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Velar–vowel coarticulation in a virtual target model of stop production

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Abstract

Velar-vowel coarticulation in English, resulting in so-called velar fronting in front vowel contexts, was studied using ultrasound imaging of the tongue during /k/ onsets of monosyllabic words with no coda or a labial coda. Ten native English speakers were recorded and analyzed. A variety of coarticulation patterns that often appear to contain small differences in typical closure location for similar vowels was found. An account of the coarticulation pattern is provided using a virtual target model of stop consonant production where there are two /k/ allophones in English, one for front vowels and one for non-front vowels. Small differences in closure location along the palate between productions within each context are the result of the trajectory of movement of the tongue from the vowel to vowel through the virtual target beyond the limit of the palate. The overall pattern is thus seen as a combination of a large planned allophonic difference between consonant closure targets and smaller phonetic differences for each particular vowel quality that are the result of coarticulation.

Keywords

Anteriority index; coarticulation; consonant; fronting; EdgeTrak; English; production; velar; virtual target; vowel; ultrasound

1.0 Introduction

Coarticulation is a robust phenomenon in speech production. Because of coarticulation, speech sounds are frequently articulated in quite different ways depending on the context in which they appear. A salient example of coarticulation is found in the case of coarticulation between velar stop consonants and vowels in English (so-called 'velar fronting'). The distinction is frequently mentioned in introductory materials on articulation and coarticulation (e.g. Ladefoged 1975; Borden, Harris, & Raphael, 1994), probably because the distinction between alternatives is large enough to be noticed by naïve speakers despite being allophonic. For example, the difference in closure location on the palate between onsets in the words *key* and *cough* is quite large. Figure 1 shows two ultrasound images of

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the tongue during the production of the velar stops in *key* and *cough* (from participant P2 in the current study). In these images, the tongue is oriented so that the tip is to the right and the tongue dorsum is to the left. A bright white line in the center of the image shows the margin between the air in the oral cavity and the tongue body. The dark region just below this white line is the upper tongue surface (see Stone, 2005). On the top, Figure 1a shows the velar constriction before /i/, a front vowel, in *key*. On the bottom, Figure 1b shows the velar before /ɔ/, a back vowel, in *cough*. The forward (rightward) shift of the tongue body in Figure 1a versus 1b is apparent. Presumably, this shift in position occurs because of anticipatory coarticulation between the production of the velar stop and the following vowel.

Keating and Lahiri (1993) suggest that velar-vowel coarticulation is continuous. In other words, more front velar production will correlate with front vowel production, and more back velar production will correlate with back vowel production. They review a range of articulatory data from a variety of languages, including English, and also examine acoustic data on velar stop release bursts. The languages analyzed in detail are Czech, Hungarian, Russian, and English. In addition, findings are summarized from studies of Catalan, Icelandic, Irish, and Swedish. However, these previous studies have primarily analyzed velar closures in a limited number of contexts (at most /i e a o u/, as in Keating and Lahiri's acoustic study) and articulatory studies have only examined velars in /i a u/ contexts. The present study aims to replicate and extend these findings by analyzing velar closure location in English in a larger variety of vowel contexts.

In this study, velar fronting refers to a coarticulatory process in adult talkers in which velar stops are produced with a fronted allophone. This process is unrelated to the process of velar fronting in child phonology, where an alveolar or alveolar sounding consonant is substituted for a velar globally or in some phonological context (e.g. Lowe, Knutson, & Monson, 1985). The two processes may be related in that coarticulation may play a role in the loss of overt contrast in children's early production of velar sounds (Scobbie, Gibbon, Hardcastle, & Fletcher, 2000).

1.1 Phonological issues

Velar fronting was of interest to Keating and Lahiri (1993) in their investigation of featural representation for velar, palatal, and palatalized consonants. They conclude that a simple front/back tongue body distinction is insufficient to capture the range of variants of these consonants. For example, fronted velars and palatals contrast in Czech, requiring a feature system that provides a distinct representation for these two types of consonants. In addition, contextual fronting appears to vary by degrees based on the following vowel, a quantitative distinction that cannot be straightforwardly captured in a phonological feature system. They conclude that tongue body frontness may be unspecified for velar consonants, and determined by coarticulation. In the Keating (1990) window model, this would be implemented as a relatively wide target window for tongue body frontness for velars, allowing a variety of tongue body position trajectories to fall within the window depending on context. This approach is compatible with the findings of Houde (1967) who suggested that there are three main components associated with tongue body movements for velars: (1) the front-back vowel gesture for the articulatory trajectory between the vowels surrounding

the velar, (2) the vertical movement required for stop closure for the velar, and (3) movement during the closure itself, in line with the overall vowel-to-vowel gesture or possibly due to oral air pressure increase due to the closure. In this description, there is no determination of tongue body frontness inherent to the velar consonant. The frontness of the tongue body during the stop closure all comes from surrounding vowel context.

The number of vowel contexts examined in studies of velar fronting has been relatively limited. Keating and Lahiri (1993) examine /i e a o u/ in their study, and from acoustic data taken from the velar burst conclude that the prominent frequency peak in the burst spectrum is distinct for all five contexts and varies systematically with vowel frontness. They do also note, however, that the spectra for front vowel contexts /i e/ appear more diffuse than the compact spectra for back vowel contexts /a o u/. A closer examination of the frequency peaks shows a rather large difference between front vowel contexts (about 3,000 Hz) and back vowel contexts (1,000–1,500 Hz). This potential qualitative difference in burst spectral peak and shape might suggest that velar closure location does not vary continuously and instead that there are two primary closure locations, with some acoustic variation within these locations due to secondary factors of tongue body shape and position due to coarticulation.

Coarticulation has been used to explain analogous assimilatory processes that were formerly analyzed phonologically. Gestural blending and overlap can obscure (or create) apparent segments as in the deletion of /t/ in *perfect memory* or the perception of an epenthetic /t/ in *prince* (Browman & Goldstein 1990). Assimilation of nasal alveolar place of articulation to a following velar stop in analyses using eletropalatography and electromagnetic articulography found variation in assimilatory behavior across ten participants, suggesting an overall phonetic rather than phonological process (Ellis & Hardcastle 2002). Of relevance to the case of velar-vowel coarticulation, it was possible to identify different articulatory strategies only when a relatively large number of participants were analyzed. In order to establish the gradient (and therefore low-level coarticulatory) or categorical (allophonic and therefore abstract phonological) nature of velar-vowel coarticulation as a process of velar fronting, a relatively large number of participants and vowel contexts need to be studied.

1.2 Simplified virtual target model for stops

Coarticulatory variability can emerge from an articulatory system with articulatory targets as the articulators move from one target location to another. In the case of stop consonants, an additional contributor to observed variability in coarticulation may be that the articulatory targets are virtual locations beyond the limits of the vocal tract. Virtual targets for stop closures have been proposed based on articulatory data examining articulatory velocity. Löfqvist & Gracco (1994, 2002) found that articulatory velocity upon closure suggests that the closure movement is aimed to extend beyond the location of closure. If the stop closure were aimed at the actual point of contact, deceleration of the articulator would be observed before contact.

Perrier, Payan, Zandipour, & Perkell (2003) investigated a virtual target model specifically for velar stop closure in /i, u, a/ contexts using a biomechanical model of the tongue. While velar fronting was not a primary focus of their study their simulations did result in context-

dependent fronting of the velar closure. Brunner, Fuchs, & Perrier (2011) extended the use of virtual stop targets to explain analogous variation in stop production in Korean between tense, aspirated, and lax stops and found articulatory movements broadly consistent with the virtual target model.

The primary focus of the Perrier et al (2003) study was to examine whether their biomechanical model could explain a tongue looping pattern where the tongue dorsum slides forward along the palate during closure, as first observed by Houde (1967) and studied in more detail in Mooshammer, Hoole, & Kühnert (1995) and Hoole, Munhall, & Mooshammer (1998). Perrier et al (2003) were successful in modelling this looping as anatomical and biomechanical consequences of contraction of the genioglossus, styloglossus, and hyoglossus muscles to create tongue dorsum closure gestures. Given their finding that the looping nature of velar closure gestures is potentially biomechanical and present for all vowel contexts, the effects of these loops on velar closure location will not be considered further in the present paper, as the ultimate goal is to evaluate the nature of the virtual targets for velar closure.

In the case of velar-vowel coarticulation in English, a virtual target model would allow variation in the closure location for a velar stop as the tongue body hits the palate on a trajectory from the preceding vowel to the virtual target and following vowel created by overlapping gestural activations (Perrier, et al, 2003). As gestures overlap, front and back vowels, like those in *key* and *cough*, could have a single virtual target with actual closure location determined in part by the vowel-to-vowel tongue body movement (Öhman, 1966). Alternatively, there could be two (or more) virtual targets. A schematic comparison of a one target model versus a two target model is shown in Figure 2. Evidence for multiple targets can be found if there are large gaps in the distribution of closure locations between distinct clusters of vowels, presumably on the basis of differences in vowel advancement.

With a single virtual target above the palate as shown on the left in Figure 2, there is a set of closure locations that are relatively evenly spaced along the palate (modulo individual physiological differences). With two widely separated virtual targets as shown on the right in Figure 2, there are still five different closure locations, but their distribution is uneven. The virtual target model provides a slightly different explanation than the window model for variation in the location of stop closure, however the phonetic and phonological questions behind either model are the same. Examining variation in closure location for a wide variety of vowel contexts may provide enough information on the distribution of closure locations to differentiate between a one target or two target model (or a one window or two window model). Is there a single phonological target/window within which phonetic variation is found, meaning that the variation that is found is entirely the product of low level coarticulation, or are there two (or more) phonological targets/windows within which phonetic variation is found? While the answer to this question is primarily a descriptive one, there are theoretical implications. In a fully exemplar model of speech production (e.g. Pierrehumbert 2001), each coarticulated kV combination could emerge as a target category for speech production. We might therefore expect a model with minimal category structure (such as the one target model or a target for each vowel category) to fit the data. The intermediate models provide some evidence for abstract but non-contrastive phonological structure,

supporting allophonic segmental categories as a component of the speech production process.

1.3 Methodological issues

Given that acoustic studies provide indirect evidence of articulator position (e.g., Stone, 1990; Watkin & Rubin, 1989; Zharkova, Hewlett, & Hardcastle, 2012), an articulatory study of velar-vowel coarticulation would provide more definitive evidence of the discrete versus continuous nature of velar fronting. Previous studies of velar stop articulation using electropalatography or articulometry have had limited samples of participants and contexts. Löfqvist & Gracco (1994) investigated velar stop production using electromagnetic midsagittal articulometry in two talkers and three vowel contexts /i a u/. Recasens, Pallarès, & Fontdevila (1997) and Liker & Gibbon (2007) used electropalatography to image velar closure in three and seven talkers, respectively, in the same three vowel contexts. All of these studies found significant effects of vowel context on horizontal location of the tongue body. However, the limited number of vowel contexts used makes it very difficult to determine whether the differences are solely due to gestural overlap or whether distinct articulatory targets are used for velar closure based on vowel advancement. Liker & Gibbon (2007) found variation between different participants in the influence of vowel context on the location of palate contact during closure.

In our own preliminary studies, closure position was measured in onset velar stops in a variety of vowel contexts in real words and pseudowords using ultrasound imaging (Wodzinski, 2004). Three participants were recorded. The stimuli covered the entire range of English vowel contexts, including diphthongs. Closure location was identified by hand in extracted ultrasound images, and quantified by the angle of elevation from the horizontal axis of the ultrasound probe to the center of the velar closure (which will be referred to as the velar closure angle in the methods below). Frontness of the following vowel was also quantified using the frequency of the second formant. We found that the correlation between the velar closure angle and the following vowel F2 was high (Pearson correlation, $r < -.7$ for all participants for both word and nonword stimuli).

The Wodzinski (2004) study had some limitations, however. First, a general disadvantage associated with ultrasound imaging is that in order to obtain the most reliable image for measurement it is desirable for the participant's head to be fixed relative to the probe (Stone & Davis, 1995) or for the collected data to be corrected for head and probe movement (Whalen, Iskarous, Tiede, Ostry, Lehner-LeHouillier, Vatikioti-Bateson, & Hailey, 2005). At the time data were collected for this experiment, neither option was available to us. In the present study, head stabilization and an acoustically transparent standoff is used in a recording procedure similar to the head and transducer support (HATS) system (Stone & Davis, 1995).

Second, the measure of closure location using velar closure angle in Wodzinski (2004) is a novel one. Additional analysis of this data by a second researcher has found measures across studies to be relatively reliable (Hardin & Frisch, 2005), but additional evaluation of this novel measurement technique is warranted. In addition, making this measurement requires the researcher to use a variety of cues to identify the extent and center of closure. Ultrasound

data is more easily analyzed using the entire imageable tongue contour which can be semiautomatically generated with current analysis software. A second aim of the present study is to compare the manual measure of velar closure location to a measure of tongue frontness derived by equation from the semi-automatically extracted tongue contour (Li, Kambhamettu, & Stone, 2005; Bressman, Thind, Bollig, Uy, Gilbert, & Irish, 2005).

2.0 Methods

2.1 Participants

Ten adult speakers, between the ages of 20 and 35, were recruited for this study from the first year undergraduate student population in Communication Sciences and Disorders at the University of South Florida. The participants included one male and nine female native speakers of Standard American English. All participants completed a basic demographic information questionnaire and had no self-reported history of speech or hearing disorders.

2.2 Stimuli

Stimuli consisted of 18 monosyllabic (CVC or CV) words. The stimuli consisted of a velar stop (/k/) onset and one of nine Standard American English vowels covering the full range from front to back vowels: /i e æ ə ɔ o u/. Each vowel was used in two different words. If a coda was present, it was either a bilabial (/p/ or /b/) or labiodental (/f/ or /v/). Labial codas were used to reduce the influence of coarticulation with the coda consonants on the tongue gestures of the velar and vowel. The word stimuli were: /i/ *key, keep*, /e/ *cay, cape*, /æ/ *cap, cab*, /ə/ *cup, cub*, /ɔ/ *curb, curve*, /ɑ/ *cop, cob*, /ɔ/ *caw, cough*, /o/ *cope, cove*, /u/ *coup, coop*. Word stimuli were produced in a carrier phrase, *Say a _____ again*, so the target was surrounded by unstressed neutral vowels. Within the carrier phrase, each stimulus word was given in standard spelling and as a phonetically transcribed word, for example, *Say a cope /kop/ again*. The 18 sentences were pseudo-randomized into a list so that the same vowel was not repeated for two items in a row. Each subject produced six repetitions of the entire stimulus list.

2.3 Procedure

The participant was seated in a wheel-less chair with his or her back against the back of the chair and his or her feet flat on the floor. The ultrasound probe and participant's head were stabilized using a halo-like device similar to the head and transducer support (HATS) system (Stone & Davis, 1995; see also Stone, 2005). Stabilization was used to minimize the amount of displacement of the head or probe during the recording session so that productions throughout the session could be compared.

The head stabilizing apparatus consists of two main vertical rails that are clamped to a table. A head stabilization halo is attached to the upper portion of the two main rails, and the holder for the probe is attached to the lower portion of the two main rails. The actual head stabilization mechanism consists of four rods that create a box structure around the subject's head. Four padded dowels that extend from each side of the halo towards the center are used to comfortably stabilize a subject's head relative to each side of the box.

The probe is stabilized by a clamp connected to a rod located between the two vertical rails. The participant is positioned so that the probe lies under the chin in the submental region beneath the base of the tongue. A 1 cm thick compressible acoustically transparent standoff was used between the subject's chin and the transducer to leave the jaw relatively free to move (Peng, Jost-Brinkmann, & Miethke, 1996). Figure 3 provides a profile picture of our head stabilizing device and exemplifies typical placement of the probe.

The tongue was imaged using an Aloka SSD-1000 ultrasound machine with a 3.5 MHz convex probe. The ultrasound transducer, located at the end of the probe, emits a high frequency sound that propagates through the tongue and is reflected by the air in the oral cavity at the upper surface of the tongue. As a result, a high contrast or distinct white line is produced at the juncture between the surface of the tongue and the air in the oral cavity. Video output from the ultrasound was recorded as digital video on a computer in DV-NTSC format at 29.97 frames per second. Simultaneously, an acoustic recording of the participant's speech production at a 48 KHz sampling rate was made using a microphone placed approximately 15 cm from the participant's mouth.

Prior to recording the stimulus set, each subject was asked to take 3 or 4 sips of water through a straw to present a clearer image of the tongue surface during recording. The experimenter also placed a digital metronome in the subject's left ear to provide him or her with a steady slow speech rate to mimic during speech production. Subjects were asked to read the entire list of stimuli six times through and were offered water to sip at their own convenience. Occasionally, the experimenter asked the participant to drink if he or she felt ultrasound the image quality was becoming poorer during the session.

2.4 Measurement

Measures were taken from the recordings to quantify the frontness-backness of the tongue during the velar stop consonant closure and during the vowel. Measures were made in two ways. Specific articulatory/acoustic landmarks in the video recording were measured by hand by the second author. Overall measures of the tongue contour during velar closure and during the following vowel were also generated semi-automatically using EdgeTrak software (Li et al, 2005).

2.4.1 Velar closure angle—Hand measurements of closure location were made using a custom made Lab View software tool. This tool works directly with video files, and allows the user to superimpose measurement points on the video without needing to extract individual measurement frames. The Lab View tool also simultaneously shows an audio waveform that was used to identify when the acoustic stop closure and release occurred.

The closure frame and closure location was chosen based on the combined information from the video and audio recordings. For each velar target, the video frame closest to the midpoint of the velar closure was located where the tongue dorsum was most visibly raised. The audio waveform was also used to identify the time where stop closure and release occurred. Typically, two or three frames were identified with apparent lingual-palatal contact and acoustic silence. Figure 4 shows a sequence of eight frames from P8 surrounding a velar closure from /ə/ to /k/ to /o/ in *Say a cove again*. Contact of the tongue dorsum with the

palate is evident in frames 3, 4, and 5. In this example, velar closure location was measured from the fourth frame.

The selected closure frame and surrounding frames were used to determine the location and extent of lingual-palatal contact. The following closure location cues were used (roughly in order of importance): (1) the direction of the tongue movement into and out of closure, (2) the flattening of the tongue body against the palate along the closure, (3) the brightness of the ultrasound reflection at the tongue surface at closure which occurs because the tongue is not moving as much during closure (Morrish, Stone, Shawker, & Sonies, 1985; Stone, Sonies, Shawker, Weiss, & Nadel, 1983). Closure location was marked on the selected closure frame by identifying the most anterior and posterior points of velar closure.

Closure location was then quantified by computing the angle from the horizontal plane from a point at the base of tongue to the midpoint between the anterior and posterior closure points. The base location for the angle was a point at the upper edge of the geniohyoid (La'Porte, Juttla, & Lingham, 2011) at the midpoint between the anterior and posterior margins of the muscle, as used in Bressman et al (2005). This location was stable across the variety of velar-vowel productions by a participant in the experiment. Quantifying closure location using an angle as in a polar coordinate system, rather than an absolute x,y coordinate provides a better representation of the vocal tract articulatory space (e.g. Laprie & Busset, 2011) and related acoustic tube models (e.g. Story, 2009).

Figure 5 shows an example of velar closure angle measurement for P8 from fourth frame extracted from the sequence in Figure 4. The "+" symbols indicate the extent of apparent lingual-palatal contact. The line and arrow indicate the resulting angle used to quantify velar closure location. A small study of inter-measurer reliability for the measurement of velar closure location in two speakers by two measurers found differences in closure points selected between two measurements of the same video to be about 3.3 mm, resulting in an average angle difference of 0.7 degrees (Hardin & Frisch, 2005). As a case in point, Figure 5 provides an example of potential ambiguities in the measurement procedure that might lead to measurement error. The marks on the figure most closely reflect the brightness of the tongue edge. The marks for closure might be placed slightly more posteriorly as the flatness of the closure and shadow of the palate that is visible due to closure look slightly more posterior. Not reflected in a still image are the dynamics of the tongue movement into and out of closure over several adjacent frames, which were taken to reflect the articulatory target for the gesture. In addition, tongue looping creates some variability in the location of closure across multiple image frames.

2.4.2 Vowel F2—Vowel frontness of the following vowel was quantified acoustically by F2. The F2 values were measured from the audio recording at the estimated steady state near the midpoint of the vowel following the velar stop. F2 values were determined automatically by linear predictive coding (LPC) analysis using Praat (Boersma, 2001). Each production was inspected by hand to ensure that F2 was tracked appropriately at the vowel midpoint. If F2 was not tracked appropriately, LPC frequency and pole parameters were adjusted to try to get an automatic measure of F2. In a few cases, appropriate LPC parameters could not be

found, and F2 was measured by hand from an extracted spectrum with the spectrogram used for reference.

2.4.3 EdgeTrak measures of tongue contour—The relative frontness or backness of the tongue body during both the velar closure and the following vowel midpoint was also measured from the tongue contour using a measure similar to Bressman’s anteriority index (Bressman et al, 2005), that will be referred to as the anteriority angle. This measure takes a weighted average of five angles across the tongue from anterior to posterior to estimate how much of the mass of the tongue body is positioned relatively forward or back in the oral cavity. Tongue contours were semi-automatically created using EdgeTrak software (Li et al, 2005). The EdgeTrak program creates a trace of the tongue edge in a video frame based on a few “seeding” points provided by the user and an analysis of the light/dark contrast between pixels in the image. For this study, the smoothness parameter (which controls how much weight the program gives to creating a mathematically smooth curve) was set to 70%.

The anteriority angle is computed from the extracted contour by taking the weighted average of the distance of the tongue surface from the midpoint of the geniohyoid-genioglossus complex at five different angles (67.5, 78.75, 90, 101.25, 112.5). Figure 6 shows the same example from P8 with the EdgeTrak contour of the tongue surface and the set of angles and distances used in the computation of anteriority angle. Each of the five angles is weighted by the distance from the tongue base to the tongue surface according to the following formula:

$$\text{anteriorityangle} = \frac{67.5 \cdot r_1 + 78.75 \cdot r_2 + 90 \cdot r_3 + 101.25 \cdot r_4 + 112.5 \cdot r_5}{r_1 + r_2 + r_3 + r_4 + r_5}$$

In the case of the example in Figure 6, the relatively longer length of r_1 and r_2 compared to r_4 and r_5 would result in an anteriority angle less than 90 for a more forward articulation.

3.0 Results

3.1 Measurement

3.1.1 Measurements of velar closure angle—Figure 7 shows each velar closure angle measurement for the nine vowel contexts for each of the ten participants. The figure is oriented in the same way as the ultrasound images, with the front of the vocal tract to the right. Each point is the measure of one velar closure production from one word. The angle of closure is located along the x-axis from a lesser angle (more front velar closure angle) on the right to a greater angle (more back velar closure angle) on the left. The vowels are presented along the y-axis with more front vowels at the top, to more back vowels at the bottom. The participants are organized in pairs, with P1 and P2 in the top row, P3 and P4 in the next row, etc.

Inspection of Figure 7 reveals some spread in the range of closure angles found for each vowel within the participants, including some cases of apparent outliers. For example in the /u/ vowel context for P2 (bottom row of the upper right graph) the closure locations range from something comparable to closures for the front vowels to ones fully within the range of other back vowels. While some of this variation is likely noise in the data, genuine

articulatory variation in closure location for the same vowel context is apparent. This variation is exemplified in Figure 8, which shows three tokens of P2's productions of *coop*. Variation in tongue body frontness across the different productions is clear, with the top image (from repetition 2) more front, the middle image (from repetition 3) and the bottom image (from repetition 5) more back. This variation in the location of closure across different imaged productions is likely a combination of genuine variability in speech production combined with temporal variation in time point where closure was captured caused by video sampling (at 29.97 frames per second). Given video sampling, the imaged closures likely vary in the degree of tongue dorsum compression against the palate as well as position in the articulatory loop for velar closure (Perrier et al, 2003).

Comparing across participants, the overall pattern of closure angle measures is relatively consistent. For all ten participants, the coarticulatory effects of vowel frontness on the velar closure angle move in a continuous range of closure locations with vowel context. The front vowel contexts appear to result in closures that are in the most forward location. For all participants, the front vowel context is more forward than the other contexts, however, for P1, P2, P5, P6, and P10, there appears to be a visible discontinuity between closure location for the front vowel contexts and the non-front vowel contexts.

Among the mid and back vowels, the /ɑ, ɔ/ contexts appear to result in the furthest back closure location across participants. For the most part, the other mid and back vowel contexts /ə, ɜ, o, u/, the closure locations are comparable. In addition, for P1, P5, P6, and P10, the closure location for the /ə/ vowel context is in back of the closure location for the /ɜ/ vowel context. For the other participants (P2, P3, P4, P7, P8, P9), the /ə/ vowel context closure location is in front of the /ɜ/ closure location. This difference may contribute to the visual perception of a distinct front vowel group, rather than a continuum of closure locations across vowel contexts.

There are also some differences in absolute measurement values between participants. The angle measures were normalized to a within tongue reference, so variation between participants in the placement of the ultrasound probe for recording is not relevant. These variations in absolute measures probably reflect actual individual differences in articulatory anatomy or gestural patterns in the production of velar stops. One participant may produce vowels further back in the oral cavity, which would correspond to a more back velar closure location, as compared to another participant. For example, for P2 the velar closure angle measurements for /i/ (67 to 75 degrees, average 72) are greater (further back along the palate) as compared to the velar closure angle measurements for /i/ for P10 (60 to 69 degrees, average 64).

3.1.2 Edgetrak-based measure of tongue position during consonant closure—

Indirect measures of consonant closure location using the anteriority angle for the tongue body during the consonant closure give similar results to the measure of closure location. The overall pattern of anteriority angle measures during the consonant closure is relatively consistent across participants, with anteriority angle smaller for front vowel contexts and larger for back vowel contexts. However, the range of values is much smaller for anteriority angle than for the actual closure location. For example, the participant with the largest range

of anteriority angles for the consonant (P6) had angles ranging from 86.0 to 90.9, a difference of less than 5 degrees. Also, unlike the direct closure location measures, the separation seen between front vowel contexts and the rest of the vowel contexts in some participants is generally less clear to visual inspection.

3.1.3 F2 measurements for vowel location—Acoustic measurement of vowel advancement was used as a predictor of context effects on velar closure location. The measure used came from the F2 of the vowel at its midpoint. As expected, smaller F2 frequency values corresponded to a more back tongue position, and larger F2 frequency values corresponded to a more front tongue position. For example, P2 has a larger mean F2 value for the front vowel /i/ (2664 Hz) as compared to a smaller mean F2 value for the back vowel /o/ (1267 Hz).

3.1.4 Edgetrak-based measure tongue position during the vowel—Anteriority angle was computed for traces of the tongue curve at vowel midpoint as a predictor of context effects on velar closure location. Values for anteriority angle for the vowel varied over a wider range than for the consonant. This finding is to be expected given the relative differences in articulatory constraint for production of /k/ versus production of nine different vowel qualities. For example, anteriority angles for the vowel in P2 ranged from 86.7 to 92.3, a range of 5.5 degrees which was a fairly typical range. This is greater than the range for anteriority angle for velar closure and P2 was the participant with the greatest variation in anteriority angle for velar closure.

As expected, anteriority angles were lower for front vowels and higher for back vowels. There was no evidence for a qualitatively distinct front vowel group in anteriority angle for the vowels, the values varied over a continuum for all ten participants. For all participants the anteriority index for the /ə/ vowel is greater than the anteriority index for the /ɔ:/ vowel, and clearly so for all but P4 and P5 where there is considerable overlap between the two distributions. This may not truly reflect fronting of the tongue body for /ɔ:/ however, as the tight bunching of the anterior part of the tongue body for /ɔ:/ might distort the anteriority angle measure.

3.2 Correlations between Measures

Correlations between all measures across productions were computed within each participant. Selected correlations that provide insight into the coarticulatory patterns between velar closure and vowel advancement or that suggest the best methodology for the measurement of velar closure and vowel advancement are shown in Tables 2, 3, and 4. For all correlations, statistical significance was set at the $p < .005$ level to adjust for the use of 10 correlations in each comparison (one per participant).

The first set of correlations assessed the influence of the vowel on the consonant closure location (i.e. the velar fronting pattern) using the two measures of closure location for the velar. In these correlations, vowel F2 is used as the index of the frontness of the context vowel, as this measure is well-established. The correlations between the primary measure in the present study, velar closure angle (VCA), and F2 ranged from -0.57 to -0.88 . These large, statistically significant correlations for all ten participants reflect the overall

continuous nature of the coarticulatory pattern between velar closure and vowel. Closure location varies with small differences in vowel advancement for all participants.

The relationship between the anteriority angle for the consonant (AA-C), a measure derived from the semi-automatic tracing of the tongue provided by EdgeTrak and the F2 of the vowel ranged from -0.55 to -0.92 . These are also large statistically significant correlations for all ten participants. For seven of the ten participants, the manual measure of velar closure angle correlates more highly with F2 than the anteriority angle for the consonant, but the two measures are largely comparable. This suggests that future studies of velar-vowel coarticulation using ultrasound imaging can use EdgeTrak tongue contour tracing, which is less ambiguous, requires less expertise, and is less labor intensive compared to manual measurement of closure location.

The second set of correlations, shown in table 3, compares the use of F2 as a measure of the frontness of the vowel with the use of the anteriority angle as a measure of frontness of the vowel. The correlations between the velar closure angle and anteriority angle for the vowel (AA-V) ranged from 0.35 to 0.81. These are moderate to high statistically significant correlations for all ten participants. The correlations for the anteriority angle measure for the consonant closure (AA-C) versus the anteriority angle measure for the vowel (AA-V) ranged from 0.37 to 0.79. These are moderate to high statistically significant correlations for all ten participants. Surprisingly, we find higher correlations between the measures of the consonant (VCA and AA-C) with vowel F2 than with anteriority angle for the vowel (AA-V) for all but two participants. For these two participants, the correlations are about the same for all measures. It would generally be expected that an articulatory measure of the vowel would better capture articulatory advancement that would influence coarticulation with the velar onset, but this was not the case.

The third set of correlations compared the alternative methods for measuring anterior/posterior tongue position for the consonant and vowel articulations directly. These correlations are shown in table 4. The correlations between the velar closure angle measure of consonant closure location (VCA) and the anteriority angle for consonant closure (AA-C) were large positive statistically significant correlations for all participants that ranged from 0.65 to 0.97. These correlations suggest that either measure of velar closure location would be useful in future studies. The relationship between the F2 value and anteriority angle for the vowel (AAV) were negative, but ranged more widely from -0.23 to -0.82 . These were statistically significant correlations for nine out of ten participants. Overall, the two vowel measures are less consistent with one another compared to the consonant measures. Given that vowel F2 better correlated with the measures of velar fronting, it would appear that the anteriority angle measure for the vowel misses some aspects of vowel articulation that are relevant to velar-vowel coarticulation.

4.0 Evaluation of a Simplified Virtual Target Model

A full simulation of the present data with an articulatory model is beyond the scope of this paper. However, a useful statistical analysis can be made that also avoids choosing any particular articulatory model. As exemplified in Figure 2, the amount of variation in palate

contact point across vowel contexts can provide information about possible groupings of contexts. If the distribution of contact points for two different vowels is basically the same, then they are more likely to have the same virtual target. The homogenous subsets analysis above suggests that different speakers may have different numbers of contextual targets for the velar stop, however, the threshold of statistical significance provides only one division of the data and does not include an assumption of the virtual target model: There will still be some systematic variation within a subset with the same virtual target due to /ə/ to virtual target to vowel trajectory differences. A different approach is taken in this section by evaluating the variation in data from the perspective of Bayesian model fitting. Specifically, for each participant a model based on fitting groups of contexts on the basis of their mean closure location (in closure angle) was created for several linguistically sensible groupings of vowel contexts. The contexts and their number of groups were: all vowels (1), front vs. non-front (2), front vs. central vs. back (3), high front vs. low front vs. central vs. low back vs. high back (5), high front vs. mid front vs. low front vs. central vs. low back vs. mid back vs. high back (7), and one context for each vowel (9). Alternatively, these could be viewed as phonologically specified windows for articulation in Keating's window model (Keating, 1990). For a grouping of vowels, the "target" velar closure angle was computed by averaging all velar closure angles for all vowel contexts in the group. For example, in a model with a front vowel group (2 or 3 vowel contexts) the average angle for all /i, e, æ/ contexts was computed for each participant. For this vowel group, the total sum of squares error between the individual measures and the means was computed and used in the next stage of the analysis.

Model fit was evaluated by the residual sum of squares error between all measures for a context and the mean for that context, corrected for the number of model parameters (vowel contexts) using the Bayes Information Criterion (BIC, Schwarz, 1978). In this type of analysis, there is no threshold of statistical significance, but the error can be examined against a penalty for the number of model parameters to look for a local minimum in information. Differences in BIC between models can be compared (Kass & Raftery, 1995). Figure 9 shows the BIC for each model for each participant by the number of context groups. For all participants the two parameter model (front vs. non-front) provides the lowest BIC or the optimal combination of model fit and fewest parameters. For 7 of the 10 participants, the three parameter model (front vs. central vs. back) is worse, but not substantially worse by the criterion of Kass & Raftery (1995). For all participants, all other models can be ruled out as considerably worse than the two parameter model. Given that in 10 out of 10 participants the two parameter model provided the best fit by BIC we can conclude that, despite individual differences in the patterns of variability seen in the data for velar closure location, all participants appear to use two distinct articulatory targets for velar closure location, one for front vowels and one for non-front vowels. This is true even for those participants whose data, by visual inspection, appear to continuously vary in velar closure location.

5.0 Discussion

5.1 Phonological issues

Overall, the pattern of velar closure location fronting in the context of different vowels is compatible with a virtual target model for stop closure where there are two allophones of the velar stop, one for front vowels and one for non-front vowels. Small amounts of variation between vowels within those allophonic contexts are still to be expected as the exact trajectory of movement will be slightly different for vowels within a group (e.g. /i/ vs. /e/). The velar fronting data are therefore compatible with a phonological model of the velar fronting process where a discrete number of contextual allophones are used that create natural classes. These findings are consistent with previous studies of velar fronting that were based on a smaller set of vowel contexts (Keating & Lahiri, 1993; Lofqvist & Gracco, 1994). These findings are also consistent with Wodzinski (2004), which used a larger set of vowel contexts but had a smaller sample of participants. The virtual target model has the ability to account for both the large variation between front and non-front contexts as well as the smaller degrees of variation within the front and non-front contexts when velar closure is measured by closure location.

In the ongoing development of the fields of phonetics and phonology it has been increasingly difficult to draw a strict line between phonetic phenomena and phonological phenomena. Rather, it appears that there are layers of generalization from the concrete, physical, and measurable to the abstract, categorical, and symbolic (Pierrehumbert, 2003; Munson, Beckman, & Edwards, 2011). The case of anticipatory velar-vowel coarticulation in English is well in line with this trend. When a larger number of talkers are measured producing /k/ in a wider variety of contexts, measurable individual differences in typical placement and degree of variability are seen within and across categories. Despite this variability, however, there is evidence to support that variability comes from two sources: A higher level distinction in virtual closure target for the /k/ depending on the vowel context, and a lower level distinction in the resulting articulatory movement as overlapping gestures are integrated into a smoothly coarticulated speech plan. The articulatory findings here are not that different from studies, for example, of vowel production that find multimodal overlapping distributions in F1 and F2 within and across speakers (Clopper, Pisoni, & de Jong, 2005). Nonetheless, listeners are able to classify the vowel that has been produced and children are able to learn distinctions for overlapping categories given evidence of a multimodal distribution (Maye, Werker, & Gerken, 2002).

5.2 Methodological issues

In this study, two different measures of velar closure location were employed, with about equal success. The velar closure angle attempted to measure the closure location directly using a variety of cues from the ultrasound video. The anteriority angle measure was derived from a semi-automatic tongue tracing using EdgeTrak. The correlations between these two measures and the measures of vowel frontness were comparable. So it would appear that the frontness of the closure location measured by the velar closure angle is directly related to the overall global frontness of tongue body measured by the anteriority angle. This straightforward relationship likely results because the tongue dorsum is used to make the

stop closure for velars and also is the primary articulator for the posture of the tongue for the following vowel context. In the case of velar articulation, at least, global measurement of the tongue contour appears to be a practical alternative to identifying articulatory landmarks directly.

In addition to the measures presented here, additional variants on these measures were also examined. This study presents the anteriority angle, a modification of Bressman's anteriority index (which itself is an adaptation of the anteriority index measure for EPG, see Gibbon & Nicolaidis, 1999). Using Bressman's anteriority index measure does not change the qualitative patterns observed using the anteriority angle, though quantitatively the correlations involving Bressman's anteriority index were lower. A measure of center of gravity of the tongue body was also explored, in an attempt to quantify tongue body frontness over the entire tongue body curve generated by Edgetrak (comparable to center of gravity measures used in EPG, as in Liker & Gibbon, 2007). Once again, this measure produced qualitatively similar results but quantitatively lower correlations. This measure also produced a larger number of outliers, as the center of gravity measure was overly sensitive to variation in imageability of the tongue tip and tongue root across individuals. The anteriority angle and Bressman's anteriority index are more stable measures as they do not rely on the extreme margins of the tongue image (Stone, 2005).

6.0 Conclusion

In this study, an extensive analysis of velar-vowel coarticulation with a relatively large number of participants was undertaken. Articulatory measures across participants were consistent, showing a direct relationship between velar consonant closure location and the location of the tongue body for the following vowel. Our findings are compatible with the original conclusions of Keating & Lahiri (1993) that velar closure location varies continuously on the basis of vowel frontness. In a virtual target model of velar stop production, however, the data support a more abstract model with two virtual target allophones, one for front vowels and one for non-front vowels. Modeling of the coarticulation data using a virtual target model with two context-dependent allophones appears to provide the best description of the data without over-fitting the details. Participant articulations vary around two general closure locations reflecting the trajectory of the tongue dorsum from the preceding /ə/ toward a virtual target location beyond the palate based on the upcoming vowel context. However, finding stability within the range of typical variability requires examining a variety of contexts for a substantial number of speakers. Only with enough data is it possible to see the emergence of phonetic categories from the inherent variability in the data.

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Highlights

- Ultrasound study of anticipatory velar-vowel coarticulation in 9 following vowel contexts by 10 speakers of American English
- Virtual target model of velar stop production is proposed with front and non-front allophones of the velar stop
- Comparison of manual articulatory measures, semi-automatic articulatory measures, and acoustic measures suggests future research may use semi-automatic measures and retain internal validity

Figure 1. Ultrasound image of velar stop closure before /i/ in *key* (top) versus /ɔ/ in *cough* (bottom) showing significant fronting of the tongue body for /k/ in *key*.

Figure 2. Schematic of planned /k/ to V trajectories in two virtual target models, with one target (left) and with two targets (right). In the one target model, variation in closure location is relatively evenly distributed along the palate. In the two target model, two allophonic groups with larger distances between closure locations are created.

Figure 3.
Head and probe stabilizing device used to minimize probe movement relative to the head across the experimental session.

Figure 4.

Sequence of eight ultrasound images of /æko/ from *Say a cove again*, with dorsum contact with the palate in frames 3, 4, and 5, frames 1–4 on the left, frames 5–8 on the right. Closure was measured from frame 4.

Figure 5. Measurement of closure location angle. Angle is computed from the midpoint of the geniohyoid to the midpoint of closure, determined by tongue edge flatness and brightness.

Figure 6.
EdgeTrak tongue contour and five angles used to compute anteriority angle.

Figure 7.

The measure of velar closure angle for each vowel context for each participant demonstrating considerable variation within and between contexts.

Figure 8.

Variability within a participant for closure location within a single word, in this case three examples of *coop* produced by P2 showing a more posterior closure (top) compared to the typical closure location (middle and bottom).

Figure 9. Model comparison for each participant using Bayes Information Criterion for six different vowel context groupings. For all 10 participants, the model with two vowel groups (front versus non-front) provides the optimal fit.

Table 2
Correlations between two measures of velar closure location and the F2 measure of vowel frontness.

Velar	Vowel	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
VCA	F2	-.88	-.84	-.83	-.78	-.64	-.82	-.57	-.78	-.73	-.83
AA-C	F2	-.92	-.64	-.70	-.75	-.71	-.80	-.55	-.78	-.67	-.70

Table 3

Comparison of F2 and anteriority angle measures of vowel advancement as predictors of velar frontness.

Velar	Vowel	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
VCA	F2	-.88	-.84	-.83	-.78	-.64	-.82	-.57	-.78	-.73	-.83
VCA	AA-V	.35	.64	.67	.60	.43	.81	.42	.78	.71	.59
AA-C	F2	-.92	-.64	-.70	-.75	-.71	-.80	-.55	-.78	-.67	-.70
AA-C	AA-V	.37	.49	.47	.64	.48	.79	.40	.78	.76	.53

Table 4

Comparison of alternative measures of consonant and vowel advancement. Correlations are generally stronger for consonant than for vowel.

M1	M2	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
VCA	AA-C	.92	.75	.80	.91	.69	.92	.65	.97	.83	.90
F2	AA-V	-.23	-.67	-.70	-.47	-.42	-.82	-.61	-.80	-.73	-.60