Lisa Davidson* and Oiwi Parker Jones

The role of recoverability in the implementation of non-phonemic glottalization in Hawaiian

https://doi.org/10.1515/lingvan-2023-0060
Received April 18, 2023; accepted January 15, 2024; published online May 31, 2024

Abstract: Previous research has shown that non-phonemic uses of glottalization are often prosodically determined in a variety of languages such as English, German, Polish, and Spanish. We examine the use of inserted glottalization in Hawaiian, a language that also has a phonemic glottal stop, to determine whether the distribution and realization of non-phonemic glottalization is conditioned by higher prosodic boundaries and/or prosodic prominence as found in other languages. The spontaneous speech data in this study comes from the Hawaiian-language radio program *Ka Leo Hawai'i*, which featured interviews with bilingual Hawaiian–English speakers in the 1970s and 1980s (Kimura, Larry (Producer). 2020. *Ka Leo Hawai'i* [radio program]. Kani'āina, the digital repository of Ka Haka 'Ula O Ke'elikōlani, College of Hawaiian Language, University of Hawai'i at Hilo. Available at: https://ulukau.org/kaniaina/). Results show that non-phonemic glottalization occurs most often before an unstressed, monophthongal single-vowel grammatical marker (/a e i o/), where it is also longer, as well as before unstressed vowels and between different flanking sounds. Full closures were more likely between identical vowels, but stress does not affect realization. These results are not consistent with the use of glottalization at higher prosodic boundaries or to mark prosodic prominence. Instead, the preponderance of non-phonemic glottalization before single-vowel grammatical markers may be to ensure that these critical markers are recoverable and not perceptually subsumed by the preceding vowel.

Keywords: glottalization; Hawaiian; prosody; recoverability

1 Introduction

1.1 The function of non-phonemic glottalization

Research on the use of glottalization as a non-phonemic or epenthetic element has shown that crosslinguistically this type of glottalization is often prosodically determined. One of the most common findings, as demonstrated in languages such as English, German, Polish, French, and Hungarian, is that non-phonemic glottalization appears at the beginning of vowel-initial words in some environments (e.g., Dilley et al. 1996; Malisz et al. 2013; Markó 2012), and that glottalization often correlates with higher prosodic boundaries or with a prominent element like a stressed syllable (Dilley et al. 1996; Fougeron 2001; Garellek 2014; Kohler 1994; Malisz et al. 2013). These conditions are typically described for languages that do not have phonemic glottal stops, which may have different properties than languages which do contain glottal stop as a phoneme. In this paper, we examine the use of inserted, or non-phonemic, glottalization in Hawaiian, which also has phonemic /ʔ/.

To set the stage for the current study, the term 'glottalization' will be used as a cover term to refer to either a period of irregular, creaky phonation, or to a full glottal closure, or to a combination of the two (creaky phonation on one or both adjacent vowels, in addition to a full closure interval; see also Garellek et al. 2021). Typically, the duration of this type of glottalization event is similar to other single phonemes in the language, and is sometimes referred to as an epenthetic glottal stop (e.g., Mitterer et al. 2019; Mohamed et al. 2019; Szczepek Reed 2014). Separately from these short periods of glottalization, longer periods of glottalization, or creaky phonation, can be

***Corresponding author: Lisa Davidson**, Department of Linguistics, New York University, 10 Washington Place, 10012-1126 New York, NY, USA, E-mail: lisa.davidson@nyu.edu
Oiwi Parker Jones, Department of Engineering Science, Oxford University, Oxford, Oxfordshire, UK, E-mail: oiwi.parkerjones@eng.ox.ac.uk

used prosodically for other reasons, such as marking the ends of sentences or phrasal meanings such as parentheticals (Davidson 2021b; González et al. 2022; Henton and Bladon 1988; Kreiman 1982; Lee 2015; Redi and Shattuck-Hufnagel 2001; Slifka 2006). This type of (frequently) longer phrasal glottalization is not further addressed in this paper.

For American English, it has been reported that glottalization can occur in a number of environments, including before vowel-initial words at the beginnings and middles of phrases, and as a hiatus resolution strategy between two vowels. Pierrehumbert and Talkin (1992) and Pierrehumbert (1995), in a lab setting, and Dilley et al. (1996), using a radio speech corpus, find word-initial glottalization is more likely for accented full vowels compared to unaccented reduced vowels, and the rates of glottalization for both types of vowels are significantly increased in utterance-initial position. Using a reading task, Davidson and Erker (2014) found that in phrase-medial position, hiatus between a vowel-final word and a vowel-initial word was resolved with glottalization more often when the first syllable of the vowel-initial word was stressed (e.g., *may* ʜ*onor*). Using articulatory data, Garellek (2014) found that for read sentences, electroglottograph contact quotient patterns for both English and Spanish speakers were more consistent with glottalization when a vowel at any prosodic boundary was stressed, but the different degrees of prosodic boundary did have an additional effect. Other studies of Spanish confirm that glottalization of vowel-initial words can occur to some degree in connected speech, especially before stressed vowels (Chappell 2013; Michnowicz and Kagan 2016; Trawick and Michnowicz 2019).

A similar effect of stressed vowels and higher prosodic boundaries on glottalization is found for German and Polish. Kohler (1994) finds that in the Kiel corpus of read speech, both full closures and creaky voice at a V#V boundary are more likely when the following vowel is stressed. Pompino-Marschall and Żygis (2011) report an effect of speech rate on how glottalization interacts with vowel stress in speeches of three politicians in German. Before stressed vowels, the full closure implementation is highest at the slowest speech rate (nearly 80 %) and decreases monotonically as speech rate increases (to around 20 %), whereas creaky voice shows exactly the opposite pattern. Malisz et al. (2013) compare rates of glottalization in speeches and dialogues for both German and Polish, showing that glottalization is less frequent in speeches for both languages, but that full closures are more likely in speeches than in dialogues in both German and Polish. For both languages, stressed vowels are more likely to have some type of glottalization, but for phrase position, whereas glottalization is more likely in Polish in phrase-initial position, it is equally likely in phrase-initial and phrase-medial position in German. As for realization, full closures are more likely both in phrase-initial position than phrase-medial position in both German and Polish. In a sentence reading task, Schwartz (2013) shows that phrase-medial V#V hiatus contexts are resolved with glottalization as often as 94 % of the time when the second vowel is stressed and 68 % of the time when it is unstressed. In contrast to these languages, Aare et al. (2017) find that creakiness in a syllable in Estonian is most likely in secondarily stressed syllables as compared to both primary stressed and unstressed syllables.

Mitterer et al. (2019) examines rates of non-phonemic glottalization in Maltese, a language that also has a phonemic glottal stop. In this study of laboratory speech, target /ʔ/-initial or /V/-initial words followed a word ending in either /a/ or /m/. About half of the /V/-initial cases are marked with glottalization, and full closures make up about 40 % of the responses after /m/ and about 15 % after /a/. While boundary strength is not overtly tested, duration of the previous word is used as a proxy for prosodic strength, and there is a correlation between length of the boundary and the likelihood that glottalization is realized as a full closure.

In the current study we investigate the use of non-phonemic glottalization in Hawaiian in spontaneous speech to determine whether the occurrence of inserted glottalization is evident at higher prosodic boundaries or in prosodically prominent positions, similar to English, German, or Polish, or whether it is conditioned by other factors. As a preview, prosody does not seem to be the primary driver; instead, glottalization occurs more often in environments where a weak element might be difficult to distinguish from adjacent words.

1.2 The phonemes and stress patterns of Hawaiian

Hawaiian is an Eastern Polynesian language which has phonemic glottal stops before vowels in word-initial and word-medial position. Hawaiian has the phonemic inventory shown in Table 1, with consonants, monophthongs

Table 1: The consonant, monophthong, and diphthong phonemes of Hawaiian.

Consonants					
	Bilabial	**Labiodental**	**Alveolar**	**Velar**	**Glottal**
Stop	p			k	ʔ
Fricative		v			h
Nasal	m		n		
Lateral			l		
Monophthongs					
	Front	**Central**	**Back**		
High	i iː		u uː		
Mid	e eː		o oː		
Low		a aː			
Diphthongs					
Short	ae, ai, ao, au, ei, eu, iu, oi, ou				
Long	aːe, aːi, aːo, aːu, eːi, oːu				

(both short and long), and (short and long) diphthongs (Elbert and Pukui 1979; Kettig 2021; Ladefoged 2001; Parker Jones 2018; Pukui and Elbert 1986; Schütz 1981).

In Hawaiian, syllables can only be of the shape CV(:) or V(:), where V: represents either a long vowel or a diphthong. Diphthongs and long vowels are heavy, and all heavy syllables are stressed, with either primary or secondary stress (Parker Jones 2018; Schütz 1978, 1981; Senturia 1998). Lexical words minimally consist of either two light syllables or one heavy syllable, but light and heavy syllables can also be combined to form longer words. The patterns and words in (1) illustrate the six templates that are found for words that only have one stress in Hawaiian (Parker Jones 2010; Schütz 1981, 2010). When these templates are combined into longer words, the rightmost stressed syllable receives primary stress, and any preceding stressed syllables are secondarily stressed, as illustrated in (2). Words with up to four light syllables have a trochaic stress pattern, with penultimate primary stress, and secondary stress on the first syllable of a four-syllable word (e.g., ['pu.ke] 'book', [ho.'pe.na] 'result', [ˌma.ka.'hi.ki] 'year'). In words with more than four light syllables, stress is not fully predictable. For example, there are different stress patterns in the five-syllable words [ˌʔe.le.ma.'ku.le] 'old man' and [ma.ˌku.a.'hi.ne] 'mother', where 'old man' has stress on the first syllable, and 'mother' has stress on the second syllable (A full account of the word-internal metrical system of Hawaiian is not germane to this paper, since we focus here on non-phonemic glottalization between two lexical items, but for more details on the stress system of Hawaiian, see Davidson and Parker Jones 2023; Parker Jones 2010; Schütz 1978, 1981, 2010).

(1) a. $'\sigma_L\ \sigma_L$ ['ma.la] 'ache'
b. $\sigma_L\ '\sigma_L\ \sigma_L$ [va.'hi.ne] 'woman'
c. $'\sigma_H$ ['au] 'I' (first person singular pronoun), ['laː] 'day'
d. $\sigma_L\ '\sigma_H$ [na.'naː] 'to snarl'
e. $'\sigma_H\ \sigma_L$ ['maː.la] 'garden'
f. $\sigma_L\ '\sigma_H\ \sigma_L$ [pa.'lao.a] 'bread'

(2) a. $ˌ\sigma_H\ '\sigma_H$ [ˌpiː.'koi] a type of club used as a weapon
b. $ˌ\sigma_L\ \sigma_L\ '\sigma_H$ [ˌpi.ha.'ʔuː] 'jam-packed'
c. $ˌ\sigma_H\ '\sigma_L\ \sigma_L$ [ˌkoː.'ʔa.la] 'to broil'
d. $ˌ\sigma_L\ \sigma_L\ '\sigma_L\ \sigma_L$ [ˌpa.ka.'la.na] 'Chinese violet'

In addition to the lexical items illustrated in (1) and (2), Hawaiian also has several morphemes and grammatical markers that are a single light syllable. These can be either CV syllables or a single short V, as exemplified in (3). While the prosodic phonology of these markers has not yet been fully developed for Hawaiian, it can be pointed out that they are written as orthographically separate from an adjacent content word, and Elbert and Pukui (1979: 18) impressionistically observe that there is often some kind of prosodic juncture between the marker and the preceding word. These markers serve many different purposes, with non-exhaustive glosses in (3) (Elbert and Pukui 1979; Kamanā and Wilson 2012). In this study, we consider a content word plus one of these function words to be a two-word sequence, as shown by the bolded elements in the sentences in (4).[1]

(3)
a.	[a]	conjunction (and), possessive allomorph
b.	[e]	infinitive, imperative, agentive
c.	[i]	object marker, locative, past tense, conjunction (while)
d.	[o]	conjunction (or), possessive allomorph
e.	[ka/ke]	allomorphs of definite marker
f.	[ko]	possessive allomorph
g.	[ma]	locative, instrumental

(4) a. [makemake **au** **i** ke kope]
Makemake *au* *i* *ke* *kope*
want 1SG OBJ the coffee
'I want the coffee.'

b. [ʔekolu **hale** **o** kimo]
'Ekolu *hale* *o* *Kimo*
three house POSS Kimo
'Kimo has three houses.'

Since Hawaiian has a glottal stop phoneme, which can occur either in intervocalic position within a word ([poʔe] 'people') or contrastively at the beginning of a word ([ʔaka] 'laughter' vs. [aka] 'shadow'), it is possible that the use of inserted glottalization is rare, or at least more restricted, in Hawaiian so as to not cause lexical confusion with words containing phonemic /ʔ/. Alternatively, it is possible that Hawaiian does employ glottalization at higher prosodic boundaries and/or at the beginning of stressed syllables, but that it is realized differently than the phoneme. Previous research on the realization of the Hawaiian glottal stop phoneme in connected speech has found that 66 % of glottal stops are produced as a period of creaky voice, 27 % with modal voicing, and only 7 % as a complete closure (Davidson 2021a; Davidson and Parker Jones 2023). These studies also found that complete closure is sensitive to prosodic word structure. Similar to de Lacy's (2004) analysis of Māori, Parker Jones (2010) includes prosodic words as a structural unit necessary for capturing the analysis of Hawaiian stress, where potential prosodic words correspond to the template shapes in (1). For the purposes of stress assignment, when heavy and light syllables in words with more than three syllables are mixed, the correspondence to the prosodic word shapes in (1) can be ambiguous (Parker Jones 2010). For example, the word *hōʻoaka* 'to open' [σ_H σ_L σ_L σ_L] could be parsed as either {(ˌho:)}{ʔo.('a.ka)} or {(ˌho:.ʔo)}{('a.ka)}). Davidson and Parker Jones (2023) found that full closures are more likely at the beginning of a prosodic word in (lexical) word-medial position (e.g., {(ˌla:)}{('ʔau)} 'tree'), as compared to lexical word-initially (e.g., {ʔe.('ha:)} 'four') or within a prosodic word (e.g., {('la.ʔa)} 'sacred'), and that neither word-initial position nor the stress of the syllable (primary stress, secondary stress, unstressed) containing glottal stop in the onset had any effect on how glottal stop was realized. Following other research demonstrating phonological and phonetic markers of word-internal metrical structure (Bennett 2013, 2018; Shaw 2007; Sugahara and Turk 2009; Vaysman 2009), Davidson and Parker Jones (2023) hypothesized that the increased rate of full closure in lexical word-medial, prosodic word-initial position may be a useful cue in Hawaiian for disambiguating potentially ambiguous prosodic word structure, as in [ˌho:.ʔo.'a.ka], that is not

1 The following abbreviations are used in examples: 1SG first person singular pronoun; CONJ conjunction; LOC locative; OBJ object marker; POSS possessive.

resolved by the stress pattern of the word. Since full closures are rare for phonemic glottal stops, and are more likely to occur word-medially, it may be that it would not cause perceptual confusion if inserted (non-phonemic) word-initial closures occur at higher prosodic boundaries and/or before initial stressed syllables, which would also be consistent with accounts of non-phonemic glottalization in other languages.

2 Methods

2.1 Participants

The spontaneous speech data in this study come from 19 bilingual speakers of Hawaiian and English who appeared on a radio show called *Ka Leo Hawai'i* in the 1970s, recorded in the studios of KCCN radio (Kimura 2020). The recordings have subsequently been digitized to mp3s and made available on the internet. The speakers were *mānaleo*, or native speakers of Hawaiian, who were interviewed by Dr. Larry Kimura (https://ulukau.org/kaniaina/?a=p&p=history). While many speakers were elderly at the time of recording, an effort was made to choose those talkers who did not speak with obvious aging-related non-modal phonation (Gorham-Rowan and Laures-Gore 2006; Xue and Deliyski 2001). The interview topics ranged from place of birth to families, education, occupations, hobbies, Hawaiian customs such as feasts or making leis, and music. The interviews ranged in length from 5 to 16 min, with most of them being a little over 10 min in length.

2.2 Materials

The focus of this study is on the non-phonemic glottalization that occurs between lexical items. Periods of glottalization occurring between two words were identified auditorily and visually by inspecting the spectrogram to determine where a transition from modal voicing to creaky voicing or a glottal stop closure occurred. The visual criteria were based on descriptions of glottalization events in papers such as Keating et al. (2015), Redi and Shattuck-Hufnagel (2001), Avelino et al. (2011), Gerfen and Baker (2005), Davidson and Erker (2014), Malisz et al. (2013), and others. Typically, creaky voice is characterized by a low and irregular fundamental frequency, and damping of the glottal pulses. For closures, the maximum duration marked as glottal insertion and not as a pause was 220 ms, provided there were no other cues to a potential pause (e.g., audible lengthening of the preceding word, F0 declination). Examples of glottalization as both creaky voice and full closure are shown in Figure 1. Non-phonemic glottalization occurring as creaky voice could be found either between two modal portions of the surrounding sound, or completely overlapping with the first or second vowel. Glottalization on vowel-initial words at the beginning of the utterance or in post-pausal position were not included in this study.

In addition to labeling the type of glottalization event, each instance was coded for the stress on the first syllable of the following word (primary stress, secondary stress, no stress), whether the surrounding vowels are identical or different, and whether the following syllable is only one short monophthong or if it contained only longer vowels or more segments. Identical or different surrounding vowels are examined because Davidson (2021a) found that phonemic glottal stops are produced with longer periods of creaky voice when they are surrounded by identical vowels, possibly because it is more important to have longer periods of modal voicing for flanking sounds when they are different in order to ensure accurate perception of those vowels. In the non-phonemic context, it is possible that glottalization is more likely between identical vowels, to ensure that adjacent vowels are not merged. For similar reasons, we also included the factor of the following sounds – a single monophthong versus all other following elements (including a single long vowel or monophthong, or a word consisting of two or more segments) – to distinguish the single-vowel grammatical markers in (3) from longer words. Since these markers are phonetically short and unstressed, but critical for determining the grammatical structure of a sentence, it is possible that speakers could use glottalization to ensure that these vowels are not coalesced into the final vowel of the preceding word.

The duration of the glottalization interval was also measured. While an interval was labeled as a full closure when it had at least 20 ms between glottal pulses, the duration of a glottalization event with full closure also

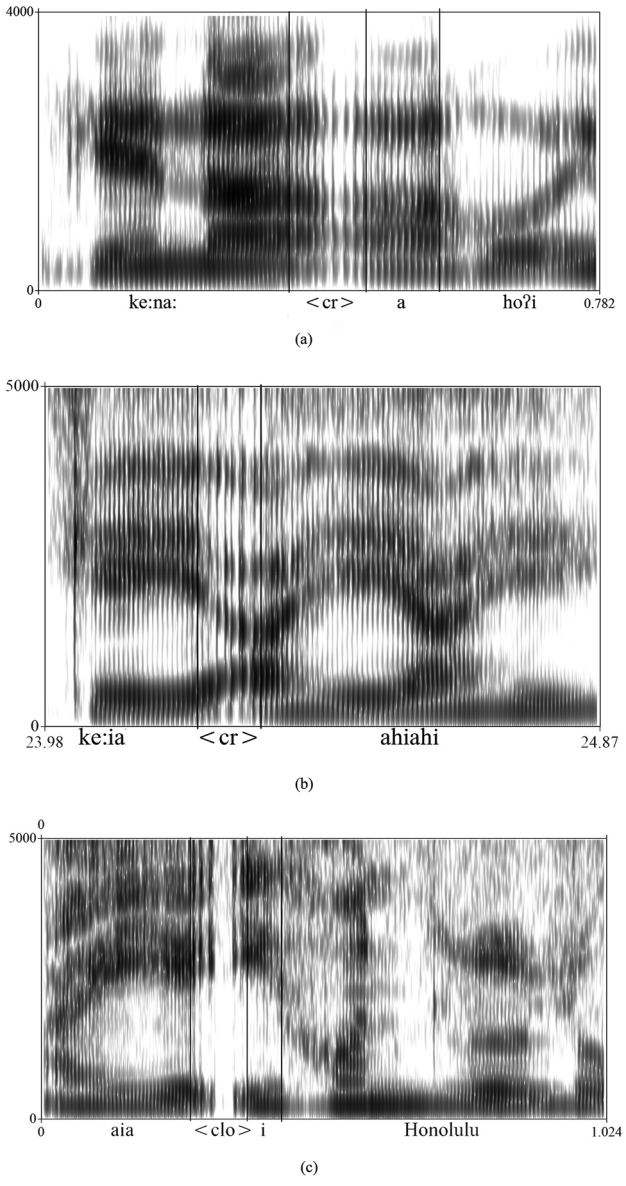

Figure 1: Creaky voice (marked with <cr>) and full closure (marked with <clo>) realizations of inserted glottalization between words or words and grammatical markers, which are indicated by vertical lines. (a) Creaky voice in [ke:na:#a] 'that CONJ', (b) creaky voice in [ke:ia#ahiahi] 'this evening', (c) full closure (plus flanking creaky voice) in [aia#i] 'there LOC'.

included any flanking creaky voice that was present (as illustrated in Figure 1c). One possibility is that if non-phonemic glottalization marks prominence, then glottalization events should be longer before stressed syllables. However, if glottalization events are more likely to ensure the recoverability of weak or confusable elements, then they may be longer between identical sounds or before a single-vowel marker.

3 Results

3.1 Distribution of non-phonemic glottalization

First, we present the descriptive outcome of where glottalization occurs in Hawaiian. There is a total of 536 instances of non-phonemic glottalization in the corpus. Their distribution according to the factors of interest breaks down as shown in Table 2.

Table 2: Distribution of the 536 instances of glottalization in terms of stress of the following syllable, flanking vowels, and number and type of following segments.

	Percentage	No. of tokens
Stress		
Primary stress	23 %	124
Secondary stress	6 %	30
No stress	71 %	382
Flanking sounds		
Identical flanking vowels	27 %	144
Different flanking vowels	73 %	392
Following segment		
Single short vowel following	57 %	307
More than a single short vowel following (i.e., a diphthong, a long vowel, or more than one segment)	43 %	229

These results indicate that glottalization events are most likely to occur before an unstressed syllable, rather than before a prominent syllable as has been found in previous work for other languages.

With respect to the flanking sounds, it is not the case that glottalization is more likely, or even equally likely, to occur when the flanking sounds are identical. We further examined what proportion of vowel#vowel sequences across word boundaries (including single-vowel grammatical markers) in the entire interview corpus is comprised of either identical or different vowels, finding that 22 % of all such combinations are identical. Taken together, this suggests that glottalization does not seem to be overrepresented between identical vowels.

The distribution of glottalization with respect to the following segment indicates that glottalization is more likely when there is only a single following short monophthong. This outcome also strongly contributes to the prevalence of glottalization before unstressed vowels. To contextualize this finding, we examined our corpus of radio transcripts to determine how often any word was followed by a single-vowel marker versus the total number of such sequences in the corpus. A word was defined as consisting of at least a long vowel or diphthong (e.g., [au] 1SG) or two or more segments (e.g., [pa:] 'fence'). In the transcripts, there were 4,058 combinations of a word plus one of [a e i o], indicating that 7.6 % of these combinations (307 of 4,058) included non-phonemic glottalization. While this is not a high proportion, it is notable that the majority of the instances of non-phonemic glottalization occurred in this environment. We also examined what proportion of word#word combinations in the overall corpus consists of a word followed by a single short monophthong, finding that they only comprise 8.18 % of all combinations. This small proportion contrasts with the finding that 57 % of the non-phonemic glottalization occurs in this environment, underscoring that glottalization occurs before grammatical marker at higher rates than would be expected from the distribution of all word#word sequences alone.

3.2 Realization as creaky voice or as full closure

The next analysis addresses whether stress, flanking sounds, and number of following segments affect whether the glottalization is realized as a full closure or as creaky voice. This was examined with a logistic regression using the packages lme4 and lmerTest in R (Bates et al. 2018; Kuznetsova et al. 2017), with "creaky voice" and "full closure" as the outcome variable, including following segments (one short monophthong, long/more than one sound), stress (primary, secondary, no stress), and flanking sounds (identical, different) as the predictors and interactions between following segment and flanking sounds and between stress and flanking sounds. No interaction between stress and following sound is included since the level of "one short monophthong" was coded as no stress for all instances. The predictors were sum-coded and speaker was included as a random intercept.

Table 3: Logistic regression for creaky voice versus full closure realization of non-phonemic glottalization.

	Estimate	*z* Value	Pr(>|*z*|)
(Intercept)	−0.609	−2.590	0.010
FollowSegs(more)	−0.019	−0.100	0.920
Stress(no stress)	−0.417	−1.524	0.128
Stress(secondary)	0.156	0.514	0.607
FlankingV(different)	−0.352	−1.955	0.05[a]
FollowSegs(more):FlankingV(diff)	0.070	0.376	0.707
Stress(no stress):FlankingV(diff)	0.265	0.973	0.330
Stress(secondary):FlankingV(diff)	−0.398	−1.314	0.189

[a]$p < 0.05$.

Results for the realization as creaky voice or full closure are shown in Table 3. The only (nearly) significant result is for flanking sounds, which indicates that realization as a full closure is more likely between identical flanking sounds (full closure for identical: 36.1 %; full closure for different: 28.3 %).

While the predictors for stress and number of following segments are not significant, they are nevertheless plotted in Figure 2 to illustrate the relative rates of creaky voice versus full closure realization of non-phonemic glottalization in Hawaiian with respect to stress and number of following segments. The creaky voice realization is more common for all types of syllables.

Since all of the cases with a single following monophthong are also unstressed, a subset of the data was created for the cases with multiple following segments only in order to more thoroughly examine the potential effect of stress on the realization of glottalization. A similar logistic regression was carried out on this subset of the data. This analysis included stress and flanking sounds, including the interaction of those predictors. The results, shown in Table 4, reveal that there are no significant differences for stress or flanking sounds in this subset only.

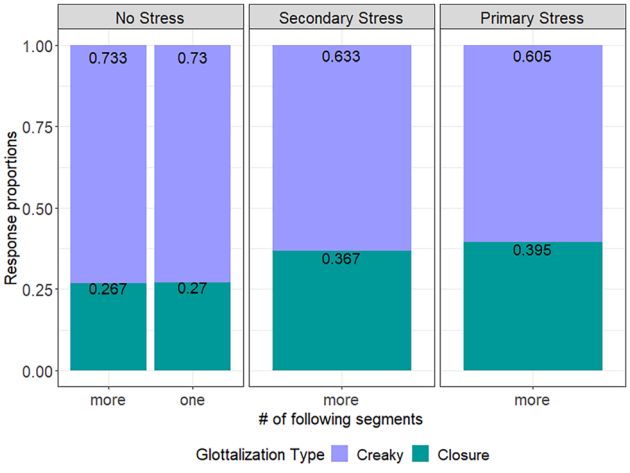

Figure 2: Proportion of creaky and full closure responses by stress and number/type of following segments (where "more" indicates long/more than one short sound).

Table 4: Logistic regression for creaky voice versus full closure realization of non-phonemic glottalization for the subset of the data with multiple following segments.

	Estimate	*z* Value	Pr(>|*z*|)
(Intercept)	−0.66	−3.10	0.002
Stress(no stress)	−0.38	−1.41	0.16
Stress(secondary)	0.09	0.29	0.77
FlankingV(different)	−0.20	−1.05	0.29
Stress(no stress):FlankingV(diff)	0.21	0.77	0.44
Stress(secondary):FlankingV(diff)	−0.31	−1.05	0.29

3.3 Duration of glottalization event

The final analysis examines whether duration of the glottalization event is affected by stress, flanking sounds, or following segments, and type of glottalization (creaky voice or full closure). This was examined with a linear regression with duration (in seconds) as the outcome variable. In addition to the main effects, interactions between glottalization type and each of following segments, stress, and flanking sounds were also included. The predictors were sum-coded and speaker was included as a random intercept.

Results for duration of the non-phonemic glottalization event are shown in Table 5. There is a significant effect of the following segments, showing that glottalization (collapsed over type) is longer before one short monophthong than before longer/multiple segments (short monophthong: 97 ms, longer/multiple segments: 91 ms). There is also a significant interaction between glottalization type and secondary stress, which occurs because full closures are shorter before secondarily stressed syllables as compared to creaky voice, which is the opposite pattern than what is found for no stress or primarily stressed syllables. This is illustrated in Figure 3. This outcome is not expected, but it should be noted that secondarily stressed syllables were a substantially smaller group compared to primary and unstressed syllables (as reported in Table 2), so it is unclear if this result is reliable, and if it would hold up with more data in this category.

4 Discussion

Previous examinations of inserted non-phonemic glottalization have typically found that it occurs to mark higher prosodic boundaries or prominent elements such as stressed syllables. However, almost all of the languages

Table 5: Linear regression for the duration of non-phonemic glottalization.

	Estimate	*t* Value	Pr(>|*t*|)
(Intercept)	0.096	27.77	<2e-16
GlotType(creaky)	0.001	0.39	0.69
FollowSegs(more)	−0.006	−2.35	0.02[a]
Stress(no stress)	−0.002	−0.49	0.63
Stress(secondary)	−0.003	−0.60	0.55
FlankingV(different)	−0.003	−1.82	0.07
GlotType(creaky):FollowSegs(more)	0.003	0.99	0.32
GlotType(creaky):Stress(no stress)	−0.003	−0.83	0.41
GlotType(creaky):Stress(secondary)	0.010	2.11	0.04[a]
GlotType(creaky):FlankingV(different)	−0.001	−0.54	0.59

[a]$p < 0.05$.

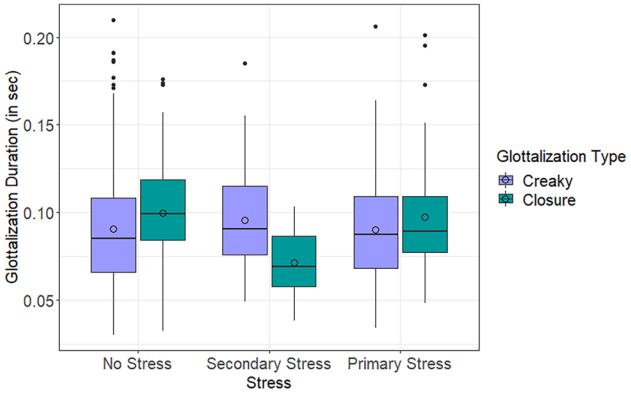

Figure 3: Duration of non-phonemic glottalization types (creaky voice, full closure) divided by stress. The lines indicate the median and the circles are the mean.

where this has been examined do not have a phonemic glottal stop (Dilley et al. 1996; Fougeron 2001; Kohler 1994; Malisz et al. 2013; Pierrehumbert 1995; Trawick and Michnowicz 2019). In Hawaiian, which has phonemic glottal stop, there is little evidence in these results that non-phonemic glottalization is used to mark prosodic prominence. With respect to syllable stress, 71 % of the instances of glottalization in our corpus occur before syllables with no stress, with the preponderance of those being single-vowel grammatical markers. Similarly, there is no effect of stress on the realization of glottalization as creaky voice versus full closure, though a prominence-based account might predict that there should be more full closures before stressed syllables. Finally, the duration of glottalization is generally not affected by the stress of the following syllable (with the sole result of shorter duration for full closure before secondarily stressed syllables likely being an unreliable effect due to a small sample size). It is also notable to observe that although these speakers are bilingual speakers of a variety of American English, they do not seem to be transferring the typical prosodic functions for glottalization from English into Hawaiian (though we have not analyzed comparable recordings of these speakers in English, so it is possible that they also do not use glottalization for prosodic strengthening in their variety of English either).

In contrast, the results indicate that glottalization occurs in Hawaiian in places where the recoverability of a sound could be threatened. The majority (57 %) of the glottalization cases occur before a single-vowel grammatical marker, of which there are only four in the language. Though the overall rates of non-phonemic glottalization use in this environment are relatively low, a possible interpretation is that glottalization is used to "protect" these phonetically weak morphemes that presumably have a high functional load in the language (for other work discussing how functional load can affect phonetic realization, see, e.g., Hall et al. 2018; Maspong and Burroni 2020; Nadeu and Renwick 2016; Saito et al. 2020; Tomaschek et al. 2021). Yet, this does not rule out a role for higher prosodic factors; while a full intonational analysis of Hawaiian has not yet been developed, it is likely that factors such as sentence-level prosody or other aspects of sentence structure interact with the lexical word + single-vowel grammatical marker cases to determine when the insertion of non-phonemic glottalization is most likely to be necessary.[2]

The longer duration of glottalization before the single vowel is potentially available to listeners as an alert that a single-vowel morpheme is upcoming, though the difference is small and may not be reliably perceptible. Similarly, the result indicating that full closures are more likely between identical flanking vowels can also be interpreted with respect to recoverability as an important factor more generally, since a full closure may be more likely even than creaky voice to ensure that the listener perceives both vowels independently (though this effect too may be conditioned by sentential prosody, since overall rates of glottalization events are not higher between identical vowels; see Table 2). The possibility that Hawaiian non-phonemic glottalization is deployed to maximize recoverability is compatible with the broader literature showing that recoverability considerations affect phonetic implementation in many different kinds of phenomena, including consonant clusters in Georgian, high vowel deletion in Japanese, and the timing of non-modal phonation and tone within a vowel in languages like Chinantec or Zapotec, among others (e.g., Avelino 2010; Chitoran et al. 2002; Elías-Ulloa 2016; Silverman 1997; Whang 2018).

The lack of sensitivity to syllabic stress in the non-phonemic cases is similar to the findings for phonemic glottal stop realization in Hawaiian (Davidson and Parker Jones 2023). In a subset of the same data used for this study, the realization of phonemic glottal stops was not sensitive to the stress of the following syllable. Instead, glottal stops were more likely to be full closures at the beginning of a prosodic word that was also word-medial. We argued that because certain syllabic combinations may have more than one possible prosodic word parse, an

2 A reviewer pointed out that 43 % of the instances of non-phonemic glottalization do not occur before a single-vowel grammatical marker, raising the question of whether there are any generalizations about the remainder of the data. Characterizing the parts of speech in Hawaiian is not a straightforward task, since many surface forms can be used as a verb, noun, or adjective, and are not always easily classified by adjacent material. There are currently not syntactic analyses of many Hawaiian phrase types that could be used as a guideline. However, further examination of the collocations containing non-phonemic glottalization indicates that another 14 % of the cases consist of a straightforward combination: a definite article or determiner + noun (e.g., *ke alanui* 'the street', *kēia ahiahi* 'this evening'), or a possessive + noun (e.g., *kona inoa* 'his/her name'). While the dearth of syntactic analyses makes it difficult to definitively characterize all of the data, it does not appear that any other combinations account for more than 4 % of the cases. It is possible that the article/determiner/possessive cases could also point to a role for broader intonation information, such as contrastive focus. This is an area for future research.

acoustic cue like the realization of glottal stop could be available to help disambiguate between possible parses. Relatedly, phonemic glottal stops are also not more likely to have full closures in word-initial position as compared to word-medial position. While it has been argued that the correlation between stronger articulations such as a full closure (or a fully voiceless [h], to give another laryngeal example) and prosodic strengthening has physiological origins such as lower subglottal pressure (Garellek et al. 2021), the Hawaiian case suggests that such effects are not inevitable. The lack of the more commonly found prosodic and prominence effects on the use and realization of both phonemic glottal stop and non-phonemic glottalization indicate that instead, the implementation of glottalization in Hawaiian in both cases may be recruited for assisting with recoverability of weaker or ambiguous elements such as prosodic word assignment or critical grammatical morphemes.

Considering that Hawaiian does have both phonemic and non-phonemic glottalization, one limitation of this study is that acoustic factors that might distinguish the types are as yet unknown. We were unable to carry out an acoustic analysis of spectral tilt or noise cues in the current data, both because the recording quality is not equally high across all of the files and because they are only available as compressed MP3 files, which can have an adverse effect on such measurements (Peña et al. 2021b). However, other research has shown that at least for English, when multiple independent sources of glottalization are present in an utterance, the glottalization types are produced distinctly. For example, English has both phrase-final creak and glottalization of /t/ in coda position, and Garellek and Seyfarth (2016) showed that phrase-final creak has lower F0, lower spectral tilt, and is noisier than /t/ glottalization from the start. In contrast, /t/ glottalization increases in noise over time. Peña et al. (2021a) also found that phrasal creak in American English differs from coda /t/ glottalization, the [ʔ] before syllabic nasals in American English (e.g., *ea[ʔ]en*), and inserted glottalization before vowel-initial words with lower F0 and H1*–H2*, and higher noise. The open question of whether Hawaiian also employs different acoustic properties to distinguish between phonemic and non-phonemic uses of glottalization could be addressed with a different set of Hawaiian data.

5 Conclusion

In Hawaiian, which contains both a phonemic glottal stop and non-phonemic glottalization, glottalization does not appear to coincide with prosodic prominence. Rather, we argued that recoverability considerations better explain where non-phonemic glottalization is most likely, such as between a content word and a single-vowel grammatical marker (e.g., [hale˷o] ‘house POSS’). In contrast, glottalization is not more likely before a following stressed syllable, nor does stress factor into either the realization of glottalization as either a period of creaky voice or full closure, or the duration of the period of glottalization. This distribution of glottalization in Hawaiian suggests that a physiological basis for laryngealization as a marker of prosodic strengthening does not require that it be recruited for that purpose. Since previous work examining the distribution of non-phonemic glottalization typically has been carried out on languages that do not also have a phonemic glottal stop, more extensive analyses of languages with a glottal stop phoneme would contribute to a better understanding of how glottalization is implemented (and, ultimately, perceived) when it is potentially used for phonemic, allophonic, prosodic, or other purposes within the same language.

Acknowledgments: We would like to thank audience members at LabPhon 2022, CUNY Graduate Center, UMass, and McMaster University, and members of the NYU PEP Lab for their feedback on this work. We are especially indebted to Professor Larry Kimura and the invaluable ʻōlelo Hawaiʻi speakers who appeared on the *Ka Leo Hawaiʻi* radio program and are reflected in this work.

References

Aare, Kätlin, Pärtel Lippus & Juraj Šimko. 2017. Creak as a feature of lexical stress in Estonian. *Proceedings of Interspeech 2017*, 1029–1033. Stockholm, Sweden.

Avelino, Heriberto. 2010. Acoustic and electroglottographic analyses of nonpathological, nonmodal phonation. *Journal of Voice* 24. 270–280.

Avelino, Heriberto, Eurie Shin & Sam Tilsen. 2011. The phonetics of laryngealization in Yucatec Maya. In Heriberto Avelino (ed.), *New perspectives in Mayan linguistics*, 1–20. Cambridge: Cambridge Scholars.

Bates, Douglas, Martin Maechler, Ben Bolker, Steven Walker, Rune Christensen, Henrik Singmann, Bin Dai, Fabian Schiepl, Gabor Grothendieck, Peter Green & John Fox. 2018. lme4: Linear mixed-effects models using Eigen and S4, version 1.1-19 [R package]. Available at: https://cran.r-project.org/web/packages/lme4/index.html.

Bennett, Ryan. 2013. The uniqueness of metrical structure: Rhythmic phonotactics in Huariapano. *Phonology* 30(3). 355–398.

Bennett, Ryan. 2018. Recursive prosodic words in Kaqchikel (Mayan). *Glossa* 3(1). 67.

Chappell, Whitney. 2013. Linguistic factors conditioning glottal constriction in Nicaraguan Spanish. *Italian Journal of Linguistics* 27. 1–42.

Chitoran, Ioana, Louis Goldstein & Dani Byrd. 2002. Gestural overlap and recoverability: Articulatory evidence from Georgian. In Natasha Warner & Carlos Gusshoven (eds.), *Papers in laboratory phonology VII*, 419–448. Berlin: Mouton de Gruyter.

Davidson, Lisa. 2021a. Effects of word position and flanking vowel on the implementation of glottal stop: Evidence from Hawaiian. *Journal of Phonetics* 88. 101075.

Davidson, Lisa. 2021b. The versatility of creaky phonation: Segmental, prosodic, and sociolinguistic uses in the world's languages. *WIREs Cognitive Science* 12(3). e1547.

Davidson, Lisa & Daniel Erker. 2014. Hiatus resolution in American English: The case against glide insertion. *Language* 90(2). 482–514.

Davidson, Lisa & Oiwi Parker Jones. 2023. Word-level prosodic and metrical influences on Hawaiian glottal stop realization. *Phonetica* 80. 225–258.

de Lacy, Paul. 2004. Maximal words and the Maori passive. In John McCarthy (ed.), *Optimality theory in phonology: A reader*, 495–512. Malden, MA: Blackwell.

Dilley, Laura, Stefanie Shattuck-Hufnagel & Mari Ostendorf. 1996. Glottalization of word-initial vowels as a function of prosodic structure. *Journal of Phonetics* 24. 423–444.

Elbert, Samuel & Mary Kawena Pukui. 1979. *Hawaiian grammar*. Honolulu: University of Hawai'i Press.

Elías-Ulloa, José. 2016. The role of prominent prosodic positions in governing laryngealization in vowels: A case study of two Panoan languages. In Heriberto Avelino, Matt Coler & Leo Wetzels (eds.), *The phonetics and phonology of laryngeal features in Native American languages*, 180–202. Leiden: Brill.

Fougeron, Cécile. 2001. Articulatory properties of initial segments in several prosodic constituents in French. *Journal of Phonetics* 29(2). 109–135.

Garellek, Marc. 2014. Voice quality strengthening and glottalization. *Journal of Phonetics* 45. 106–113.

Garellek, Marc, Yuan Chai, Yaqian Huang & Maxine Van Doren. 2021. Voicing of glottal consonants and non-modal vowels. *Journal of the International Phonetic Association* 53(2). 305–332.

Garellek, Marc & Scott Seyfarth. 2016. Acoustic differences between English /t/ glottalization and phrasal creak. *Proceedings of interspeech 2016*, 1054–1058. San Francisco.

Gerfen, Chip & Kirk Baker. 2005. The production and perception of laryngealized vowels in Coatzospan Mixtec. *Journal of Phonetics* 33(3). 311–334.

González, Carolina, Christine Weissglass & Daniel Bates. 2022. Creaky voice and prosodic boundaries in Spanish: An acoustic study. *Studies in Hispanic and Lusophone Linguistics* 15(1). 33–65.

Gorham-Rowan, Mary M. & Jacqueline Laures-Gore. 2006. Acoustic-perceptual correlates of voice quality in elderly men and women. *Journal of Communication Disorders* 39(3). 171–184.

Hall, Kathleen Currie, Elizabeth Hume, T. Florian Jaeger & Andrew Wedel. 2018. The role of predictability in shaping phonological patterns. *Linguistics Vanguard* 4(s2). https://doi.org/10.1515/lingvan-2017-0027.

Henton, Caroline & Anthony Bladon. 1988. Creak as a sociophonetic marker. In Larry Hyman & C. Li (eds.), *Language, speech and mind: Studies in honor of Victoria A. Fromkin*, 3–29. London: Routledge.

Kamanā, Kauanoe & William Wilson. 2012. *Nā Kai 'Ewalu*. Hilo, HI: Hale Kuamo'o Hawaiian Language Center.

Keating, Patricia, Marc Garellek & Jody Kreiman. 2015. Acoustic properties of different kinds of creaky voice. In The Scottish Consortium for ICPhS 2015 (ed.), *Proceedings of the 18th international congress of phonetic sciences*. Glasgow. https://www.internationalphoneticassociation.org/icphs-proceedings/ICPhS2015/Papers/ICPHS0821.pdf (accessed 14 May 2024).

Kettig, Thomas. 2021. *Ha'ina 'ia mai ana ka puana: The vowels of 'ōlelo Hawai'i*. Honolulu: University of Hawai'i at Mānoa PhD dissertation.

Kimura, Larry (Producer). 2020. *Ka Leo Hawai'i* [radio program]. Kani'āina, the digital repository of Ka Haka 'Ula O Ke'elikōlani, College of Hawaiian Language, University of Hawai'i at Hilo. Available at: https://ulukau.org/kaniaina/.

Kohler, Klaus J. 1994. Glottal stops and glottalization in German. *Phonetica* 51. 38–51.

Kreiman, Jody. 1982. Perception of sentence and paragraph boundaries in natural conversation. *Journal of Phonetics* 10. 163–175.

Kuznetsova, Alexandra, Per Bruun Brockhoff & Rune Christensen. 2017. lmerTest package: Tests in linear mixed effects models. *Journal of Statistical Software* 82(13). 1–26.

Ladefoged, Peter. 2001. *Vowels and consonants*. Oxford: Blackwell.

Lee, Sinae. 2015. Creaky voice as a phonational device marking parenthetical segments in talk. *Journal of Sociolinguistics* 19(3). 275–302.

Malisz, Zofia, Marzena Żygis & Bernd Pompino-Marschall. 2013. Rhythmic structure effects on glottalisation: A study of different speech styles in Polish and German. *Laboratory Phonology* 4(1). 119–158.

Markó, Alexandra. 2012. Boundary marking in Hungarian V(#)V clusters with special regard to the role of irregular phonation. *The Phonetician* 105–106. 7–26.

Maspong, Sireemas & Francesco Burroni. 2020. Functional load modulates speech production, but not speech perception: Evidence from Thai vowel length. In Mark Tiede, Douglas Whalen & Vincent Gracco (eds.), *Proceedings of the 12th international seminar on speech production*. Providence, RI. https://www.researchgate.net/publication/353368027_Functional_Load_modulates_speech_production_but_not_speech_perception_Evidence_from_Thai_vowel_length (accessed 15 May 2024).

Michnowicz, Jim & Laura Kagan. 2016. On glottal stops in Yucatan Spanish. In Sandro Sessarego & Fernando Tejedo-Herrero (eds.), *Spanish language and sociolinguistic analysis*, 219–239. Amsterdam: John Benjamins.

Mitterer, Holger, Sahyang Kim & Taehong Cho. 2019. The glottal stop between segmental and suprasegmental processing: The case of Maltese. *Journal of Memory and Language* 108. 104034.

Mohamed, Sherez, Carolina González & Antje Muntendam. 2019. Arabic–Spanish language contact in Puerto Rico: A case of glottal stop epenthesis. *Languages* 4(4). 93.

Nadeu, Marianna & Margaret E. L. Renwick. 2016. Variation in the lexical distribution and implementation of phonetically similar phonemes in Catalan. *Journal of Phonetics* 58. 22–47.

Parker Jones, Oiwi. 2010. *A computational phonology and morphology of Hawaiian*. Oxford, UK: University of Oxford DPhil. thesis.

Parker Jones, Oiwi. 2018. Hawaiian. *Journal of the International Phonetic Association* 48(1). 103–115.

Peña, Jailyn, Lisa Davidson & Shmico Orosco. 2021a. The independence of phrasal creak and segmental glottalization in American English. *Journal of the Acoustical Society of America Express Letters* 1(7). 075205.

Peña, Jailyn, Alicia Mason & Lisa Davidson. 2021b. The effects of audio compression on voice quality measurements. *Journal of the Acoustical Society of America* 150(4). A356.

Pierrehumbert, Janet. 1995. Prosodic effects on glottal allophones. In Osamu Fujimura & M. Hirano (eds.), *Vocal fold physiology: Voice quality control*, 39–60. San Diego: Singular Publishing Group.

Pierrehumbert, Janet & David Talkin. 1992. Lenition of /h/ and glottal stop. In Gerard Docherty & D. Robert Ladd (eds.), *Papers in laboratory phonology II: Gesture, segment, prosody*, 90–116. Cambridge: Cambridge University Press.

Pompino-Marschall, Bernd & Marzena Żygis. 2011. Glottal marking of vowel-initial words in German. In Wai-Sum Lee & Eric Zee (eds.), *Proceedings of the 17th international congress of phonetic sciences*, 1626–1629. Hong Kong. https://www.internationalphoneticassociation.org/icphs/icphs2011 (accessed 8 May 2024).

Pukui, Mary Kawena & Samuel Elbert. 1986. *Hawaiian dictionary: Hawaiian–English, English–Hawaiian*. Honolulu: University of Hawai'i Press.

Redi, Laura & Stefanie Shattuck-Hufnagel. 2001. Variation in the realization of glottalization in normal speakers. *Journal of Phonetics* 29(4). 407–429.

Saito, Motoki, Fabian Tomaschek & R. Harald Baayen. 2020. Relative functional load determines co-articulatory movements of the tongue tip. In Mark Tiede, Douglas Whalen & Vincent Gracco (eds.), *Proceedings of the 12th international seminar on speech production*. Providence, RI. https://api.semanticscholar.org/CorpusID:252043257 (accessed 15 May 2024).

Schütz, Albert. 1978. Accent in two Oceanic languages. *Anthropological Linguistics* 20(4). 141–149.

Schütz, Albert. 1981. A reanalysis of the Hawaiian vowel system. *Oceanic Linguistics* 20(1). 1–43.

Schütz, Albert. 2010. Measures and morphemes: A functional approach to Hawaiian accent. In John Bowden, Nikolaus P. Himmelmann & Malcolm Ross (eds.), *A journey through Austronesian and Papuan linguistic and cultural space: Papers in honor of Andrew Pawley*, 405–422. Canberra: Pacific Linguistics.

Schwartz, Geoffrey. 2013. Vowel hiatus at Polish word boundaries – Phonetic realization and phonological implications. *Poznan Studies in Contemporary Linguistics* 49(4). 557–585.

Senturia, Martha. 1998. *A Prosodic theory of hiatus resolution*. San Diego: University of California San Diego PhD dissertation.

Shaw, Jason. 2007. /ti/~/tʃi/ contrast preservation in Japanese loans parasitic on segmental cues to prosodic structure. In Jürgen Trouvain & William Barry (eds.), *Proceedings of the 16th international congress of phonetic sciences*, 1365–1368. Saabrücken: Universität des Saarlandes.

Silverman, Daniel. 1997. *Phasing and recoverability*. New York: Garland Press.

Slifka, Janet. 2006. Some physiological correlates to regular and irregular phonation at the end of an utterance. *Journal of Voice* 20(2). 171–186.

Sugahara, Mariko & Alice Turk. 2009. Durational correlates of English sublexical constituent structure. *Phonology* 26. 477–524.

Szczepek Reed, Beatrice. 2014. Phonetic practices for action formation: Glottalization versus linking of TCU-initial vowels in German. *Journal of Pragmatics* 62. 13–29.

Tomaschek, Fabian, Ingo Plag, Mirjam Ernestus & R. Harald Baayen. 2021. Phonetic effects of morphology and context: Modeling the duration of word-final S in English with naïve discriminative learning. *Journal of Linguistics* 57(1). 123–161.

Trawick, Sonya & Jim Michnowicz. 2019. Glottal insertion before vowel-initial words in the Spanish of Asunción, Paraguay. In Gregory Thomson & Scott Alvord (eds.), *Contact, community and connections: Current approaches to Spanish in multilingual populations*, 147–171. Wilmington, DE: Vernon Press.

Vaysman, Olga. 2009. *Segmental alternations and metrical theory*. Cambridge, MA: MIT PhD dissertation.

Whang, James. 2018. Recoverability-driven coarticulation: Acoustic evidence from Japanese high vowel devoicing. *Journal of the Acoustical Society of America* 143(2). 1159–1172.

Xue, Steve An & Dimitar Deliyski. 2001. Effects of aging on selected acoustic voice parameters: Preliminary normative data and educational implications. *Educational Gerontology* 27(2). 159–168.