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On the phonetic realization and variation of consonant geminates in Sakha

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Abstract. This study examines the phonetic realization of geminates of different manners of articulation in an underdocumented Turkic language Sakha using production data from a native speaker. Meanwhile, the temporal compensation between geminates and their surrounding vowels is examined by varying the length of the vowels surrounding the target consonants. Results show that in Sakha, geminates differ from their singleton counterparts mainly by showing a longer overall consonant duration. Regardless, gemination is realized differently for consonants with different manners of articulation. Finally, vowel length is an enhancement cue for the realization of geminates.

Keywords. Sakha; consonant gemination; vowel length; phonetics; duration

1. Introduction. Gemination, or consonant length contrast, is defined as the articulation of a consonant for a longer period of time than that of a singleton consonant. By convention, it is often represented by a doubled letter (e.g., /C/ vs. /CC/). The existence of gemination has been reported as a distinctive feature for many languages such as Arabic, Finnish, Japanese, Italian, Swedish, Malayalam, among many others. As one of the Turkic languages spoken in Yakutia (Krueger 1962), Sakha displays a rich inventory of true geminates for voiceless consonants at word-medial position (e.g., VCV vs. VCCV). However, how geminates of different consonant types are phonetically realized in this language has received little attention to date. The present study reports on the phonetic realization of geminates of different manners of articulation in Sakha, with the goal of contributing to the cross-linguistic specification of consonant gemination. Further, since vowel length is also phonemic in this language such that both short and long vowels can occur before or after geminate consonants, this paper also reports on the temporal compensation between geminates and their surrounding vowels by varying the length of surrounding vowels.

Elicitation based on word lists first shows that in Sakha not only is there a geminate-singleton opposition acoustically manifested in long-short duration for most consonant types, but also for some consonants, gemination results in a qualitative change (e.g., the voiceless uvular fricative becomes an affricate when it gets geminated). In terms of the effect of surrounding vowels, we find that short vowels preceding the geminates are likely to be longer, while short vowels that follow tend to be shorter. Conversely, long vowels preceding the geminates tend to be shorter. Vowel length thus is an enhancement cue for the geminates. Taken together, features of longer duration and stronger articulation suggest that in Sakha, geminate consonants are fortis. Moreover, geminates coordinate with their surrounding vowels temporally.

1.1. NOT ALL GEMINATES ARE CREATED EQUAL. For intervocalic geminates at word-medial position, the existence of durational difference between singleton and geminate consonants has been reported to be a robust cue for gemination in various languages (e.g., Aoyama & Reid (2006) on Guinaang Bontok; Arvaniti & Tserdanelis (2000) on Cypriot Greek; Chang 2000, Payne 2005,

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2006 on Italian; Local & Simpson 1999 on Malayalam; Cohn et al. 1999 on three Indonesian languages; Deal 2012 on Shoshoni; Hamzah et al. 2016 on Kelantan Malay; Issa 2015 on Libyan Arabic; Khattab 2007 on Lebanese Arabic, and more). However, the exact geminate-to-singleton duration ratio is very language specific. For instance, the duration ratio of stops varies greatly from language to language: Madureses has so far the lowest duration ratio of 1.5:1 (Cohn et al. 1999), whereas Swiss German has so far the highest duration ratio of 3:1 (Kraehenmann 2011).

Apart from the cross-linguistic differences, the geminate-to-singleton duration ratio also varies depending on different manners of articulation. For instance, within Cypriot Greek, the geminate-to-singleton duration ratio for stops is 1.6:1, while for rhotics, the ratio is 2.5:1. In Italian, the geminate-to-singleton ratio for fricatives is 1.5:1 and this ratio becomes 2.3:1 for laterals. Through the investigation of the timing characteristics of the singleton-geminate contrasts in three Indonesia languages (Buginese, Madurese, and Toba Batak), Cohn et al. (1999) find that of all the consonant types, geminate voiced stops and fricatives have the largest singleton-geminate ratios, suggesting again that the magnitude of the singleton-geminate length contrast varies as the result of different manners of articulation.

Other than durational differences, previous studies have also shown that the contrast between geminate and non-geminate consonants is far more than just duration. In fact, different manners of articulation might realize the length contrast through different secondary cues. In the case of word-medial stop geminates, for example, in addition to closure duration, VOT has also been reported as an important cue. In Cypriot Greek, geminate stops have longer VOT (Arvaniti 2001) whereas in Turkish, VOT is shorter in geminates (Lahiri & Hankamer 1988). Along similar lines, Arvaniti & Tserdanelis (2000) have examined the acoustic correlates of the geminate consonants of Cypriot Greek and have found that there also exists an increase of aspiration in geminate stops and affricates. Change of manner of articulation for the alveolar trill /r/ has also been found. Payne (2005) has conducted a formant analysis of lateral geminates in Italian and a more palatalized tongue configuration in geminates has been reported, as the geminate lateral displays a lower F1 and higher F2 and F3. In a more recent study done by Mitterer (2018), it is revealed that in Maltese, the amount of voicing during closure and the spectral properties of frication noises are stronger for geminate glottal stops than for oral ones.

All these studies clearly show that not all geminates are created equal. Not only is the realization of gemination language specific but also it is highly dependent on the manner of articulation.

1.2. Temporal compensation and gemination. For languages with geminates at word-medial position, another important phenomenon that is becoming the subject of heavy empirical scrutiny is the effect of adjacent vowels (e.g., Doty et al. 2007; Issa 2015; Khattab 2007; Local & Simpson 1999). With regard to the preceding vowel, Maddieson (1985) points out a topologically common pattern: there exists an inverse relationship between vowel duration and consonant length with vowels preceding geminates being generally shorter. This has been tested true for some languages such as Italian, Buginese, Madurese and Toba Batak, among many others (e.g., Lahiri & Hankamer 1988; Cohn et al. 1999; Esposito & Di Benedetto 1999; Issa 2015). For instance, Al-Tamimi (2004) has conducted a spectrographic study on Jordanian Arabic to investigate the temporal relationship between the intervocalic singleton and geminate sonorants as well as the vowels that precede them (e.g., CVCV vs. CVCCV; CVVCV vs. CVVCCV). It is found that there is a significantly negative relationship between the preconsonant vowel and the intervocalic sonorants. Nevertheless, such an inverse relationship does not hold in all languages with consonant length contrast. For instance, in languages such as Japanese, Finnish, and Polish, vowels preceding geminates are lengthened rather than shortened (e.g., Idemaru 2005; Malisz 2009). These findings seem to suggest that the duration of vowel before geminates is also language-specific. For languages such as Turkish, Hungarian and Punjabi, no durational differences have been reported between the preceding vowels in singletons and geminates (e.g., Lahiri & Hankamer 1988; Ham 2013).

In terms of the effect of the duration of the following vowel, overall much less work has been done. Again, cross-linguistic differences abound in this respect. For instance, in their study of Maltese word-initial gemination, Galea et al. (2015) find that the duration of the following tonic vowel plays no role in distinguishing geminates from singletons. Nevertheless, the vowel after word-medial geminates in Japanese has been reported to be shorter than that after singletons (Idemaru 2005). In Finnish, a different pattern has been reported. In their study on singleton and geminate stops in Finnish, Doty et al. (2007) find that the duration of the following vowel shows an inverse relationship with the length of the preconsonantal vowel. That is to say, when the preceding vowel is long, the following vowel would be short and vice versa.

Taken together, it is not hard to see that a lot of work has been done to look at either the relationship between the preceding vowel and gemination (Arvaniti & Tserdanelis 2000) or the relationship between the following vowel and gemination (Galea et al. 2015). However, very few studies have looked at the effect of preceding and following vowels at the same time. This might be due to different possibilities that can be found in different languages. One study conducted by O'Dell & Malisz (2016) indeed has investigated the role played by the duration of both the preceding and following vowel in Finnish and Polish, but it mainly focuses on the mechanisms of consonantal quantity perception. Therefore, for most languages with geminates, it is still not clear how the gemination and vowel duration covary on the production side. This study aims to contribute to this line of research using data from Sakha.

2. About Sakha: some basic facts. Sakha, also known as Yakut, is one of the Turkic languages spoken in the federal republic of Yakutia in the Russian Federation in Eastern Siberia. Sakha is a quantity language in which both vowels and consonants are contrastive for length. On the one hand, there exists a full set of eight long and short vowels and they are contrastive word-initially, word-medially and word-finally; On the other hand, all consonants except for voiced ones (/b/, /s/[1], /d/, /ʁ/, /h/, /r/, /j/, /ʤ/) can appear as geminates, but only at word-medial position. Therefore, singleton and geminate consonants in Sakha are only contrastive at word-medial position. More detailed information about vowel and consonant inventories in Sakha can be found in Table 1 and Table 2 respectively.

In the literature, a distinction has been made between tautomorphemic geminates and heteromorphemic geminates based on how geminates are derived. Tautomorphemic geminates (e.g., VCCV), also known as underlying true geminates, refer to geminates belonging to a single morpheme and composed of one set of phonological features. Heteromorphemic geminates (VC+CV → VCCV), on the other hand, known as fake geminates, refer to those geminates that are formed by concatenation of morphemes and end up having two identical sets of phonological features linked to two consonant slots (Miller 1987). In Sakha, both true geminates and fake geminates can be found. In particular, fake geminates in Sakha are primarily derived through regressive as-

[1] Notably, intervocalic /s/ becomes /h/ in Sakha

similation due to morphological processes like suffixation (e.g., *at* ‘horse’ + -*LAr* ‘plural suffix’ → *a**tt**ar ‘horses’*; *atax* ‘leg’ + -*GA* ‘dative case’ → *ata**xx**a ‘to a leg’)*. However, exploratory analysis shows that as an agglutinative language, geminates produced cross-morpheme boundaries do not seem to differ qualitatively from geminates produced within-morpheme boundaries, therefore, this study focuses on the analysis of true lexical geminates in Sakha.

	Front	Front	Back	Back
High	unrounded, short: i	rounded, short : y	unrounded, short: ɯ	rounded, short: u
High	unrounded, long: iː	rounded, long: yː	unrounded, long: ɯː	rounded, long: uː
Low	unrounded, short: ɛ	rounded, short: œ	unrounded, short: ɑ	rounded, short: ɔ
Low	unrounded, long: ɛː	rounded, long: œː	unrounded, long: ɑː	rounded, long: ɔː
Diphthongs:	ɛ, yø, uo, ɯɑ			

Table 1. Vowel inventory in Sakha

	Labial	Alveolar	(Alveo)Palatal	Velar	Uvular	Glottal
Plosive	p(pp) b	t(tt) d		k(kk) g		
Nasal	m(mm)	n(nn)	ɲ	ŋ(ŋŋ)		
Tap		r				
Fricative		s z			χ(χχ) ʁ	h
Affricate			ʧ(ʧʧ) ʤ			
Approximant		l(ll)	j			

Table 2. Consonant inventory in Sakha

3. The current study. Continuing along these lines on cross-linguistic studies on consonant gemination, this study looks at the realization of consonant geminates using the production data from Sakha. Taking advantage of the phonemic contrast between long and short vowels as well as singleton and geminate consonants, this study conducts a quantitative analysis of geminate realization in Sakha with a focus on various aspects of consonant duration. Using (near-)minimal pairs of singletons and geminates in different temporal arrangements (VCV vs. VCCV; VVCV vs. VVCCV; VCVV vs. VCCVV), we further probe the influence of the surrounding vowel length on the realization of the contrast between singletons and geminates. Word lists for different manners of articulation are constructed and further elicited from a female native speaker of Sakha in a carrier sentence. Notably, although in Sakha, nine out of 20 consonants have geminates, consonants from the same manner of articulation are assumed to pattern together. Therefore this study focuses on six of them with each representing one type of manner of articulation. Patterns of approximants and affricates are illustrated respectively through the analysis of lateral /l/ and ʧ/. /n/ is analyzed as a representative for nasals. Patterns of fricatives are examined through the uvular fricative /χ/. Finally, for voiceless stops, we focus on the analysis of both /t/ and /k/ as they also differ in place of articulation. Using data collected, this study aims to address the following research questions:

Q1: For different manners of articulation, how geminates are generally realized?

Q2: Would the length of surrounding vowels influences the realization of geminates or would gemination influence the duration of the surrounding vowels?

Q3: Would geminates read in isolation (list reading) behave differently from those read in a carrier sentence (sentence reading)?

The remainder of the paper is structured as follows. Section 4 introduces the present study's methods. Details about experimental design and analysis can be found in this section. Section 5 presents results of the quantitative analysis. Section 6 discusses the implications of our key findings and Section 7 concludes the paper.

4. Method.

4.1. SPEAKER. A female native speaker of Sakha, with no known speech defects, served as the speaker for this study. The speaker was in her mid-twenties and lived in Yakutia at the time of recording. Apart from being fluent in English and Russian, she also has some knowledge about Japanese and Italian. Since Sakha is her first language, she is native as to the purposes of this study.

4.2. MATERIALS. For each consonant type, a word list was compiled with all the contrasting consonants at word-medial position. In order to further understand the influence of surrounding vowels on geminate realization, word pairs in different temporal arrangements were elicited in which the vowel preceding and the vowel following the consonant alternated between short-short (VCV vs. VCCV), short-long (VCVV vs. VCCVV), long-short (VVCV vs. VVCCV), and long-long (VVCVV vs. VVCCVV). Finding (near)-minimal pairs for all consonant types that allow geminates in all templates was challenging due to the low frequency of occurrence of target pairs in certain templates. Therefore, in order to fully capture the length effect of surrounding vowels, some possible but non-existent words were also elicited to pair with either its singleton or geminate counterpart so that all the templates were filled up. For instance, for stops /t/ and /tt/, certain templates turn out to be impossible to allow both singletons and geminates. In this case, if a word with a singleton /t/ in a certain template can be found, its geminate was made up using the same word phonotactics while replacing the singleton /t/ with a geminate /tt/ (e.g., *biiter*, meaning 'or', was paired up with a made-up word *biitter*, which according to the speaker, sounds like a possible Sakha word and she also had no trouble producing it). For stops, the template VVC(C)V had this fill-up issue. All the templates worked for the contrast between singleton /l/ and geminate /ll/. For the nasal /n/ vs. /nn/, the template VVC(C)VV did not quite work, therefore pairs were made up for this category. For the uvular fricative /χ/, minimal pairs could only be found for templates VC(C)V and VVC(C)V. For the affricate /ʧ/, templates including VC(C)VV and VVC(C)VV had made-up singletons or geminates. For the voiceless velar stop /k/, templates VC(C)VV and VVC(C)VV had either made-up singletons or made-up geminates.

Recall that in Sakha not all consonants allow length contrast word-medially, for each manner of articulation, words of one representational consonant from each category were elicited: For stops, word lists of /t/ vs. /tt/ and /k/ vs. /kk/ were compiled and elicited; For fricatives, words of /χ/ vs. /χχ/ were compiled and elicited; For approximants, words of /l/ vs. /ll/ were compiled and listed; For nasals, words of /n/ vs. /nn/ were compiled and elicited; And finally for affricates, words of /ʧ/ vs. /ʧʧ/ were compiled and elicited. The full set of word lists for each consonant type can be found in the Appendix.

4.3. ELICITATION. Data included in this study was collected through more than 10 individual elicitation sessions with the speaker. Each elicitation session lasted between 10 to 20 minutes. For each elicitation session, lists of words were prepared beforehand and presented in a randomized order during elicitation using a powerpoint presentation. All the words were taken from a Yakut-English dictionary and double-checked by the speaker. Words were presented primarily using the Sakha alphabet in Cyrillic script. Changes were made immediately for those words that were not written/interpreted correctly. After the list-checking, for all the words, the speaker was then asked to read aloud each word three times in a carrier sentence: "biligin _ dien tɯlɯ ɛt"(Please say the word_). The speaker was encouraged to produce each token in a conversational and natural way, avoiding hyperarticulation, as changes in the rate of speech have been reported to affect the duration of the segments (Pickett et al. 1999). In the end, three tokens were collected for each target word from the speaker.

4.4. RECORDINGS. All the recordings took place over Zoom. The speaker was recorded individually using the built-in microphone of Macbook air 2017 model through the local recording function of Zoom. Recordings were digitized at a sampling rate of 32,000 kHz and 32 bit sample width. Recordings were saved in mp4 format and then configured for wav format using the software Audacity. The resulting audio data files were then analyzed using the software program Praat (Boersma 2006).

4.5. MEASUREMENTS AND ANALYSIS. Each target word was isolated, segmented and annotated using Praat. Segmental boundaries were placed manually based on the visual inspection of simultaneous spectrographic and waveform displays. The duration of single and geminate consonants were measured in miliseconds. Different segmentation criteria were adopted for different types of consonants based on their acoustic characteristics.

For **vowels**, the onset was marked as the temporal point where the higher formants of the vowel started to appear on the spectrogram (together with the first regular glottal pulses on the wavefrom if it is preceded by a stop or a fricative) and the end of the vowel was marked as the point where the amplitude in the waveform suddenly decreased, while the higher formant structure in the spectrogram also disappears. This criterion applies to both the preceding vowel V1 and the following vowel V2.

In terms of **intervocalic consonants**, in general, the onset of consonants was placed at the end of the preceding voicing while the ending point was placed before the onset of the following vowels. In particular, for **stops** /t(t)/ and /k(k)/, the closure duration and VOT were measured separately. The closure duration was measured from the beginning of the stop closure to the release. VOT was measured as the interval between the release of the stop and the onset of the following vowel. For **fricative** /χ(χ)/, the duration was measured from the start of the aperiodic noise to the start of the following vowel. The consonant duration of the **affricate** /ʧ(ʧ)/ was measured from the start of the closure of the stop element in the affricate to the start of the following vowel and at the same time, closure duration and frication duration were separated, similar to the segmentation criterion of stops. For the **lateral** /l(l)/, left boundaries were placed when a drop in intensity in the waveform as well as in formant frequency in the spectrogram was seen. Right boundaries were placed when intensity and formant frequency increased again to signal the start of the following vowel. Finally, for the **nasal** /n(n)/, similar to the lateral /l/, left boundaries were placed where there was a pronounced drop in intensity relative to adjacent segments and right boundaries were placed at the point where formant frenquency and intensity started to increase.

After the segmentation, all the duration information was extracted using a Praat script. In the end, a total number of 1361 observations were further analyzed. Analyses of different consonant types were conducted separately. Pair-wise t-tests were conducted in the R statistical environment(Team et al. 2013) and plots were created using ggplot(Wickham 2016).

5. Results. Recall that in this study, for each consonant type, we aim to probe: 1) How geminate consonants are realized in general; 2) Whether the realization of geminates is further conditioned by the length of surrounding vowels or vice versa; Since analyses of each consonant were done separately, for clarity purposes, in the following sections, results are also reported separately for each consonant type.

5.1. ALVEOLAR STOP. We begin with the singleton-geminate contrast in the alveolar voiceless stop /t/. Figure 1 shows the mean duration (ms) for both singleton /t/ and geminate /tt/ and their relationship with surrounding vowels for different templates. Overall, the geminate /tt/ has much longer closure duration than its singleton counterpart. Differences in VOT are quite small, but the singleton /t/ seems to have slightly longer VOT duration than the geminate /tt/. For /VCV/ vs. /VCCV/, it seems that the preceding vowel V1 of the singleton /t/ on average is shorter than that of the geminate /tt/, whereas the following vowel V2 for singleton /t/ appears to be longer compared to the vowel following the geminate /tt/. But for both singleton /t/ and geminate /tt/, they are longer than their surrounding vowels. Statistically significant comparisons are highlighted through a little black bar throughout the paper for clarification purposes.

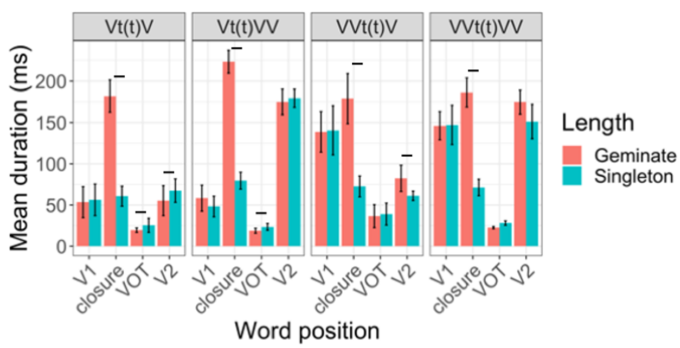


Figure 1. /t/ vs. /tt/ in different templates

Multiple Welch two sample t-tests were conducted to further detect whether the durational differences observed in each pairwise comparison are significant or not. For pairs with two surrounding short vowels (**VtV vs. VttV**), V1 duration is not significantly different between singleton /t/ and geminate /tt/, t(32.80)= 0.44, $p = 0.66$. Both closure duration and VOT are significantly different between singleton /t/ and geminate /tt/: singleton /t/ has a much shorter closure duration, t(28.7) = -22.10, $p < 0.001$, and a longer VOT, t(19.143) = 2.68, $p = 0.01$. Moreover, the durational difference in the following vowel V2 also turns out to be significant as the V2 duration for the singleton /t/ is significantly longer, t(31.94) = 2.21, $p = 0.03$.

When the preceding vowel V1 becomes long (**VVtV vs. VVttV**), these patterns still hold: t(15.44) = 0.15, $p = 0.89$ for V1, t(10.71) = -9.73, $p < 0.001$ for closure duration, and t(15.97)= 0.39, $p = 0.70$ for VOT. However, V2 duration turns out to be significantly different between singleton /t/ and geminate /tt/, t(10.01)= -3.74, $p < 0.01$, as the vowel following the geminate /tt/ is much longer.

When the following vowel V2 becomes long (**VtVV vs. VttVV**), except for V1 duration, t(20.74)= -1.81, $p = 0.09$,and V2 duration , t(19.31)= 0.82, $p = 0.42$, singleton /t/ and geminate /tt/ differ significantly in closure duration, t(19.84) = -30.03, $p < 0.001$ and VOT duration, t(24.89) = 3.38, $p < 0.01$. When both the preceding vowel V1 and the following vowel V2 become lengthened (**VVtVV vs. VVttVV**), VOT difference no longer turns out to be significant, t(2.51) = 3.40, $p = 0.06$. Closure difference is still significant, with the singleton /t/ showing a much shorter closure duration, t(6.64) = -12.49, $p < 0.001$). The duration of V1 and V2 between the singleton /t/ and geminate /tt/ are not significantly different, t(3.08) = 0.06, $p = 0.95$ for V1 comparison and t(3.03) = -1.75, $p = 0.18$ for V2 comparison.

Based on these results, it is not hard to tell that, for the voiceless stop /t/, the reliable cue for geminate realization is the closure duration, with the geminate /tt/ in general having a much longer closure duration than that of its singleton counterpart. Across all the templates, the preceding vowel does not seem to differ, however, the duration of the following short vowel sometimes differs between the singleton /t/ and geminate /tt/ when the preceding vowel becomes long. However, more data is needed to further disentangle the patterns of VOT differences as its effect seems quite unstable at this point.

5.2. VELAR STOP. We now turn to the singleton-geminate contrast in the voiceless velar stop /k/. Figure 2 shows that geminate /kk/ has longer duration than the singleton /k/ in all respects including closure duration, VOT, as well as the whole segment. In terms of their surrounding vowels, the preceding vowel V1 for the singleton /k/ on average is shorter than that of the geminate /kk/. For the following vowel V2, V2 is shorter in duration for the geminate /kk/.

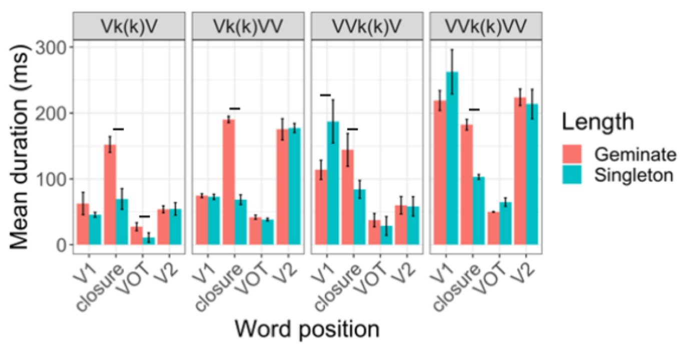


Figure 2. Mean duration of /k/ vs. /kk/ across two contexts

Welch two sample t-tests were conducted to further detect whether the durational differences observed in each pair-wise comparison are statistically significant or not. For pairs with two surrounding short vowels (**VkV vs. VkkV**), singleton /k/ and geminate /kk/ again do not differ significantly in V1 duration, t(4.38) = -2.20, $p = 0.09$, and V2 duration, t (6.26)= 0.12, $p = 0.91$. But they do differ significantly in closure duration, t(7.45) = -9.35, $p < 0.001$) and VOT, t(7.83) = -3.91, $p < 0.01$, suggesting /k/ has a significantly shorter closure duration as well as VOT than /kk/.

When the preceding vowel V1 becomes long (**VVkV vs. VVkkV**), the singleton /k/ has a significantly longer V1 duration than the geminate /kk/, t(11.40) = 6.12, $p < 0.001$. The singleton /k/ is significantly shorter in closure duration, t(10.59) = -6.06, df = 10.588, $p < 0.001$. In this case, the singleton /k/ and geminate /kk/ do not differ significantly in both VOT, t(14.41) = -1.49, $p = 0.16$ and V2 duration, t(14.99) = -0.22, $p = 0.83$.

When the following vowel V2 becomes long (**VkVV vs. VkkVV**), the preceding vowel V1 of the singleton /k/ does not significantly differ from the vowel preceding the geminate /kk/, t(3.65) = -0.64, $p = 0.56$. The singleton /k/ and geminate /kk/ also do not differ significantly in VOT, t (3.41)= -1.61, $p = 0.19$, and the duration of the following vowel V2, t (2.73) = 0.20, $p =$ 0.86. Finally, the singleton /k/ has a significantly shorter closure duration, t(3.40) = -23.64, $p <$ 0.001.

When both the preceding vowel V1 and the following vowel V2 become long (**VVkVV vs. VVkkVV**), only the difference in closure duration turns out to be statistically significant, t (2.80) = -15.356, $p < 0.001$, suggesting that the singleton /k/ has a much shorter closure duration. The singleton /k/ and geminate /kk/ do not differ significantly in V1 duration, t(2.79)=2.04, $p = 0.14$, VOT, t(2.03) = 3.94, $p = 0.06$, as well as V2 duration, t(3.17) = -0.70, $p = 0.53$.

Taken together, again, in terms of the gemination in the voiceless velar stop /k/, the most prominent and stable cue that distinguishes a geminate /kk/ from a singleton /k/ across different contexts as well as temporal arrangements is the closure duration, which is much longer for the geminate /kk/. When the preceding vowel becomes longer, it seems that a long vowel preceding a geminate is significantly shorter than preceding a singleton. The patterns of VOT seem to be intriguing and whether the VOT matters or not might still need more tokens from more speakers.

5.3. AFFRICATE. We now continue with the length contrast in the affricate /ʧ/. Figure 3 shows that the geminate /ʧʧ/ has longer duration than the singleton /ʧ/ in all respects including closure duration, frication duration, as well as the whole segment. In terms of the relationship between /ʧ/ (also /ʧʧ/) and their surrounding vowel V1 and V2, the preceding vowel of the singleton /k/ on average is shorter than that of the geminate /ʧʧ/. However, this relationship is inversed for the following vowel V2: the vowel following the singleton /ʧ/ is longer in duration than the one following the geminate /ʧʧ/.

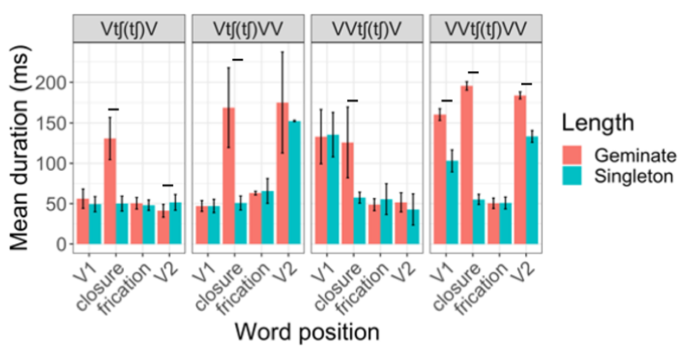


Figure 3. Mean duration of /ʧ/ vs. /ʧʧ/ across two contexts

Welch two sample t-tests were conducted for all the templates to further detect whether the durational differences observed in each pairwise comparison are significant or not. For pairs with two surrounding short vowels (**VʧV vs. VʧʧV**), the singleton /ʧ/ and the geminate /ʧ/ still do not differ significantly in the duration of their preceding vowel V1, t(17.98) = -1.42, $p = 0.17$. When words are embedded in a carrier sentence, the singleton /ʧ/ has significantly shorter closure duration, t(12.97) = -9.52, $p < 0.001$, but the difference in frication duration no longer significantly differs, t(17.81) = -0.78, $p = 0.44$. However, the vowel that follows the the singleton /ʧ/ V2 is signficantly longer than the following vowel of the geminate /ʧʧ/, t(15.37) = 2.59, $p = 0.02$.

When the preceding vowel V1 becomes long (**VVʧV vs. VVʧʧV**), the singleton /ʧ/ and the geminate /ʧʧ/ do not differ significantly in the duration of the preceding vowel, t(15.40) = 0.17, $p = 0.87$, the following vowel, t(13.26) = -1.17, $p = 0.26$, and frication duration, t(10.37) = 1.01, $p = 0.34$, but the geminate /ʧʧ/ does have a significantly longer closure duration, t(8.39) = -4.64, $p < 0.01$.

When the following vowel V2 becomes long (**VʧVV vs. VʧʧVV**), the singleton /ʧ/ and geminate /ʧʧ/ do not differ significantly in V1 duration, t(1.89)= -0.00, $p = 1.00$, frication duration, t(1.03) = 0.24, $p = 0.85$, and V2 duration, t(2.00) = -0.63, $p = 0.59$. Only the difference in closure duration is significant with the singleton /ʧ/ showing a much shorter closure duration, t(2.18) = -4.07, $p = 0.05$.

When both the preceding vowel V1 and the following vowel V2 become long (**VVʧVV vs. VVʧʧVV**), the durational difference in V1 is statistically significant, with the vowel preceding the singleton /ʧ/ becoming much shorter, t(3.02) = -6.46, $p = 0.01$. No difference is found for frication duration, t(3.93) = 0.07, $p = 0.95$. But the singleton has a significantly shorter closure duration, t (3.85)= -29.65, $p < 0.001$ and the vowel following the singleton /ʧ/ is significantly shorter as well, t(3.22) = -10.42, $p < 0.01$.

It seems that for the affricate /ʧ/, the closure duration still remains to be a prominent cue for the realization of the length contrast across the board. The difference in the duration of their surrounding vowels only reaches statistical significance when both the preceding vowel and the following vowel become lengthened.

5.4. Lateral. After knowing about the gemination in obstruents, we now look at how gemination is realized for sonorants through the analysis of /l(l)/ and /n(n)/. We start from the lateral /l/ vs. /ll/. According to Figure 4, the geminate /ll/ has a much longer duration than the singleton /l/. The preceding vowel V1 of the singleton /l/ is shorter in duration than that of the geminate /ll/ whereas the following vowel V2 of the singleton /l/ is longer than V2 of the geminate /ll/.

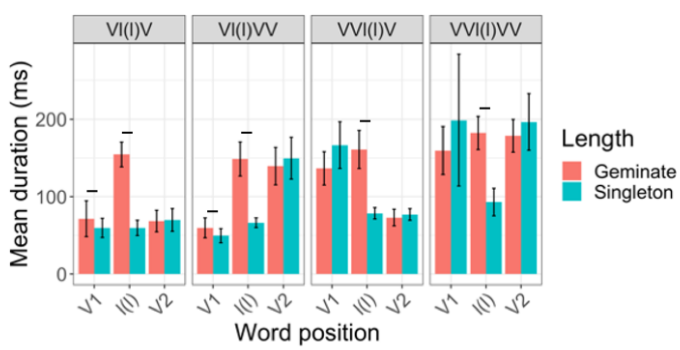


Figure 4. Mean duration of /l/ vs. /ll/ across two contexts

Multiple Welch two sample t-tests were conducted to further detect whether the durational differences observed in each pairwise comparison are significant or not. For pairs with two surrounding short vowels (**VlV vs. VllV**), the singleton /l/ has a significantly shorter V1, t(30.65) = -2.07, $p = 0.05$, and shorter consonant duration, t(33.38) = -23.16, $p < 0.001$, but they do not differ in the duration of the vowel that follows, t(39.89) = 0.32, $p = 0.75$.

When the preceding vowel V1 becomes long (**VVlV vs. VVllV**), the consonant interval between singleton and geminate still is significantly different, with /l/ being significantly shorter than /ll/, t(5.88) = -7.89, $p < 0.001$. Both the preceding vowel V1 and the following vowel V2 do not significantly differ, t(9.05) = 1.99, $p = 0.08$ for V1 comparison, and t(8.92)= 0.75, $p = 0.47$ for V2 comparison.

When the following vowel V2 becomes long (**VlVV vs. VllVV**), the preceding vowel V1 of /l/ is significantly shorter than the preceding vowel V1 of /ll/, t(17.91) = -2.18, $p = 0.04$. /l/ is significantly shorter than /ll/, t(11.50) = -11.98, $p < 0.001$. The vowel that follows the singleton /l/ does not differ significantly from the vowel that follows the geminate /ll/, t(20.99) = 0.96, $p = 0.35$.

When both the preceding vowel V1 and the following vowel V2 become long (**VVlVV vs. VVllVV**), only /ll/ is significantly longer than /l/, t(7.86) = -7.46, $p < 0.001$, and there is no significant difference in both V1, t(6.52) = 1.05, $p = 0.33$, and V2, t(8.18) = 1.01, $p = 0.34$.

In the gemination of /l/, duration itself is still the main factor that distinguishes a geminate /ll/ from a singleton /l/. The patterns of surrounding vowels are still a little bit inconsistent as the preceding vowel might matter more in the template of Vl(l)V but not when it becomes a long vowel. More data from more speakers might be needed to further figure out the roles of the surrounding vowels in conditioning the gemination in /l/.

5.5. NASAL. Finally, we examine the patterns for /n/. As illustrated in Figure 5, geminate /nn/ has longer duration than the singleton /n/. In terms of their preceding vowel V1 and following vowel V2, it is clear that the preceding vowel of the singleton /n/ is shorter than that of the geminate /nn/, but the singleton /n/ has a longer following vowel V2, compared with the following vowel V2 of the geminate /nn/. Within the same word, the V1 duration is shorter than /n/ in VnV and the V1 duration is shorter than /nn/ in VnnV. For V2, even though V2 in VnV is longer than /n/ but it is still shorter than /nn/ in VnnV.

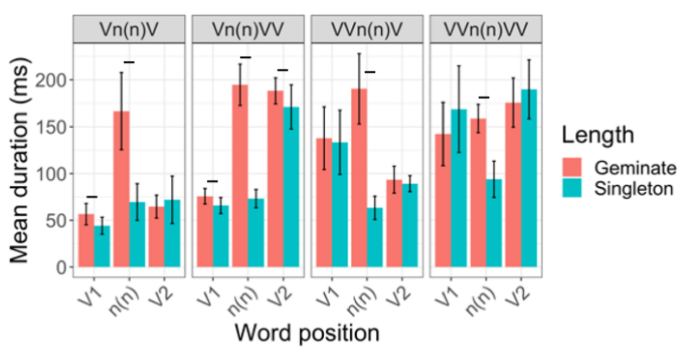


Figure 5. Mean duration of /l/ vs. /ll/ across two contexts

Multiple Welch two sample t-tests were conducted to test whether the durational difference observed in each pairwise comparison is statistically significant or not. For pairs with two surrounding short vowels (**VnV vs. VnnV**), in *List reading*, no significant durational difference has been found between the preceding vowel V1 of the singleton /n/ and that of the geminate /nn/, t(23.32) = -0.71, $p = 0.49$. Unsurprisingly, the singleton /n/ is significantly shorter than the geminate /nn/, t(15.06) = -12.67, $p < 0.001$. The duration of the vowels that follow /n/ and /nn/ is not significantly different from each other, t(19.32) = 1.23, $p = 0.23$. In *Sentence reading*, still, /nn/ is significantly longer than /n/ in duration, t(19.23) = -7.85, $p < 0.001$ and they do not differ significantly from each other in terms of the duration of the following vowel V2, t(15.31) = 0.90, $p = 0.38$. But in sentence reading, the duration of the vowel preceding /n/ is significantly shorter than that of the preceding vowel of /nn/, t(23.90) = -3.07, $p < 0.01$.

When the preceding vowel V1 becomes long (**VVnV vs. VVnnV**), in *List reading*, the singleton /n/ and the geminate /nn/ differ significantly in the preceding vowel (V1) duration, with V1 before /n/ being significantly longer. t(18.38) = 4.76, $p < 0.001$. /nn/ is significantly longer in duration than /n/, t(10.90) = -22.21, $p < 0.001$ but it does not significantly differ from /n/ with regard to the duration of the vowel that follows, t(18.85) = 1.12, $p = 0.28$. In *Sentence reading*, the singleton /n/ is significantly shorter in duration than the geminate /nn/, t(9.34) = -9.79, $p < 0.001$. But they do not differ significantly in the duration of both the preceding vowel V1, t(17.61) = -0.30, $p = 0.77$, and the following vowel V2, t(12.21) = -0.80, $p = 0.44$.

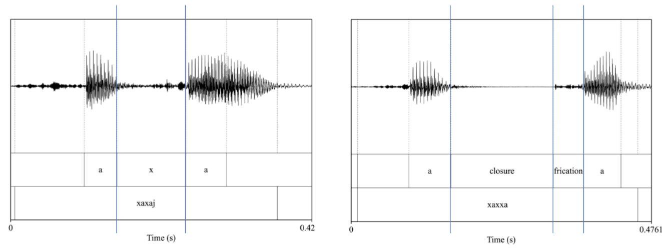
When the following vowel V2 becomes long (**VnVV vs. VnnVV**), in *List reading*, no significant difference has been found for the vowel preceding /n/ and the /nn/, t(21.96) = 1.14, $p = 0.27$, as well as the vowel following /n/ and /nn/, t(19.12) = -0.51, $p = 0.62$. But the duration of /n/ is significantly shorter than the duration of /nn/, t(13.64) = -10.02, $p < 0.001$. In *Sentence reading*, however, VnVV differs from VnVV systematically in V1 duration, consonant duration as well as V2 duration, with V1 in VnVV being significantly shorter, t(21.98) = -2.89, $p < 0.01$, /n/ being significantly shorter, t(15.22) = -17.48, $p < 0.001$, as well as V2 being significantly shorter, t(17.84) = -2.18, $p = 0.04$.

When both the preceding vowel V1 and the following vowel V2 become long (**VVnVV vs. VVnnVV**), in *List reading*, there is no significant difference in duration between the vowel preceding /n/ and the vowel preceding /nn/, t(20.99) = 0.81,$p = 0.43$. /n/ itself is significantly shorter than /nn/, t(20.43) = -8.63, $p < 0.001$. But the vowel that follows /n/ is significantly longer than the vowel that follows /nn/, t(18.11) = 2.35, $p = 0.03$. In *Sentence reading*, only the duration of /n/ is significantly shorter than /nn/, t(20.69) = -9.13, $p < 0.001$. The singleton /n/ and the geminate /nn/ do not differ significantly in V1 duration, t(20.16) = 1.61, $p = 0.12$ and V2 duration, t(21.32) = 1.20, $p = 0.24$.

In the case of nasal gemination, similar to patterns of the lateral /l/, the primary difference between a singleton /n/ and a geminate /nn/ is the nasal duration with the geminate /nn/ displaying a much longer duration than its singleton counterpart.

5.6. Uvular fricative. So far, we have found that in Sakha, for most obstruents including stops and affricates as well as sonorants including laterals and nasals, geminates differ from their singleton counterparts mainly by showing a longer duration. Turning to the uvular fricative /χ/, however, other than the durational difference, the singleton fricative /χ/ also becomes an affricate after gemination, showing a change in the manner of articulation. As shown in Figure 6, on the left panel is the waveform of a singleton /χ/ flanked by two short vowels in the word *xaxaj*, meaning ‘to pay attention to’. On the right panel is the waveform of a geminate /χχ/ flanked by the same two short vowels in the word *xaxxan*, meaning ‘owl’. At first glance, not only the total duration of the geminate /χχ/ is longer, but also the original singleton fricative /χ/ becomes an affricate that is made up of both closure and frication.

6. Discussion. In this paper, we have conducted a systematic analysis of geminate consonants in Sakha. As expected, duration is a very robust cue for gemination for all types of consonants



/χ/ in xaxaj /χ χ / in xaxxaj

Figure 6. Mean duration of /χ/ vs. /χχ/ across two contexts

that have been investigated. Crucially, for stops or affricates, closure duration is more important than either VOT or frication duration. For fricatives, when geminated, not only the consonant duration gets prolonged, its manner also changes from a fricative to an affricate. These findings of geminates displaying longer duration and stronger articulation implicate that geminates in Sakha are fortis. In addition to duration, we have also investigated the durational variation of surrounding vowels. We further find that, the vowel preceding the geminates is also likely to be longer. However, the vowel that follows the geminate segments normally becomes shorter, which can be attributed to how speech production is planned. Stronger production beforehand consumes the articulatory energy such that less energy is available for following segments during production, making the vowel following a geminate become shorter than it should be.

In phonetic theory, the terms fortis and lenis have been used in two main dimensions: On the one hand, fortis indicates greater articulatory energy applied in speech while lenis indicates less energy; On the other hand, the fortis-lenis dichotomy has also been related to matters of duration, with fortis referring to long consonants and lenis referring to short consonants (Ladefoged & Maddieson 1996). In Sakha, geminate consonants are always longer in duration than their singleton counterparts. The geminate-to-singleton ratio varies depending on different manners of articulation, with affricates showing the highest ratio of around 3:1. But for all the consonant types, geminates are more than twice as long as singletons. For stops as well as affricates, the durational contrast lies in their difference in closure duration, suggesting a stronger constriction. For fricatives, gemination is correlated with the change of manner of articulation with a geminated fricative becoming an affricate. These facts all indicate that consonant geminates in Sakha should be treated as fortis.

It has been suggested that since geminate consonants are longer than non-geminate consonants, there should exist a reciprocal length relationship with preceding vowels (Chang 2000). Based on patterns in Sakha, The pattern seems to be more complicated. For all consonant types, when the surrounding vowels are short, the preceding vowel seems to be longer in the geminates, even though the statistical significance of this difference varies depending on the type of the consonant. In this respect, Sakha behaves like languages such as Polish and Finnish which also have slightly longer preceding vowels before geminates (O'Dell & Malisz 2016). Interestingly, the vowel that follows geminates in Sakha has the tendency to become shorter, which we argue, might be related to restrictions under speech planning. Speech production is coordinative such that the preceding vowel and the following vowel would covary to make sure a reliable realization of length contrast as well as an easy articulation. When both the preceding vowel and the following vowel become long, the surrounding long vowels tend to be shorter for the geminates than for the singletons. This further suggests that in Sakha, consonants geminates are always produced with a reliable durational contrast while at the same time coordinating coordination its surrounding segments.

Still, some intriguing patterns remain to be solved. Although for cases such as stops and affricates, closure duration has proved to be a very consistent and powerful cue across the board to differ singleton stops/affricates from their geminate counterparts, when the length of the surrounding vowels or the context changes, VOT and frication duration also seem to matter. Given the current data that we have, these patterns do not seem to be consistent. Therefore, in the future work, it is necessary to elicit more data from different speakers to further probe this question.

7. Conclusion. This paper examines consonant geminates in Sakha. Crucial take-home messages include: 1) Sakha geminates in general can be understood as fortis given its stronger articulation; 2) Duration is the most robust cue in Sakha gemination; 3) Gemination realization in Sakha is coordinative. If the vowel preceding the geminate is longer, the vowel following the geminates is usually shorter. However, there still remains a lot to be done in order to have a better understanding of consonant gemination in this language. First of all, more tokens from more speakers should be collected in future work in order to gain a more consistent and stable pattern. A full picture of geminates as well as their relationship with the surrounding vowels in Sakha can be better understood when more data become available. In addition, if possible, a comparison with more naturalistic data such as sociolinguistic interviews could be more revealing about how gemination is realized in a more naturalistic setting. Finally, since this study examines Sakha geminates from the production side, in future work, more studies can be done to see how geminates are perceived in this language.

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