Glottal stops before word-initial vowels in American English: distribution and acoustic characteristics

Marc Garellek
(marcgarellek@ucla.edu)

Abstract

Despite abundant research on the distribution of glottal stops and glottalization in English and other languages, it is still unclear which factors matter most in predicting where glottal stops occur. In this study, logistic mixed-effects regression modeling is used to predict the occurrence of word-initial full glottal stops ([ʔ]) vs. no voicing irregularity. The results indicate that prominence and phrasing are overwhelmingly the most important factors in predicting full glottal stop occurrence. Additionally, prominent word-initial vowels that are not preceded by [ʔ] show acoustic correlates of glottal constriction, whereas non-prominent phrase-initial vowels do not. Rather, phrase-initial voicing (even for sonorants) is less regular, but in a manner inconsistent with glottal constriction. Therefore, not all cases of voicing irregularity on word-initial vowels should be attributed to the presence of a glottal stop gesture.

1 Introduction

The goal of this study is to address two issues regarding word-initial glottal stops in American English: which factors are most important in predicting where full glottal stops (plosive [ʔ]) occur, and whether incomplete glottal stops can be detected acoustically. In American English, glottal stops can occur in three phonological positions. First, they occur optionally before vowel-initial words (which I call *word-initial glottalization*), such that 'apple' may be pronounced without a glottal stop as [æpl], or with one as [ʔæpl]. Second, glottal stops also occur during optional *glottal reinforcement* (Higginbottom 1964, Esling et al. 2005, Huffman 2005, Sumner and Samuel 2005), during which coda stops (often unreleased) are produced with simultaneous adduction of the vocal folds. For example, 'cat' may be pronounced [kʰæʔ͡t]. Third, glottal stops occur as an allophone of /t/ post-tonically before syllabic nasals, such that 'button' is usually pronounced [ˈbʌʔn̩].

In this study, I focus on word-initial glottalization, which is found not only in American English, but possibly in all languages that do not contrast /#ʔV/ and /#V/. Although cross-linguistically widespread, it is clear that the frequency of glottal stop insertion before vowel-initial words may differ across languages. For example, it is thought to be rare in Spanish, common in English and German, and almost across-the-board in Czech (Bissiri and Volín 2010, Bissiri et al. 2011, Pompino-Marschall and Żygis 2011).

1.1 Factors that contribute to the occurrence of word-initial glottalization

Many researchers have investigated (for a variety of languages) the factors that promote the occurrence of word-initial glottalization. These may be segmental, lexical, prosodic, or sociolinguistic. In English, segmental factors include hiatus (V#V) environments (Umeda 1978, Dilley et al. 1996, Pierrehumbert 1995, Mompeán and Gómez 2011, Davidson and Erker 2012) and word-initial back vowels are found to glottalize more frequently than non-back vowels (Umeda 1978). As for lexical factors, content words exhibit more frequent glottalization than function words (Umeda 1978). Sociolingusitically, women are known to use glottalization more than men (Byrd 1994, Dilley et al. 1996). Prosodically, the presence of stress and/or a pitch accent on the word-initial vowel, as well as a larger juncture with the preceding word, are known to promote glottalization (Pierrehumbert and Talkin 1992, Pierrehumbert 1995, Dilley et al. 1996). Researchers working on other languages have found additional factors that promote the occurrence of word-initial glottalization, including presence of a preceding pause (Kohler 1994) as well as speech rate and low vowel quality (Brunner and Żygis 2011, Pompino-Marschall and Żygis 2011) for German.

Despite abundant interest in the topic, there has been little investigation of which factors are most important for promoting glottalization. That is, we know what factors play a role in the occurrence of glottalization, but we don't know how important they are compared to each other. Furthermore, some factors are correlated with others, e.g. changes in speech rate are correlated with changes in prosody, and the distinction between function vs. content correlates with differences in lexical frequency. A model predicting glottal stop occurrence should take into account all these factors, and determine which are most important.

1.2 Voicing irregularity vs. incomplete glottal stops

Determining patterns in glottal stop occurrence is difficult, because it is currently unclear what should count as a glottal stop – that is, how to differentiate incomplete glottal stops from other forms of acoustic irregularity. The attested factors mentioned above tend to predict *all* forms of voicing irregularity, including full glottal stops ([ʔ]) as well as any other type of voicing irregularity during vowels (e.g., changes in pulse-to-pulse frequency and/or amplitude). Although full glottal stops [ʔ] are almost certainly a result of a glottal stop target, it is not necessarily the case that all cases of voicing irregularity are too. For example, voicing irregularity can be due to incomplete glottal stops (lenited [ʔ̞]), but also to phrase-final creak (Kreiman 1982, Redi and Shattuck-Hufnagel 2001). Phrase-final creak is articulatorily distinct from glottal stops, in that it may involve abduction rather than adduction of the vocal folds, and may occur on any voiced sound occurring at the end of a phrase (Slifka 2006). Because glottal stops and creak are derived from distinct articulations, it is likely that some of the factors that are known to promote the occurrence of glottal stops/voicing irregularity (as a unified group) in fact increase the likelihood of creak alone. Therefore, the second goal of this study is to determine which cases of acoustic irregularity are due to a glottal stop gesture, and which are due to creak.

As just noted, in most previous studies, many of languages other than English, all forms of voicing irregularity (which I assume can be derived from phrase-final creak or from incomplete glottal stops) are studied as a single group (Bissiri and Volín 2010, Bissiri et al. 2011, Pompino-Marschall and Żygis 2011). This might be due to the fact that phrase-final creak is known largely as an English phenomenon, so researchers might assume that any form of voicing irregularity on a word-initial vowel must be due to word-initial glottalization. I argue here that the potential for creak as the origin of voicing irregularity should not be ignored for any language or in any position. Phrase-final creak occurs when the subglottal pressure is low, and therefore, at the ends of utterances (Slifka 2006). Theoretically, voiced sounds produced with low subglottal pressure can have irregular voicing not from a glottal stop gesture, but because of the low subglottal pressure. The effects of subglottal pressure should be true for any language. This holds not only for the ends of utterances, but also for the start of utterances, where the subglottal pressure is also low. Epstein (2002) found that the start of an English utterance has distinct, tenser voice quality compared to later portions, which suggests that the laxer phonation during creak (as found by Slifka (2006)) may not occur utterance-initially. However, Epstein (2002) did not determine the precise duration and extent of tense phonation, so it is possible that tenseness begins later in the utterance, perhaps to counteract utterance-initial laxness that might be due to low subglottal pressure. The possibility of voicing irregularity due to low subglottal pressure implies that a word-initial vowel with visible creaky voice might be irregular because of phrasal position, and not necessarily because of the presence of a glottal stop gesture.

Therefore, in this study I hope to determine which factors are most important in predicting where full glottal stops occur in English. The second goal is to determine whether the same factors cause laryngealization (phonation with increased glottal closure), such that these factors can be shown to predict not only full [ʔ], but also incomplete glottal stops.

2 Method

In this section, I describe the method used to analyze the differences between full vs. incomplete glottal stops for vowel-initial words in English.

2.1 The Boston University radio news corpus

The corpus analyzed here is the Boston University (BU) Radio News Corpus (Ostendorf et al. 1995). The main motivation for using the BU radio news corpus was the fact that it is labeled for prosody. Another reason was that it has been analyzed for glottalization, both vowel-initial and in all word positions, by Dilley et al. (1996) and Redi and Shattuck-Hufnagel (2001). Thus, comparison with previous work is facilitated by using the same corpus. The section of the corpus used in the present work is from the Labnews corpus, consisting of radio news read in the laboratory. The four speakers analyzed in this study form a subset of the newscasters analyzed by Dilley et al. (1996). Compared with the previous study, one speaker (f3) was not analyzed here due to time constraints. All speakers read the same news reports. The speakers were adults aged 25 to 40 years old, and with no perceived regional accent. Two female speakers (f1a, f2b) and two male speakers (m1b, m2b) are analyzed below.

The speech was digitized using a 16 kHz sampling rate (16 bits). Other corpus details can be found in Dilley et al. (1996). The corpus had already been labeled for prosody using the Tones and Break Indices (ToBI) system by one or two transcribers. For the cases of two transcribers, the inter-transcriber reliability was generally high (Ostendorf et al. 1995).

In the ToBI labeling system the tone and break index tiers provide the core prosodic analysis. The tone tier in Mainstream American English (MAE)-ToBI (Beckman and Ayers Elam 1997) consists of labels for high (H) and low (L) tones marked with diacritics indicating their intonational function as parts of pitch accents (indicated by an asterisk, e.g. H*), as phrase boundary tones, which indicate the edges of intonation phrases (indicated by a following %, e.g. H%) or as intermediate phrase accents, which indicate smaller prosodic phrasal tones (indicated by a following dash, e.g. H-).

The break index tier is used to mark the prosodic grouping of words in an utterance. The end of each word is coded for the perceived strength of its association with the next word, on a scale from 0 (for the strongest perceived juncture) to 4 (for the most disjoint). A break index of 3 usually corresponds to the end of an intermediate phrase (iP) in English, whereas a break index of 4 typically corresponds to the end of an intonation phrase (IP). In MAE-ToBI, a break index of 0 is normally used for the ends of proclitics and function words closely conjoined to the following word, and a break index of 1 for words within the same intermediate phrase. A break index of 2 is used when the perceived tone/break mismatches the perceived grouping, either because a phrase boundary is perceived in the absence of a phrase accent, or because there is a phrase accent in the absence of a perceived phrasal boundary. Because in this corpus the presence of a breath or pause following a break index of 4 was transcribed, I will refer to this as the end of an utterance within a breath group, labeled as break index 5 (cf. Price et al. 1991). The utterance domain above the phrasal one has been shown to exhibit greater levels of prosodic strengthening (Fougeron and Keating 1997, Keating et al. 2003), and thus could be relevant for the present study.

2.2 Coding of the BU news radio corpus for the present study

In the present study, all vowel-initial words were extracted from the corpus. A total of 2087 vowel-initial words were extracted for the four speakers, as shown in Table 4. This number is smaller than that analyzed by Dilley et al. (1996) because, due to time constraints, not all the paragraphs from the Labnews corpus were analyzed. In addition to word-initial vowels, 1298 word-initial sonorants (/j, w, l, ɹ, m, n/) were extracted, as well as the following vowels. For example, for a word like *Massachusetts*, the initial /m/ and following /æ/ were extracted from the corpus. Sonorant-initial words will be used to determine whether word-initial glottalization is found for all voiced sounds. In total, 1291 vowels following word-initial sonorants were extracted. This means that seven post-sonorant vowels were not extracted from the total of 1298 sonorant-initial words. These were all cases of a sonorant followed by a syllabic [ɫ̩] (e.g. *will* pronounced as [wɫ̩]), where the boundary between vowel and coda was hard to determine or did not exist.

The corpus was then coded by two undergraduate research assistants trained at labeling acoustic irregularity. The coders were unaware of the purpose of the study, and thus were unbiased in their coding. In addition to coding for presence and type of irregularity (to be described below), the coders also transcribed the presence of a variety of other factors, described in further detail below. I then reviewed the corpus data and arbitrated on between-coder differences. The agreement rate for codings of irregularity was over 90%.

Generally, the coding of voicing irregularity followed that described by Dilley et al. (1996) and Redi and Shattuck-Hufnagel (2001). First, the coders rated whether there was a percept of 'glottalization', regardless of whether the percept was due to a glottal stop. Tokens with weak percepts of glottalization with no clear acoustic evidence for voicing irregularity were labeled as glottalized, unlike in Dilley et al. (1996), where such tokens were excluded from the analysis. We included these tokens for the purposes of the quantitative analysis described below. Such tokens represented only 2% of total words in the corpus, and therefore were unlikely to have a significant influence on the subsequent analysis.

Second, if there was a percept of glottalization, the coders labeled the *type* of aperiodicity found, based on inspection of the waveform. This labeling provides visual support for the percept of glottalization, but the individual types of aperiodicity will not be analyzed below. Four types were identified, three of which (aperiodicity, diplophonia, and creak) following the description by Redi and Shattuck-Hufnagel (2001). *Aperiodicity* is defined as pulse-to-pulse irregularity, either as jitter or as visible noise. *Diplophonia* refers to irregularity characterized by regular alternation in shape, duration, or amplitude of glottal periods. Thus, for diplophonia the pulse-to-pulse alternation is sustained, in contrast to the sudden, unpredictable changes to pulse shape found for 'aperiodicity.' *Creak* refers to low F0 accompanied by near-total damping of glottal pulses, commonly (but not exclusively) found phrase-finally. Redi and Shattuck-Hufnagel (2001) identify another type of irregularity which they term *glottal squeak*, but such cases were not found in this corpus, probably because in that study the authors identified cases of irregularity occurring anywhere in a word, not just word-initially. Together, aperiodicity, diplophonia, creak (and squeak) represent the cases of *voicing irregularity*. In this study, a *full glottal stop* was also identified. In the corpus, [ʔ] only occurred before word-initial vowels; no cases of [ʔ] as an allophone of /t/ were extracted. Thus, [ʔ] was characterized by a period of silence of at least two pulses, followed by a burst and subsequent onset of phonation (due to the following vowel) which becomes increasingly modal. If preceded by a voiced sound, the glottal stop often showed an impulse (visually distinct from the pulses belonging to the preceding voiced sound) right before the glottal closure (evidenced by the absence of a signal in the waveform). This likely corresponds to the energy produced by the abrupt closure of the vocal folds. An example of [ʔ] is shown in Figure 1.

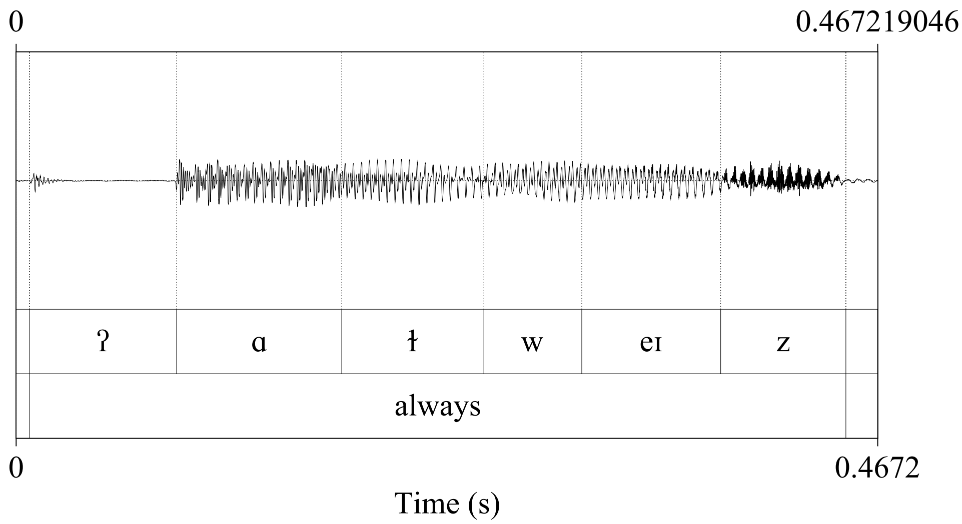

Figure 1: Example of a glottal stop at the onset of ‘always,’ uttered by speaker f1a.

In principle, it is difficult to determine, for a vowel-vowel sequence with creak between the two vowels, whether any of the creaky pulses are in fact the burst of a glottal stop. However, in practice such difficulty differentiating creak from full glottal stops rarely arose. Pulses during creak, though irregular in period, were not separated by more than a two-pulse period of silence. Thus, there was rarely a debate whether a sequence of two vowels corresponded to [v̰#v] vs. [v̰#ʔv]. These problematic cases corresponded to 8-10 incidents, and were labeled conservatively as just having creak.

Different types of irregularity were sometimes found for the same segment, and so multiple types could be coded per token. For example, diplophonia was sometimes found during intervals of creak. Additionally, aperiodic and/or creak-like phonation was sometimes found after a glottal stop. For example, in Figure 1, the vowel following the glottal stop begins with aperiodicity.

2.3 Other factors in the analysis

In addition to coding for presence and type of glottalization, the coders also recorded prosodic, lexical, and segmental information. The prosodic factors are summarized in Table 1. The factor ‘prominence’ refers to a syllable with prosodic prominence, either due to the presence of a pitch accent, or if the syllable belonged to a function word, but had an unreduced vowel (e.g. [ænd] for *and*), or both. Thus, prominence represents a superset of pitch-accented syllables. The reason for including this factor was that some vowels had perceived prominence, but no pitch accent was marked in the BU Corpus. Further inspection sometimes revealed a pitch excursion indicative of a potential pitch accent despite none being coded, but usually the vowel was unreduced, which is unexpected for function words. The absence of expected vowel reduction is not typically used as a cue for vowel prominence, but the coders agreed that these words were more prominent than expected. Often these words occurred phrase-initially, suggesting that the absence of vowel reduction is related to phrase-initial strengthening (Cho and Keating 2009). Thus, in phrase-initial position, vowels – even when not pitch-accented – are nonetheless more strongly articulated and thus more perceptually prominent than they would be phrase-medially.

Aside from prosodic factors, lexical and segmental factors were also included, and they are summarized in Table 2. Lexical frequencies were taken from the SUBTLEX$_{\mathrm{WF}}$-US corpus, whose lexical frequencies are thought to be more representative of currently-spoken English than are those from older corpora (Brysbaert and New 2009).

Table 1: Prosodic analysis factors.

Factor	Explanation
Preceding break index	Break index (from 0-5) between target word and prec. word
Following break index	Break index (from 0-5) between target word and foll. word
Pitch accent	Presence of pitch accent on target syllable
Pitch accent type	Type of pitch accent on target syllable (H*, L*, etc.)
Prominence	Presence of a pitch accent and/or unreduced, stressed vowel
Boundary tone	Presence of boundary tone/phrase accent on target syllable
Boundary tone type	Type of boundary tone/phrase accent on target syllable
Preceding pause	Presence of a pause before target syllable
Preceding glot.	Presence of glottalization-like irregularity on preceding syllable

Table 2: Segmental and lexical factors in the analysis.

Factor	Explanation
Vowel	The type of vowel in the target syllable
Vowel height	Whether the target vowel was high, mid, or low
Vowel frontness	Whether the target vowel was front, central, or back
Vowel length	Whether the target vowel was tense or lax
Word	The word containing the target syllable
Log frequency of word	Log frequency of target word
Word type	Whether target word a content or function word
Preceding sound	Final sound of preceding word
Hiatus	Potential for hiatus (i.e. prec. sound was a vowel)
Vowel quality of prec. vowel	Height, frontness, and length of prec. vowel.
Prec. word	The word preceding the target syllable
Log freq. of prec. word	Log frequency of the prec. word
Prec. word type	Whether prec. word was content or function word

2.4 Acoustic measures

In addition to the qualitative factors mentioned above, I obtained quantitative data from acoustic measures to provide a gradient analysis of the strength of glottalization. These measures can also help determine which cases of voicing irregularity are in fact lenited stops [ʔ̰] vs. phrasal creak, provided the two differ in their acoustic realization. The acoustic measures included in the analysis, along with their relation to voice quality, are described in Table 3. To obtain the measures, the coders manually segmented the word-initial vowels in the corpus. Although segment boundaries had already been provided in the corpus, many had been aligned automatically, and many files had not been checked for segment boundaries. VoiceSauce (Shue et al. 2011) was then run over the entire sound file (not just the labeled vowels), because many tokens were so short that they required longer windows of analysis in order to obtain acoustic measures. The acoustic measures were then averaged over the entire vowel's duration.

If voicing irregularity in the corpus is only due to increased adduction (i.e., a glottal stop target), the spectral and noise measures listed in Table 3 are expected to be lower than for vowels with no voicing irregularity. In addition, laryngealized phonation often involves a decrease in fundamental frequency or F0. In particular, voicing with increased closure typically shows lower values of H1*-H2* (Garellek and Keating 2011), and lower values of the measure (either corrected or uncorrected for vowel formants) are correlated with higher values of flow adduction quotient (Holmberg et al. 1995), increased values of EGG contact quotient (DiCanio 2009, Kuang 2011, Esposito 2012), and lower open quotient derived from glottal area (Shue et al. 2010). Therefore, H1*-H2* is taken to be the likeliest acoustic measure to be correlated with increased glottal closure.

Table 3: Acoustic measures in the analysis. Asterisks indicate measures corrected for formants.

Measure	Explanation	Relation to voice quality
F0	Fundamental frequency	Pitch, correlated with prosodic tones and stress
Duration	Length of vowel	Correlated with prominence, prosodic position (Cole et al. 2010)
H1*-H2*	Difference between amplitudes of first two harmonics	Thought to be positively correlated with open quotient (OQ) (Holmberg et al. 1995)
H2*-H4*	Difference between amplitudes of second and fourth harmonics	Thought to be correlated with vocal fold stiffness (Zhang et al. 2011), and used in the perception of breathiness (Kreiman et al. 2011)
H1*-A1*	Difference in amplitudes of first harmonic and harmonic nearest F1	Correlated with breathiness, thought to be related to presence of a posterior gap (Hanson et al. 2001)
H1*-A2* H1*-A3*	Difference in amplitudes of first harmonic and harmonic nearest F2, F3	Correlated with overall spectral tilt, perhaps due to abruptness of closure (Stevens 1977, Hanson et al. 2001)
CPP	Noise measure	Correlated with modal vs. non-modal voice (Garellek and Keating 2011)
HNR	Noise measure (in four spectral bands)	Correlated with modal vs. non-modal voice (Garellek and Keating 2011)
Energy	Measure of loudness	Correlated with prominence (Kochanski et al. 2005)

3 Results

Of the 2010 vowel-initial words extracted from the corpus, 1060 or 53% showed at least one form of irregularity. Only 300 or about 15% of all word-initial vowels had full glottal stops. Vowel-initial words showing a form of voicing irregularity with no glottal stop accounted for 37% of all vowel-initial words and about 72% of cases of irregular word-initial vowels (vowels with a glottal stop, aperiodicity, diplophonia, and/or creak). Not surprisingly, none of the vowels after sonorants (e.g., the /æ/ in *Massachusetts*) had glottal stops, but about 20% showed voicing irregularity. 30% of the sonorants had irregular voicing, and only three cases of glottal stops before sonorants were documented. This number is virtually negligible, and these cases are likely instances of creak with a long lag between the first pulse and the next. Across speakers, the rates of voicing irregularity and glottal stops were 27% of all tokens for f1a, 39% for f2b, 26% for m1b, and 31% for m2b. The distribution of [ʔ] and other forms of glottalization is shown in Table 4, and the proportion of each type of irregularity for initial vowels, sonorants, and post-sonorant vowels is shown in Figure 2. The glottalization rates are similar to those found by Dilley et al. (1996) in their analysis of the same corpus, though they did not look specifically at cases of full [ʔ]. The rate of full [ʔ] occurrence is larger here than what was found for two British English speakers by Bissiri and Volín (2010), but smaller than was found in German by Pompino-Marschall and Żygis (2011).

Table 4: Distribution of tokens and irregularity across the four speakers. Tokens with a full glottal stop [ʔ] vs. forms of voicing irregularity ([ʔ̰, ̰]) are indicated in parentheses.

	Speaker	Total number of tokens	Word-initial vowels	Word-initial sonorants	Vowels after word-initial sonorants
	f1a	944 (126; 148)	395 (125; 89)	283 (1; 23)	266 (0; 36)
	f2b	1281 (82; 421)	568 (81; 285)	356 (1; 60)	357 (0; 76)
	m1b	1128 (30; 263)	512 (30; 199)	309 (0; 14)	307 (0; 48)
	m2b	1246 (65; 316)	535 (64; 185)	350 (1; 37)	361 (0; 94)
Total		4599 (303; 1149)	2010 (300; 760)	1298 (3; 391)	1291 (0; 254)

3.1 Predicting full glottal stop occurrence

To predict where full glottal stops [ʔ] occur, the data were first subset into cases of word-initial vowels with either a full [ʔ] and cases of no perceived/visual voicing irregularity. A mixed-effects logistic regression model was fitted to these data using the *lmer()* function in the *lme4* package (Bates et al. 2008) in *R* (R Development Core Team 2011), following Baayen (2008). The model's dependent variable was presence of [ʔ] vs. no perceived/visual voicing irregularity, and had 14 independent variables from the factors listed in Tables 1 and 2 above: previous break, pitch accent, prominence, hiatus, following break, word type, vowel height, length, and backness, presence of preceding pause and glottalization, word frequency, preceding word frequency, and preceding word type. An interaction term (presence of hiatus:preceding glottalization) was included because it improved the model's fit (which was assessed by the *anova* function in *R*, following Baayen (2008)). Speaker and word were included as random intercepts. The results are shown in Table 5. The coefficient estimates indicate the direction of significance, with a positive coefficient indicating an increase in the odds of there being a full glottal stop. Both an increase in preceding break

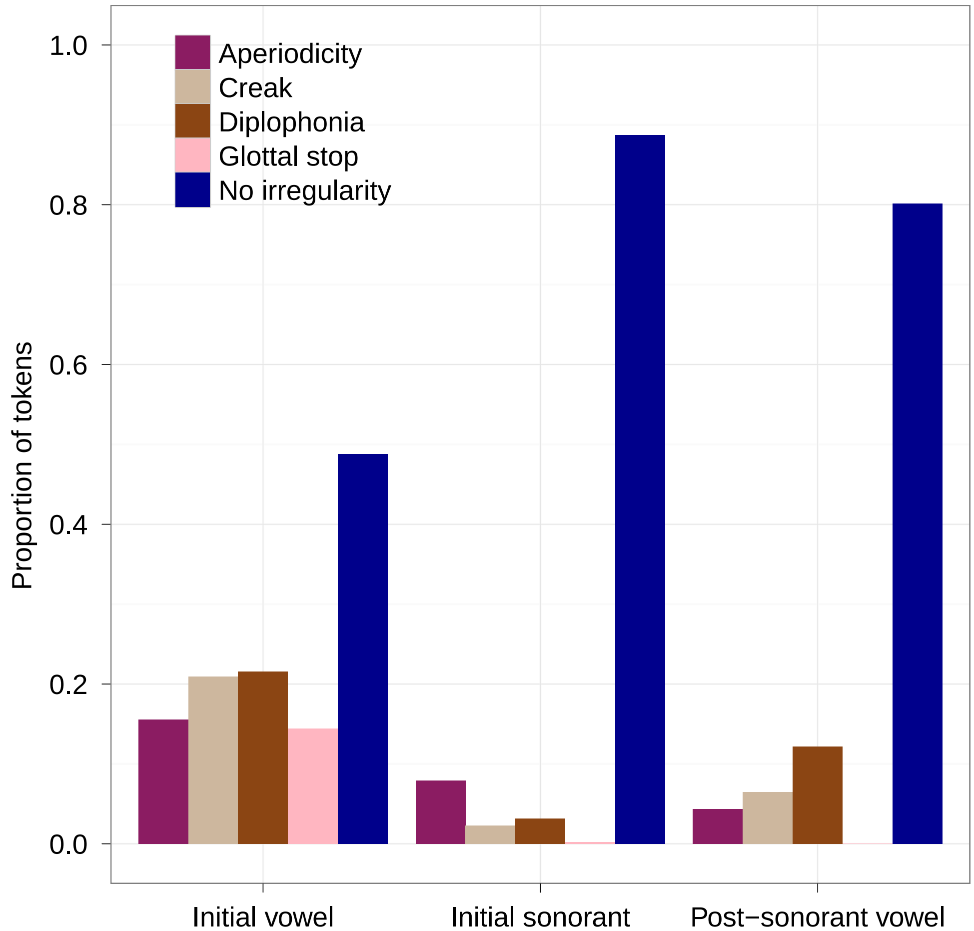

Figure 2: Proportion of each type of irregularity for word-initial vowels, word-initial sonorants, and post-sonorant vowels. More than one type of irregularity can be present on a given token, so the sum of irregularity types can exceed 1.

index and presence of prominence on the following vowel increased the likelihood of glottal stop occurrence, and these factors were the most significant in the model. The effects of phrasal domain and prominence can be seen in Figure 3. Prominent vowels were more likely to be preceded by [ʔ], regardless of the preceding break. But the phrasal domain was also significant, with rates of glottal stop occurrence decreasing with a decrease in preceding break index.

Other significant predictors included presence of a preceding pause and preceding 'glottalization,' both of which increased the likelihood of obtaining a full [ʔ]. A preceding pause might increase the likelihood of a glottal stop for two reasons. First, pauses had already been marked in the corpus, but it was apparent to the coders that some of these represented the closure durations for glottal stops rather than true pauses. Second, true pauses increase the dissociation between two words, such that a break index of 4 with no pause is weaker than a 4 followed by a pause. Preceding glottalization (mostly from phrase-final creak) might increase the likelihood of there being a following glottal stop because the vocal folds are mostly abducted and closing irregularly during creak (Slifka 2006). Thus, vocal fold closure for [ʔ] could help resume phonation after a period

Table 5: Results of logistic regression model predicting occurrence of [ʔ] vs. no glottalization for vowel-initial words.

	Coef β	SE(β)	**z**	**p**
Intercept	−6.15	1.24	−5.0	**<.0001**
Preceding break	1.19	0.14	8.4	**<.0001**
Hiatus=Y	−0.06	0.41	−0.1	>0.9
Accent=Y	0.41	0.31	1.3	>0.2
Prominence=Y	4.03	0.38	10.6	**<.0001**
Preceding glottalization=Y	1.26	0.32	3.9	**<.0001**
Following break	0.24	0.13	1.8	>0.1
Word type=function	−0.03	0.60	0.0	>1
Vowel frontness=front	0.26	0.64	0.4	>0.7
Vowel frontness=central	1.00	0.76	1.3	>0.2
Vowel height=low	0.57	0.52	1.1	>0.3
Vowel height=mid	−0.08	0.56	−0.1	>0.9
Vowel length=lax	0.06	0.54	0.1	>0.9
Preceding pause=Y	2.12	0.40	5.3	**<.0001**
Log freq. word	−0.22	0.19	−1.1	>0.3
Log freq. preceding word	−0.30	0.16	−1.9	>0.1
Preceding word type=function	1.15	0.47	2.4	**<.05**
Hiatus=Y:Preceding glottalization=Y	1.96	0.75	2.6	**<.01**

of creak if the vocal folds are vibrating irregularly. There was a significant interaction between preceding glottalization and vowel-vowel hiatus, as shown in Figure 4. A hiatus environment (i.e. a vowel-initial word that was preceded by a word ending in a vowel) was found to be a significant predictor of full [ʔ] only when the preceding word ended in glottalization (i.e., with some form of irregularity).

The final predictor to emerge as significant from the model (though much less so than prominence or preceding break) was the preceding word type. A preceding function word (compared to a content word) increased the likelihood of a word-initial vowel's being preceded by a full glottal stop, possibly because a glottal stop will render the vowel-initial word more prominent by preventing the function word from becoming a proclitic on the target word. For example, the sequence 'the only' is likely to be pronounced without a clear boundary between the determiner and the adjective ([ðioʊnli]). If produced with a full glottal stop ([ðəʔoʊnli]), the boundary between the determiner and the adjective is clearly defined, which might increase the degree of perceived prominence of the content word to listeners because the function word has not become a proclitic.

The relative importance of each of the significant factors was also assessed by comparing the full model to smaller models, each lacking one of the significant factors. This form of model comparison, done by means of the *anova* function in *R*, provides a chi-squared statistic and p-value indicating whether the full model provides a significantly better fit to the data than the model with a factor removed (Baayen 2008). The results mirror the z-scores of the estimates in the full model, indicating that the most important factors are, in order, prominence > preceding break > preceding glottalization > preceding pause > hiatus > preceding word type.

In sum, full glottal stops are more likely to occur when the vowel-initial word is phrase-initial and when the vowel is prominent. Preceding pauses or glottalization, hiatus, and the preceding

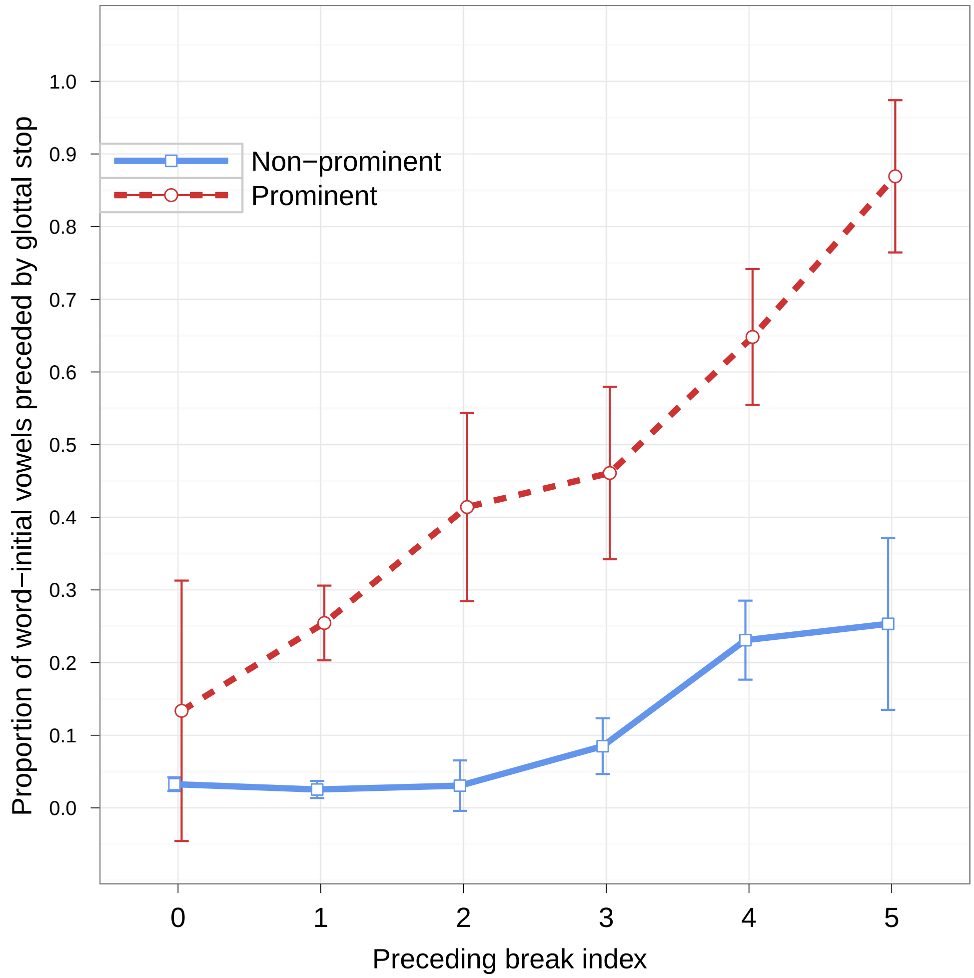

Figure 3: Proportion [ʔ] for vowel-initial words as a function of preceding break index and prominence. Error bars indicate 95% confidence intervals.

word type were also found to be significant predictors of full glottal stops, but much less so than prominence and preceding break index. By considering only the effects of prominence and phrasal position, it is possible to account for 95% of cases of [ʔ], as shown in Figure 5. Prominence alone is able to account for three quarters of cases, and phrase-initial position for nearly seven of ten cases.

Knowing now that the vast majority of full glottal stops occur in prominent and/or phrase-initial environments, I will look at cases of word-initial vowels *without* full glottal stops to determine if they show voice quality that is characteristic of laryngealization, i.e. voicing with longer vocal fold closure. If they do, I assume that the laryngealization in prominent and/or phase-initial environments is due to incomplete glottal stops ([ʔ̰]), because these same environments are known to be the most important factors in predicting full glottal stops. First I will look at the voice quality of vowels that are preceded by [ʔ], to use as the basis for comparison.

3.2 Voice quality of vowels following [ʔ]

Although it is not possible to obtain acoustic measures of voice quality for a (voiceless) [ʔ], the voice quality of the following vowel can be investigated. To do so, I ran a logistic regression

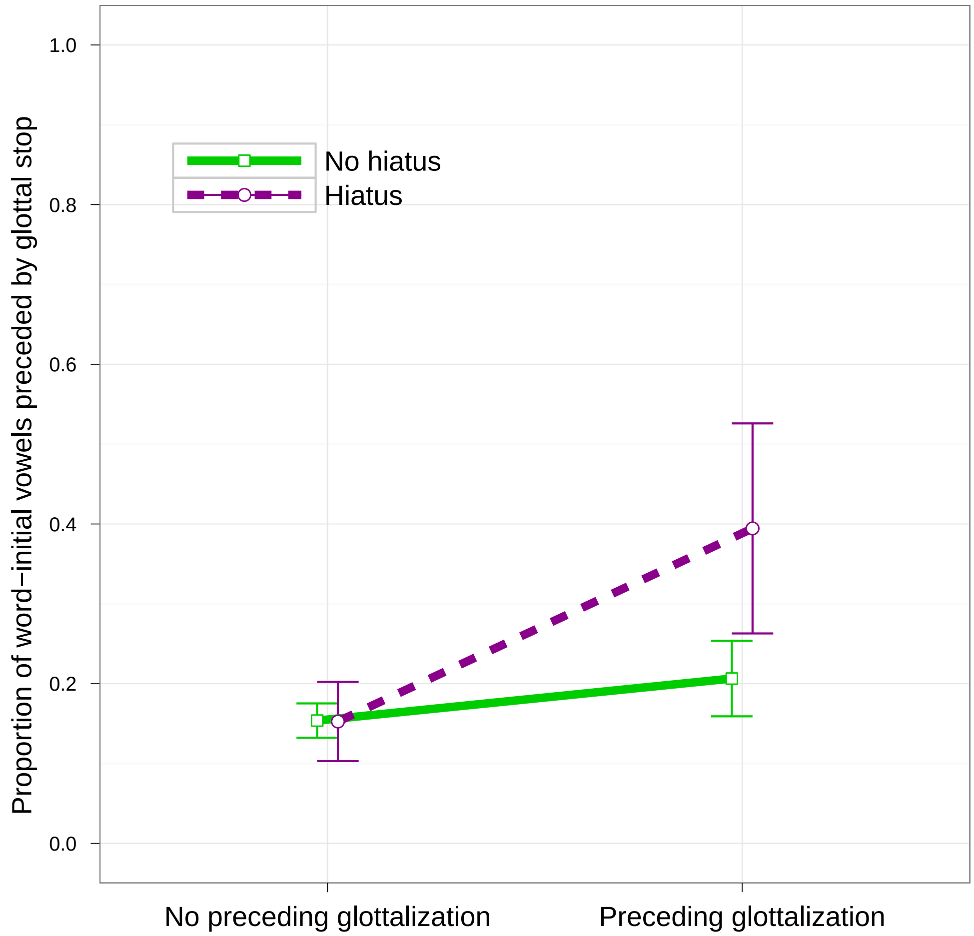

Figure 4: Interaction between vowel hiatus and preceding glottalization in the occurrence of [ʔ]. Error bars indicate 95% confidence intervals.

model predicting [ʔ] vs. no glottalization to determine which acoustic measures differentiate vowels following glottal stops from sounds with no visual/auditory cues to glottalization. A logistic mixed-effects model was fitted to the data, with [ʔ] vs. no glottalization as the dependent variable, the 13 acoustic measures (listed in Table 3) as fixed effects, and item, sound, and speaker as random intercepts. In addition, a random slope of duration by speaker was included because it improved the model's fit. No interaction terms between any acoustic measures significantly improved model fit. The results are shown in Table 6. Many acoustic measures differentiated vowels following [ʔ] from other sounds. The most important factor was duration, which is longer for vowels following [ʔ] than for vowels with no glottalization. This is probably an effect of prominence, given that duration is a known correlate of prominence (see Turk and Sawusch (1996), Fant et al. (2000), Cole et al. (2010), and references therein), or of phrasal position. HNR <1500Hz, H1*-A2*, and H1*-H2* are significantly lower for vowels following [ʔ], consistent with the idea that vowels after a glottal stop are laryngealized. Interestingly, HNR <2500 Hz was significantly higher for these vowels, which must be due to a boost in harmonic energy in the frequencies between 1500 Hz and 2500 Hz. The abrupt closure of the vocal folds during laryngealization is known to increase energy in the higher frequencies (Kreiman and Sidtis 2011), and these results imply that the energy boost

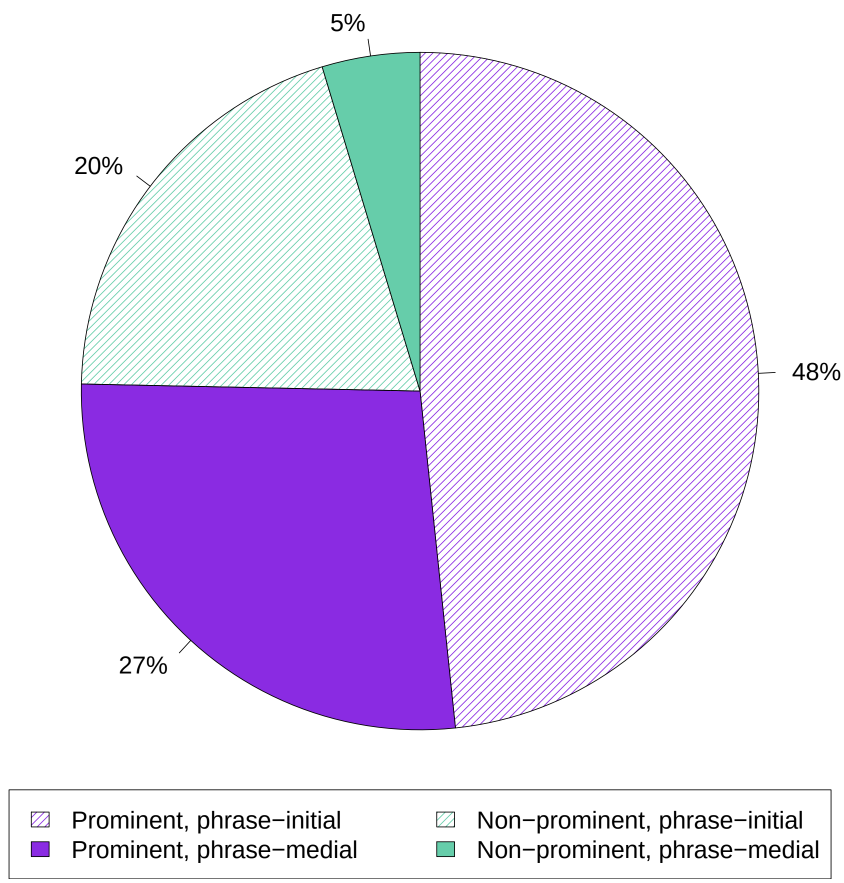

Figure 5: Distribution of full glottal stops [ʔ] as a function of prominence and phrasal position. Prominence (violet dashed and solid slices) accounts for 75% of the occurrences [ʔ], phrase-initial position (dashed slices) accounts for 68% of occurrences. 95% of full glottal stops can be attributed either to prominence, or phrase-initial position, or to both.

is within the 1500 Hz to 2500 Hz range.

Another surprising finding is that H1*-A1* was higher for vowels following [ʔ]. Higher values of H1*-A1* might relate to posterior opening of the cartilaginous glottis, with higher values of the measure correlated with larger posterior gaps and thus breathiness (Hanson et al. 2001). Activation of the vocal fold abductor muscle (the PCA) is known to occur before the release of a hard glottal attack, and this activation forces the arytenoids apart (Hirose and Gay 1973), perhaps causing H1*-A1* to rise.

Finally, the decrease in energy in vowels following [ʔ] is attributed to laryngealization following the release of the glottal stop (as suggested by the lower values of H1*-H2* and H1*-A2*). Therefore, although most of these vowels following [ʔ] are prominent, and loudness is a cue to

Table 6: Significance of the fixed effects in the logistic model predicting vowels following [ʔ] vs. initial vowels with no glottalization from the acoustic measures.

	Coef β	SE(β)	**z**	**p**
Intercept	−6.65	0.59	−11.2	**<.0001**
H1*-H2*	−0.11	0.05	−2.1	**<.05**
H2*-H4*	0.05	0.04	1.3	>0.2
H1*-A1*	0.14	0.05	3.1	**<.01**
H1*-A2*	−0.22	0.04	−5.5	**<.0001**
H1*-A3*	0.04	0.02	1.7	>0.1
F0	0.02	0.00	4.1	**<.0001**
Duration	0.04	0.01	7.5	**<.0001**
HNR < 500Hz	−0.02	0.05	−0.4	>0.7
HNR < 1500Hz	−0.44	0.08	−5.6	**<.0001**
HNR < 2500Hz	0.33	0.13	2.5	**<.05**
HNR < 3500Hz	−0.17	0.10	−1.7	>0.1
CPP	−0.27	0.08	−3.4	**<.001**
Energy	−0.36	0.13	−2.8	**<.01**

prominence (Kochanski et al. 2005; but cf. Turk and Sawusch 1996), vowels following [ʔ] are not louder, probably because of the laryngealized voice quality, which often shows a decrease in energy (Gordon and Ladefoged 2001).

Thus, vowels following [ʔ] show acoustic characteristics typical of laryngealized phonation produced with increased glottal closure and aperiodicity. These effects are strong enough to affect the voice quality measures after they have been averaged over the entire vowel's duration. One notable exception is that H1*-A1* is higher for these vowels, which could be due to abduction of the arytenoids necessary to resume phonation after a glottal stop.

Knowing now what factors predict full [ʔ], and what the acoustic consequences of glottal stops on following vowels are, we can investigate which cases of voicing irregularity are consistent with incomplete glottal stops [ʔ̞].

3.3 Acoustic effects of prominence vs. phrasal strengthening on word-initial vowels

The results from Section 3.1 show that the frequency of occurrence of a glottal stop can be affected mostly by prominence and phrasal domain. If these environments are the most important predictors of full [ʔ], I hypothesize that they should also be good predictors of incomplete [ʔ̞] as well. To test this, I look at the voice quality of vowels without a full [ʔ], to see if they show characteristics of laryngealization, which would be consistent with the presence of an incomplete glottal stop. Note that by 'laryngealization' I refer specifically to voice quality with increased glottal closure.

What acoustically would support the claim that a vowel shows increased closure? Recall from Section 2.4 that H1*-H2* is taken to be the likeliest acoustic measure to be correlated with increased glottal closure. Indeed, lower values of H1*-H2* are found for vowels following full [ʔ], as shown in Table 6. To test if lower values of H1*-H2* are associated with prominence on vowel-initial words that are not preceded by [ʔ], I fitted a linear mixed-effects model predicting H1*-H2* as a function of the prominence and phrasing (preceding break index). Speaker, sound, and word were included as random intercepts, as well as a random slope of F0 by speaker. A larger random structure did not improve the model's fit, nor did including a prominence*phrasing interaction term. Because MCMC sampling is not yet implemented for models with random correlation parameters, a t-value greater than 2 or less than -2 is considered significant (Baayen 2008). The results of the linear model are shown in Table 7.

Table 7: Results of the linear regression model predicting H1*-H2* as a function of prominence and preceding break index for word-initial vowels with no preceding [ʔ].

	Coef β	SE(β)	t-value
Intercept	2.32	0.54	**4.27***
Prominence=Y	−0.70	0.21	**-3.39***
Preceding break index=increasing	0.11	0.06	1.83

The results of the linear regression analysis show that H1*-H2* is lower under prominence, but no significant change is found for the effect of phrasing. This is consistent with the idea that all prominent word-initial vowels – even those with no [ʔ] – are produced with increased vocal fold adduction. A large preceding break index is associated with an increase in H1*-H2*, though this pattern is not significant. This is inconsistent with the assumption that higher prosodic phrases triggers an increase in glottal stops. Therefore, for word-initial vowels that are not preceded by [ʔ], prominence induces greater laryngealization (based on lower values of H1*-H2*), whereas higher prosodic domains do not. The main effects of prominence and prosodic domain on H1*-H2* are illustrated in Figure 6. Prominent word-initial vowels have significantly lower values of H1*-H2*, but (non-prominent) phrase-initial vowels show no change in H1*-H2* relative to phrase-initial non-prominent vowels.

If prominence (rather than prosodic domain) is associated with incomplete glottal stops, why are full glottal stops [ʔ] more likely phrase-initially? Based on the acoustic findings of this section, I assume that prominence is responsible for the presence of a glottal stop gesture, which may be realized either incompletely as [ʔ̰] or as full glottal stop [ʔ]. On the other hand, phrasal position accounts mostly for prosodic strengthening, which results in more instances of *full* glottal stops phrase- and utterance-initially than phrase-medially. However, some cases of [ʔ] are found before non-prominent initial vowels: over 20% after break index 4 (IP-initial) have full [ʔ]. This issue will be discussed more in Section 4 below. In the following section, I look at word-initial sonorants, to determine whether their voice quality is similarly affected by prominence and phrasal domain.

3.4 Acoustic effects of prominence vs. phrasal strengthening on word-initial sonorants and their following vowels

If the lowering of H1*-H2* for prominent vowel-initial words is due to a glottal stop gesture, then we would expect that such lowering would not occur for word-initial sonorants or their following vowels, because these positions are never preceded by a glottal stop in English. To test this, I fitted a linear mixed-effects model to both word-initial sonorants or their following vowels, in order to predict H1*-H2* as a function of the prominence and phrasing (preceding break index). Speaker, sound, and word were included as random intercepts, as well as a random slope of F0 by speaker. These models are identical in structure to that fitted to the word-initial vowels. For word-initial

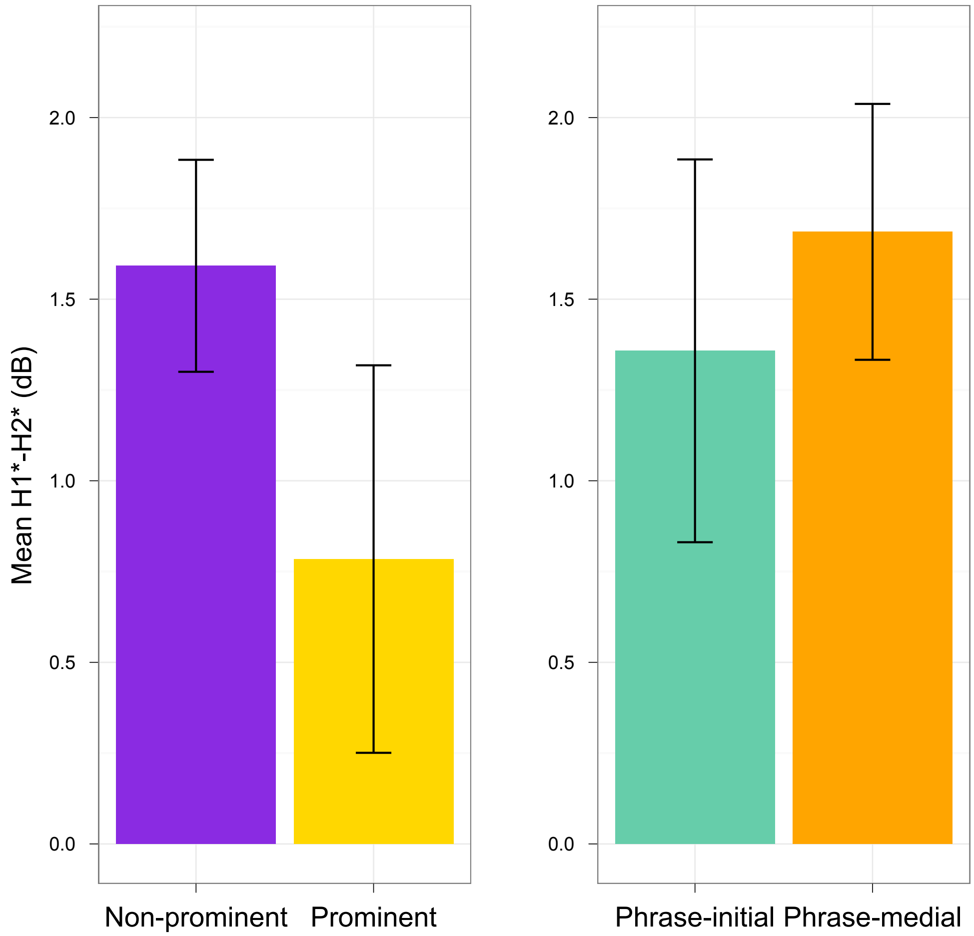

Figure 6: H1*-H2* as a function of prominence and phrasing. Error bars indicate 95% confidence intervals. The difference in H1*-H2* as a function of prominence is significant; no difference as a function of phrasing is found.

sonorants, both H1*-H2* and uncorrected H1-H2 were used as the dependent variable, because formant tracking errors during the sonorants affected the values of (corrected) H1*-H2*.

The results (Table 8) show no change in H1*-H2* as a function of prominence for word-initial sonorants or their following vowels. The same was true when uncorrected H1-H2 was used as the dependent variable for the word-initial sonorants (Table 8b). However, a higher preceding break index was found to induce higher values of H1*-H2* for post-sonorant vowels (Table 8a), and higher values of uncorrected H1-H2 for word-initial sonorants.

These results show that, unlike for word-initial vowels, H1*-H2* is not lower under prominence. This is consistent with the hypothesis that only word-initial vowels should show laryngealization, because only they are preceded by a glottal stop gesture. The increase in H1*-H2*/H1-H2 as a function of phrasing for word-initial sonorants and their following vowels suggests that phrase-initial voicing is generally breathier. The effects of phrasing on the noise measure CPP support this. As seen in Figure 7, CPP is lower at higher break indices for *all* voiced segments. Therefore, the acoustic effect of phrasing on voice quality is an increase in H1*-H2* and a decrease in CPP, consistent with the idea that phrase-initial voicing has a higher open quotient and more noise.

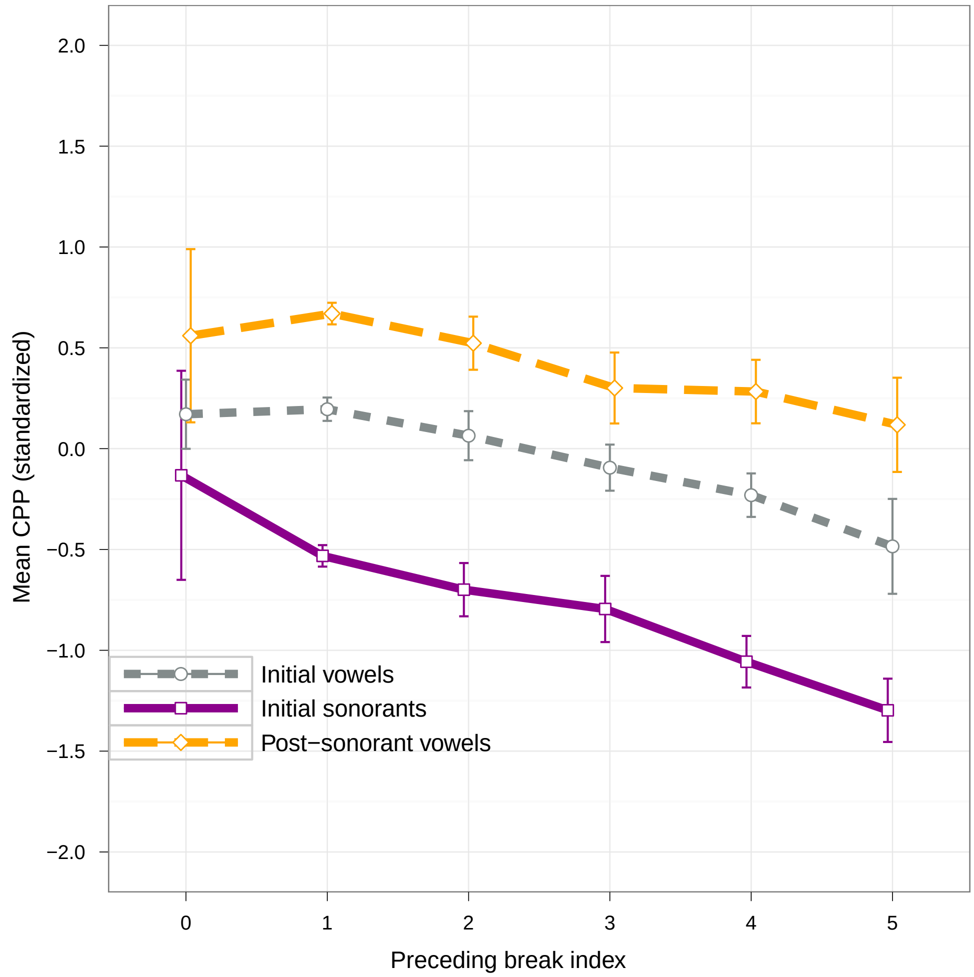

Figure 7: CPP as a function of preceding break index for word-initial vowels, word-initial sonorants, and vowels following word-initial sonorants ('post-sonorant' vowels). Error bars indicate 95% confidence intervals.

4 Discussion

This study sought to answer two questions regarding word-initial glottal stops:

1. Which factors matter most in predicting the occurrence of glottal stops?
2. Which cases of voicing irregularity are due to glottal stop gestures that have been realized with incomplete closure?

I claim that, because in English voicing irregularity can be due not only to glottal stop gestures but also to phrasal creak, the factors that best predict glottal stops should be investigated first only for full glottal stops [ʔ]. The results from Section 3.1 show that [ʔ] is predicted largely by prominence and phrase-initial position, which together can account for 95% of cases of full glottal

	Coef β	SE(β)	t-value
Intercept	3.44	0.59	**5.82***
Prominence=Y	0.07	0.21	0.34
Preceding break index=increasing	0.04	0.08	0.44

(a) H1*-H2* for word-initial sonorants.

	Coef β	SE(β)	t-value
Intercept	−1.83	0.49	**-3.77***
Prominence=Y	0.02	0.18	0.12
Preceding break index=increasing	0.76	0.07	**10.76***

(b) H1-H2 (uncorrected) for word-initial sonorants.

	Coef β	SE(β)	t-value
Intercept	1.85	0.42	**4.42***
Prominence=Y	0.11	0.18	0.60
Preceding break index=increasing	0.19	0.07	**2.76***

(c) H1*-H2* for post-sonorant vowels.

Table 8: Results of the linear regression model predicting H1*-H2*/H1-H2 as a function of prominence and preceding break index for word-initial sonorants and post-sonorant vowels.

stops. This finding is in line with previous researchers, who have shown that prominence (accent or stress) and phrasing are important in predicting glottal stops and/or glottalization (Pierrehumbert and Talkin 1992, Pierrehumbert 1995, Dilley et al. 1996, Redi and Shattuck-Hufnagel 2001).

To determine which cases of voicing irregularity could be due to glottal stops that have been realized incompletely, in Section 3.3 I looked at the effects of prominence and phrasal position on the acoustic properties of word-initial vowels. I focused on these two factors because they are by far the most important factors in predicting full [ʔ] occurrence, and are therefore also likely to predict occurrences of incomplete [ʔ̞]. The results show that prominence can in fact be used to predict laryngealization that is typical of voicing with increased glottal closure. However, this is only true for word-initial vowels. This result is expected if prominent word-initial vowels are likely to be preceded by a glottal stop gesture. In contrast, word-initial sonorants and their following vowels do not show laryngealized phonation when prominent. Indeed, they are also never preceded by a full glottal stop.

On the other hand, phrasing does not seem to affect the voice quality of initial vowels differently than initial sonorants or their following vowels. Instead, all voiced segments show noisier phonation at the onset of higher prosodic domains, as shown in Figure 7. This does not mean that phrasing never accounts for the presence of a glottal stop. As shown in Figures 3 and 5, about 20% of phrase-initial *non-prominent* vowels are preceded by full glottal stops, and about the same percentage of cases of [ʔ] can be explained by phrasing and not by prominence. However, in general, onsets of higher prosodic domains yield noisier phonation that is more characteristic of creak with increased abduction, because the noisier phonation is found for all initial voiced segments (indeed, even when averaged over the entire first syllable).

4.1 Glottal stops and prosodic strengthening

The results of this study indicate that glottal stops (before word-initial vowels) are largely dependent on prosody. They are more common and more likely to be realized as full stops when the following vowel is prominent and phrase-initial. Nevertheless, phrasal domain and prominence have distinct influences on word-initial vowels: prominence appears to be responsible for the glottal stop gesture, regardless of the phrasal domain in which the vowel-initial word is located. On the other hand, prosodic domain is associated mostly with the strength of the glottal gesture, such that a glottal stop is more likely to be realized with full constriction phrase- and utterance-initially than phrase-medially. All phrase-initial voiced segments tend to have irregular voicing. Thus, the presence of acoustic irregularity cannot be taken as indication of a glottal stop gesture in English. It seems that the clearest indication of the presence of a glottal stop target is a decrease in H1*-H2*, which is not found for all irregular vowels, but generally only prominent ones. Distinct behavior of prominence vs. phrasal domain is attested for other segments in English (Cho 2005, Cho and Keating 2009), so it is not surprising that the two forms of strengthening affect vowel-initial words differently.

By focusing the analysis only on the roles of prominence and phrasal domain, I have possibly overlooked some cases of word-initial glottal stops that might be due to other factors. But given the predominant influence of prominence and phrasal domain, I assume that these cases are rare. 95% of occurrences of full [ʔ] are accounted for by a model with only prominence and phrasal domain as factors, and we now infer that prominence is not only responsible for the strength of the gesture, but also for its very presence. Therefore, I assume that cases of incomplete glottal stops that might have been missed are rare.

With these results in mind, we can conclude that glottal stops are not found before all word-initial vowels (a hypothesis discussed by Pierrehumbert and Talkin (1992) and Dilley et al. (1996)), but are best viewed as an *inserted segment* before certain word-initial vowels in English. The support for the glottal stop as an inserted segment of English comes from the fact that cases of either full or incomplete glottal stops cannot be a result of strengthening the voicing gesture in strong positions, because only *vowels* in strong positions show evidence for full or incomplete glottal stops. Therefore, if word-initial glottalization were viewed as a reflex of strengthened voicing, we would expect word-initial sonorants to show signs of laryngealization. Nor does prominence result in more laryngealized vowels in general. Rather, the results of this study reveal that only *word-initial* vowels are laryngealized when prominent. It is also possible that syllable-initial vowels word-internally (e.g. the /æ/ in 'react') would be preceded by a glottal stop under prominence, though results by Davidson and Erker (2012) show that glottal stops and glottalization are rare in word-internal hiatus environments. Thus, glottal stop insertion in English appears to be an instance of initial 'consonantalization' of word-initial vowels, which is consistent with prosodic strengthening (Pierrehumbert and Talkin 1992). Surprisingly though, this process is usually not a form of initial strengthening (cf. Borroff (2007)), but rather a type of *prominence* strengthening particular to initial vowels.

4.2 Presence and function of phrase-initial voicing irregularity

The main acoustic characteristic of phrase-initial, non-prominent vowels (viz. a decrease in periodicity) is shared by all voiced segments. Why would all voiced sounds be less periodic phrase-initially? I argue that phrase-initial voicing is often 'creaky', similar to phrase-final voicing, but to a lesser extent. Phrase-initial voiced segments show higher values of H1*-H2* (possibly correlated with an open glottis) and lower values of CPP, correlated with a decrease in periodicity. As mentioned above, phrase-final creak (especially at the end of a breath group or utterance) is thought to be triggered by low subglottal pressure (Slifka 2006), which is also low at the *onsets* of breath groups. Thus, unless vocal fold stiffness and/or adduction increases, the low subglottal pressure utterance-initially could induce irregular phonation.

However, subglottal pressure for utterance-medial phrasal onsets is not necessarily low, so it is unclear why all phrasal onsets show decreased periodicity. A similar effect is found for coda-devoicing (e.g. /b/ → [p] in coda position). The aerodynamic/laryngeal conditions that favor coda-devoicing are only found utterance-finally (Westbury and Keating 1986), yet the process often generalizes to all word-final or even syllable-final positions in some languages (see Myers (2012) for a review). The decrease in periodicity found at phrasal onsets could perhaps be understood as phonologization of utterance-initial voicing irregularity down the prosodic hierarchy. That is, although respiratory constraints on voicing are only present at the onsets of utterances, the outcome (irregular voicing) is produced by speakers at the onsets of all phrases, even utterance-medially. This might be perceptually motivated: phrase-initial irregularity may serve as a perceptual cue to phrasal boundaries, as has been posited for creak in general (Slifka 2007).

5 Conclusion

This study answers two questions about the distribution and acoustics of word-initial glottal stops in American English. First, full glottal stops [ʔ] are predicted overwhelmingly by prominence and phrasing. Second, incomplete glottal stops are found only for prominent vowels, as shown acoustically by a drop in H1*-H2* for prominent word-initial vowels. Thus, although full glottal stops are more common phrase-initially, not all phrase-initial vowels are preceded by a glottal stop gesture. Rather, if a glottal stop gesture occurs phrase-initially, it is more likely that the gesture will be strengthened and thus realized as a full [ʔ]. Otherwise, when no glottal closure gesture is present, all voiced segments are less periodic, but often show an increase in H1*-H2*. This is taken to be a phrasal phenomenon that is independent of glottal stop distribution and that is perhaps related acoustically to phrase-final creak.

Much of the present analysis rests on the assumption that H1*-H2* is a correlate of glottal opening, which is somewhat controversial (Kreiman et al. 2008). Therefore, in an ongoing study I aim to confirm the acoustic results on the role of prominence vs. phrasal domain using articulatory measures from electroglottography (EGG), for a larger group of speakers and for speakers of Spanish, where glottalization is thought to be infrequent (Bissiri et al. 2011).

References

Baayen, R. H. (2008). *Analyzing Linguistic Data. A practical introduction to statistics.* Cambridge University Press, Cambridge.

Bates, D., Maechler, M., and Dai, B. (2008). *lme4: Linear mixed-effects models using S4 classes.* [Computer software program], available from `http://lme4.r-forge.r-project.org/`.

Beckman, M. E. and Ayers Elam, G. (1997). *Guidelines for ToBI labelling, Version 3.* The Ohio State University Research Foundation.

Bissiri, M. P., Lecumberri, M. L., Cooke, M., and Volín, J. (2011). The role of word-initial glottal stops in recognizing English words. In *Proceedings of Interspeech 2011*, Florence, Italy.

Bissiri, M. P. and Volín, J. (2010). Prosodic structure as a predictor of glottal stops before word-initial vowels in Czech English. In *Proceedings of the 20th Czech-German Workshop on Speech Processing*.

Borroff, M. L. (2007). *A landmark underspecification account of the patterning of glottal stop*. PhD thesis, Stony Brook University.

Brunner, J. and Żygis, M. (2011). Why do glottal stops and low vowels like each other? In *Proceedings of the 17th International Congress of Phonetic Sciences (ICPhS 17)*, pages 376–379.

Brysbaert, M. and New, B. (2009). Moving beyond Kučera and Francis: A critical evaluation of current word frequency norms and the introduction of a new and improved word frequency measure for American English. *Behavior Research Methods*, 41:977–990.

Byrd, D. (1994). Relations of sex and dialect to reduction. *Speech Communication*, 15:39–54.

Cho, T. (2005). Prosodic strengthening and featural enhancement: Evidence from acoustic and articulatory realizations of /ɑ,i/ in English. *Journal of the Acoustical Society of America*, 117:3867–3878.

Cho, T. and Keating, P. (2009). Effects of initial position versus prominence in English. *Journal of Phonetics*, 37:466–485.

Cole, J., Mo, Y., and Hasegawa-Johnson, M. (2010). Signal-based and expectation-based factors in the perception of prosodic prominence. *Journal of Laboratory Phonology*, 1:425–452.

Davidson, L. and Erker, D. (2012). Hiatus resolution in American English: the case against glide insertion. Unpublished manuscript, NYU.

DiCanio, C. T. (2009). The phonetics of register in Takhian Thong Chong. *Journal of the International Phonetic Association*, 39:162–188.

Dilley, L., Shattuck-Hufnagel, S., and Ostendorf, M. (1996). Glottalization of word-initial vowels as a function of prosodic structure. *Journal of Phonetics*, 24:423–444.

Epstein, M. A. (2002). *Voice quality and prosody in English*. PhD thesis, UCLA.

Esling, J. H., Fraser, K. E., and Harris, J. G. (2005). Glottal stop, glottalized resonants, and pharyngeals: A reinterpretation with evidence from a laryngoscopic study of Nuuchahnulth (Nootka). *Journal of Phonetics*, 33:383–410.

Esposito, C. M. (2012). An acoustic and electroglottographic study of White Hmong phonation. *Journal of Phonetics*, 40:466–476.

Fant, G., Kruckenberg, A., and Liljencrants, J. (2000). Acoustic-phonetic analysis of prominence in Swedish. In Botinis, A., editor, *Intonation: analysis, modelling and technology*, pages 55–86. Kluwer Academic Publishers, Dordrecht.

Fougeron, C. and Keating, P. A. (1997). Articulatory strengthening at edges of prosodic domains. *Journal of the Acoustical Society of America*, 101:3728–3740.

Garellek, M. and Keating, P. (2011). The acoustic consequences of phonation and tone interactions in Jalapa Mazatec. *Journal of the International Phonetic Association*, 41:185–205.

Gordon, M. and Ladefoged, P. (2001). Phonation types: a cross-linguistic overview. *Journal of Phonetics*, 29:383–406.

Hanson, H. M., Stevens, K. N., Kuo, H.-K. J., Chen, M. Y., and Slifka, J. (2001). Towards models of phonation. *Journal of Phonetics*, 29:451–480.

Higginbottom, E. (1964). Glottal reinforcement in English. *Transactions of the Philological Society*, 63:129–142.

Hirose, H. and Gay, T. (1973). Laryngeal control in vocal attack. *Folia Phoniatrica*, 25:203–213.

Holmberg, E. B., Hillman, R. E., Perkell, J. S., Guiod, P., and Goldman, S. L. (1995). Comparisons among aerodynamic, electroglottographic, and acoustic spectral measures of female voice. *Journal of Speech and Hearing Research*, 38:1212–1223.

Huffman, M. K. (2005). Segmental and prosodic effects on coda glottalization. *Journal of Phonetics*, 33:335–362.

Keating, P., Cho, T., Fougeron, C., and Hsu, C.-S. (2003). Domain-initial articulatory strengthening in four languages. In Local, J., Ogden, R., and Temple, R., editors, *Phonetic Interpretation (Papers in Laboratory Phonology 6)*, pages 143–161. Cambridge University Press, Cambridge.

Kochanski, G., Grabe, E., Coleman, J., and Rosner, B. (2005). Loudness predicts prominence: fundamental frequency lends little. *Journal of the Acoustical Society of America*, 118:1038–1054.

Kohler, K. J. (1994). Glottal stops and glottalization in German. Data and theory of connected speech processes. *Phonetica*, 51:38–51.

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

Kreiman, J., Garellek, M., and Esposito, C. (2011). Perceptual importance of the voice source spectrum from H2 to 2 kHz. *Journal of the Acoustical Society of America*, 130:2570.

Kreiman, J., Iseli, M., Neubauer, J., Shue, Y.-L., Gerratt, B. R., and Alwan, A. (2008). The relationship between open quotient and H1*-H2*. *Journal of the Acoustical Society of America*, 124:2495.

Kreiman, J. and Sidtis, D. (2011). *Foundations of Voice Studies*. Wiley-Blackwell, Oxford.

Kuang, J. (2011). Production and perception of the phonation contrast in Yi. Master's thesis, UCLA.

Mompeán, J. and Gómez, F. A. (2011). Hiatus resolution strategies in non-rhotic English: the case of /r/-liaison. In *Proceedings of the International Conference of Phonetic Sciences (ICPhS 17)*, pages 1414–1417, Hong Kong.

Myers, S. (2012). Final devoicing: Production and perception studies. In Borowsky, T., Kawahara, S., and Sugahara, M., editors, *Prosody Matters: Essays in honor of Elisabeth Selkirk*. Equinox Publishing, London.

Ostendorf, M., Price, P. J., and Shattuck-Hufnagel, S. (1995). The Boston University radio news corpus. Technical Report ECS-95-001, Boston University.

Pierrehumbert, J. (1995). Prosodic effects on glottal allophones. In Fujimura, O. and Hirano, M., editors, *Vocal fold physiology: voice quality control*, pages 39–60. Singular Publishing Group, San Diego.

Pierrehumbert, J. and Talkin, D. (1992). Lenition of /h/ and glottal stop. In Docherty, G. J. and Ladd, D. R., editors, *Papers in Laboratory Phonology II*, pages 90–117. Cambridge University Press, Cambridge.

Pompino-Marschall, B. and Żygis, M. (2011). Glottal marking of vowel-initial words in german. In *Proceedings of the 17th International Congress of Phonetic Sciences (ICPhS 17)*, pages 1626–1629, Hong Kong.

Price, P. J., Ostendorf, M., Shattuck-Hufnagel, S., and Fong, C. (1991). The use of prosody in syntactic disambiguation. *Journal of the Acoustical Society of America*, 90:2956–2970.

R Development Core Team (2011). *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing, Vienna, Austria.

Redi, L. and Shattuck-Hufnagel, S. (2001). Variation in the realization of glottalization in normal speakers. *Journal of Phonetics*, 29:407–429.

Shue, Y.-L., Chen, G., and Alwan, A. (2010). On the interdependencies between voice quality, glottal gaps, and voice-source related acoustic measures. In *Proceedings of Interspeech 2010*, pages 34–37.

Shue, Y.-L., Keating, P. A., Vicenik, C., and Yu, K. (2011). VoiceSauce: A program for voice analysis. In *Proceedings of the International Congress of Phonetic Sciences (ICPhS 17)*, pages 1846–1849, Hong Kong.

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

Slifka, J. (2007). Irregular phonation and its preferred role as cue to silence in phonological systems. In *Proceedings of the International Congress of Phonetic Sciences (ICPhS 16)*, pages 229–232, Saarbrücken.

Stevens, K. N. (1977). Physics of laryngeal behavior and larynx modes. *Phonetica*, 34:264–279.

Sumner, M. and Samuel, A. G. (2005). Perception and representation of regular variation: The case of final /t/. *Journal of Memory and Language*, 52:322–338.

Turk, A. E. and Sawusch, J. R. (1996). The processing of duration and intensity cues to prominence. *Journal of the Acoustical Society of America*, 99:3782–3790.

Umeda, N. (1978). Occurrence of glottal stops in fluent speech. *Journal of the Acoustical Society of America*, 64:88–94.

Westbury, J. R. and Keating, P. A. (1986). On the naturalness of stop consonant voicing. *Journal of Linguistics*, 22:145–166.

Zhang, Z., Kreiman, J., and Gerratt, B. R. (2011). Perceptual sensitivity to changes in vocal fold geometry and stiffness. *Journal of the Acoustical Society of America*, 129:2529.