aspirate, and then the dental and alveolo-palatal aspirates. For the non-aspirates, the voiceless interval of the bilabial non-aspirate is the longest. The velar non-aspirate does not differ significantly from either the bilabial or the dental non-aspirates, although the voiceless interval of the dental non-aspirate is significantly shorter than the bilabial non-aspirate. The alveolo-palatal non-aspirate evidences the shortest voiceless interval compared to the bilabial, velar, and dental non-aspirates. The voiceless interval of the aspirated obstruents is significantly longer preceding high vowels, while the voiceless interval of the alveolo-palatal non-aspirate is the longest and the bilabial and velar non-aspirates are the shortest before high vowels. The voiceless interval of the dental non-aspirate before high vowels does not differ significantly from the other non-aspirates. Finally, in an interaction with place, the voiceless interval is the longest for the alveolo-palatal aspirate before front vowels compared to the other aspirates, while the voiceless interval of the non-aspirates is significantly longer before front vowels.

5 Discussion

In this study of the effects of place, nasality, tone, and vowel quality on the VOT, closure duration, and voiceless interval of the stops and affricates of N. Pwo, we recorded stop and affricate-initial words in a carrier phrase, then measured the voiced closure, voiceless closure, and release of these obstruents. Due to the large effect of type (voiceless unaspirated, voiceless aspirated, and voiced obstruents), we modelled the results for each type, first with VOT (release) as the dependent variable, then closure duration (voiced closure + voiceless closure), and the voiceless interval (voiceless closure + release). In the discussion to follow, VOT results are considered first (Section 5.1), followed by the closure duration (Section 5.2) and voiceless interval results (Section 5.3).

5.1 Voice onset time

Effects on VOT included place (Section 5.1.1), nasality (Section 5.1.2), tone (Section 5.1.3), and vowel quality (Section 5.1.4).

5.1.1 Place effects

We predicted that VOT would be the longest for the alveolo-palatal affricates, followed by the velars, then the dentals, and finally the bilabials, although it was possible that the difference in VOT between the dentals and bilabials would not be significant. As expected, the N. Pwo aspirated alveolo-palatal affricate exhibits the longest VOT, followed by the velar aspirate. The bilabial and dental aspirates have the shortest VOT, which does not differ significantly. This pattern is in line with Kayan, a related Karenic language (Luangthongkum 2010), where VOT is not significantly different between the alveolar and bilabial aspirated

stops. Non-significant differences between the bilabial and alveolar or dental stops have also been reported for other languages (Lisker & Abramson 1964, Cho & Ladefoged 1999).

For the non-aspirates, the alveolo-palatal affricate has the longest VOT, followed by the velar non-aspirate. However, the bilabial non-aspirate has the next longest VOT, while the dental non-aspirate has the shortest VOT. Although this pattern of bilabial stops with longer VOT is uncommon, it is not unheard of. Lisker & Abramson (1964) report such a pattern for Tamil voiceless unaspirated plosives.

5.1.2 Nasality effects

Nasalized vowels affected the VOT of both the aspirated and unaspirated obstruents. For the aspirated obstruents, VOT is significantly longer before oral vowels, while the VOT of the alveolo-palatal, velar, and dental non-aspirates is significantly longer before oral vowels compared to the bilabial non-aspirate.

The N. Pwo results are the opposite of the findings of Walker (1999) and Silva (2008). One possible explanation for longer VOT before N. Pwo oral vowels is that anticipatory velopharyngeal coarticulation disperses the build-up of stop air pressure allowing for an earlier onset of voicing. In the case of Walker (1999) and Silva (2008), where longer VOT is found in a nasal harmony context, anticipatory velopharyngeal coarticulation is less likely because speakers have to create sufficient velopharyngeal closure so that oral pressure can be achieved to produce a burst release, likely creating a situation that increases the VOT in a nasal context. This interaction between VOT and nasality could be explored by comparing a language with phonemic nasalization to a language that has incomplete nasalization. The production of nasality has also been shown to involve lingual, labial, pharyngeal, and velic articulations to different degrees by speakers of Northern Metropolitan French (Carignan 2014). Given this situation, further exploration of the interaction of VOT with nasalized vowels and in nasal harmony contexts, both acoustically and articulatorily, is necessary.

5.1.3 Tone effects

When we considered the influence of tone on VOT, the longest VOT was predicted to occur preceding the N. Pwo mid tone, which rises slightly, as well as the low tone. The shortest VOT was predicted to occur preceding the glottalized and falling tones. For both the voiceless aspirated and unaspirated obstruents, the longest VOT occurred consistently preceding the mid tone. The low tone, which falls slightly, was associated with the next longest VOT for the aspirated obstruents, while unaspirated VOT preceding the low tone did not differ significantly from the mid tone. The shortest VOT occurred preceding the falling-glottalized tone, while VOT preceding the high, falling, and mid-glottalized tones ranged between these two extremes.

The association of the longest VOT with the N. Pwo mid and low tones and shortest VOT with the falling and glottalized tones is in keeping with the results for Hakka. In Hakka, VOT preceding both Tone 1 (24) and Tone 5 (11) is significantly longer for both aspirated and unaspirated voiceless stops. VOT is the shortest preceding stopped-syllable tones for both unaspirated stops (Tone 8 (55)) and aspirated stops (Tone 4 (32), Tone 8 (55)). Phonetically, the N. Pwo glottalized tones are considered to consist of pitch with a final glottal stop, which makes them comparable with the Hakka stopped-syllable tones. One difference, however, is that VOT preceding the N. Pwo falling tone is shorter along with the two glottalized tones, which differs from the Hakka pattern where only the closed syllable tones have the shortest VOT. However, Mandarin aspirated stops also exhibit significantly shorter VOT before Tone 4, a falling tone.

Based on the results for Mandarin, Hakka, Sgaw Karen, and N. Pwo, it appears that the VOT of voiceless stops is likely to be shorter before falling or glottalized tones, which are likely of shorter duration than the mid, low, and high tones. However, in Sgaw Karen the

results indicate that VOT before breathy tones can be even shorter, even though the duration of the glottalized tones is shorter than the breathy tones. Recall that Sgaw Karen aspirated stops do not occur with the low breathy tone and their occurrence with the high breathy tone is rare. Also, the VOT of unaspirated stops is the shortest before breathy tones in Sgaw Karen. So, the Sgaw Karen results indicate that neither aspiration nor tone duration can account for shorter VOT preceding breathy tones.

One possible explanation for these patterns is that increased oral flow and stiffer vocal folds in preparation for the rising tones causes longer VOT. Liu et al. (2008) also provide a similar explanation for longer VOT with rising tones. However, this explanation does not account for the longer VOT before a low tone in open syllables, a pattern observed in both Hakka and N. Pwo. Furthermore, since breathy phonation requires less articulatory effort (Marasek 1997, Gick et al. 2013), it makes sense that the Sgaw Karen breathy tones are associated with the shortest VOT.

Another possible contributor to tonal effects on VOT is the fundamental frequency of the following vowel, which has been shown to be significantly higher following an aspirated consonant (House & Fairbanks 1953, Hombert, Ohala & Ewan 1979, Francis et al. 2006, Kirby 2018). Since VOT tends to be longer before high vowels, this circumstance could contribute to longer VOT before rising tones, although Kirby (2018) found that the effect of aspiration on the f_0 of the following vowel was absent when target words appeared in a carrier phrase, which was the context of the N. Pwo tokens. The present results, which investigate the effect of tone on VOT, and these other results that investigate the effect of stops on the fundamental frequency of the following vowel suggest a need for further research on the two-way interaction between VOT and tone.

5.1.4 Vowel quality effects

Concerning vowel height, we predicted that VOT would, in general, be longer preceding high vowels. In N. Pwo, VOT is significantly longer preceding high vowels for both voiceless aspirates and non-aspirates. This result is in line with the findings in other languages (Rochet & Fei 1991, Nearey & Rochet 1994, Morris et al. 2008). Like the explanation for the tone results, longer VOT before high vowels may be due to an increase in the tension of the vocal folds and their length. Based on their study of the effect of vowels on the vocal mechanism, Higgins, Netsell & Schulte (1998: 723) suggest that vowel effects may be brought about by ‘a combination of the mechanical influence of laryngeal cartilage position, the suspected reflexive coupling of supralaryngeal and laryngeal neurons, and learned neural adjustments on the part of the speaker’.

For vowel advancement, we predicted that the VOT of the dental, alveolo-palatal, and velar voiceless aspirated and voiceless unaspirated obstruents would be the longest before front vowels, while the VOT of bilabial stops would be the shortest. For N. Pwo, the VOT of the alveolo-palatal aspirate is significantly longer before front vowels, followed by the velar and dental aspirates, with the VOT of the bilabial aspirate the shortest before a front vowel, as predicted. The voiceless unaspirated obstruents showed no effect of vowel advancement.

To summarize, the N. Pwo place effects on VOT behaved as expected, except that the VOT of the bilabial unaspirated stop was significantly longer than the dental unaspirated stop. We also found that nasality, tone, and vowel quality played a significant part in predicting the duration of VOT.

5.2 Closure duration

The question for closure duration was whether VOT and closure duration are in a reciprocal relationship when affected by vowel quality, a post-obstruent nasalized vowel, or tone. Place effects on closure duration were expected to pattern in the opposite direction of place effects on VOT, based on the findings of Weismer (1980), Walker (1999), and Silva (2008). Thus, longer closure duration accompanies shorter VOT and vice versa (Maddieson 1999).

In N. Pwo, the patterns of place are largely reciprocal between VOT and closure duration for both the voiceless aspirated and unaspirated obstruents. Both the bilabial and dental aspirates show the shortest VOT, while only the bilabial aspirate evidences the longest closure duration. The next longest closure duration is shared by both the dental and velar aspirates. These results are like the Yao (2007) results, which showed that the closure duration of the aspirated bilabial was significantly longer than both the alveolar and velar aspirates. Between the alveolar and velar aspirates, the difference in closure duration was not as significant, which parallels the N. Pwo pattern where the difference between the dental and velar aspirate closure duration was not significant. For the unaspirated obstruents, the VOT of the alveolo-palatal and velar non-aspirates is in a reciprocal relationship; the alveolo-palatal non-aspirate shows the longest VOT and the shortest closure duration, followed by the velar non-aspirate. The only departure from full reciprocity is that the VOT of the bilabial non-aspirate is significantly longer than the dental non-aspirate, while the difference between the closure durations of the bilabial and dental non-aspirates is not significant. As Yao (2007) concluded, both VOT and closure duration are affected by different aspects of the context. As a result, VOT and closure duration do not exhibit perfectly reciprocal patterns.

Tone is the only other context effect that shows a reciprocal pattern between VOT and closure duration, although this only holds for the aspirated obstruents. For the aspirated obstruents, the longest VOT occurs preceding the mid tone, with the low tone the next longest. The shortest VOT occurs preceding the falling and falling-glottalized tones. This pattern is reversed somewhat for aspirated closure duration where the longest closure duration occurs preceding the mid-glottalized and falling-glottalized tones, which does not differ significantly from the closure duration preceding a falling tone. The shortest closure duration occurs preceding both the mid and high tones, which do not differ significantly from the low tone.

As for the other obstruent types, non-aspirate closure duration is not affected by tone, while the voiced closure of voiced stops evidences a similar pattern to voiceless aspirated closure. The longest voiced closure occurs preceding the falling-glottalized tone and the shortest voiced closure occurs preceding the high, mid, and falling tones. The voiced closure preceding the low tone stands in-between the falling-glottalized and high, mid, and falling tones.

Nasality was the only context effect that did not affect the closure duration of any of the obstruent types. This means that VOT is longer before oral vowels with no change in closure duration before either oral or nasal vowels. This was not the case for either of the nasal harmony languages (Walker 1999, Silva 2008), where longer VOT in nasal words correlated with shorter closure duration.

Finally, both vowel height and vowel advancement showed an overall parallel relationship between VOT and closure duration for the voiceless obstruents. This means that both VOT and closure duration are the longest preceding high, front vowels. However, in a place interaction with vowel height, the results showed a reciprocal pattern. Specifically, the bilabial non-aspirate has the longest VOT and the alveolo-palatal non-aspirate has the shortest VOT before high vowels. In contrast, the dental and alveolo-palatal non-aspirates have the longest closure duration, and the bilabial and velar non-aspirates have the shortest closure duration before high vowels. If there is a place interaction with vowel advancement, the pattern parallels the longest to shortest VOT or closure duration by place. Thus, before front vowels, the alveolo-palatal aspirate has the longest VOT and the bilabial aspirate has the shortest VOT, while the bilabial non-aspirate has the longest closure duration and the dental, velar, and alveolo-palatal non-aspirates have the shortest closure duration. As for the voiced closure of the voiced stops, it is also significantly longer preceding both high and front vowels. This result is contrary to our prediction that voiced closure would not be affected by vowel advancement, based on the lack of a vowel advancement effect on French voiced stops (Nearey & Rochet 1994).

This account of context effects on VOT and closure duration has described three general patterns: 1) a reciprocal pattern for place between voiceless VOT and closure duration and

voiceless aspirated tone, 2) an effect of nasality on VOT but not on closure duration, and 3) a parallel pattern between VOT and closure duration for both vowel height and vowel advancement if no place interactions are involved. Voiced stops are in a class of their own due to their voiced closure without any VOT, although context effects pattern similarly to voiceless closure duration. By including the voiceless interval in the discussion some suggestions for the reasons for the N. Pwo patterns can be proposed.

5.3 The voiceless interval

For the voiceless interval (voiceless closure + voice onset time), the question was whether the voiceless interval could be affected by place, vowel quality, nasality, or tone. Table 14 summarizes the results for VOT, closure duration, and the voiceless interval together. The results in Table 14 demonstrate that the voiceless interval is not constant and is subject to context effects, contrary to reports that the voiceless interval remains constant regardless of place (Suomi 1980, Weismer 1980) or nasality (Walker 1999), although whether the voiceless interval is constant could be language-specific, based on Walker's (1999) report that the voiceless interval is constant between oral and nasal words, while Silva (2008) reports that the voiceless interval is not constant for another Amazonian nasal harmony language.

Table 14 Context effects on VOT, closure duration and the voiceless interval (longest to shortest).

Effects	VOT	Closure duration	Voiceless interval
<i>Aspirated</i>			
Place	$t\text{c}^h > k^h > p^h/t^h$	$p^h > t^h/k^h > t\text{c}^h$	$k^h > p^h > t^h/t\text{c}^h$
Nasality	Oral > Nasal	None	Oral > Nasal
Tone	$M > L = H = MQ = F = FQ$	MQ/FQ (F) (L) M/H	None
Vowel Height	High > Non-High	High > Non-High	High > Non-High
Vowel Advancement	Front $t\text{c}^h > k^h/t^h > p^h$	Front > Back	Front $t\text{c}^h > p^h/t^h/k^h$
<i>Unaspirated</i>			
Place	$t\text{c} > k > p > t$	$p/t > k > t\text{c}$	$p(k) t > t\text{c}$
Nasality	Oral $t\text{c}/k(t) p$	None	Oral > Nasal
Tone	M/L (H, F, MQ) FQ	None	None
Vowel Height	High $p(t, k) t\text{c}$	High $t/t\text{c} > p/k$	High $t\text{c}(t) p/k$
Vowel Advancement	None	Front $p > t/k/t\text{c}$	Front > Back
<i>Voiced</i>			
Place		$b > d$	
Nasality		None	
Tone		FQ (L) H/M/F	
Vowel Height		High > Non-High	
Vowel Advancement		Front > Back	

Note: Slashes between items (e.g. p^h/t^h) indicate no significant difference in VOT, closure duration, or voiceless interval duration. Configurations like High $p(t, k) t\text{c}$ indicate that VOT before high vowels is not significantly different between (t, k) or p and $t\text{c}$, while VOT before high vowels is significantly different between p and $t\text{c}$.

These context effects pattern in one of three ways in relation to VOT and closure duration. In the first pattern, the context effect is the same across VOT, closure duration, and the voiceless interval. This would indicate that the context effect affects the whole consonant. In the second pattern, a context effect on the voiceless interval is the same as either VOT or closure duration. If the voiceless interval patterns the same as VOT, this would mean that the context effect influences VOT more than closure duration. The opposite is true when the voiceless interval patterns the same as closure duration. Finally, in the third pattern, a context

effect does not affect the voiceless interval and the effect on VOT and closure duration is in a reciprocal relationship.

Considering context effects that affect the whole consonant, vowel height is the only effect that patterns the same across VOT, closure duration, and the voiceless interval. Thus, VOT, closure duration, and the voiceless interval are all significantly longer before high vowels. It is possible that it takes more time to build up the tension necessary to produce a high vowel, which involves the entire voiceless interval. This same reasoning would apply to the closure of voiced stops, which is also significantly longer before high vowels.

Vowel advancement presents mixed patterns when place interactions occur. In general, the longest VOT, closure duration, and voiceless interval occur before front vowels. Even with a place interaction, it is the aspirated alveolo-palatal affricate that has the longest VOT and voiceless interval before front vowels. In contrast, we found no effect of vowel advancement on the VOT of unaspirated obstruents, while closure duration is the longest for the bilabial non-aspirate before front vowels as opposed to the other obstruents. The voiceless interval of the non-aspirates is also the longest before front vowels. This pattern also holds for the voiced closure of voiced stops. Taken together, it appears that vowel advancement is also a property of the whole consonant, although it is possible that the short-lag VOT of unaspirated obstruents may not allow for a vowel advancement effect.

Considering the second pattern in which context effects on the voiceless interval are similar to either VOT or closure duration, place effects on closure duration and the voiceless interval are similar for all obstruent types. These place effects are the opposite for VOT. This would seem to indicate that the influence of place is stronger on closure duration than VOT. In contrast, nasality only affects VOT and the voiceless interval. Since nasality affects both VOT and the voiceless interval in N. Pwo, this might indicate that the influence of nasality is stronger on VOT than closure duration.

In the third pattern, the voiceless interval shows no effect of tone. In addition, tone only affects the closure duration of the aspirated obstruents and the voiced stops. For the aspirated obstruents, tone effects on closure duration are the opposite of VOT; VOT is the longest before the mid tone, while closure duration is the shortest before the mid tone. In this instance, tonal effects cancel each other out, which may be the reason that tone has no effect on the voiceless interval. Voiced closure parallels the pattern of the aspirated obstruent closure duration to some extent. Like the aspirated obstruents, the longest voiced closure occurs preceding the falling-glottalized tone and the shortest closure duration occurs preceding the high, mid, and falling tones.

In sum, vowel quality effects largely impact the acoustic characteristics of the whole consonant. In contrast, place has a stronger influence on closure duration, while nasality has a stronger influence on VOT. Finally, tone does not affect the length of the voiceless interval at all and the reciprocal patterns of tonal effects on VOT and closure duration cancel each other out for the aspirated obstruents, while the effect of tone on the voiced closure of the voiced stops patterns like the effect of tone on the closure duration of the aspirated obstruents.

6 Conclusion

In addition to our primary goal of documenting some acoustic aspects of N. Pwo Karen for the first time, we set out to answer three questions. The first question was concerned with whether the VOT of N. Pwo stops and affricates is affected by tone, vowel quality, and nasality, since N. Pwo is a ‘true voicing’ language, with a three-way distinction in stops. We found that VOT is affected by all three of these context effects.

The second question asked whether VOT and closure duration evidence a reciprocal relationship when affected by vowel quality, a post-obstruent nasalized vowel, or tone. In

a reciprocal relationship, when VOT is long, closure duration is short and when closure duration is long, VOT is short. We found that only place and tone had reciprocal effects on VOT and closure duration, while nasality only affected VOT, and vowel quality effects were similar for VOT and closure duration.

The third question asked whether the voiceless interval was affected by place, vowel quality, nasality, and tone. We found that the voiceless interval was affected by place, nasality, and vowel quality, but not tone. These patterns show that the voiceless interval in N. Pwo is not constant.

It is apparent from this study that in order to develop an understanding of the laryngeal timing of obstruents, it is necessary to examine at least closure duration, in addition to VOT, while keeping in mind that context has an effect on both VOT and closure duration, as well as the voiceless interval.

In addition, questions remain, especially about the effects of nasality and tone on VOT and closure duration. For both tone and nasality, the configuration of a language's tonal or nasal inventory seems to have a bearing on their effects, considering the divergent patterns of nasal harmony contexts and post-obstruent nasalized vowels. In addition, obstruents have been shown to affect the fundamental frequency of the following vowel. The interaction of this pattern with the effects of tone on obstruents needs to be considered together. Finally, more studies of tone effects on VOT, closure duration, and the voiceless interval are needed to determine whether the patterns seen in N. Pwo are found in other languages with a similar tonal inventory. Furthermore, tonal duration measurements would provide insight into tonal effects on laryngeal timing.

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Appendix A. Word list

Segment	Front		Central		Back
/p/	pí	pê	pé	pú	pō
	pî	pék ^h í	pēlē	pù	pō̃
	pé	pēt ^h ēt ^h ə	pē [?] pê	pû [?]	pỗ
	pénì	pè	pē [?]	pō̃	pō̃ [?]
	pē	pêxwēi [?]		pỗ	
/t/	tí	tê	tē	tú	tô
	tî	tē [?]	tê	tū ^h p ^h ê	tō̃
	tí [?]	tê	tē [?]	tú [?]	tỗ
	tè		tē [?] dēi [?] bē	tō	

Segment	Front		Central	Back	
/tɕ/	tɕī	tɕê	tɕē	tɕū	tɕō
	tɕî	tɕêʔ	tɕê	tɕū	tɕò
	tɕē		tɕê	tɕû	tɕô
	tɕè		tɕêʔ	tɕû	tɕõ
	tɕê			tɕûʔ	tɕõʔ
				tɕõʔ	
/k/	kīk ^h ōʔ	kēuɕê	kē	kū	kō
	kīlō	kê	kē	kū	kô
	kī	kēʔ	kê	kû	kó
	kíʔ		kê ^h t ^h ē	kû	kô
	kē		kêʔ	kûʔ	kóʔ
	kē		kêʔ	kó	kóʔ
/p ^h /	p ^h ī	p ^h è	p ^h é	p ^h ú	p ^h ōʔ
	p ^h í	p ^h è	p ^h é	p ^h ú	p ^h óʔmî
	p ^h īsē	p ^h êʔ	p ^h ē	p ^h ū	p ^h õ
	p ^h ī	p ^h é	p ^h è	p ^h û	p ^h ò
	p ^h î	p ^h ê	p ^h ê	p ^h û	p ^h ô
	p ^h î	p ^h è	p ^h ê	p ^h ûʔ	
	p ^h īʔ	p ^h ê	p ^h êʔ	p ^h ó	
	p ^h é	p ^h êʔk ^h ū	p ^h êʔxwēiʔ	p ^h ò	
/t ^h /	t ^h ī	t ^h é	t ^h é	t ^h ú	t ^h ó
	t ^h í	t ^h è	t ^h é	t ^h ū	t ^h õ
	t ^h ī	t ^h è	t ^h ē	t ^h û	t ^h ò
	t ^h î	t ^h ê	t ^h è	t ^h û	t ^h ô
	t ^h î	t ^h ê	t ^h êʔ	t ^h ûʔ	t ^h óʔt ^h éʔ
	t ^h īp ^h êʔ	t ^h êʔ	t ^h êʔ	t ^h ó	
	t ^h î	t ^h é		t ^h õ	
	t ^h īʔ	t ^h ê		t ^h ô	
		t ^h è			
		t ^h ê			
		t ^h êʔ			

Segment	Front		Central		Back
/tʰ/	tʰítʰõ	tʰé	tʰé	tʰú	tʰó
	tʰí	tʰē	tʰē	tʰú	tʰò
	tʰī	tʰē	tʰē	tʰū	tʰõ?
	tʰī	tʰê	tʰê	tʰū	tʰõ
	tʰi	tʰē?	tʰê	tʰù	tʰõ
	tʰípʰõ?	tʰé	tʰê?	tʰū	tʰõ
	tʰí?	tʰē		tʰú	tʰõ
	tʰé ē?	tʰê		tʰú?	
/kʰ/	kʰí	kʰē	kʰé	kʰú	kʰólê
	kʰí	kʰè	kʰé	kʰū	kʰõ?
	kʰī?ū	kʰê	kʰē	kʰū	kʰõ
	kʰī	kʰé	kʰê	kʰù	kʰõçê
	kʰī	kʰē	kʰêxê?	kʰû	kʰõtʰêkʰéi
	kʰí?	kʰè	kʰê?	kʰú?	kʰõ?nê
	kʰé	kʰê	kʰê?	kʰó	
/b/	bībū	bē	bē	bú	bô
	bī	bê	bètçī	bú?	bõ
	bì	bé?	bê	bō	bò
	bē		bê	bō	bô
	bê		bê?	bò	bõ?
/d/	dí	dē	dé	dū	dô
	dī	dē	dē	dū	dõ
	dī	dè	dê	dū	dô
	dî	dê	dê	dú?	dõ?
	dî	dê	dê?	dō	
	dí?tʰəpʰó	dē		dó	
	dê				

Appendix B. Distribution of context effects

Table A1 Quantity of vowel, tone, and place combinations in the data set.

V	Bilabial						Dental						Velar						Alveolo-Palatal					
	H	M	L	F	MQ	FQ	H	M	L	F	MQ	FQ	H	M	L	F	MQ	FQ	H	M	L	F	MQ	FQ
i	49	24	48	24	0	24	71	48	24	70	0	71	48	48	0	0	0	46	24	48	24	48	0	24
e	48	24	24	47	24	0	24	23	48	72	48	0	0	48	0	23	0	0	24	48	24	43	24	0
ɛ	47	96	48	71	24	23	24	48	24	71	24	0	24	49	23	48	23	0	24	24	24	23	0	24
ɤ	24	0	24	48	48	71	24	24	0	24	24	71	24	0	0	24	47	47	24	0	0	47	23	49
u	24	24	47	24	0	70	24	47	24	0	0	71	24	47	24	0	0	48	23	48	24	47	0	48
o	24	24	24	0	24	0	24	48	0	72	0	0	24	0	0	24	23	0	0	24	24	24	24	0
ɔ	0	0	23	0	24	24	0	0	0	0	0	48	0	0	0	0	48	23	0	0	0	0	24	0
ĩ	23	47	25	0	0	0	24	24	22	48	0	0	24	48	23	0	0	0	24	24	24	0	0	0
ẽ	24	24	24	0	0	0	0	24	48	48	0	0	24	24	24	0	0	0	24	24	0	0	0	0
ẽ̃	49	72	24	48	0	0	47	71	24	48	0	0	47	46	24	48	0	0	24	49	0	48	0	0
ũ	48	0	24	0	0	0	24	48	24	24	0	0	0	48	24	46	0	0	24	48	24	24	0	0
õ	0	47	24	48	0	0	0	24	0	24	0	0	24	24	0	24	0	0	23	0	25	0	0	0
õ̃	24	73	48	70	0	0	24	71	24	73	0	0	46	24	24	24	0	0	25	48	23	47	0	0

H = High, M = Mid, L = Low, F = Falling, MQ = Mid-glottalized, FQ = Falling-glottalized

Dark grey shading indicates an impossible vowel + tone combination. Lighter grey shading indicates a possible vowel/tone combination that does not occur in the data set.

References

- Abramson, Arthur S. 1989. Laryngeal control in the plosives of Standard Thai. *PASAA: Notes and News About Language Teaching and Linguistics in Thailand* 19, 85–93.
- Abramson, Arthur S. 1995. Laryngeal timing in Karen obstruents. In Fredericka Bell-Berti & Lawrence J. Raphael (eds.), *Producing speech: Contemporary issues, for Katherine Safford Harris*, 155–165. New York: AIP Press.
- Abramson, Arthur S. & Leigh Lisker. 1972. Voice timing in Korean stops. In André Rigault & René Charbonneau (eds.), *Proceedings of the Seventh International Congress of Phonetic Sciences (ICPhS VII)*, 439–446. The Hague & Paris: Mouton.
- Abramson, Arthur S. & D. H. Whalen. 2017. Voice Onset Time (VOT) at 50: Theoretical and practical issues in measuring voicing distinctions. *Journal of Phonetics* 63, 75–86.
- Andruski, Jean E. & Martha Ratliff. 2000. Phonation types in production of phonological tone: The case of Green Mong. *Journal of the International Phonetic Association* 30(1–2), 37–61.
- Bates, Douglas, Martin Mächler, Benjamin M. Bolker & Steven C. Walker. 2015. Fitting linear mixed-effects models using *lme4*. *Journal of Statistical Software* 67(1), 1–48.
- Bates, Douglas, Martin Maechler, Ben[jamin M.] Bolker, Steven [C.] Walker, Rune Haubo Bojesen Christensen, Henrik Singmann, Bin Dai, Fabian Scheipl, Gabor Grothendieck & Peter Green. 2019. *lme4: Linear mixed-effects models using “Eigen” and S4*. R package version 1.1-21.
- Boersma, Paul & David Weenink. 2012. Praat: Doing phonetics by computer [computer program]. Version 5.3.14. <http://www.praat.org/>.
- Brunelle, Marc. 2009. Tone perception in Northern and Southern Vietnamese. *Journal of Phonetics* 37, 79–96.
- Brunelle, Marc & Joshua Finkeldey. 2011. Tone perception in Sgaw Karen. In Wai Sum Lee & Eric Zee (eds.), *Proceedings of the 17th International Congress of Phonetic Sciences (ICPhS XVII)*, 372–375. Hong Kong: City University of Hong Kong.
- Carignan, Christopher. 2014. An acoustic and articulatory examination of the “oral” in “nasal”: The oral articulations of French nasal vowels are not arbitrary. *Journal of Phonetics* 46, 23–33.
- Chao, Kuan-Yi & Li-mei Chen. 2008. A cross-linguistic study of voice onset time in stop consonant productions. *International Journal of Computational Linguistics & Chinese Language Processing* 13(2), 215–232.
- Chao, Yuen Ren. 1967. *Mandarin primer: An intensive course in spoken Chinese*. Cambridge, MA: Harvard University Press.
- Chen, Li-mei, Kuan-Yi Chao & Jui-Feng Peng. 2007. VOT productions of word-initial stops in Mandarin and English: A cross-language study. In Kuang-Hua Chen & Berlin Chen (eds.), *ROCLING 2007 poster papers*, 303–317. Taipei: The Association for Computational Linguistics and Chinese Language Processing (ACLCLP).
- Chen, Li-mei, Jui-Feng Peng & Kuan-Yi Chao. 2009. The effect of lexical tones on voice onset time. *Proceedings 11th IEEE International Symposium on Multimedia*, San Diego, CA, 552–557.
- Cho, Taehong & Peter Ladefoged. 1999. Variation and universals in VOT: Evidence from 18 languages. *Journal of Phonetics* 27(2), 207–229.
- Cooke, Joseph R., J. Edwin Hudspeth & James A. Morris. 1976. Phlong (Pwo Karen of Hot District, Chiang Mai). In William Smalley (ed.), *Phonemes and orthography: Language planning in ten minority languages of Thailand* (Pacific Linguistics C 43), 187–220. Canberra: Australian National University.
- Davidson, Lisa. 2016. Variability in the implementation of voicing in American English obstruents. *Journal of Phonetics* 54, 35–50.
- Docherty, Gerald J. 1992. *The timing of voicing in British English obstruents*. Berlin: De Gruyter Mouton.
- Duanmu, San. 1994. The phonology of the glottal stop in Garo. *Linguistics of the Tibeto-Burman Area* 17(2), 69–82.
- Francis, Alexander L., Valter Ciocca, Virginia Ka Man Wong & Jess Ka Lam Chan. 2006. Is fundamental frequency a cue to aspiration in initial stops? *The Journal of the Acoustical Society of America* 120(5), 2884–2895.

- Gick, Brian, Ian Wilson & Donald Derrick. 2013. *Articulatory phonetics*. Oxford: Wiley-Blackwell.
- Higgins, Maureen B., Ronald Netsell & Laura Schulte. 1998. Vowel-related differences in laryngeal articulatory and phonatory function. *Journal of Speech, Language, and Hearing Research* 41(4), 712–24.
- Hombert, Jean-Marie, John J. Ohala & William G. Ewan. 1979. Phonetic explanations for the development of tones. *Language* 55(1), 37–58.
- House, Arthur S. & Grant Fairbanks. 1953. The influence of consonant environment upon the secondary acoustical characteristics of vowels. *The Journal of the Acoustical Society of America* 25(1), 105–113.
- Kirby, James P. 2018. Onset pitch perturbations and the cross-linguistic implementation of voicing: Evidence from tonal and non-tonal languages. *Journal of Phonetics* 71, 326–354.
- Klatt, Dennis H. 1975. Voice onset time, frication, and aspiration in word-initial consonant clusters. *Journal of Speech and Hearing Research* 18(4), 686–706.
- Kuznetsova, Alexandra & Per Bruun Brockhoff, Rune Haubo Bojesen Christensen & Sofie Pødenphant Jensen. 2019. *lmerTest*: Tests in linear mixed effects models. R package version 3.1-1. <https://github.com/runehaubo/lmerTestR>.
- Lisker, Leigh & Arthur S. Abramson. 1964. A cross-language study of voicing in initial stops: Acoustical measurements. *Word* 20(3), 384–422.
- Liu, Hanjun, Manwa L. Ng, Mingxi Wan, Supin Wang & Yi Zhang. 2008. The effect of tonal changes on voice onset time in Mandarin esophageal speech. *Journal of Voice* 22(2), 210–218.
- Luangthongkum, Theraphan. 2010. A comparison between the speech of brass-coiled necked and non-brass-coiled necked Kayan speakers: An acoustic study. *The 20th Anniversary Meeting of the Southeast Asian Linguistics Society*, 10–11 June 2010, Zurich, Switzerland. http://www.arts.chula.ac.th/~ling/Karen/pages/presents-conference/2_SEALS_XX_Theraphan.pdf.
- Maddieson, Ian. 1999. Phonetic universals. In William J. Hardcastle & John Laver (eds.), *The handbook of phonetic sciences*, 13–44. Orlando, FL: Academic Press.
- Marasek, Krzysztof. 1997. EGG & voice quality. *Institute for Natural Language Processing: Experimental Phonetics*. <https://www2.ims.uni-stuttgart.de/EGG/> (19 June 2019).
- Morris, Richard J., Christopher R. McCrea & Kaileen D. Herring. 2008. Voice onset time differences between adult males and females: Isolated syllables. *Journal of Phonetics* 36(2), 308–317.
- Nearey, Terrance M. & Bernard L. Rochet. 1994. Effects of place of articulation and vowel context on VOT production and perception for French and English stops. *Journal of the International Phonetic Association* 24(1), 1–18.
- Phillips, Audra. 2009. Omkoi Pwo Karen phonology and orthography. *PYU Working Papers in Linguistics* 5. https://inter.payap.ac.th/wp-content/uploads/linguistics_workingpapers/Omkoi_Pwo_Karen_Phonology_and_Orthography.pdf.
- Pitt, Mark A., Keith Johnson, Elizabeth Hume, Scott Kiesling & William Raymond. 2005. The Buckeye corpus of conversational speech: Labeling conventions and a test of transcriber reliability. *Speech Communication* 45, 89–95.
- Pittayaporn, Pittayawat. 2015. Typologizing sesquisyllabicity. In Nicholas J. Enfield & Bernard Comrie (eds.), *Languages of Mainland Southeast Asia: The state of the art* (Pacific Linguistics 649), 500–528. Berlin: De Gruyter Mouton.
- R Core Team. 2019. *R: A language and environment for statistical computing*. Vienna: R Foundation for Statistical Computing.
- Rochet, Bernard L. & Yanmei Fei. 1991. Effect of consonant and vowel context on Mandarin Chinese VOT: Production and perception. *Canadian Acoustics* 19(4), 105–106.
- Silva, Wilson. 2008. Acoustic analysis of voiceless obstruents and nasal harmony in Desano. *Amerindia* 32, 301–319.
- Sun, Xiaole. 2016. Interaction between breathy tones and aspirated consonants in S'gaw Karen. In C. DiCanio, J. Malins, J. Good, K. Michelson, J. Jaeger & H. Keily (eds.), *Proceedings of the 5th International Symposium on Tonal Aspects of Languages 2016*, 121–124. Buffalo, NY: University at Buffalo.

- Suomi, Kari. 1980. *Voicing in English and Finnish stops: A typological comparison with an interlanguage study of the two languages in contact* (Turun Yliopiston Suomalaisen Ja Yleisen Kielitieteen Laitoksen Julkaisuja 10). Turku: Department of Finnish and General Linguistics of the University of Turku.
- Walker, Rachel. 1999. Guaraní voiceless stops in oral versus nasal contexts: An acoustical study. *Journal of the International Phonetic Association* 29(1), 63–94.
- Weismer, Gary. 1980. Control of the voicing distinction for intervocalic stops and fricatives: Some data and theoretical considerations. *Journal of Phonetics* 8, 427–438.
- Yao, Yao. 2007. Closure duration and VOT of word-initial voiceless plosives in English in spontaneous connected speech. *UC Berkeley PhonLab Annual Report* 3, 183–225.