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Opening or closing? An electroglottographic analysis of voiceless coda consonants in Australian English

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Abstract

In voiceless sounds, the glottis may be spread or constricted. Glottal spreading is associated with breathiness, and constriction with glottalisation. In many dialects of English, glottalisation often occurs with coda /t/ and sometimes with /p, k/, suggesting coda stop voicelessness is achieved through glottal constriction. Conversely, voiceless coda fricatives are associated with breathiness of the preceding vowel, with voicelessness achieved through glottal spreading. However, analyses specifically measuring glottal activity in coda consonant contexts in English are sparse. We conducted an electroglottographic analysis of vowels preceding voiceless codas /p, t, k, s/ to examine how coda voicelessness is achieved in Australian English (AusE). We found that coda /t/ and /p/ show glottal constriction towards vowel offset. Conversely, /k/ patterns with /s/ and exhibits glottal spreading. This suggests that different glottal configurations are used to achieve coda voicelessness in AusE.

Index Terms: articulatory phonetics, voice quality, stop place of articulation, electroglottography, Australian English

1. Introduction

There are two main mechanisms for achieving voicelessness in speech: spreading of the vocal folds/glottis as occurs in the production of [h], or complete closure of the vocal folds/glottis as occurs in the production of [ʔ]. That is, to produce a voiceless coda, the glottis can be either spread or constricted to inhibit vocal fold vibration [1]. The use of glottal spreading may result in breathy voice or aspiration during the gestural transition between vowel and coda [2, 3], while glottal constriction may result in a period of laryngealisation or glottalisation [1].

Breathiness in surrounding phonemes suggests that General American English (GenAmE) voiceless fricatives are produced through glottal spreading [2, 4, 5, 6]. Aerodynamically, this is likely because a spread glottis both inhibits voicing and allows greater airflow into the oral cavity to help maintain higher intraoral pressure necessary for producing the noise source in fricative production [3, 7]. For stops, voicelessness can be achieved through either vocal fold spreading or constriction during stop closure [8]. In onset, foot-initial position voiceless stops are produced with a spread glottis [2, 8] as evidenced by the lengthy post-aspiration present after the release of the stop and prior to the onset of vowel related voicing. However, strategies for coda voiceless stops appear to be more variable across English varieties. In Irish English [9] and Aberystwyth English [10], breathiness and preaspiration has been observed in vowels preceding voiceless coda stops, while glottalisation is common preceding voiceless stops in GenAmE [3, 11, 12, 13, 14], many British English varieties [15], New Zealand English [16] and Australian English (AusE) [17, 18, 19, 20].

Within a variety, strategies to achieve voicelessness in coda stops may also differ. Coda glottalisation is most commonly observed in coda /t/, is sometimes found in coda /p/ syllables and less frequently found in coda /k/ syllables in GenAmE [3, 11, 12, 13, 14]. In Aberystwyth English, breathiness occurs at higher rates preceding /k/ and /t/ than preceding coda /p/ [10]. Both physiological and sociolinguistic reasons for these patterns have been proposed [3, 10].

In AusE, glottalisation was first documented in coda /t/ syllables in the 1980s [17]. Since then, similar to GenAmE, glottalisation has been shown to occur most commonly preceding coda /t/ but also more rarely before /p/ and /k/ [18]. However, a recent study has found similar rates of glottalisation in unstressed syllables with /p, t, k/ codas [19].

It has been suggested in [3] that voicelessness in coda stops at all places of articulation in GenAmE is typically realised through glottal constriction rather than spreading and that the higher rate of perceptible/observable glottalisation in coda /t/ contexts in this variety is due to the increased tendency for lenition of /t/ [21]. According to this theory, glottalisation is perceptible/visible if speakers reduce or completely omit the oral constriction of /t/, or if the oral constriction is not aligned with the glottal constriction. Otherwise, the oral constriction has a masking effect on glottalisation. Such masking is assumed to occur more commonly for /p, k/ [3]. However, this has yet to be empirically confirmed through articulatory analysis, and for different varieties of English.

Electroglottography (EGG) is a non-invasive method for indirectly observing vocal fold activity during phonation. EGG measures variation in the conductance between two electrodes placed on either side of the thyroid cartilage. Conductance between the electrodes changes as a function of vocal fold contact area during speech. Unlike acoustic measures of glottalisation and breathiness, EGG signals are not masked by supralaryngeal constrictions, making this method highly suitable for examining glottal activity during obstruents. We are not aware of previous EGG studies of AusE codas.

One measure of vocal fold constriction/spreading derived from the EGG signal is the open quotient (OQ). OQ is calculated by dividing the duration of glottal opening by the duration of the entire glottal cycle. More information on OQ is provided in Subsection 1.3. Higher OQ values indicate that the glottis is spread for a larger portion of the entire glottal cycle, which occurs during breathiness, whereas lower OQ values indicate the glottis is constricted for a larger portion of the entire glottal cycle, as occurs during glottalisation.

This study aims to examine glottal spreading/closing as a function of voiceless coda stop place of articulation in young AusE speakers. In line with Seyfarth and Garellek [3] who propose that differences observed in glottalisation by coda stop place of articulation in GenAmE is due to variable masking of

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glottalisation by supralaryngeal gestures rather than phonation, we predict that OQ will decrease (indicating increasing glottal constriction) to a similar extent across vowels preceding coda stops at three different places of articulation. Conversely, vowels preceding coda /s/ will be characterised by increasing OQs (increasing glottal spreading) towards their offsets.

This research will improve our understanding of the implementation of coda stop voicelessness in AusE and aid in predicting voice quality patterns in this variety in the future.

2. Methods

2.1. Participants

Six monolingual Australian English speakers (F: 5; M: 1; 18-31 years, mean age 24.2 years) were recruited from Macquarie University, Sydney NSW. All participants were born and schooled in Australia and reported no previous history of speech and/or hearing impairments.

2.2. Experimental materials

The corpus contained 29 target CVC monosyllables, where C1 was selected from /p, t, k, f, s, ʃ, h/, V = /iː, ɐː, oː/, and C2 = /p, t, k, s/. C1 was varied to capture the voiceless stops and fricatives of AusE while maximising the number of lexical tokens, V was varied to capture three peripheral vowels of the AusE vowel system, C2 was varied to capture the three voiceless stops of AusE. Three words (*peace* /piːs/, *pass* /pɐːs/ and *force* /foːs/) containing coda /s/ were also included to represent a context where voicelessness is achieved through glottal spreading.

Stimuli were presented orthographically via computer screen in six randomised blocks of 30 items. Each carrier phrase was present on screen for 2000 ms with a 400 ms break between each phrase. Target words were produced in the carrier phrases *Say XXX NOW one more time* and *Say XXX LONG one more time*, where the word in capitals was accented. The post-target words were chosen as they both have a sonorant onset, an environment which has been shown to increase the likelihood of coda glottalisation in the target word in AusE [23]. Each target word was produced in each carrier phrase three times.

In the present paper we analyse tokens containing the low /ɐː/ vowel where C1 = /t, k, h/ and C2 = /p, t, k/, in addition to the /s/ final *pass*, for a total of 60 tokens per participant.

2.3. Data collection and analysis

Laryngeal activity was captured using a Laryngograph microProcessor EGG-D200. Synchronised audio recordings were captured on an EGG-D200 electret condenser microphone at a sampling rate of 48 kHz.

All acoustic and EGG analysis was undertaken in Praat [22]. First, vowel onsets were determined by onset of voicing for /p/ and /t/ initial target words and the presence of higher formants (F2 and F3) for /h/ initial tokens. Vowel offsets were placed at F2 offset; in the case of glottalised tokens, vowel offset was placed at the final glottal pulse [23]. Note that while this method can capture increased glottal spreading during the vowel, it cannot capture any instances of voiceless preaspiration that may be present after the cessation of phonation. Second, OQ values for the preceding vowel were measured using the Praatdet script [24]. Before calculating OQ the raw EGG waveforms were high-pass filtered at 75 Hz. OQ closing peaks were located from the first derivative of the EGG waveform (dEGG) and opening peaks were determined using "Howard's method" with threshold set at 0.43, in line with previous studies [25, 26]. As we were interested in the effect of coda identity on OQ, we analysed only the final 50% of vowel OQ values.

Prior to analysis, we excluded all tokens with mispronunciations or with an accent on the target word, as determined by the first author. Of 360 analysed total tokens, 13 were excluded due to mispronunciation, and 10 were excluded due to multiply-pulsed voice, which cannot be analysed accurately with Praatdet software [24].

2.4. Statistical analysis

Data were analysed with generalised additive mixed models (GAMMs) using the mgcv [27] and itsadug [28] packages in R [29]. OQ was modelled with two parametric terms to account for coda identity (4 levels: /s, p, t, k/ where /s/ = 0) and post-target word (2 levels: *long, now,* where *long* = 0). The model also included a smooth over normalised vowel duration by coda, a smooth over normalised vowel duration by post-target word and a random smooth over normalised vowel duration by post-target word for each participant. For each model, basis functions were set to ten (k = 11) and an AR1 error term was included to account for autocorrelation in the models.

3. Results

The data below relate to six speakers and 4043 OQ measurements. In the figures below, increasing slopes (increasing OQ) indicate increased vocal fold spreading, and decreasing slopes (decreasing OQ) indicate increased vocal fold constriction during the glottal cycle. Figure 1 illustrates the mean OQ trajectories in the final 50% portion of vowels preceding /p, t, k/ and /s/ for each speaker. From Figure 1, we can see increasing OQs for all participants in the context of coda /s/, although W1 and M1 show only minimal increases. This indicates that for the majority of speakers their glottis is spread for a greater portion of the glottal cycle in the last 20 – 30% of normalised vowel duration, as would be expected in this voiceless fricative context. Conversely, for vowels preceding /t/, a negative OQ slope is observed for five of six speakers indicating increased glottal constriction approaching vowel offset. M1 is the only speaker to show minimal change in OQ in the coda /t/ environment. For vowels preceding coda /p/ we generally observe a similar pattern to that found for vowels preceding coda /t/ with a negative gradient observed for W2, W3, W4 and W5. Finally, for vowels preceding coda /k/ five participants showed positive slopes in OQ approaching the vowel offset (W1 and W4 show only minimal positive OQ) , indicating that, like vowels preceding coda /s/, there is increased glottal spreading approaching /k/ in these speakers . W3, however, shows a negative slope approaching vowel offset; nevertheless, this is less steep than for vowels preceding /t/ and /p/ produced by this speaker.

The model (Table 1) showed significant parametric (i.e., constant) differences for /t/ and /p/ compared to the reference level of /s/ (both $p < 0.0001$), whereas no significant parametric difference was found for /k/. In addition, significant non-linear differences from the reference level of /s/ were found for both /t/ and /p/ ($p < 0.0001$). A significant non-linear difference was also found for /k/ ($p = 0.043$), but this was only slightly below the 0.05 alpha level for significance and thus should be interpreted with caution. These results indicate that vowels preceding both /t/ and /p/ have significantly lower OQ values in their final 50% than vowels preceding /s/. In addition, both /t/

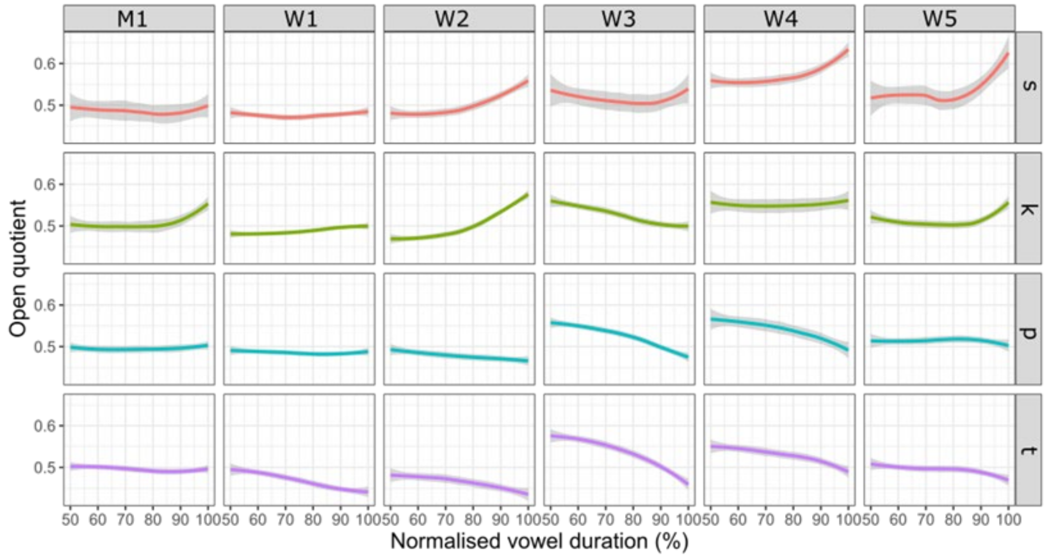

Figure 1 *Average OQ trajectories for final 50% of normalised vowel duration. Increasing OQ values indicate greater glottal spreading; decreasing OQ values indicate greater glottal constriction.*

and /p/ show significant differences in trajectory shape compared to vowels preceding /s/. Figure 2 illustrates the predicted OQ trajectories in the /p, t, k, s/ contexts and shows that while vowels preceding coda /s/ show a rising trajectory, in the case of /t, p/ the trajectories are falling. Vowels preceding coda /k/ show a rising pattern that is similar to /s/, although some differences are visible towards the end of the vowel. These can be seen in Figure 3, which shows the difference between the two trajectories over normalised time. There were no significant effects (parametric or non-linear) of following word.

Table 1. *Summary of parametric and non-linear effects in GAMM analysing Open Quotient in the final 50% portion of vowels preceding voiceless codas (Coda: ref = /s/; Foll. Word: ref = long).*

Effect	P-values
Coda (k) - Parametric	.294
Coda (t) Parametric	< .0001
Coda (p) Parametric	< .0001
Foll. word (now) Parametric	.942
Coda (k) Non-linear	.043
Coda (t) Non-linear	< .0001
Coda (p) Non-linear	< .0001

4. Discussion

In this study, we examined the effect of coda voicelessness on phonation in the latter half of the preceding vowel. Consistent with previous studies, we predicted that OQ would increase towards the vowel offset for vowels preceding /s/, while vowels preceding voiceless codas would exhibit decreasing OQ towards their offset, indicative of glottal constriction. Our findings partially confirm this prediction. Overall, vowels preceding coda /t/ and /p/ demonstrated decreasing OQ towards their offset. However, contrary to expectations, vowels preceding coda /k/ had increasing OQ towards their offset. This suggests that, similar to voiceless fricatives, voicelessness in coda /k/ is achieved through glottal spreading in AusE.

Seyfarth and Garellek [3] suggest that in GenAmE, voiceless coda stops at all places of articulation are characterised by a glottal constriction gesture, and that differences in acoustic measures of glottalisation do not arise from differences in phonatory setting but rather from differences in the supralaryngeal constriction properties of stops at various places of articulation: oral constriction gestures may mask the acoustic consequences of glottal constriction, with /t/ more likely to exhibit a reduced or omitted oral constriction gesture than /p/ and /k/, leading to higher rates of perceptible glottalisation in vowels preceding /t/. However, our findings suggest that differences in glottal activity between the three voiceless coda stops in AusE may also contribute to different rates of glottalisation. In addition to /t/, we also observed increasing glottalisation towards vowel offset in the coda /p/ context, although this appears to occur to a lesser extent than in vowels preceding /t/, as evidenced by the less steep negative OQ slope. In five of six participants, /k/ did not exhibit evidence of glottal constriction, but rather patterned with /s/, showing evidence of glottal spreading.

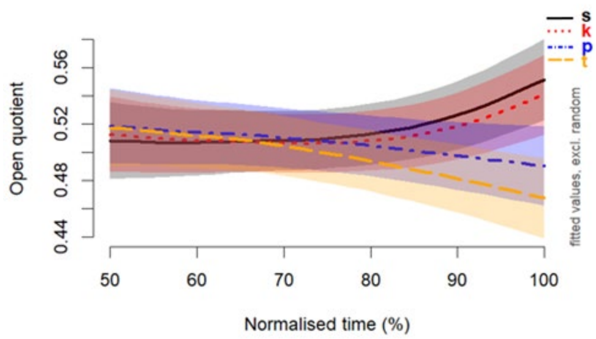

Figure 2 *Predicted open quotient by normalised time based on GAMM analysis. Increasing OQ = greater glottal spreading; decreasing OQ =greater glottal constriction*

Previous acoustic studies suggest that glottal constriction is used to achieve coda voicelessness in AusE [18, 19], similar to GenAmE. The falling OQs observed in this study for vowels preceding coda /t/ are consistent with this finding. Similarly, we found falling OQ values towards the offset of vowels preceding coda /p/, suggesting that voicelessness is achieved through glottal constriction in coda /p/ as well, although perhaps to a lesser degree. This is consistent with studies that have also observed some glottalisation for coda /p/ in AusE [18, 19]. However, our finding that vowels preceding coda /k/ had rising OQ offsets suggests a glottal spreading gesture is used to achieve coda voicelessness at this place of articulation. While evidence of glottalisation in association with coda /k/ in AusE has previously been reported in a small number of studies, this has been linked to particular lexical items (e.g., 'like') [18], and found in unstressed syllables of trochees produced in isolation [19], so it is possible that glottalisation in conjunction with /k/ in these studies may have been due to the influence of other factors. Future work should examine whether there is evidence of glottalisation with coda /k/ in naturalistic speech in AusE.

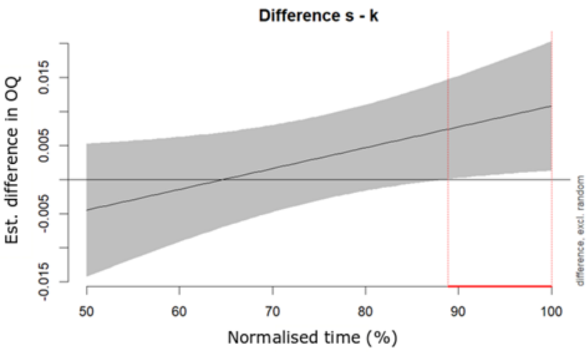

Figure 3 *Predicted difference between /s/ and /k/ open quotient values by normalised time based on GAMM analysis. Positive estimated difference in OQ indicate that OQ of /s/ is greater than OQ of /k/. Red interval shows interval where confidence intervals for /k/ and /s/ are non-overlapping.*

There was some variation in the strategies used by speakers to achieve coda voicelessness. Specifically, speakers W3 and W4 exhibited higher levels of overall OQ compared to the other speakers, which may indicate increased breathiness in general. As shown in Figure 1, these speakers also appear to exhibit steeper OQ falls towards vowel offset in the coda /t/ and /p/ contexts. W3 showed decreased OQ towards vowel offset for vowels preceding /p, t, k/, suggesting the use of a glottal constriction gesture to achieve voicelessness for all coda stops. However, W4 exhibited only a small increase in OQ towards vowel offset in /k/ final syllables. Future studies should investigate how individual voice qualities interact with the implementation of coda voicelessness. Individual speakers may use different strategies to achieve voicelessness, or particular strategies may have sociolinguistic relevance [3]. We will explore these questions further as we extend this research.

This study was limited by a small number of speakers, and an uneven sampling of gender, with only one male speaker included. Previous work has found gender to be a relevant factor in the use of glottalisation in coda voiceless stops in AusE [19], so it remains an open question whether these patterns will generalise to a greater sample of males. The present study also only focused on a single vowel context: previous research has shown that vowel quality can affect the likelihood of glottalisation, with low vowels being more prone to glottalisation than high vowels [23, 30, 31, 32]. Additionally, the post-target word environment was limited to the sonorants /l, n/, which are known to be conducive to glottalisation [3, 13, 14, 20]. Therefore, examination of other preceding vowels and a greater variety of environments may yield different results and would provide a more complete view of how coda voicelessness is achieved in AusE. Finally, only a single simple measure of voice quality, OQ, was used, and more varied types of analysis are required to further illuminate voicelessness in AusE.

While we are unable to offer an immediate explanation as to why /k/ patterned differently from /p/ and /t/ in this analysis, future work could examine the relationship between lingual and laryngeal gestures, including the vertical height of the larynx, and possible associations with coda stop place of articulation. As glottalisation is associated with raised larynx and breathy voice with lowered larynx [33] there may be physiological or aerodynamic reasons for the patterns observed here. Esling et al. [33] provide detail of the complexity of the lower vocal tract in their Laryngeal Articulator Model providing a framework for future articulatory analyses of voice quality and the relationship between supralaryngeal and laryngeal gestures in speech.

5. Conclusions

We examined how coda voicelessness is achieved in /p, t, k, s/ final codas in AusE. We found decreasing OQs in the offset of vowels preceding coda /t/ and /p/ suggesting that voicelessness for these consonants is achieved through glottal constriction, in line with observations from GenAmE. However, we found that vowels preceding both coda /k/ and /s/ were characterised by increasing OQs towards vowel offset, suggesting that voicelessness in these codas is achieved through glottal spreading [2, 3]. These results suggest that, in AusE, differences in glottal gestures determine the prevalence of glottalisation rather than masking of glottal gestures by supralaryngeal configuration. They also demonstrate that, within a single class of consonants (stops), coda voicelessness can be achieved with varying glottal configurations (spreading for /k/ vs. constriction for /p/ and /t/), although individual voice quality may also contribute to variation. Future work will be needed to establish the nuances of contextual, prosodic and/or sociophonetic variability in the strategies speakers use to achieve coda voicelessness in AusE.

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