DE GRUYTER Phonetica 2023; 80(3–4): 225–258

Research Article

Lisa Davidson* and Oiwi Parker Jones

Word-level prosodic and metrical influences on Hawaiian glottal stop realization

https://doi.org/10.1515/phon-2022-0031
Received September 14, 2022; accepted May 16, 2023; published online June 15, 2023

Abstract: Previous research on the phonetic realization of Hawaiian glottal stops has shown that it can be produced several ways, including with creaky voice, full closure, or modal voice. This study investigates whether the realization is conditioned by word-level prosodic or metrical factors, which would be consistent with research demonstrating that segmental distribution and phonetic realization can be sensitive to word-internal structure. At the same time, it has also been shown that prosodic prominence, such as syllable stress, can affect phonetic realization. Data come from the 1970s–80s radio program Ka Leo Hawaiʻi. Using Parker Jones' (Parker Jones, Oiwi. 2010. *A computational phonology and morphology of Hawaiian*. University of Oxford DPhil. thesis) computational prosodic grammar, words were parsed and glottal stops were automatically coded for word position, syllable stress, and prosodic word position. The frequency of the word containing the glottal stop was also calculated. Results show that full glottal closures are more likely at the beginning of a prosodic word, especially in word-medial position. Glottal stops with full closure in lexical word initial position are more likely in lower frequency words. The findings for Hawaiian glottal stop suggest that prosodic prominence does not condition a stronger realization, but rather, the role of the prosodic word is similar to other languages exhibiting phonetic cues to word-level prosodic structure.

Keywords: creaky phonation; glottal stops; Hawaiian; prosodic words

***Corresponding author: Lisa Davidson**, Department of Linguistics, New York University, 10 Washington Place, New York, NY 10003, USA, E-mail: lisa.davidson@nyu.edu
Oiwi Parker Jones, Department of Engineering Science, University of Oxford, Oxford, UK, E-mail: oiwi.parkerjones@eng.ox.ac.uk

1 Introduction

1.1 Word-level prosodic and metrical influences on the phonetic realization of consonants

Research on the effect of prosodic and metrical boundaries on the realization of consonantal phonetic detail has shown that elements ranging from word-internal boundaries, such as feet or prosodic words, to word edges, to phrase boundaries can influence acoustic and articulatory implementation (e.g., Bombien et al. 2010; Cho 2004; Cho and Keating 2001, 2009; Cole et al. 2007; Fougeron 2001; Fougeron and Keating 1997; Katz 2021; Pierrehumbert and Talkin 1992; Shaw 2007; Sugahara and Turk 2009). Similarly, prosodic prominence, such as syllabic stress or accentual prominence can also affect phonetic implementations of consonants (e.g., Avesani et al. 2007; Bombien et al. 2007; Cho 2006b; Cho and Keating 2009; de Jong 1995; Garellek 2014; Katsika and Tsai 2021; Turk and White 1999). In this paper, we focus on whether prosodic and metrical considerations at the level of the word affect the realization of the phonemic glottal stop in Hawaiian within connected speech. In particular, we focus on whether syllabic stress, prosodic word boundaries, or lexical item (word) boundaries influence the implementation of glottal stop. This study follows up on Davidson (2021), which demonstrated that Hawaiian glottal stops can be produced on a continuum from modal to creaky voicing to a full closure (Davidson 2021; see also Garellek et al. 2021: on the continuum of glottal articulation), but which did not examine whether word-level prosodic factors condition these possible realizations.

The motivation for examining the effect of word-level prosodic and metrical factors on consonant realization comes from research which has argued that in some languages, metrical structure can be signaled by either phonological processes or phonetic implementation. Starting with phonological processes, there is evidence that the foot and the prosodic word are critical domains for explaining the patterning of consonants. For example, it has been argued that the realization of /t/ as a flap in American English is foot-sensitive (e.g., Harris and Kaye 1990; Kiparsky 1979; Turk 1992). Harris (2004) contends that foot structure can account for the phonetic implementation of stops in Danish and Ibibio (see also Akinlabi and Urua 2002); Vaysman (2009) provides a more detailed analyses of Ibibio by arguing that intervocalic consonants cannot lenite if they are at the beginning of a word-internal prosodic word, but crucially, all of the Ibibio accounts attribute the pattern to word-medial metrical boundaries. In order to account for the epenthesis of coda /h/ in Huariapano, Bennett (2013) argues for a maximal foot structure that requires segmental augmentation of the first syllable, whether that syllable is stressed or not.

Similarly, Bennett (2018) maintains that the behavior of syllable-initial glottal stops in Kaqchikel is a diagnostic for positing unbounded, iterative recursion of the prosodic words. Vaysman (2009) presents the case of consonant gradation in Nganasan, demonstrating a process of obstruent lenition that occurs only when the consonants are foot-initial, including in word-medial feet, but lenition is otherwise blocked, and it does not correspond to stress placement. Hudu (2022) claims that debuccalization of /k, g, s/ to [ʔ] in Dagbani only occurs when these sounds are foot-medial, and not at the edge of a foot.

While many processes that are used as diagnostics to establish metrical structure in this disparate set of languages are generally considered segmental and are not strictly about the phonetic details of the consonant, it has also been suggested that word-level considerations and metrical structure can also affect how consonants are phonetically realized. For example, at the level of word edge versus word internal phonetic implementation, much of the recent literature on the phonetic properties of consonant lenition (especially in American English) argues that weakening of stops (whether to voiced, spirantized or approximant implementations) cannot be accounted for by a phonological process, but is rather a result of prosodically-controlled changes in gestural duration (e.g., Cohen Priva and Gleason 2020; Katz 2016, 2021; Parrell and Narayanan 2018). In one case where phonetic cues appear to be dependent on foot structure (as opposed to just being word-medial), Shaw (2007) demonstrates that fricative duration in Japanese [tʃ] in foot-initial position, whether word-initial or word-internal, is longer than when it is either foot-medial or extrametrical. Sugahara and Turk (2009) argue that durational lengthening evidence distinguishing Level I (i.e., derivational suffixes such as *-al*) and Level II (i.e., inflectional suffixes such as *-ing, -ed, -s*) suffixed words in Scottish English is consistent with analyses that posit different prosodic word structure for these two types of words.

Another word-level factor that has been shown to condition consonant implementation is syllable stress. In languages with aspirated stops such as English, Danish and Lakhota, voice onset time (VOT) has been shown to be longer in stops in the onset of stressed syllables than in unstressed ones (Cho 2006a; Lisker and Abramson 1967; Puggaard 2019; Sprinkle 2022: though not all studies show a significant effect, see Cho and Keating 2009). Cho and Keating (2009) do show that closure duration of both stops and nasal duration consonants in the onset of a stressed syllable in English are longer than for unstressed syllables. In Dutch, the burst duration of the fortis /t/ is longest in unstressed syllables and shortest in stressed syllables, which is interpreted as a fortition effect (Cho and McQueen 2005). A similar effect is found for unaspirated stops in Yakima Sahaptin (Hargus 2005). However, in many other languages with unaspirated stops, such as Spanish, Plains Cree, or Sierra Norte de Puebla Nahuatl, VOT is not affected by prosodic prominence (Hodgson 2021; Kakadelis 2018; Simonet et al. 2014). In some Australian languages, the tonic syllable has an effect on the duration of the following consonant. For example, in Warlpiri and Mawng, C_2 in a word with a shape like ˈC_1VC_2V has a longer duration than the pre-tonic consonant, or consonants that follow an unstressed syllable (Fletcher et al. 2015; Pentland 2004). In a different Australian language, Pitjantjatjara, there are differences in spectral center of gravity in stop bursts depending on whether they are in stressed or unstressed syllables, which is interpreted as an enhancement of the phonological feature [grave] in stressed position (Tabain and Butcher 2015).

In this study, we return to the question of whether word-level metrical and prosodic elements condition the phonetic realization of consonants, specifically with respect to phonemic glottal stops in Hawaiian. In the study of Hawaiian that is the precursor to the current study, Davidson (2021) found that the realization of phonemic glottal stops is conditioned by word position and by whether the flanking vowels are identical or different. In Hawaiian, glottal stops can occur either in intervocalic position within a word (e.g. [poʔe] ‘people’), or contrastively at the beginning of the word (e.g. [ʔaka] ‘laughter’ vs. [aka] ‘shadow’). Full closures were rare overall, accounting for only 7 % of the results. For tokens that are produced with creaky voice, the study distinguished between possible locations and extent of creaky voice: creak between two modal vowels, creak on V1, creak on V2, or creak over the whole vowel-vowel interval. Longer periods of creak, including whole creak and creak on V2, are less likely in word initial position, and whole creak occurs at greater rates when the flanking vowels are identical. Full closures were less likely between identical flanking vowels, but there was no effect of word position on the realization of full closures. However, Davidson (2021) did not include any further metrical or prosodic information beyond word position, such as syllable stress, prosodic word position, or vowel weight which may affect the realization of glottal stop.

Previous work on the factors affecting the realization of phonemic glottal stop is sparse, despite Ladefoged and Maddieson’s (1996: 75) famous quote: “In the great majority of languages we have heard, glottal stops are apt to fall short of complete closure, especially in intervocalic positions.” While DiCanio (2012) does not examine prosodic information in his study of Itunyoso Triqui, he does find a difference in implementation depending on whether the glottal stop is intervocalic within a word, or in coda position at the end of the word. Whereas the intervocalic glottalization is almost never produced as a full closure, the coda glottal stop is more likely to be produced as a full glottal closure. In Mayan languages, such as Uspanteko, the realization of glottal stop as full closure or a period of creaky voice in part depends on whether it is adjacent to a consonant or intervocalic (Bennett et al. 2022). After a consonant, it is frequently a full closure. A study of Cook Islands Māori finds that in conversational speech, the realization of glottal stop depends on dialect. In two of the five dialects that were examined, a period of creaky voice alternated with full closure fairly evenly, while two other dialects had larger rates of no closure or creakiness at all, and the last dialect had mostly full closures (Nicholas and Coto-Solano 2019).

One language in which the realization of glottal stop has been studied in some detail is Maltese. Mitterer (2018) finds that geminate glottal stops are produced as full closures about 80 % of the time, versus less than 20 % for singletons. While it has been assumed that geminates have prosodically greater weight than singletons, which may be predicted to have stronger articulations (i.e. full closures), Mitterer also finds that the influence of phonological quantity cannot be disentangled from the finding that geminate glottal stops also have a significantly longer duration. Mitterer et al. (2019) compares the realization of phonemic glottal stop to non-phonemic glottalization in word-initial (but phrase-medial) position in laboratory speech in Maltese, where the target word followed either a word ending in /a/ or in /m/. In this type of elicitation, phonemic glottal stops are realized as full closure nearly 80 % of the time after /m/, and 50 % after /a/. As for non-phonemic cases, about half are marked with glottalization, and full closures make up about 40 % of the responses after /m/ even for non-phonemic glottalization. Though there is not an explicit manipulation of boundary type in this study, 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.

Beyond the level of the word, previous research has shown that glottalization can be used non-phonemically to demarcate prosodic boundaries and indicate degree of strength. In English, word-initial glottalization occurs optionally for vowel initial words, and is more likely to be found when the vowel is stressed than when it is unstressed (Davidson and Erker 2014; Dilley et al. 1996; Pierrehumbert 1995; Pierrehumbert and Talkin 1992). Similar findings regarding the effect of stress have been reported for several varieties of Spanish (Chappell 2013; Michnowicz and Kagan 2016; Trawick and Michnowicz 2019), German (Kohler 1994; Malisz et al. 2013; Pompino-Marschall and Żygis 2011) and Polish (Malisz et al. 2013; Schwartz 2013). Malisz et al. (2013) also report specifically on how the glottal stop is realized, showing that full closures are more likely both in phrase-initial position than medial position, and before stressed vowels in both German and Polish. Using articulatory data, Garellek (2014) found that for sentences produced in a laboratory context, electroglottograph (EGG) contact quotient patterns for both English and Spanish speakers were more consistent with glottalization when a vowel at any prosodic boundary was stressed. In this case, the different degrees of prosodic boundary (utterance initial, IP-initial, ip-initial, and ip-medial) did not lead to significant differences in contact quotient rates.

Taken together, the studies of both phonemic glottal stops and non-phonemic glottalization reveal that in many languages, glottalization can be manipulated in service of indicating prosodic boundaries or prominence. Cross-linguistically, the rates of glottalization vary quite a bit by language, from rarely (e.g., Yucatecan Spanish) to almost obligatorily in some environments (e.g., Polish or German). Likewise, the specific implementation—whether full closure or glottalization—can also be affected by prosodic factors. Garellek et al. (2021) discuss realization of glottalization gestures as part of a phonatory continuum from most open glottis (aspirated or breathy) to most closed (creaky voice or full closure) (see also Gordon and Ladefoged 2001). They argue that while the representation of these gestures may be generally specified for aspiration (as in sounds with breathy voice quality) or glottalization, they are not necessarily specified for the magnitude of the gesture, which can then be determined by other pressures, such as those governing prosodic strengthening (e.g., Cho 2005; Cho and Keating 2001; Fougeron 2001; Fougeron and Keating 1997; Keating et al. 2003) or reduction/lenition (Cohen Priva and Gleason 2020; Gurevich 2011; Katz 2016, 2021; Lavoie 2001).

In the context of the current study of Hawaiian glottal stops, if full closure is considered the extreme of the glottalization end of the continuum, then one possibility is that full closure will be more likely when pressure from prosodic prominence is exerted, such as in the onset of a stressed syllable, or in word initial position, as compared to word medial and unstressed position. To date, the motivation for this possibility comes mainly from the insertion of non-phonemic glottalization, which may behave differently, though evidence from Maltese may also suggest that these types of effects are at play for phonemic glottal stops in that language (Mitterer 2023). However, another possibility is that realization of the phonemic glottal stop could instead reflect the word-internal metrical structure of Hawaiian words, as has been shown for languages like Kaqchikel, Nganasan, Ibibio, Dagbani, Japanese, or Scottish English. These two potential influences on phonetic realization are investigated in this study.

1.2 Glottal stops and metrical structure in Hawaiian

Ka ʻŌlelo Hawaiʻi, or Hawaiian, is an Eastern Polynesian language spoken today across the eight major Hawaiian Islands, located in the North Pacific Ocean. Hawaiian is currently in the midst of a successful language revitalization effort, following its near demise after the United States military and American businessmen overthrew the Hawaiian Kingdom in 1893 and the new government they imposed banned the use of Hawaiian in schools in 1896 (Wilson 2013). Before this, Hawaiian was the primary lingua franca of the Islands, used broadly in all domains including government, business, and education, as well as at home. After this point, Hawaiian language use began a precipitous decline, and eventually community and family language transfer diminished on most of the Hawaiian islands (Brenzinger and Heinrich 2013; Wilson 2013). Milestones in the revitalization of the Hawaiian language include: (1) the Hawaiian language radio show Ka Leo Hawai‘i (KLH) which ran from 1972 to 1988 and which featured interviews with elders who had learned the language via intergenerational transfer; (2) the establishment of the ‘Aha Pūnana Leo preschools in 1983; (3) the lifting of the 1896 ban on Hawaiian as a medium for teaching in the public schools in 1986; and (4) the establishment of Ka Papahana Kaiapuni, a Hawaiian-medium program in the public schools in 1987 (Kawai’ae’a et al. 2007; Warner 2001; Wilson and Kamanā 2001). Today, Modern Hawaiian-medium education can be found from pre-school through PhD-granting programs at the University of Hawai‘i. Counting the number of Modern Hawaiian speakers today is difficult, but according to the American Community survey from 2009 to 2013, 18,610 respondents reported speaking Hawaiian at home (U.S. Census Bureau, 2009–2013). Since little previous linguistic work has been carried out on either pre-revitalization Hawaiian or Modern Hawaiian, the similarities and differences between the sound systems of these varieties remains largely unknown.

Hawaiian has phonemic glottal stops before vowels in word-initial and word-medial position. Hawaiian has a comparatively small consonant inventory, shown in (1), and a relatively large set of vowels (both short and long) and diphthongs, shown in (2–4) (Elbert and Pukui 1979; Kettig 2021; Ladefoged 2001; Parker Jones 2018; Pukui and Elbert 1986; Schütz 1981):

(1)

	Bilabial	Labiodental	Alveolar	Velar	Glottal
Stop	p			k	ʔ
Fricative		v			h
Nasal	m		n		
Lateral			l		

(2)

	Front	Central	Back
High	i iː		u uː
Mid	e eː		o oː
Low		a aː	

(3) Short diphthongs: /ae/, /ai/, /ao/, /au/, /ei/, /eu/, /iu/, /oi/, /ou/

(4) Long diphthongs: /aːe/, /aːi/, /aːo/, /aːu/, /eːi/, /oːu/

As noted above, in word initial position, glottal stop is contrastive. In word-medial position, glottal stop can occur before or after any kind of vowel, whether it is monophthongal, diphthongal, short, or long. Examples of various combinations of vowels flanking a glottal stop are provided in (5) and (6), though these options are not exhaustive.

(5) Monophthongs only, including short and long vowels
- a. /VʔV/ [p**uʔa**] ‘to excrete’
- b. /Vːʔ V/ [p**uːʔu**lu] ‘group, crowd’
- c. /VʔVː/ [k**oʔuː**] ‘damp, moist’
- d. /VːʔVː/ [p**uːʔaː**] ‘flock, herd’

(6) Monophthongs and diphthongs (/V_D/), including short and long vowels
- a. /V_DʔV/ [h**auʔo**li] ‘happy’
- b. /VʔV_D/ [n**aʔau**] ‘guts’
- c. /V_DʔV_D/ [ʔ**aoʔao**] ‘side’
- d. /V_DʔVː/ [ʔ**aiʔeː**] ‘debt’
- e. /VːʔV_D/ [l**aːʔau**] ‘tree’
- f. /VʔVː$_D$/ [mak**aʔaːi**nana] ‘commoner’
- g. /Vː$_D$ʔV/ [m**aːiʔu**ʔu] ‘claw’

In the stress system of Hawaiian, syllables with diphthongs and long vowels are heavy, and all heavy syllables are stressed, either with primary or secondary stress (Parker Jones 2018; Schütz 1978, 1981; Senturia 1998). The patterns and words in (7) illustrate the six templates that are found for words that only have one stress in Hawaiian (Parker Jones 2010; Schütz 1981, 2010). Parker Jones (2010) considers these templates, first proposed by Schütz (1981), to be possible prosodic word shapes in Hawaiian; we return to this point below.

(7)
- a. {ˈσ_L σ_L} – [ˈma.la] ‘ache’
- b. {σ_Lˈ σ_L σ_L} – [va.ˈhi.ne] ‘woman’
- c. {ˈσ_H} – [ˈkai] ‘ocean’, [ˈlaː] ‘day’
- d. {σ_Lˈσ_H} – [na.ˈnaː] ‘to snarl’
- e. {ˈσ_H σ_L} – [ˈmaː.la] ‘garden’
- f. {σ_Lˈσ_H σ_L} – [pa.ˈlao.a] ‘bread’

The Hawaiian stress pattern has been compared to the right-to-left moraic trochee analysis of Fijian (Alderete and MacMillan 2015; Hayes 1995; Kenstowicz 2007), but this analysis is complicated by the fact that long words composed of more than three light syllables do not follow a predictable stress pattern (Parker Jones 2010; Schütz 1978, 1981, 2010). Famously, Hawaiian allows words like [ˌʔe.le.ma.ˈku.le] ‘old man’ and [ma.ˌku.a.ˈhi.ne] ‘mother’, where ‘old man’ has stress on the first syllable, and ‘mother’ has stress on the second syllable. It is typically agreed that the rightmost stress in a word is primary. Whereas Hayes (1995) treats any words in Fijian that did not match his right-to-left trochaic analysis as lexical exceptions, this is not plausible for Hawaiian because the words with five light syllables split about evenly between these two possible stress patterns (Parker Jones 2010; Pukui and Elbert 1986).

Parker Jones (2010) develops a probabilistic context free grammar to determine the likelihood of the prosodic structure of Hawaiian words. Similar to de Lacy's (2004) analysis of Māori, Parker Jones implements both prosodic words and metrical feet in the parser to capture the analysis of Hawaiian stress, where potential prosodic words correspond to the template shapes in (7) (marked throughout the paper in curly brackets). Metrical feet are bimoraic, consisting of two syllables or one heavy syllable, where the leftmost syllable in the foot is stressed, as shown in (8).

(8) a. {(ˈσ_L σ_L)} – [ˈma.la] 'ache'
b. {σ_L(ˈσ_L σ_L)} – [va.ˈhi.ne] 'woman'
c. {(ˈσ_H)} – [ˈkai] 'ocean'
d. {σ_L(ˈσ_H)} – [na.ˈna:] 'to snarl'
e. {(ˈσ_H σ_L)} – [ˈma:.la] 'garden'
f. {σ_L(ˈσ_H σ_L)} – [pa.ˈlao.a] 'bread'

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 (7) can be ambiguous (Parker Jones 2010). For example, a word consisting of σ_H σ_L σ_H could be either {ˌσ_H σ_L}{ˈσ_H} or {ˌσ_H}{σ_Lˈσ_H} but this can be considered a *spurious ambiguity* because stress assignment is the same in both cases. However, other combinations of syllables lead to more than one possibility for stress assignment. For example, the sequence σ_H σ_L σ_L σ_H could be realized either as a word with two stresses {ˌσ_H σ_L}{σ_L ˈσ_H}, as in [{ˌmu:.na}{mu.ˈna:}] 'to eat sparingly' or with three stresses {ˌσ_H}{ˌσ_L σ_L}{ˈσ_H}, as in {ˌʔo:}{ˌko.le}{ˈhao} 'moonshine'.

While most analyses of stress in Polynesian languages such as Māori, Samoan, or other accounts of Hawaiian, allow that lexical words can contain one or more prosodic words to ensure appropriate stress assignment (Alderete and MacMillan 2015; de Lacy 2004; Senturia 1998; Zuraw et al. 2014), these analyses are typically focused on reduplication, compounds or affixation which allows them to straightforwardly posit that each morphological constituent contributes and is associated with its own prosodic word. However, Parker Jones (2010) and Schütz (2010) both argue that in Hawaiian, there is not a strong correspondence between prosodic words and morphological constituents, and that a word can contain multiple prosodic words that do not neatly match up to morphological boundaries. In some cases, such as /napoʔo-na/ 'to set-NMLZ', the nominalizing suffix /-na/ must form part of a prosodic word with material from the stem (i.e. {ˌna.po}{ˈʔo.na}, since the suffix [na] does not meet the minimal word requirement for Hawaiian (Alderete and MacMillan 2015; de

Lacy 2004). In other cases, however, there are words with more than three syllables that do not seem to have obvious morphological structure which still require prosodic word boundaries in order to ensure the appropriate stress placement, such as {(ˌpu.le)}{le(ˈhu.a)} ‘butterfly’ (cf. *{pu(ˌle.le)}{(ˈhu.a)}).

We follow Parker Jones (2010) and Schütz (2010) in assuming that multiple prosodic words in a single lexical item can be necessary to capture the observed stress patterns of Hawaiian, whether a word is morphologically complex or not. While we leave it for future work to present a full analysis of the prosodic structure of monomorphemic and multimorphemic words in Hawaiian, and in comparison to other Polynesian languages, we note that other research on Polynesian and Austronesian languages has also speculated about the appropriate higher prosodic level for a lexical item that contains multiple prosodic words. For example, Brown (2015) proposed that the Phonological Phrase is the next level above the prosodic word in Māori, capturing both utterances like [e#{no.ho} $_{\text{PrWd}}$]$_{\text{P-Phrase}}$ ‘IMP-sit’, where the first element does not meet the minimal word requirement, as well as what are considered to be single lexical items such as [{ta.ko.to} $_{\text{PrWd}}$]$_{\text{P-Phrase}}$ ‘sit down!’. In Samoan, Zuraw et al. (2014) proposed that words that are considered single lexical items can be composed of multiple prosodic words, but they “leave open the question of whether the two prosodic words in (a) combine to form a larger prosodic word, or attach directly to the next level up, such as a Phonological Phrase” (p. 285). Bennett (2018) develops a recursive prosodic word analysis for Kaqchikel in order to account for patterns of glottal stop insertion and degemination. Providing a prosodic analysis of Hawaiian that includes levels above the prosodic word is beyond the scope of this study, so for the purposes of this paper, we will use the cover term “lexical word” or “lexical item” (abbreviated as “word” in the diagrams in (9)–(13), where it is contrasted with PrWd) to account for the dictionary entries/orthographic words in Hawaiian that can contain one or more PrWds.

The goal of this study is to determine whether word-level elements that have been established for the prosodic and metrical system of Hawaiian to date, including lexical word boundaries, prosodic word boundaries, stressed versus unstressed syllables, and heavy versus light syllables, affect whether phonemic glottal stops in Hawaiian are implemented as full closures or as creaky voice. This study uses the data reported in Davidson (2021) to determine whether full closures also correspond to prominent prosodic environments, as they are more likely to for non-phonemic uses of glottalization, or whether the word-internal metrical structure affects realization. We hypothesize that stressed syllables may condition the presence of full closure. As for word position, the analysis in Davidson (2021) did not find greater rates of full closure at the beginnings of words, but this variable is examined here again because it is included in other studies examining prosodic effects on glottalization. The prosodic word boundary is another element which may interact with glottal stop realization, especially since a phonetic cue to prosodic word position may assist listeners in determining the metrical structure of a word that has multiple potential parses. We do not independently examine foot-initial boundaries in the analysis; they are conflated with stress, since the left edge of a foot boundary always coincides with a stressed syllable.

2 Methods

2.1 Participants

The spontaneous speech data used in this study are the same as in Davidson (2021). The talkers are 8 (4 M, 4 F) bilingual speakers of Hawaiian and English who appeared on a radio show called Ka Leo Hawaiʻi in 1972 or 1973. The purpose of the radio show, as explained by the host Larry Lindsey Kimura, was to interview *mānaleo*, or native speakers of Hawaiian (http://ulukau.org/kaniaina/?a=p&p=history). While the speakers were elderly, an effort was made to choose those speakers who did not have obvious aging-related general creaky or breathy voice (Gorham-Rowan and Laures-Gore 2006; Xue and Deliyski 2001). Transcripts for these speakers are available on the ulukau.org website.

Recordings were made in the studios of KCCN radio in Hawaiʻi on reel-to-reel tape, which were then digitized to mp3s for uploading to the internet. The speakers in this study were in the studio with the host, and not calling in on the telephone. The interview topics ranged from place of birth to families, education, occupations, hobbies such as fishing or sailing, Hawaiian customs such as feasts or making leis, and music. Typically, the host asked questions and provided the speakers with ample time for uninterrupted responses. The interviews ranged in length from 5 to 16 min, with an average of 11 min. The number of glottal stops per speaker is found in Table 1.

Table 1: Number of tokens per speaker.

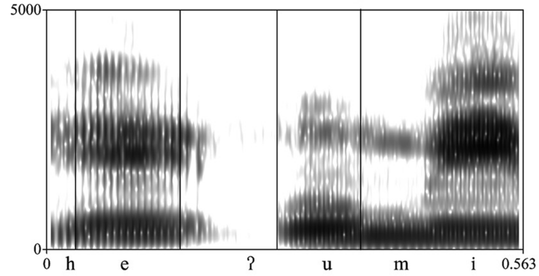
Speaker initials	AN	LG	HM	MC	LK	AP	AK	LH
# of tokens	145	125	105	102	87	70	62	62

2.2 Materials

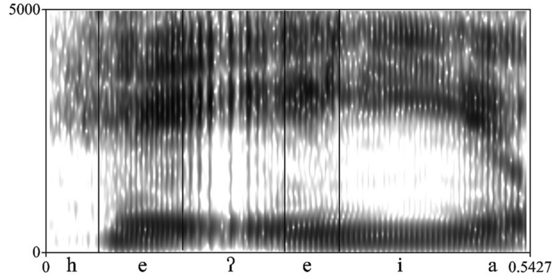
Glottal stops were identified via the *ʻokina* in the orthography in the transcript (e.g., *Hawaiʻi* /havaiʔi/, *poʻe* /poʔe/ 'people', *ʻumi* /ʔumi/ 'ten'). It has been noted that an *ʻokina* in the orthography does not necessarily mean that a word is currently pronounced with a glottal stop (Romaine 2002), so any words containing the *ʻokina* that were not produced with any phonetic instantiation of the glottal stop (as defined by the criteria laid out below) by any of the speakers were removed; this led to the elimination of 2 words (2 total utterances).

The realization of the /ʔ/ phoneme was determined by looking for the presence of a full glottal closure, creaky voice, or other indicator on a spectrogram. The visual criteria we followed were based on descriptions of glottalization events in various previous studies, including Keating et al. (2015), Redi and Shattuck-Hufnagel (2001), Avelino et al. (2011), Gerfen and Baker (2005), Davidson and Erker (2014), and others. The consensus from these papers is that glottalization realized as creaky voice is characterized by a low and irregular fundamental frequency, and damping of the glottal pulses. The focus of Davidson (2021) was on the duration and timing of the glottalization event, so a number of different realizations of creaky voice were catalogued, including a modal voice-creaky voice-modal voice configuration (mid-creak), creak only on the first vowel (V1 creak), creak only on the second vowel (V2 creak), and creak on the whole vowel-vowel interval (whole creak). In other tokens, the glottalization event was realized with a period of complete closure. In a small number of cases, there was no evidence of creaky voice, but rather the token was modally voiced with a dip in intensity that was sometimes accompanied by at least a slight dip in F0. Lastly, some tokens were realized without any acoustic or perceptual evidence of a glottal stop (though other instances of these words were produced by other speakers with glottalization, as discussed above regarding the ʻ*okina*).

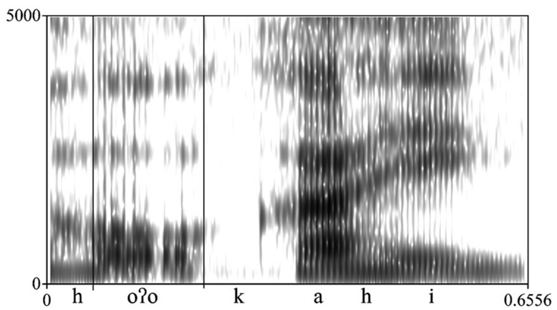
In this study, we are not focused on the timing of glottalization, so all of the tokens realized with creaky voice (mid-creak, V1 creak, V2 creak, whole creak) are grouped together into a single category of "Creaky Voice" tokens (N = 502, 66 %). The second category we consider is "Full Closure" (N = 52, 7 %), and the third is "Modal/ Intensity Dip" (N = 205, 27 %). The third group includes tokens that were produced with modal voicing only, including those that had a dip in intensity. While an intensity dip in the absence of nonmodal phonation or a full closure could be a cue to a phonemic glottal stop in Hawaiian, there is currently no evidence to confirm this, so all modally phonated tokens are grouped together for this study. Examples of the creaky and full closure realizations are provided in Figure 1 (images all of the creaky realizations are provided in Davidson 2021).



(a) ‘Full glottal closure’ realization in *he ‘umi* [he#ʔumi] (‘ten are’)

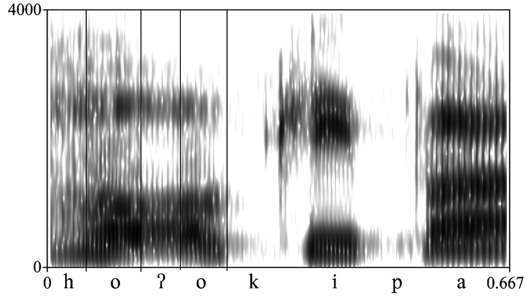


(b) ‘Creaky voice’ realization (modal-creaky-modal) in *He‘eia* [heʔ̰eia] (place name) ([ʔ̰] indicates creaky voice flanked by two modal vowels)



(c) ‘Creaky voice’ realization (whole creak) in *ho‘okahi* [ho̰o̰kahi] (‘one only, alone’)

Figure 1: Different categorizations of glottal stop realization. The glottal stop symbol [ʔ] in the segmentation in each spectrogram indicates the portion corresponding to the different realization type. In the creaky voice realization with whole creak, [ʔ] is included in the interval with the vowel since it is difficult to isolate a portion corresponding solely to the glottal stop. The phonetic transcription in the caption is a closer indication of how the target interval is produced. (a) ‘Full glottal closure’ realization in *he ‘umi* [he#ʔumi] (‘ten are’). (b) ‘Creaky voice’ realization (modal-creaky-modal) in *He‘eia* [heʔ̰eia] (place name) ([ʔ̰] indicates creaky voice flanked by two modal vowels). (c) ‘Creaky voice’ realization (whole creak) in *ho‘okahi* [ho̰o̰kahi] (‘one only, alone’). (d) ‘Intensity dip’ realization in *ho‘okipa* [hookipa] (‘hospitality’).



(d) 'Intensity dip' realization in *ho'okipa* [hookipa] ('hospitality')

Figure 1: Continued.

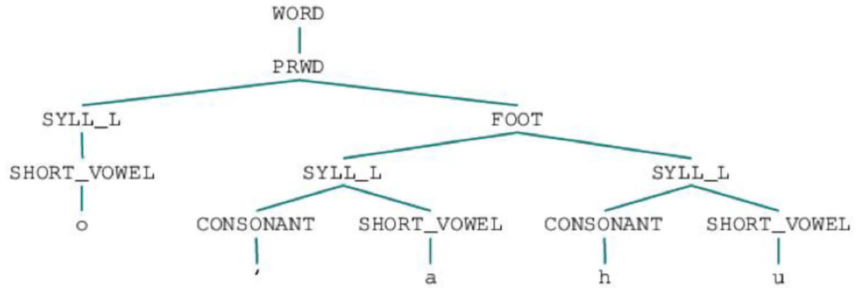
2.3 Prosodic and metrical feature extraction

In addition to identifying whether the glottal stop phoneme is realized as full closure, creaky or modal/intensity dip, we developed a semi-automated pipeline to categorize each word containing a glottal stop for the following properties:

- *Before an unstressed, primary stressed, or secondary stressed syllable*: unstressed: [ˈpo.**ʔe**] 'people'; primary stressed: [o.ˈ**ʔa.**hu] (place name); secondary stressed [ˌ**ʔu.**mi.ˌku:.ˌma:ˈi.va] 'nineteen'
- *Onset of a light or heavy syllable (long vowel or diphthong)*: light: [**ʔe.**ˈlu.a] 'two'; heavy: [ˌ**ʔ**oi.ˈha.na] *occupation*
- *Prosodic word initial or prosodic word medial*: PrWd-initial: [{ˌha:}{ˈ**ʔa.**vi}] 'to give, grant'; PrWd-medial [{ˈlu.**ʔu}**] 'to dive'
- *Lexical word initial or lexical word medial*: initial: [**ʔo.**ˈha.na] 'family'; medial: [ˈa.**ʔo**] 'instruction, teaching'

There were three parts to the pipeline. The first part used a variant of the computational prosodic grammar developed in Parker Jones (2010) to parse the words into their prosodic constituents. A description of the grammar is provided in Appendix A. To illustrate, the place name *O'ahu* was normalized and then parsed as in (9). Text normalization, where uppercase letters are converted to lowercase, results in a one-to-one correspondence between symbols in the modern Hawaiian orthography and Hawaiian phonemic analysis (Parker Jones 2010, 2018; Parker Jones and Shillingford 2018). Thus in (9) we show the parse tree for the text-normalized word *o'ahu* /oʔahu/, followed by the associated bracketed parse which will be important for the next part of the pipeline. In the following parses, SYLL_L and SYLL_H refer to light and heavy syllables, respectively. Stress is not marked by the parser because it is predictable based on foot assignment: the leftmost syllable in a foot is stressed, and the rightmost stress in the word is the primary stress.

(9) Parse for *O‘ahu* {o('ʔa.hu)}



(WORD (PRWD (SYLL_L (SHORT_VOWEL o)) (FOOT (SYLL_L (CONSONANT ‘) (SHORT_VOWEL a)) (SYLL_L (CONSONANT h) (SHORT_VOWEL u)))))

Similar bracketed parses for *‘oihana* ‘occupation’, *hā‘awi* ‘to give’, and *‘ohana* ‘family’ are given in (10), (11), and (12), respectively.

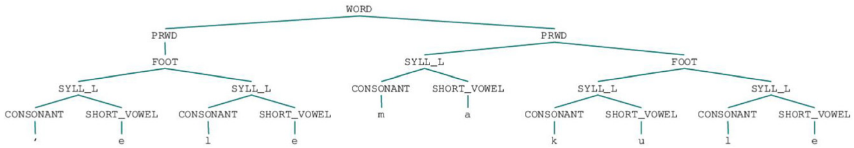
(10) Parse for *‘oihana*, corresponding to {(ˌʔoi)}{('ha.na)}
(WORD (PRWD (FOOT (SYLL_H (CONSONANT ‘) (SHORT_DIPHTHONG o i))))
(PRWD (FOOT (SYLL_L (CONSONANT h) (SHORT_VOWEL a))(SYLL_L (CONSONANT n) (SHORT_VOWEL a)))))

(11) Parse for *hā‘awi*, corresponding to {(ˌha:)}{('ʔa.vi)}
(WORD (PRWD (FOOT (SYLL_H (CONSONANT h) (LONG_VOWEL ā))))(PRWD (FOOT (SYLL_L (CONSONANT ‘) (SHORT_VOWEL a)) (SYLL_L (CONSONANT v) (SHORT_VOWEL i)))))

(12) Parse for *‘ohana*, corresponding to {ʔo('ha.na)}
(WORD (PRWD (SYLL_L (CONSONANT ‘) (SHORT_VOWEL o)) (FOOT (SYLL_L (CONSONANT h) (SHORT_VOWEL a)) (SYLL_L (CONSONANT n) (SHORT_VOWEL a))))

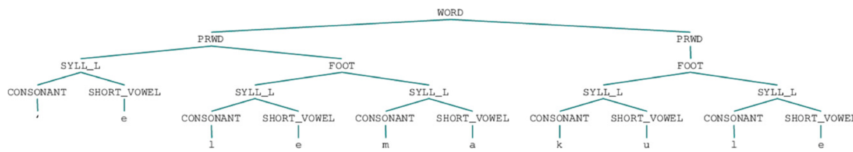
For the second step in the pipeline, we intervened manually to resolve ambiguous parses, as in (13), which shows the two parses for the word *‘elemakule* ‘old man’.

(13) Two parses for *‘elemakule*
a. {(ˌʔe.le)}{ma('ku.le)}



(WORD (PRWD (FOOT (SYLL_L (CONSONANT ‘) (SHORT_VOWEL e)) (SYLL_L (CONSONANT l) (SHORT_VOWEL e)))) (PRWD (SYLL_L (CONSONANT m) (SHORT_VOWEL a)) (FOOT (SYLL_L (CONSONANT k) (SHORT_VOWEL u)) (SYLL_L (CONSONANT l) (SHORT_VOWEL e)))))

b. *{ʔe(ˌle.ma)}{(ˈku.le)}



(WORD (PRWD (SYLL_L (CONSONANT ‘) (SHORT_VOWEL e)) (FOOT (SYLL_L (CONSONANT l) (SHORT_VOWEL e)) (SYLL_L (CONSONANT m) (SHORT_VOWEL a)))) (PRWD (FOOT (SYLL_L (CONSONANT k) (SHORT_VOWEL u)) (SYLL_L (CONSONANT l) (SHORT_VOWEL e)))))

Although ambiguities such as these can be resolved in a fully-automatic way, with over 96 % accuracy on unseen data (Parker Jones 2010), we intervened manually in this study to ensure 100 % accuracy. In cases of “spurious ambiguity”, where multiple parses result in the same stress assignment (Parker Jones 2010; Schütz 1981), ambiguity was resolved by following the citation form in the standard Hawaiian dictionary (Pukui and Elbert 1986). An example is the word *hō‘oaka* ‘to open’, which is parsed by the grammar as either {(ˌho:)}{ʔo.(ˈa.ka)} or {(ˌho:.ʔo)}{(ˈa.ka)}. We follow the dictionary in parsing this word as {(ˌho:)}{ʔo.(ˈa.ka)}.

For the final step in the pipeline, we used regular expression matching to find which bracketed word parses contained a glottal stop phoneme in the following contexts: (a) in a primary or secondary stressed syllable; (b) as the onset of a heavy syllable; (c) in the initial syllable of a PrWd; and/or (d) in the initial syllable of the lexical word. As the initial syllable in a foot is always stressed, case (a) also describes the initial syllable in a metrical foot.

The first feature to extract was whether the syllable with the glottal stop was stressed or not. Words that satisfy this constraint matched one of the two patterns in (14):

(14) Patterns where a phonemic glottal stop is in stressed syllable
a. .*(FOOT (SYLL_L (CONSONANT ‘).*
b. .*(FOOT (SYLL_H (CONSONANT ‘).*

Using regular expression matching, where .* matches any substring, the bracketed parses that contain at least one of the two patterns in (14) were classified as *glottal stop in stressed syllable*. If there was more than one stressed syllable in a word, then the rightmost one was classified as primary stressed, and the other(s) as secondary stressed. All other words were classified as not having a glottal stop in a stressed syllable.

The second feature we wanted to extract concerned heavy syllables:

(15) Pattern where a phonemic glottal stop is the onset of a heavy syllable
.*(SYLL_H (CONSONANT ‘).*

There is a close relationship between the patterns in (14) and (15), as (15) is a substring of the pattern in (14b). This follows from the fact that heavy syllables are always stressed (Parker Jones 2010, 2018), but stressed syllables are not always heavy – hence, the pattern in (14a). The pattern in (15) will thus match the parse for {ˌ**ʔoi**}{ˈha.na} but not for {ˌha:}{ˈ**ʔa**.vi}. In one case, the glottal stop is in a heavy syllable ([**ʔoi**]), in the other, it is in a light syllable ([**ʔa**]).

To find cases where the phonemic glottal stop was in the initial syllable of a PrWd, we used the patterns in (16):

(16) Phonemic glottal stop in the initial syllable of a PrWd
a. .*(PRWD (SYLL_L (CONSONANT ‘).*
b. .*(PRWD (FOOT (SYLL_L (CONSONANT ‘).*
c. .*(PRWD (FOOT (SYLL_H (CONSONANT ‘).*

These three patterns account for cases where the initial syllable is unfooted (e.g., {**ʔo**(ˈha.na)}), as well as for cases in which the initial syllable of the foot is light (e.g., {(ˌha:)}{(ˈ**ʔa**.vi)}) or heavy (e.g., {(ˌ**ʔoi**)}{(ˈha.na)}).

Finally, word initial phonemic glottal stops were found using the patterns in (17):

(17) Phonemic glottal stop in the initial syllable of the lexical word
a. (WORD (PRWD (SYLL_L (CONSONANT ‘).*
b. (WORD (PRWD (FOOT (SYLL_L (CONSONANT ‘).*
c. (WORD (PRWD (FOOT (SYLL_H (CONSONANT ‘).*

These are almost identical to the patterns in (16), but with the further word-level constraint. The patterns in (17) will match bracketed parses for words like {**ʔo**(ˈha.na)} and {(ˌ**ʔoi**)}{(ˈha.na)}, but not {(ˌha:)}{(ˈ**ʔa**.vi)} (see bracketed parse in (11)).

To summarize, the result of the pipeline was to generate prosodic features for each word, where each word was normalized and parsed, disambiguated if necessary, and then matched against a set of regular expressions. This resulted in tabular data for whether a phonemic glottal stop was in a stressed syllable, heavy syllable, PrWd-initial, and/or (lexical) word initial, as illustrated in Table 2.

Table 2: Prosodic features extracted for example words.

	Phonemic glottal stop				
Parsed word	**Primary stress**	**Secondary stress**	**Heavy syllable**	**PrWd-initial**	**Word-initial**
{o('ʔa.hu)}	✓	✗	✗	✗	✗
{(ˌʔoi)}{('ha.na)}	✗	✓	✓	✓	✓
{(ˌha:)}{('ʔa.vi)}	✓	✗	✗	✓	✗
{ʔo('ha.na)}	✗	✗	✗	✓	✓
{(pu.ʔa)}	✗	✗	✗	✗	✗

2.4 Word frequencies

Frequencies for words in the transcripts were obtained using an independent modern Hawaiian text corpus of about 1.6 M words (Parker Jones and Shillingford 2018). This text corpus was normalized and tokenized in Python, using NLTK's 'RegexptTokenizer' (Bird et al. 2009). Tokens were excluded if they contained numerals (0 1 2 3 4 5 6 7 8 9) or punctuation (! " & ' ( ) , - . / : ; ? [ ] –). All word counts were adjusted using add-1 smoothing before computing base-10 log probabilities, to avoid taking logs of zero.

3 Results

Since the glottal stop realizations were coded into three possible types, these results are first analyzed with a multinomial logistic regression model using the 'VGAM' package in R (Yee 2015). The dependent variable is glottalization type, which can be creaky voice, full closure, or modal/intensity dip. For the full data set, the fixed effects are lexical word position (word-initial, word-medial), vowel stress (primary stressed, secondary stressed, unstressed), prosodic word position (PrWd-initial, PrWd-medial), and a linear predictor of word frequency, which has been centered around the mean in this and subsequent analyses. The baselines are creaky voice for glottalization type, word-medial, unstressed, and PrWd-medial. Sum-coding is used for this analysis. We follow up with a mixed effects binomial regression for each glottalization type, which allows us to explore an analysis with random effects, and to look more closely at how each glottalization type fares.

We do not include interactions in the multinomial model, since the factors do not allow for a full cross with adequate numbers; for example, in word-medial position, there are a total of only 3 tokens where glottal stop is PrWd-initial but unstressed (2 full closures, 1 creaky voice, 0 modal/intensity dip). We also did not include light/heavy syllable in the first analysis, because heavy syllables always have either primary or secondary stress, so these two factors are confounded. In a subsequent analysis, we examine only light syllables to determine if there is an effect of stress on a subset of the data where stressed and unstressed syllables are both allowable.

Results are shown in Table 3 and the effect of PrWd is illustrated in Figure 2, where the results are presented both for the main effect of PrWd (top), and also faceted by word position (bottom). Since word-initial position always corresponds with the left edge of the PrWd, it is not possible to be word-initial but PrWd-medial, so the bottom plot in Figure 2 highlights the difference between PrWd-initial and medial for the full closure realization in word-medial position in the right facet of the graph. There is a significant result only for full closures in PrWd-initial position, which is due to the outcome that full closures are more likely in PrWd-initial position. Most effects for the full closure and modal realizations in the multinomial model are negative since creaky is the predominant response, but the positive signs for PrWd-initial position occurs because full closure and modal responses are more likely in PrWd-initial position relative to PrWd-medial position (significant only for full closures), but the opposite is true for the creaky realization, as shown in the top graph in Figure 2. It is also notable that the full closure realization for PrWd-initial position is considerably higher in word-medial position (22.5 %) than in word-initial position (9.6 %), as shown in the bottom graph.

The results of the multinomial model can be further explored with a set of binomial regressions that compare creaky productions collapsing over all others, full closures to all others, and modal productions to all others, which allows us to more

Table 3: Statistical output for multinomial analysis of glottalization types for the whole dataset.

	Estimate	**Std. error**	***z* Value**	**Pr (>|*z*|)**
(Intercept):closure	−3.021	0.262	−11.537	<0.001*
(Intercept):modal	−0.938	0.108	−8.728	<0.001*
word_initial:closure	−0.682	0.556	−1.225	0.221
word_initial:modal	−0.108	0.460	−0.235	0.814
stress_primary:closure	−0.131	0.488	−0.268	0.789
stress_primary:modal	−0.375	0.301	−1.247	0.212
stress_secondary:closure	−0.064	0.583	−0.11	0.912
stress_secondary:modal	−0.373	0.399	−0.937	0.349
prwd_initial:closure	2.098	0.674	3.111	0.002*
prwd_initial:modal	0.574	0.502	1.144	0.252
log_freq:closure	−0.106	0.170	−0.622	0.534
log_freq:modal	0.144	0.098	1.465	0.143

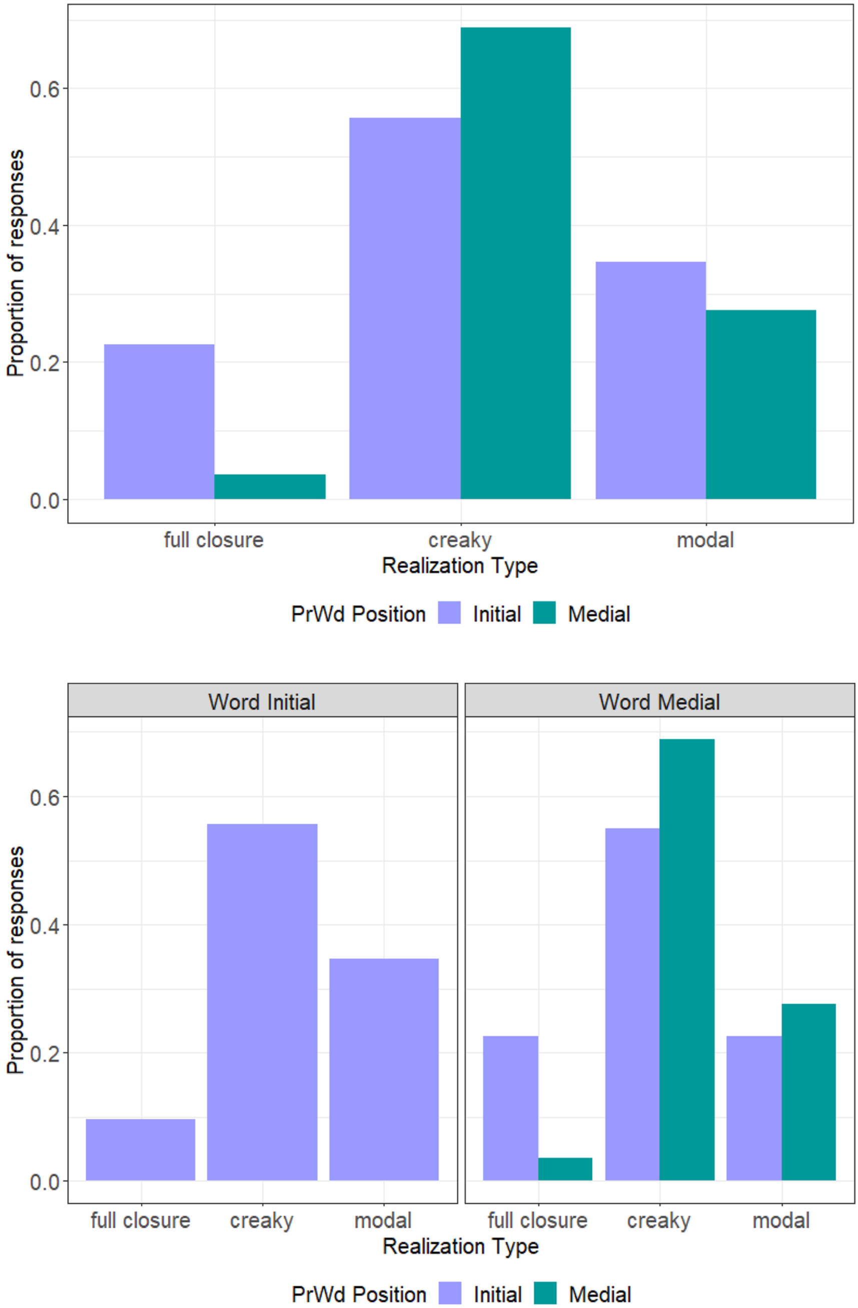


Figure 2: (Top) Proportion of glottalization type responses for PrWd position only. (Bottom) Proportion of glottalization type responses for PrWd position, divided by lexical word position.

Table 4: Counts and proportions for each glottalization type.

	Creaky		Closure		Modal	
	N	Proportion	*N*	Proportion	*N*	Proportion
Primary	141	0.62	25	0.11	60	0.27
Secondary	45	0.65	8	0.12	16	0.23
Unstressed	315	0.68	19	0.04	129	0.28
Prwd-initial	173	0.60	36	0.13	80	0.28
Prwd-medial	328	0.70	16	0.03	125	0.27
Word-initial	151	0.61	27	0.11	71	0.29
Word-medial	350	0.69	25	0.05	134	0.26

closely inspect the effects on each response type and also to include speaker as a random intercept. Numerical results are presented in Table 4 and statistical results, which are similar to the multinomial results, in Table 5. PrWd initial is significant for both creaky voice (decreased rates) and full closure (increased rates), but word position is not significant. In these results, however, there is a significant effect of stress that shows up primarily in the modal responses, indicating that there are fewer modal realizations before either primary or secondary stress. However, full closures are not affected by stress. Moreover, word frequency indicates that modal tokens are more likely for higher frequency words, and that creaky tokens are marginally less likely, at the $p = 0.056$ level. We return to the effects of frequency below.

While neither stress nor word position have conditioned full closures in any models so far, previous research in other languages has suggested that stressed syllables in word-initial position in particular are a more likely position for a stronger articulatory production. Therefore, to confirm the evidence up to this point that this does not seem to be the case for Hawaiian, we focused on word-initial tokens only and carried out a binomial regression with the full closure response versus all others, with speaker as a random intercept. In this analysis, PrWd position is left out, since word-initial glottal stops are also in PrWd-initial position; only vowel stress and lexical frequency are included. Results in Table 5 indicate that there are no effects of stress here either, but for word-initial position, glottal stops produced with full closure are significantly less likely to be in higher frequency words. The frequency results from both Tables 5 and 6 are illustrated in Figure 3.

Lastly, we investigated whether effects of stress can be found for light syllables only, which are not confounded with stress the way heavy syllables are. For this multinomial analysis, lexical word position, vowel stress, PrWd position and lexical

Table 5: Statistical output for binomial analyses of glottalization types for the whole dataset.

	CREAKY			CLOSURE			MODAL		
	Est.	***z* Value**	**Pr (>|*z*|)**	**Est.**	***z* Value**	**Pr (>|*z*|)**	**Est.**	***z* Value**	**Pr (>|*z*|)**
(Intercept)	0.894	3.105	0.002[a]	−3.633	−9.073	<0.001[a]	−1.27	−2.778	0.005*
word_initial	0.431	1.054	0.292	−0.666	−1.195	0.232	0.049	0.100	0.920
stress_primary	0.561	1.912	0.06[b]	0.062	0.135	0.893	−0.712	−2.093	0.036*
stress_secondary	0.697	1.753	0.08	0.350	0.609	0.542	−1.051	−2.256	0.024*
prwd_initial	−1.237	−2.728	0.006[a]	1.981	3.065	0.002[a]	0.471	0.868	0.386
log_freq	−0.186	−1.912	0.056[b]	−0.192	−1.091	0.275	0.305	2.789	0.005*

Table 6: Statistical output for binomial analysis of full closure for lexical word-initial instances of glottal stop.

	Estimate	Std. error	*z* Value	Pr (>|*z*|)
(Intercept)	−3.038	0.703	−4.320	<0.001[a]
stress_primary	1.085	0.740	1.465	0.143
stress_secondary	0.417	0.763	0.546	0.585
log_freq	−0.633	0.243	−2.605	0.009[a]

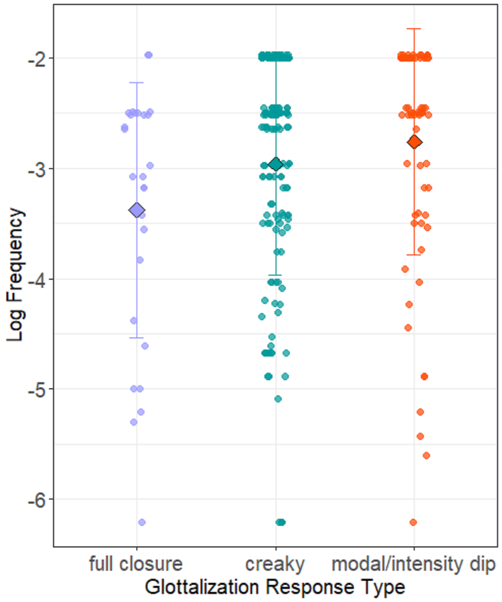


Figure 3: Frequency distribution for each glottalization response type for glottal stops in lexical word-initial position. The diamond indicates the mean for the group, and the error bars are the standard deviation. A more negative number is lower frequency. The dots clustered below 6 correspond to words that were not present in the written corpus used to calculate frequency.

frequency (centered) are the fixed effects, with the same baselines as in Table 2. Results in Table 7 show that the effect of PrWd-initial position is still present for full closure, but no other effects emerge.

The analyses in this section demonstrate two main findings. First, regarding the word-internal metrical variables, full closure implementations increase in PrWd-initial position. Notably, as illustrated in Figure 2, it is word-medial position where this effect stands out. Word position is not significant in any of the analyses that contain it as a variable and stress is never a significant factor in conditioning full closures. These findings are not consistent with the literature examining non-phonemic glottalization which often finds that word edges and prominence

Table 7: Statistical output for multinomial analysis of glottalization types for instances of glottal stop in light syllables.

	Estimate	Std. error	*z* Value	Pr (>|*z*|)
(Intercept):closure	−2.154	0.250	−8.632	<0.001*
(Intercept):modal	−1.057	0.229	−4.617	<0.001*
word_initial:closure	0.618	0.345	1.790	0.073
word_initial:modal	0.176	0.261	0.674	0.50
stress_primary:closure	−0.116	0.355	−0.326	0.744
stress_primary:modal	0.373	0.288	1.295	0.195
stress_secondary:closure	−0.534	0.385	−1.388	0.165
stress_secondary:modal	0.050	0.288	0.172	0.863
prwd_initial:closure	−1.388	0.419	−3.310	0.001*
prwd_initial:modal	−0.425	0.292	−1.458	0.145
log_freq:closure	0.038	0.213	0.178	0.858
log_freq:modal	0.129	0.108	1.197	0.231

condition the presence of glottalization and in some cases, greater rates of full closure. Instead, the results are more in line with the literature demonstrating that word-internal metrical boundaries can be phonetically signaled, variably in the case of Hawaiian. Second, there is evidence that full closures are less likely in words that have a higher lexical frequency. These two results will be discussed in more detail in the discussion.

4 Discussion

This study of the realization of glottal stops in Hawaiian was motivated by a number of factors. First, there is a limited number of studies examining what phonetic factors affect the implementation of phonemic glottal stop. Since the realization of the glottal stop in Hawaiian is not potentially also affected by tone or contrastive voice quality on adjacent sounds, we can focus more narrowly on whether there are effects of prominence and of word-internal metrical structure on the realization of glottal stops. Like many other languages, glottal stops in Hawaiian are most commonly realized as a period creaky voice (e.g., Frazier 2013; Garellek et al. 2021; Ladefoged and Maddieson 1996; Quick 2003; Whalen et al. 2016), but can also be produced as either a full closure or with modal voicing (sometimes with a drop in intensity and/or F0).

We hypothesized that realization as a full closure could be most likely either in positions that are prosodically higher or more prominent, such as word-initial position or before a stressed syllable, which has been shown to favor stronger articulations. Such a result would be consistent with the sketch laid out in Garellek et al. (2021) that more extreme glottal articulations such as a more devoiced glottal element, including full closure, are favored in positions that undergo prosodic strengthening. An alternative hypothesis was that the realization of glottal stop may instead be influenced by word-internal metrical structure, such as prosodic word-initial position. It should be noted that a limitation of this study is that we did not investigate the effects of prominence above the word, such as phrasal accent or other intonational influences. This is because there currently is no model of intonation for Hawaiian that could be used to parse the conversational speech we are reporting on in this study. For that reason, we have limited this investigation to word-level factors.

The first result of this study was that prominence factors and word edges did not lead to a greater likelihood of realizing glottal stop as a full closure. There was no evidence that syllable stress, even primary stress compared to secondary stress and unstressed syllables, conditioned full glottal closure. Likewise, lexical word initial position did not influence realization compared to word medial position. Instead, the metrical factor conditioning greater rates of full closure was PrWd-initial position in lexical word *medial* position, which typically is not considered a location of prosodic strengthening. While PrWd-initial position could be considered a stronger boundary than PrWd-medial position, it is presumably not more prosodically prominent than word-initial position or a stressed syllable, especially in lexical word medial position.

The effect of PrWd is more consistent with the literature reporting phonetic sensitivity to metrical structure. It is perhaps most similar to the analysis that Vaysman (2009) provides for Ibibio, where she argues that oral stops do not lenite word medially if they are also in PrWd-initial position, though in Ibibio this pattern seems to be categorical rather than variable as it is in Hawaiian. Since the full closure does not seem to be required in PrWd initial position word medially in Hawaiian, it is likely that there is yet another factor conditioning this realization. The increase of full closure implementations in PrWd-initial position for word-medial glottal stops is interesting given the potential ambiguities in metrical structure assignment discussed in previous work on Hawaiian and related languages (Hayes 1995; Parker Jones 2010; Schütz 1978, 1981, 2010). As discussed in Section 1.2, a word of the form $\sigma_H\ \sigma_L\ \sigma_L\ \sigma_H$ could be realized as either {ˌ$\sigma_H\ \sigma_L$}{σ_L ˈσ_H}, {(ˌmu:.na)}{(mu.ˈna:)} ‘to eat sparingly’ or as {ˌσ_H}{ˌ$\sigma_L\ \sigma_L$}{ˈσ_H}, {(ˌʔo:)}{(ˌko.le)}{(ˈhao)} ‘moonshine’. In these cases, stress will determine what the prosodic parse must be. However, in other cases, there can be ambiguous PrWd parses that are not resolved by stress, which can be illustrated with a word containing multiple glottal stops. For example, the word *hāʻeʻena* [ha:ʔeʔena] ‘shy’ could be parsed either as {(ˌha:)}{ʔe(ˈʔe.na)} or as {(ˌha:ʔe)}{(ˈʔe.na)}. In this case, the boundary of the second

PrWd potentially could have either of the two glottal stops at the start, so a phonetic cue such as full closure might be helpful for determining the appropriate structure. As introduced in Section 2.3, a word of similar structure in the corpus is *hōʻoaka* [ho:ʔoaka] ‘to open’, which could be parsed as either {(ˌho:)}{ʔo.(ˈa.ka)} or {(ˌho:.ʔo)}{(ˈa.ka)}. This word was categorized as having the glottal stop at the beginning of the second PrWd, based on the parse indicated by the standard reference dictionary of Hawaiian (Pukui and Elbert 1986), and the two instances that we find of this word in the corpus are produced with a full closure. Thus, it may be that phonetic realization could be useful as a means to signal a particular structure in a word that is metrically ambiguous based on its stress pattern alone.

The second result of this study is that modal realizations were generally more likely in higher frequency words and creaky realizations were less likely. For the main dataset, there was no effect for full closures, but for the analysis isolating lexical word initial position, full closures were found in words with a lower lexical frequency, as compared to the other possible realizations. These results may be a phonetic reflex of the tendency for higher frequency words to be more reduced, and by contrast, lower frequency words to be less reduced (e.g., Bell et al. 2009; Fidelholtz 1975; Gahl 2008; Jurafsky et al. 2001; Munson and Solomon 2004: see also Jaeger and Buz 2018 for a review of this literature). While this literature is more often framed as the reduction of high frequency words, the variable implementation of full closure in Hawaiian is arguably a strengthening effect, since the majority of all glottal stops in any position are produced as a period of glottalization (of varying length). This outcome is in line with other findings like that in Zhao and Jurafsky (2009), who examined the interaction between lexical frequency and tone in Cantonese, and found that low frequency words have tone contours that are more distinct than those in higher frequency words. Munson and Solomon (2004) demonstrated that the vowel space of less frequent words is more dispersed than their counterparts in more frequent words in English. Mousikou and Rastle (2015) showed that initial consonant durations in English have a tendency to be longer in lower frequency words compared to higher frequency words. But even in these cases that report on the phonetic properties of lower frequency words, it is unclear if they are demonstrating strengthening, or are the baseline from which high frequency words are then shortened or otherwise reduced. Relatedly, research on predictability, which is not exactly the same as lexical frequency as it takes into account the surrounding context in addition to word frequency (Bell et al. 2009; Cohen Priva 2017; Cohen Priva and Jaeger 2018), has argued that words with lower predictability may be more likely to show effects of hyperarticulation (Hall et al. 2018). While it is beyond the scope of this study to evaluate our spontaneous speech for the influence of predictability, it is possible that the word-initial glottal stops that are produced as full closures in this study are a result of accumulated effects of both low frequency and low predictability. If so, such a factor could help explain why there is an increase in full closure realizations in some environments, but creaky voice realizations are still predominant.

5 Conclusions

This study demonstrates that in Hawaiian, the realization of a glottal stop phoneme as a full glottal closure is conditioned by word internal metrical boundaries, in this case a prosodic word boundary. This is consistent with the literature demonstrating that foot or PrWd structure can condition both segmental options and phonetic realization, but not with the broader literature which has reported stronger articulations produced at higher prosodic boundaries or before prominent syllables. In the case of Hawaiian, the full closure realization is more likely at a word-medial PrWd boundary, which may help to distinguish the appropriate parse in words that otherwise have ambiguous metrical structure. At the same time, when full closures are found in word-initial position, it is for a different reason; they are more likely in lower frequency words, which may be a reflex of a tendency to have hyperarticulation in less frequent or less predictable words. This is a potential area of future study, as is an examination of the effects of prosody beyond the word on consonantal realization.

Acknowledgments: We would like to thank our two reviewers, audience members at UCLA, UCSD, UMass, McMaster University, LabPhon 2022, and members of the NYU PEP Lab for their feedback on this work. We are especially indebted to Professor Larry Kimura and the invaluable voices of the Hawaiian speakers who appeared on the Ka Leo Hawaiʻi radio program and are reflected in this work: Henry Hanalē Machado, Lydia Līlia Wahinemaikaʻi Hale, Alice Kema, Abraham Piʻianāiʻa, Alice Kuʻuleialohapoinaʻole Nāmakelua, Mālia Craver and Louis Kaulanaʻula Grace. We also thank Katie Drager and Andrea Berez-Kroeker at the University of Hawaiʻi.
Research funding: This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.
Author contributions statement: Designing the experiment: LD and OPJ; data analysis: LD; computational analysis: OPJ; discussion of the results: LD and OPJ; writing up the paper: LD and OPJ.
Competing interests: The authors declare no conflicts of interest.
Statement of ethics: The local Institutional Review Board deemed the study exempt from review. It was conducted using publicly available data from a radio program, archived at the website https://ulukau.org/kaniaina/.

Appendix A: Computational prosodic grammar

Here we briefly describe the implementation of the prosodic grammar used to parse Hawaiian words. It is based on the Probabilistic Context-Free Grammar in Parker Jones (2010). As we did not require the rule probabilities, we implemented a simplified Context-Free Grammar (CFG) where the top-level rules expanded from a WORD category, to one or more PRWDs:

(18) WORD → $PRWD^+$

In practice, however, we did not require more than seven PRWDs for a WORD.

We modelled two types of prosodic words (in curly brackets), one consisting of a foot alone (e.g. {('ma.la)} 'ache'), and another consisting of a light syllable followed by a foot ({va('hi.ne)} 'woman'):

(19) PRWD → FOOT | SYLL_L FOOT

We modelled three types of feet (in parentheses), corresponding to a heavy syllable alone (e.g. {('kai)} 'sea'), a heavy syllable followed by a light syllable ({('ma:)la} 'garden'), or a light syllable followed by a heavy syllable ({na('na:)} 'to snarl'):

(20) FOOT → SYLL_H | SYLL_H SYLL_L | SYLL_L SYLL_H

Moving on to the syllables (separated by periods or higher brackets), we modelled one light syllable rule, with an optional consonant onset:

(21) SYLL_L → (CONSONANT) SHORT_VOWEL

We modelled three kinds of heavy syllables, again with an optional consonant onsets:

(22) SYLL_H → (CONSONANT) LONG_VOWEL | (CONSONANT) SHORT_DIPHTHONG | (CONSONANT) LONG_DIPHTHONG

In the CFG, light syllables are characterized as having a short vowel, whereas heavy syllables contain a long vowel or a diphthong. Hawaiian diphthongs, as we see below, are called "short" if they contain two short vowels or "long" if they contain a combination of long vowel and short vowel (Schütz 1981).

We included rules for Hawaiian's eight native consonants:

(23) CONSONANT → h | k | l | m | n | p | w | ‘

Note that the grammar was written to parse normalized text in the modern Hawaiian orthography, which is why the consonant rules expand into *w* rather than /v/ and into ‘ rather than /ʔ/. For the grammar to parse loanwords, we further modelled foreign consonants (Parker Jones 2009, 2018):

(24) CONSONANT → b | c | d | f | g | j | q | r | s | t | v | x | y | z | ch | kr | st | ng

Finally, the vowel rules were split into groups for short vowels, long vowels, short diphthongs, and long diphthongs:

(25) SHORT_VOWEL → a | e | i | o | u

(26) LONG_VOWEL → ā | ē | ī | ō | ū

(27) SHORT_DIPHTHONG → ae | ai | ao | au | ei | eu | iu | oi | ou

(28) LONG_DIPHTHONG → āe | āi | āo | āu | ēi | ōu

These rules, as we have seen in the main text in (12), are capable of producing multiple derivations for some input strings. Given the inherent ambiguity of the CFG, input strings were parsed using a chart parser (Kay 1986), implemented in Python using NLTK's 'ChartParser' (Bird et al. 2009).

References

Akinlabi, Akinbiyi & Eno Urua. 2002. Foot structure in the Ibibio verb. *Journal of African Languages and Linguistics* 23. 119–160.

Alderete, John & Kayleigh MacMillan. 2015. Reduplication in Hawaiian: Variations on a theme of minimal word. *Natural Language & Linguistic Theory* 33(1). 1–45.

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.

Avesani, Cinzia, Mario Vayra & Claudio Zmarich. 2007. On the articulatory basis of prominence in Italian. In Jürgen Trouvain & William John Barry (eds.), *Proceedings of the XVIth international congress of phonetic sciences*, 981–984. Saarbrücken, Germany: Universität des Saarlandes.

Bell, Alan, Jason M. Brenier, Michelle Gregory, Cynthia Girand & Dan Jurafsky. 2009. Predictability effects on durations of content and function words in conversational English. *Journal of Memory and Language* 60(1). 92–111.

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.

Bennett, Ryan, Meg Harvey, Robert Henderson & Tomás Alberto Méndez López. 2022. The phonetics and phonology of Uspanteko (Mayan). *Language and Linguistics Compass* 16(9). e12467.

Bird, Steven, Ewan Klein & Edward Loper. 2009. *Natural language processing with Python*. Sebastopol, CA: O'Reilly Media.

Bombien, Lasse, Christine Mooshammer, Philip Hoole & Barbara Kühnert. 2010. Prosodic and segmental effects on EPG contact patterns of word-initial German clusters. *Journal of Phonetics* 38(3). 388–403.

Bombien, Lasse, Christine Mooshammer, Philip Hoole, Tamara Rathcke & Barbara Kuehnert. 2007. Articulatory strengthening in initial German /kl/ clusters under prosodic variation. In

Jürgen Trouvain & William J. Barry (eds.), *Proceedings of the XVIth international congress of phonetic sciences*, 457–460. Saarbücken, Germany: Universität des Saarlandes.
Brenzinger, Matthias & Patrick Heinrich. 2013. The return of Hawaiian: Language networks of the revival movement. *Current Issues in Language Planning* 14. 300–316.
Brown, Jason. 2015. The minimal phonological phrase: Evidence from Māori. *Oceanic Linguistics* 54(2). 507–533.
Chappell, Whitney. 2013. Linguistic factors conditioning glottal constriction in Nicaraguan Spanish. *Italian Journal of Linguistics* 27. 1–42.
Cho, Taehong. 2004. Prosodically conditioned strengthening and vowel-to-vowel coarticulation in English. *Journal of Phonetics* 32. 141–176.
Cho, Taehong. 2005. Prosodic strengthening and featural enhancement: Evidence from acoustic and articulatory realizations of /a,i/ in English. *Journal of the Acoustical Society of America* 33. 121–157.
Cho, Taehong. 2006a. An acoustic study of the stress and intonational system in Lakhota: A preliminary report. *Speech Sciences* 13. 23–42.
Cho, Taehong. 2006b. Manifestation of prosodic structure in articulatory variation: Evidence from lip kinematics in English. In Louis Goldstein, Doug H. Whalen & Catherine T. Best (eds.), *Papers in laboratory phonology VIII: Varieties of phonological competence (phonology and phonetics)*, 519–548. Berlin: Mouton de Gruyter.
Cho, Taehong & James M. McQueen. 2005. Prosodic influences on consonant production in Dutch: Effects of prosodic boundaries, phrasal accent and lexical stress. *Journal of Phonetics* 33(2). 121–157.
Cho, Taehong & Patricia Keating. 2001. Articulatory and acoustic studies on domain-initial strengthening in Korean. *Journal of Phonetics* 29. 155–190.
Cho, Taehong & Patricia Keating. 2009. Effects of initial position versus prominence in English. *Journal of Phonetics* 37(4). 466–485.
Cohen Priva, Uriel. 2017. Informativity and the actuation of lenition. *Language* 93(3). 569–597.
Cohen Priva, Uriel & Emily Gleason. 2020. The causal structure of lenition: A case for the causal precedence of durational shortening. *Language* 92. 413–448.
Cohen Priva, Uriel & Florian Jaeger. 2018. The interdependence of frequency, predictability, and informativity in the segmental domain. *Linguistics Vanguard* 4. s2.
Cole, Jennifer, Heejin Kim, Hansook Choi & Mark Hasegawa-Johnson. 2007. Prosodic effects on acoustic cues to stop voicing and place of articulation: Evidence from Radio News speech. *Journal of Phonetics* 35(2). 180–209.
Davidson, Lisa. 2021. Effects of word position and flanking vowel on the implementation of glottal stop: Evidence from Hawaiian. *Journal of Phonetics* 88. 101075.
Davidson, Lisa & Daniel Erker. 2014. Hiatus resolution in American English: The case against glide insertion. *Language* 90(2). 482–514.
de Jong, Kenneth. 1995. The supraglottal articulation of prominence in English: Linguistic stress as localized hyperarticulation. *Journal of the Acoustical Society of America* 97. 491–504.
de Lacy, Paul. 2004. Maximal words and the Maori passive. In John J. McCarthy (ed.), *Optimality theory in phonology: A reader*, 495–512 Malden, MA: Blackwell.
DiCanio, Christian. 2012. Coarticulation between tone and glottal consonants in Itunyoso Trique. *Journal of Phonetics* 40. 162–176.
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 Hawaii Press.

Fidelholtz, James L. 1975. Word frequency and vowel reduction in English. In Robin E. Grossman, James San & Timothy J. Vance (eds.), *Papers from the eleventh regional meeting of the Chicago Linguistic Society*, 200–213. Chicago: CLS.

Fletcher, Janet, Hywel Stoakes, Deborah Loakes & Ruth Singer. 2015. Accentual prominence and consonant strengthening and lengthening in Mawng. In The Scottish Consortium for ICPhS 2015. (ed.), *Proceedings of the 18th international congress of phonetic sciences*. Glasgow, UK: University of Glasgow.

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

Fougeron, Cécile & Patricia Keating. 1997. Articulatory strengthening at the edges of prosodic domains. *Journal of the Acoustical Society of America* 101. 3728–3740.

Frazier, Melissa. 2013. The phonetics of Yucatec Maya and the typology of laryngeal complexity. *Language Typology and Universals* 66. 7–21.

Gahl, Susanne. 2008. Time and thyme are not homophones: The effect of lemma frequency on word durations in spontaneous speech. *Language* 84(3). 474–496.

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*. 1–28. https://doi.org/10.1017/s0025100321000116.

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

Gordon, Matthew & Peter Ladefoged. 2001. Phonation types: A cross-linguistic overview. *Journal of Phonetics* 29. 383–406.

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.

Gurevich, Naomi. 2011. Lenition. In Marc van Oostendorp, Colin J. Ewen, Elizabeth Hume & Keren Rice (eds.), *The Blackwell companion to phonology*, 1559–1575. New York: Blackwell Publishing.

Hall, Kathleen Currie, Elizabeth Hume, Florian Jaeger & Andrew Wedel. 2018. The role of predictability in shaping phonological patterns. *Linguistics Vanguard* 4. s2.

Hargus, Sharon. 2005. Prosody in two Athabaskan languages of Northern British Columbia. In Sharon Hargus & Keren Rice (eds.), *Athabaskan prosody*, 393–423. Amsterdam: John Benjamins Publishing Company.

Harris, John. 2004. Release the captive coda: The foot as a domain of phonetic interpretation. In John Local, Richard Ogden & Rosalind Temple (eds.), *Papers in laboratory phonology*, vol. 6, 103–129. Cambridge: Cambridge University Press.

Harris, John & Jonathan Kaye. 1990. A tale of two cities: London glottaling and New York City tapping. *The Linguistic Review* 7(3). 251–274.

Hayes, Bruce. 1995. *Metrical stress theory: Principles and case studies*. Chicago: University of Chicago Press.

Hodgson, Merion. 2021. *Voice onset time in Plains Cree*. Alberta: University of Calgary MA thesis.

Hudu, Fusheini. 2022. Defining the prosodic word with segmental processes in Dagbani. *Acta Linguistica Academica* 63(2). 271–300.

Jaeger, Florian & Esteban Buz. 2018. Signal reduction and linguistic encoding. In *The handbook of psycholinguistics*, 38–81. Malden, MA: Wiley Blackwell.

Jurafsky, Daniel, Alan Bell, Michelle Gregory & William Raymond. 2001. Probabilistic relations between words: Evidence from reduction in lexical production. In Joan L. Bybee & Paul J. Hopper (eds.), *Frequency and the emergence of linguistic structure*, 229–254. Amsterdam: Benjamins.

Kakadelis, Stephanie. 2018. *Phonetic properties of oral stops in three languages with no voicing distinction*. New York: CUNY Graduate Center PhD Dissertation.
Katsika, Argyro & Karen Tsai. 2021. The supralaryngeal articulation of stress and accent in Greek. *Journal of Phonetics* 88. 101085.
Katz, Jonah. 2016. Lenition, perception and neutralisation. *Phonology* 33(1). 43–85.
Katz, Jonah. 2021. Intervocalic lenition is not phonological: Evidence from Campidanese Sardinian. *Phonology* 38(4). 651–692.
Kawai'ae'a, Keiki, Alohalani Kaluhiokalani Houseman & Makalapua Alencastre. 2007. Pūʻā i ka ʻŌlelo, Ola ka ʻOhana: Three generations of Hawaiian language revitalization. *Hūlili: Multidisciplinary Research on Hawaiian Well-Being* 4. 183–237.
Kay, Martin. 1986. Algorithm schemata and data structures in syntactic processing. In Barbara J. Grosz & Bonnie Lynn Webber (eds.), *Readings in natural language processing*, 35–70. Los Altos, CA: Morgan Kauffman Publishers.
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, UK: University of Glasgow.
Keating, Patricia, Taehong Cho, Cécile Fougeron & Chai-Shune Hsu. 2003. Domain-initial strengthening in four languages. In John Local, Richard Ogden & Rosalind Temple (eds.), *Phonetic interpretation (Papers in Laboratory Phonology 6)*, 143–161. Cambridge: Cambridge University Press.
Kenstowicz, Michael. 2007. Salience and similarity in loanword adaptation: A case study from Fijian. *Language Sciences* 29. 316–340.
Kettig, Thomas. 2021. *Haʻina ʻia mai ana ka puana: The vowels of ʻōlelo Hawaiʻi*. Mānoa, Hawaiʻi: University of Hawaii at Mānoa PhD dissertation.
Kiparsky, Paul. 1979. Metrical structure assignment is cyclic. *Linguistic Inquiry* 10. 421–441.
Kohler, Klaus J. 1994. Glottal stops and glottalization in German. *Phonetica* 51. 38–51.
Ladefoged, Peter. 2001. *Vowels and consonants*. Oxford: Blackwell.
Ladefoged, Peter & Ian Maddieson. 1996. *The sounds of the world's languages*. Oxford: Blackwell.
Lavoie, Lisa. 2001. *Consonant strength: Phonological patterns and phonetic manifestations*. New York: Garland.
Lisker, Leigh & Arthur S. Abramson. 1967. Some effects of context on voice onset time in English stops. *Language and Speech* 10(1). 1–28.
Malisz, Zofia, Marzena Zygis & 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.
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. 2018. Not all geminates are created equal: Evidence from Maltese glottal consonants. *Journal of Phonetics* 66. 28–44.
Mitterer, Holger. 2023. Limits of audience design: Epenthetic glottal stops in Maltese. OSF Project. https://osf.io/8ejh3/ (accessed 9 March 2023).
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.
Mousikou, Petroula & Kathleen Rastle. 2015. Lexical frequency effects on articulation: A comparison of picture naming and reading aloud. *Frontiers in Psychology* 6. 1571.
Munson, Benjamin & Nancy Pearl Solomon. 2004. The effect of phonological neighborhood density on vowel articulation. *Journal of Speech, Language and Hearing Research* 47(5). 1048–1058.

Nicholas, Sally Akevai & Rolando Coto-Solano. 2019. Glottal variation, teacher training and language revitalization in the Cook Islands. In *Proceedings of the 19th international congress of phonetic sciences*, 3602–3606. Canberra, Australia: Australasian Speech Science and Technology Association Inc.
Parker Jones, Oiwi. 2009. Loanwords in Hawaiian. In Martin Haspelmath & Uri Tadmor (eds.), *Loanwords in the world's languages*, 771–789. Berlin: De Gruyter Mouton.
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.
Parker Jones, Oiwi & Brendan Shillingford. 2018. Composing RNNs and FSTs for small data: Recovering missing characters in old Hawaiian text. Paper presented at the 32nd Annual Conference on Neural Information Processing Systems IRASL Workshop, Montreal.
Parrell, Benjamin & Shrikanth Narayanan. 2018. Explaining coronal reduction: Prosodic structure and articulatory posture. *Phonetica* 75(2). 151–181.
Pentland, Christina. 2004. *Stress in Warlpiri: Stress domains and word-level prosody*. Brisbane: University of Queensland.
Pierrehumbert, Janet. 1995. Prosodic effects on glottal allophones. In Osamu Fujimura & Minoru 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 J. Docherty & 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 *Proceedings of the 17th international congress of phonetic sciences*, 1626–1629. Malden, MA: Blackwell.
Puggaard, Rasmus. 2019. Modeling regional variation in voice onset time of Jutlandic varieties of Danish. In Hans Van de Velde, Nanna Haug Hilton & Remco Knooihuizen (eds.), *Selected papers from the tenth international conference on language variation in Europe*, 79–110. Amsterdam: John Benjamins.
Pukui, Mary Kawena & Samuel Elbert. 1986. *Hawaiian dictionary: Hawaiian-English, English-Hawaiian*. Honolulu: University of Hawaii Press.
Quick, Philip. 2003. *A grammar of the Pendau language*. Canberra, Australia: Australian National University PhD Dissertation.
Redi, Laura & Stefanie Shattuck-Hufnagel. 2001. Variation in the realization of glottalization in normal speakers. *Journal of Phonetics* 29(4). 407–429.
Romaine, Suzanne. 2002. Signs of identity, signs of discord: Glottal goofs and the green grocer's glottal in debates on Hawaiian orthography. *Journal of Linguistic Anthropology* 12(2). 189–224.
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, CA: 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 John Barry (eds.), *Proceedings of the XVIth international congress of phonetic sciences*, 1365–1368. Saarbrücken, Germany: Universität des Saarlandes.

Simonet, Miquel, Joseph Casillas & Yamile Diaz. 2014. The effects of stress/accent on VOT depend on language (English, Spanish), consonant (/d/, /t/) and linguistic experience (monolinguals, bilinguals). Malden, MA: Blackwell In Nick Campbell, Dafydd Gibbon & Daniel Hirst (eds.), *Proceedings of the 7th International Conference on Speech Prosody*, 202–206. Dublin: Trinity College Dublin.
Sprinkle, McKinley. 2022. *In search of phonetic evidence for prosodically-motivated aspiration*. Williamsburg, VA: College of William and Mary BA thesis.
Sugahara, Mariko & Alice Turk. 2009. Durational correlates of English sublexical constituent structure. *Phonology* 26. 477–524.
Tabain, Marija & Andrew Butcher. 2015. Lexical stress and stop bursts in Pitjantjatjara: Feature enhancement of neutralized apicals and the coronal/velar contrast. *Journal of Phonetics* 50. 67–80.
Trawick, Sonya & Jim Michnowicz. 2019. Glottal insertion before vowel-initial words in the Spanish of Asunción, Paraguay. In Gregory L. Thomson & Scott M. Alvord (eds.), *Contact, community and connections: Current approaches to Spanish in multilingual populations*, 147–171. Wilmington, DE: Vernon Press.
Turk, Alice. 1992. The American English flapping rule and the effect of stress on stop consonant durations. *Working Papers of the Cornell Phonetics Laboratory* 7. 103–133.
Turk, Alice & Laurence White. 1999. Structural influences on accentual lengthening in English. *Journal of Phonetics* 27. 171–206.
Vaysman, Olga. 2009. *Segmental alternations and metrical theory*. Cambridge, MA: MIT PhD dissertation.
Warner, Sam L. No'Eau 2001. The movement to revitalize Hawaiian language and culture. In Leanne Hinton & Ken Hale (eds.), *The green book of language revitalization in practice*, 133–146. Leiden: Brill.
Whalen, Doug H., Christian DiCanio, Christopher Geissler & Hannah King. 2016. Acoustic realization of a distinctive, frequent glottal stop: The Arapaho example. *The Journal of the Acoustical Society of America* 139(4). 2212–2213.
Wilson, William. 2013. Assessing Hawaiian. In Antony John Kunnan (ed.), *The companion to language assessment*, 1748–1758. Malden, MA: Wiley.
Wilson, William & Kauanoe Kamanā. 2001. Mai Loko Mai O ka ʻIʻini: Proceeding from a dream. In Leanne Hinton & Ken Hale (eds.), *The green book of language revitalization in practice*, 147–176. Leiden: Brill.
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.
Yee, Thomas W. 2015. *Vector generalized linear and additive models: With an implementation in R*. New York: Springer.
Zhao, Yuan & Dan Jurafsky. 2009. The effect of lexical frequency and Lombard reflex on tone hyperarticulation. *Journal of Phonetics* 37(2). 231–247.
Zuraw, Kie, Kristine M. Yu & Robyn Orfitelli. 2014. The word-level prosody of Samoan. *Phonology* 31(2). 271–327.