19

Jaw Cycles and Linguistic Syllables in Adult English

Melissa A. Redford [1]

&

Paul van Donkelaar [2]

[1] *Department of Linguistics*

The University of Oregon

Eugene, Oregon, USA

[2] *Department of Human Physiology*

The University of Oregon

Eugene, Oregon, USA

Overview

In this chapter, we examine whether ideas from Professor MacNeilage's Frame/Content Theory of the Evolution of Speech Production (MacNeilage, 1998) apply to linguistic syllables in adult speech. The relevant ideas are that jaw movement is independent of segmental articulation, and that the jaw is recruited to help solve the serial order problem for speech. Specifically, MacNeilage argues that in ontogeny and phylogeny speech-like behavior - the production of consonant-vowel strings - first emerges when phonation is married to the cyclic open-close movement of the jaw. The result of this marriage is the proto-syllable: a structured segment grouping, which becomes elaborated with time as motor control of the tongue, lips, and velum becomes more sophisticated. Together with Professor Davis and other colleagues, MacNeilage has amassed substantial evidence to support the hypothesis of a Frame/Content mode of speech production in development (e.g., Davis & MacNeilage, 1995; MacNeilage, Davis, Matyear, 1997; MacNeilage & Davis, 2000).

The specific questions addressed in this chapter are as follows. Does the jaw cycle continue to define syllables in adult speech, as suggested by the cross-language distribution of certain hallmark patterns of a Frame/Content mode of production (MacNeilage, Davis, Matyear, Kinney, 2000). Or, is jaw movement subordinate to segment articulation, as suggested by more traditional articulatory phonetic accounts of jaw movement in speech (e.g., Perkell, 1969; Gracco, 1994; Stone & Vatikiotis-Bateson, 1995).

The initial data we present suggest that jaw movement is influenced, but not tied to segmental articulation. However, the data also suggest that any functional correspondence between the jaw cycle and the syllable is weak at best. Whereas a weak correspondence between the cycle and the syllable may be sufficient to condition sound change in the directions predicted by an extended Frame/Content Theory (e.g., MacNeilage et al., 2000), it is insufficient to explain syllable production in the adult. Instead, it may be that syllabic motor routines are so highly practiced that their execution can be achieved in the same integrated and holistic sense described for individual segments (e.g., Fowler & Saltzman, 1993) and without consistent reference to the frame upon which they were originally organized.

The Hypothesis

Redford (2000) hypothesized that the Frame/Content mode of production might be extended to adult speech to provide an explanation for several phonological and phonetic patterns associated with linguistic syllables. The argument departed from two observations and an assumption. The observations were (1) that segments within a syllable are organized so that they increase and decrease in sonority according to the Sonority Sequencing Principle (SSP; Hooper, 1972; Selkirk, 1982; Clements, 1990); and (2) that sonority correlates with jaw openness, such that more sonorous segments are articulated with more jaw opening than less sonorous segments (Lindblom, 1983). The assumption was that sonority sequencing reflects segment sequencing according to the jaw cycle (as in Lindblom, 1983; Butt, 1992). Redford reasoned that if the SSP is central to a definition of a syllable, as is generally assumed (see, e.g., Kenstowitcz, 1994), and the jaw cycle explains the SSP, then the jaw cycle could provide an articulatory basis for the syllable.

If the jaw cycle provides an articulatory basis for the syllable, then it should explain other syllable-related phonological and phonetic patterns beside the SSP. Redford (2000) argued that it could. To take a phonological example, Redford argued that the cross-language preference for syllable-onsets over syllable-offsets (Bell & Hooper, 1978) might emerge from the oft-noted asymmetry between jaw opening and closing (Sussman, MacNeilage, Hanson, 1973; Kuehn & Moll, 1976; Kelso, Vatikiotis-Bateson, Saltzman, Kay, 1985; Gracco, 1994). In particular, the faster closing movement of the jaw might disfavor consonantal articulation because of the speed-accuracy trade-off (Fitts, 1954), assuming that faster jaw closing is a property of the cycle and is independent of linguistic targets.

The hypothesis that the jaw cycle provides a frame for segmental articulation in adult speech as it does in child speech is attractive because of its power to explain a wide variety of syllable-related sound patterns. The hypothesis is at odds, however, with the view derived from the study of adult segmental articulation. The dominant view in adult articulatory phonetics is that jaw movement follows from segmental articulation (e.g., Perkell, 1969; Gracco, 1994; Stone & Vatikiotis-Bateson, 1995). The jaw is raised during the consonant and lowered during the vowel. If the jaw follows segmental articulation, then jaw height maxima and minima represent consonant and vowel targets respectively, and the alternation between the two (i.e., the cycle) is a mere epiphenomenon of consonant-vowel sequencing in language.

Evidence for this segment-first view of jaw movement comes from the fact that the jaw maxima and minima can be predicted by the location and degree of vocal tract constriction that defines segmental articulation. For instance, consonants that are made with greater and more anterior constrictions of the vocal tract are associated with more jaw raising than those that are made with lesser or more posterior constrictions (Keating, Lindblom, Lubker, Kreiman, 1992). However, the maximal vocal tract constrictions achieved by the tongue are not always temporally aligned with maximal jaw closure (Stone & Vatikiotis-Bateson, 1995). This is surprising if the jaw is part of the coordinative structure that defines segmental articulation (Fowler & Saltzman, 1993), and leaves open the possibility that jaw movement is independently specified.

In summary, it is possible to identify two competing views of jaw movement in speech. One view follows from the Frame/Content Theory and suggests that segmental articulation is timed to correspond to the jaw cycle in such a way that syllables can be defined by cycles. The other view follows from articulatory phonetics and suggests that segmental articulation constrains jaw movement, such that cycles emerge from segment sequencing restrictions within syllables. The experiments described below were aimed at corroborating one or the other of these views by examining the relationship between jaw cycles and English syllables in adult speech.

The Production of CVC, CCVC, CVCC Syllables

The goal of this experiment was to determine the relationship between the jaw cycle and segment groupings that we would intuitively characterize as syllables in adult English.

Methods

One male and two female native English-speaking adults participated in the experiment. All three spoke a West-coast dialect of American English. The participants produced CVC, CCVC, and CVCC syllables in the frame sentence "Say ____ eight times." The different syllables all shared the same vowel, /ɑ/, and one of three consonants, /ɹ, l, t/, that occurred in either the onset or offset position and either as a singleton onset or as the internal member of a cluster. For example, the stimuli for the /ɹ/ series were /ɹɑt/ *rot*, /tɑɹ/ *tar*, /tɹɑt/ *trot*, /tɑɹt/ *tart*. As in this example, labial segments were avoided for all stimuli, so as not to interfere with the measurement of jaw kinematics. Participants produced each of the stimuli 5 times in individually randomized orders for a total of 60 tokens per speaker (20 per series X 3 series).

Procedure

Speakers were seated in a darkened room and read the stimuli off a computer monitor. Stimulus presentation was controlled by software that automatically randomized the stimuli, presented each for several seconds, and then advanced to the next after a short interval. Jaw movement and speech acoustics were recorded simultaneously by two separate computers during the subjects' responses. Jaw movement was recorded on one computer using a Watsmart system consisting of infrared light emitting diodes (LEDs) and two infrared-sensitive cameras. Two LEDs were used. The one that measured jaw movement was attached to a neoprene chin-guard that was taped below the chin to the speaker's mandible. The other marker was attached to the bridge of the nose to provide a reference point for the jaw movement. Speech acoustics were captured by a high quality microphone and recorded directly onto the second computer. The stimulus presentation computer simultaneously triggered the jaw movement and the speech acoustic recording computers at the beginning of each trial. The following acoustic and movement measures were then made on the recordings.

Acoustic Duration

Segment onsets and offsets were identified using standard phonetic procedures (e.g., Klatt, 1976): the acoustic waveform was displayed as a spectrograph and an oscillograph. Following an obstruent consonant or vowel closure, the boundaries of liquid consonants were identified at the beginning of periodicity and the corresponding rise in signal amplitude. Following a vowel, the boundaries were identified at an abrupt decrease in energy and frequency changes in the waveform. The boundaries between liquid consonants and the vowel nucleus of the syllable were determined by a change in the waveform, a decrease in overall energy, and a low F3 for /ɹ/ and an antiformant between F1 and F2 for /l/. The boundaries of stop consonants were identified at the offset/onset of adjacent vowels or liquids as indicated by an abrupt decrease or increase in the energy of the periodic waveform. If a stop was released in final position, stop duration was measured from the offset of periodicity on the initial border to the offset of aspiration on the final border. Otherwise the final border was measured as the onset of the following vowel in *eight*. This practice allowed for measurement consistency, but it probably overestimated the actual articulation time of a final stop. The stimuli also included the alveolar fricative /s/ (e.g., /stɑk/ *stock*). The boundaries of this segment were identified at the onset to the offset of noisy energy.

Movement Measures

Next, the temporal onsets of the segments were aligned with the jaw movement waveform and the cycle maxima (peaks) and minima (troughs) were identified for the target syllable (see Figure 1). The duration, displacement and velocity of jaw movement were calculated for the demicycle, that is, the portion of the cycle corresponding to either the movement from cycle peak to trough or the movement from cycle trough to peak. Several additional measures were also made to describe the relationship between the jaw cycle and the articulation of the target segments in the syllable. Specifically, jaw height at segment onset was calculated for the shared consonants, /ɹ, l, t/, and vowel, /ɑ/. The time of segment onset from the relevant cycle peaks (for the consonants) and troughs (for the vowel) was also calculated. Figure 1 depicts these latter measurement types.

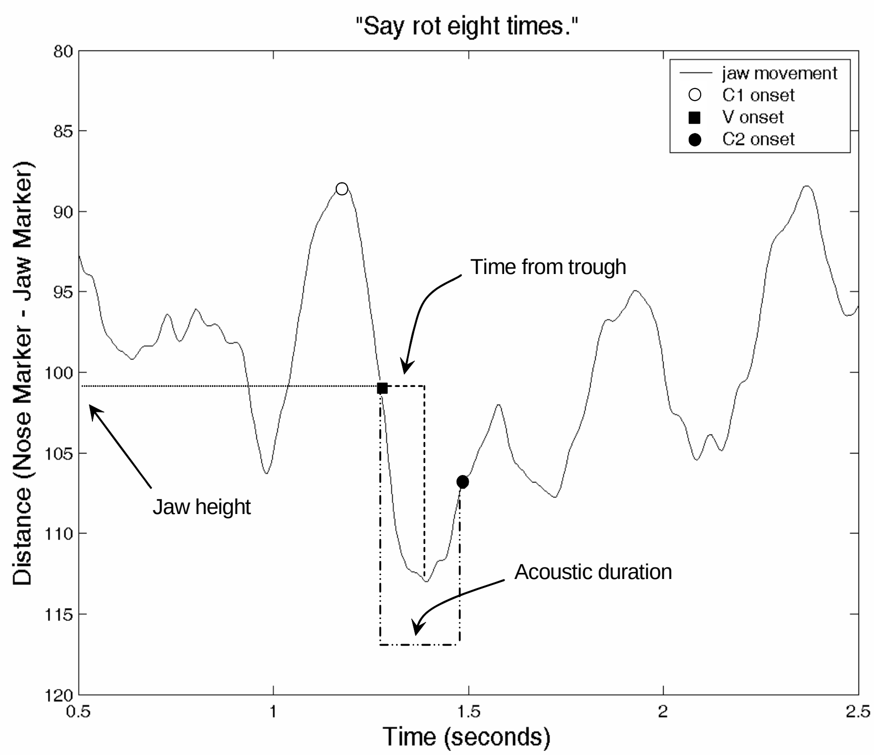

Figure 1.

The movement waveform is shown for the target syllable *rot* in the frame “Say ___ eight times.” The temporal onsets of the acoustic segments are plotted on the waveform. The figure also shows how measures relating segmental articulation to the jaw cycle were calculated. The example measures are for the /ɑ/ in *rot*.

Predictions

The hypothesis that segmental articulation follows jaw movement predicts that the segments of a syllable will be timed to correspond to the opening and closing movement of the cycle. Syllable onsets will be articulated during the opening phase of a cycle, and syllable offsets will be articulated during the closing phase.

Internal members of a cluster will be articulated further from the peak of the cycle and closer to its trough.

The hypothesis that jaw movement follows from segmental articulation predicts that the target jaw position should be reached at approximately the same time during the articulation of a segment regardless of syllable position. So, for example, in the V___V frame of the present experiment, the proportion of a consonant articulated during opening or closing should not be affected by syllable position.

Results

Overall, the results suggest a correspondence between the jaw cycle and syllable structure, but jaw movement is also clearly influenced by segmental articulation. We present the results on demicycle characteristics for different syllable positions, followed by the results relating segments-by-position to location within the cycle.

Demicycle Characteristics

Demicycle characteristics were analyzed as the first step in the evaluation of the relationship between the cycle and the syllable. Demicycle duration, displacement, and peak velocity covary and so were entered as dependent variables in a 3-way multivariate analysis of variance (MANOVA) with Speaker, Syllable (C**C**V, **C**V, V**C**, V**C**C), and Consonant (r, l, t) as fixed factors. The test showed that the variables jointly varied systematically with Syllable and Consonant [Pillai's Trace, $F = 8.144$, $p < .01$] and with Speaker and Syllable [Pillai's Trace, $F = 4.693$, $p < .01$]. The presence of Speaker differences in particular obscured the expected asymmetry in opening and closing peak velocity, as indicated by the lack of an effect of syllable position in a follow-up univariate analysis on peak velocity. However, other follow-up analyses showed an asymmetry in displacement—opening displacement was greater than closing displacement [$F(1, 135) = 158.276$], and a corresponding asymmetry in duration [$F(1, 135) = 14.654$, $p < .01$].

Neither speaker differences nor differences between consonant types obscured the effect of syllable structure on the variables. Follow-up univariate analyses adjusted for multiple comparisons indicated that demicycles associated with the articulation of complex onsets and offsets were greater in duration, displacement, and velocity than those associated with the articulation of simple onsets and offsets [duration, $F(1, 135) = 77.993$, $p < .01$; displacement, $F(1, 135) = 23.805$, $p < .01$; peak velocity, $F(1, 135) = 7.541$, $p < .01$]. This latter result is most likely due to the sequential articulation of consonants rather than to syllable shape per se.

In sum, duration and displacement were greater during jaw opening than during jaw closing, and during the articulation of complex onsets/offsets than during the articulation of simple onsets/offsets.

Segment Height and the Cycle

The relationship between segment articulation and the jaw cycle was evaluated more directly by analyzing jaw height at the onset of segment articulation. Jaw height (measured as the difference between the nose and jaw markers) at segment onset was evaluated as a function of Speaker, Syllable, and Consonant. Consonant height at segment onset was significantly affected by Syllable [$F(3, 135) = 10.076$, $p < .01$] and Consonant [$F(2, 135) = 8.506$, $p < .01$], but not by the interaction of these factors or by interactions with Speaker. Both singleton consonants and those in a cluster were initiated at a more open point on the cycle in syllable-offset position than in syllable-onset position. The alveolar stop was initiated at a more open point on the cycle than either alveolar liquid. In contrast, vowel height at onset interacted with Syllable and Consonant [$F(6, 135) = 2.575$, $p < .05$], but the fact that neither factor alone significantly affected height indicated significant variability across the different Syllable and Consonant combinations.

Given the lack of an effect of Syllable on vowel height at onset, the Syllable effect on consonant height is more easily understood as resulting from the asymmetry of the opening and closing demicycles than in terms of segment duration characteristics.

Segment Duration and the Cycle

The final analysis was aimed at directly testing the relationship between segments and the cycle. The hypothesis that segment groups are sequenced according to the jaw cycle predicted that consonants in onset position would be articulated during the opening phase of the cycle and those in offset position would be articulated during the closing phase. The alternative prediction was that syllable position would be irrelevant, and that target jaw positions would be reached at the same time during the articulation of the consonant. With respect to vowels, only the hypothesis that jaw movement follows segmental articulation makes the specific prediction that the target jaw position for vowels should be reached at the same time during vowel articulation regardless of syllable shape.

To evaluate the predictions, we calculated the proportion of consonant articulation within the cycle. For onset position (**C**VC or C**C**VC) this meant subtracting the duration of articulation prior to the first peak of the cycle from the total duration of the consonant, and then dividing the adjusted duration by the total duration. A similar procedure was applied to offset position (CV**C** or CV**C**C), but the adjusted duration was that which occurred prior to the second peak in the cycle. So, the measure indicated the proportion of consonantal articulation during jaw opening for onset position and during jaw closing for offset position.

Figure 2 shows the proportion of consonantal duration articulated within the cycle for consonants in the different syllable positions and onset/offset types. This significant effect of Syllable interacted with Speaker [$F(6, 135) = 6.889$, $p < .01$] and Consonant [$F(6, 135) = 3.890$, $p < .01$], but the general pattern captured by the simple effect [$F(3, 135) = 25.021$, $p < .01$] was evident in spite of the systematic variation. In particular, and as shown in Figure 2, a larger proportion of consonantal articulation occurred during the opening phase for consonants in onset position and during the closing phase for consonants in offset position than vice versa.

The figure also suggests a certain directionality to the relationship between jaw movement and segmental articulation. If the cycle peaks represent the consonantal target for the jaw, then we can see that this target was achieved at different points during the articulation of the consonants in different syllable positions. For instance, the target was attained roughly 40% of the way through the articulation of simple onsets (**C**VC), and closer to 60% of the way through the articulation for simple offsets (CV**C**).

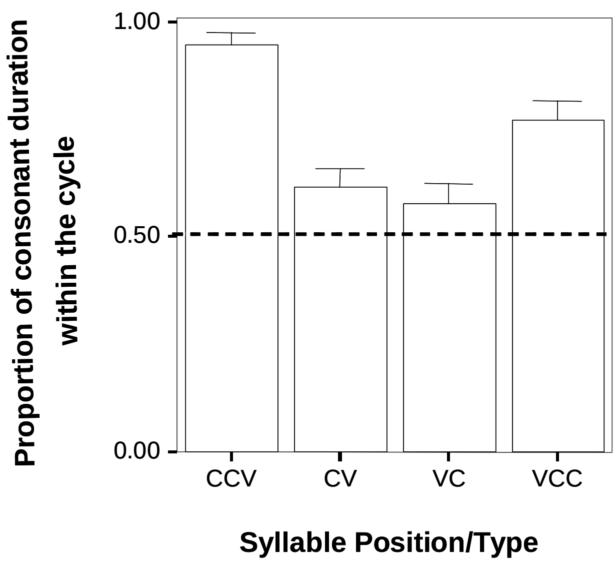

Figure 2.

The proportion of consonantal articulation within the cycle is shown as a function of the target segment's location: C**C**V, **C**V, V**C**, V**C**C. The duration of articulation following or preceding a peak (consonantal target) was divided by the total duration of articulation to obtain the proportions shown in the Figure. If the jaw had peaked midway through the articulation of the consonant, then the proportions would all be at .50, or even with the dotted line.

The difference in target attainment as a function of syllable shape is more striking for vowels, if the cycle minimum is taken as the articulatory target for the vowel. Figure 3 shows that the proportion of vowel duration prior to the trough varies for the different syllable types.

As shown in Figure 3, the vowel target is attained roughly 70% of the way through the vowel in CCVC syllables and roughly 40% of the way though in CVCC syllables. Univariate analyses with Speaker, Syllable, and Consonant as fixed factors confirm the systematic differences by syllable position and type [$F(3, 135) = 15.414$, $p < .01$], even though the differences interact to a certain degree with speaker and consonant type as well [$F(12, 135) = 2.670$, $p < .01$]. This result is not predicted by the view that jaw movement merely follows from segmental articulation. It is more consistent with the finding of greater jaw displacement in initial position than in final position, that is, with attributes that follow from the jaw cycle.

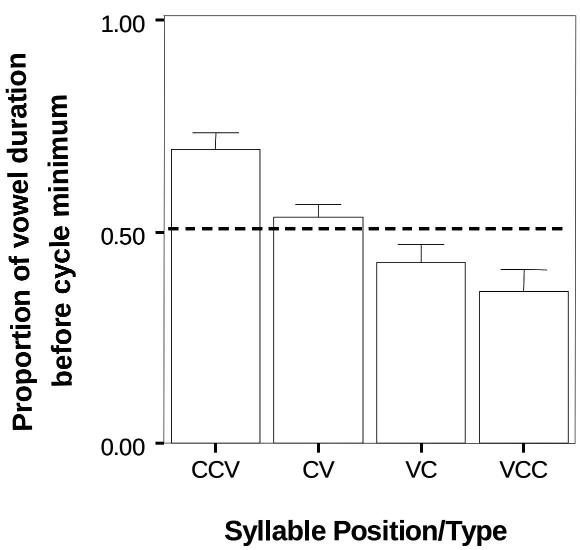

Figure 3.

The proportion of vowel articulation prior to the cycle trough (vocalic target) is shown as a function of the target segment's location: C**C**V, **C**V, V**C**, V**C**C. If the jaw had troughed midway through the articulation of the vowel, then the proportions would all be at .50, or even with the dotted line.

Discussion

Experiment 1 examined jaw movement as a function of syllable position and type. The relationship between segmental articulation and jaw movement was then explored. We would argue that the overall results point to the importance of syllable structure in the sequential articulation of segments, but it is not clear from this experiment whether jaw movement defines the syllable or whether it is defined by it. For example, the direction of the opening and closing asymmetry was not predicted, but is arguably better understood as a suprasegmental effect rather than as a segmental one. In the present context, the smaller displacement during jaw closing relative to jaw opening could signify that final consonants were undershot, which is consistent with other accounts of syllable position-dependent differences in segmental articulation (Sussman, Bessell, Dalston, Majors, 1997; Redford & Diehl, 1999). On this view, the observed differences between opening and closing could have been determined by linguistic factors, for instance, by the need for greater perceptual distinctiveness in onset position.

On the other hand, it is possible to use the asymmetry result to argue for the priority of sequential coarticulatory constraints on jaw movement, which would de facto argue against the idea of any meaningful relationship between the cycle and the syllable. For example, the relevant VCV and VCCV sequences under analysis were meant to be identical, but the vowel offset in the initial part of the frame, s*ay*, is more closed than the onset of the vowel in the latter part of the frame, *eight*, due to the diphthongization of the mid-front tense vowel in American English. So the latter part of the syllable-final diphthong in *say* could have boosted the initial peak of the cycle associated with the target syllable, thereby increasing displacement from peak to trough during opening relative to closing.

In order to determine whether the observed relationship between the cycle and the syllable reflects more than segment-to-segment coarticulatory constraints, we conducted an additional experiment in which we held sound sequences constant and varied syllable boundaries by inserting a word boundary either before or between two identical consonants.

Boundary Manipulations on VCCV Sequences

The goal of this experiment was to assess whether the relationship observed between the jaw cycle and syllable structure in Experiment 1 represented a meaningful relationship or a fortuitous one borne of coarticulatory constraints on the sequential articulation of segments.

Methods

The speakers, procedures, and measurements were identical to Experiment 1. The stimuli were different. In this experiment, the target stimuli were adjacent words that created an intervocalic two-consonant sequence. Syllable structure was manipulated via boundary location while segmental content was held constant: *high trot* vs. *might rot*, *my slot* vs. *nice lot*, *my snot* vs. *nice knot*, *my stock* vs. *nice talk*, *hi Scott* vs. *nice cot*.

The stimuli were repeated 5 times, and produced in randomized order in the frame sentence “Say ___ eight times.” Speakers used the same intonational contour for the V.CCV and VC.CV segmentations.

Results

Overall, the results indicate a complex relationship between suprasegmental structure, segmental articulation, and jaw movement. Jaw movement differed as a function of boundary location, but it appeared that the direction of influence was from suprasegmental structure to jaw movement and not vice versa. The suggestion that suprasegmental factors influence jaw movement and not segmental factors is based on the results, which suggest that jaw movement is somewhat independent of segmental articulation. In particular, there appears to be only a loose temporal connection between the attainment of maximal jaw closure and consonantal articulation. The evidence suggests, though, that consonantal articulation may be timed to correspond to aspects of the cycle. In particular, the onset of consonantal articulation may be timed to correspond to particular jaw heights. Below, boundary-dependent differences in the relative acoustic durations of C1 and C2 are noted first, then the results on demicycle characteristics are presented, followed by the results on the relationship between segmental articulation and jaw movement.

Acoustic Duration

The literature on phonetic juncture indicates that the segmental duration is affected by position relative to a boundary [see, e.g., Klatt (1976) for a classic description of the correlations between linguistic structure and patterns of segment duration]. Such boundary-dependent changes in acoustic duration were also noted in the present experiment. The relative acoustic duration of C1 and C2 in the VCCV sequences was analyzed in a 3-way ANOVA with Speaker, Boundary (VC.CV, V.CCV), and Sequence (-tr-, -sl-, -sn-, -st-, -sk-) as factors. The results showed that the measure of relative consonantal duration, namely, a C1-to-C2 duration ratio, was significantly affected by boundary location across all speakers and all sequence types [$F(1, 120) = 310.36$, $p < .01$]. A pre-consonantal (V.CCV) boundary was associated with larger ratios, that is, with long C1s and short C2s. A transconsonantal (VC.CV) boundary was associated with smaller ratios, that is, with C1s and C2s of similar durations.

Although the relative duration of C1 and C2 varied with boundary location, the total consonantal duration (C1+C2) did not. Instead, the total consonantal duration varied differently for different combinations of Boundary and Sequence [$F(4, 120) = 12.759$, $p < .01$].

Unlike consonantal duration, the relative acoustic duration of V1 and V2 were not systematically affected by boundary location or any other variable. That is, there were no significant effects of Speaker, Boundary, or Sequence on a V1:V2 ratio.

Demicycle Characteristics

As a first step towards evaluating the relationship between suprasegmental patterns and the jaw cycle, demicycle characteristics were evaluated according to the fixed factors of Speaker, Boundary, and Sequence.

A MANOVA with closing duration, displacement, and peak velocity as dependent variables showed that these variables varied jointly with all three factors [Pillai's trace, $F = 2.771$, $p < .01$]. The effect of Boundary alone on the variables was also significant [Pillai's trace, $F = 10.849$, $p < .01$]. A MANOVA on opening duration, displacement, and peak velocity showed systematic variation by Sequence [Pillai's trace, $F = 11.816$, $p < .01$], but no other factors or combination of factors affected the dependent variables associated with jaw opening.

Follow-up univariate analyses on the closing variables showed that only closing duration varied systematically with Boundary [$F(1, 120) = 30.751$, $p < .01$]. Closing duration was longer when the boundary occurred before the consonant sequence (e.g., *high trot*) than when it occurred between the consonants (e.g., *might rot*).

Longer closing durations leading into the articulation of a complex onset (e.g., *high trot*) were not due to differences in peak or trough height. The simple effect of Boundary was absent in 3-way univariate analyses of these two variables. Sequence did, however, systematically affect peak height [$F(4, 120) = 150.646$, $p < .01$]. Post hoc tests showed that the distance between the nose and jaw marker was smallest (i.e., greatest closure) for peaks associated with stimuli that had intervocalic *-tr-* sequences ($p < .01$). There were no other significant differences in peak height between other sequence types.

Overall, these results suggest that jaw movement is affected by suprasegmental structure, but not in the way that would be expected. If the syllable and the cycle were functionally related, then the articulation of V.CCV sequences would have resulted in greater duration/displacement during jaw opening, not jaw closing.

Segment Height and the Cycle

Analyses showed that neither vowel nor consonant height varied systematically with boundary location. Jaw height varied systematically, though differently, for V1 and C1 with different combinations of Speaker, Boundary, and Sequence [V1: $F(8, 120) = 2.404$, $p < .05$; C1: $F(8, 120) = 4.228$, $p < .01$]. Different Speaker and Boundary combinations affected C2 and V2 height differently as well [C2: $F(2, 120) = 4.471$, $p < .05$; V2: $F(2, 120) = 4.014$, $p <.05$]. Although there were no systematic effects of Boundary on jaw height, Sequence was found to systematically effect the height of C2 [$F(4, 120) = 22.751$, $p < .01$]. Post hoc tests showed that /ɹ/ was systematically initiated with a higher (more closed) jaw position than any of the other consonants ($p < .01$). Height at initiation did not differ between the other consonants /l, n, t, k/.

Overall, these results suggest that jaw height at the onset of articulation is correlated with segmental variables, but not with suprasegmental variables.

Segment Duration and the Cycle

As in Experiment 1, the relationship between syllable structure and the jaw cycle was tested by analyzing the proportion of C1 and C2 that was articulated during jaw closing and jaw opening respectively. This analysis indicated some significant differences as a function of the fixed factors; however, these were not in the anticipated direction. A relationship between the syllable and the cycle would predict that the proportion of C1 articulated duration the closing portion of the cycle would be less for a V.CCV segmentation than for a VC.CV segmentation, and that the proportion of C2 articulated during the opening cycle would be greater for a V.CCV segmentation than a VC.CV segmentation. The results are inconsistent with this prediction, and are in opposite direction for C2.

The proportion of C1 articulated during the closing portion of the cycle differed with different combinations of Boundary location and Sequence type [$F(4, 119) = 3.334$, $p < .05$]. The variability was such that there was no simple effect for Boundary (see Figure 6). The proportion of C2 articulated during the opening portion of the subsequent cycle also differed with different combinations of Boundary location and Sequence type [$F(4, 119) = 2.511$, $p < .05$], but the simple effect of Boundary was also significant [$F(1, 119) = 17.626$, $p < .01$]. Nonetheless, variability in the timing of C2 with respect to the offset/onset peak was also high (see Figure 4).

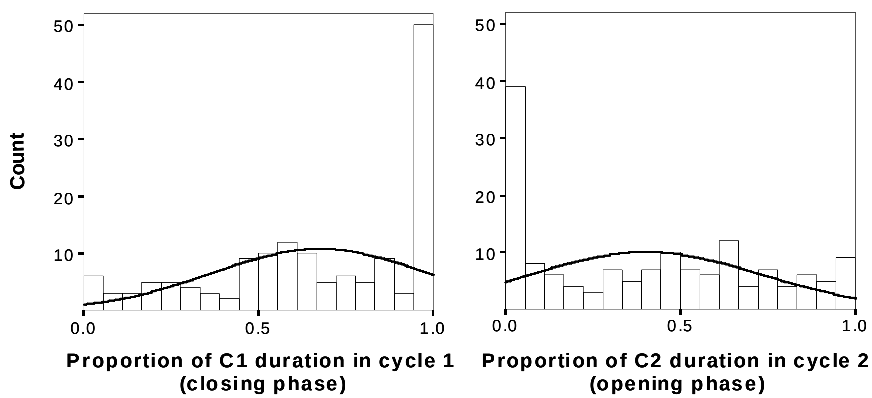

Figure 4.

Histograms show the variability associated with the articulation of consonants relative to the peak. In the majority of cases, C1 and C2 are articulated during the closing phase of cycle 1.

Figure 4 shows histograms for proportion of C1 in cycle 1 and proportion of C2 in cycle 2. C1 is most often articulated almost entirely during the closing phase of cycle 1, and similarly for C2. In other words, neither singleton onset nor complex onsets are usually coarticulated with the following vowel - the vowel to which they belong according to linguistic segmentations of the sequences.

The result that both consonants are usually articulated during the closing phase of cycle 1 rather than during the opening phase of cycle 2, particularly during production of V.CCV stimuli, was unexpected. In order to evaluate whether this surprising result was due to differences in the displacement of the closing and opening phases in cycle 1 and cycle 2 respectively, we compared the phases on this variable. Two-tailed t-tests showed that closing displacement in cycle 1 was greater than opening displacement in cycle 2 [$t(149) = 11.925$, $p < .01$]. A corresponding asymmetry in duration was also found, but this asymmetry presumably interacted with Boundary, as described in the section on demicycle characteristics.

It is likely that the difference in opening and closing displacement followed from the asymmetry of the vowels in the sequences. V1 was the diphthong /ɑi/, V2 was the monophthong /ɑ/. The vowel asymmetry translated into an asymmetry in the degree of opening attained in the two cycles. Maximal opening for cycle 1 was greater than that attained in cycle 2, as indicated in a two-tailed t-test [$t(149) = 11.925$, $p < .01$].

So, a possible interpretation of the results is that the consonants were preferentially articulated during the closing phase of cycle 1 rather than the opening phase of cycle 2 because cycle 1 had more “room” relative to cycle 2. Similarly, the finding that a greater proportion of C2 was articulated during jaw closing in V.CCV relative to VC.CV stimuli might have been due to the longer closing durations of the cycle associated with the initial portion of the V.CCV stimuli.

Discussion

The results from Experiment 2 suggest that the jaw cycle reflects aspects of suprasegmental structure, but there is little to suggest a constant or functional relationship between the cycle and linguistic syllable of adult English. The closing phase that followed V1 was longer for stimuli associated with V.CCV type stimuli than for those associated with VC.CV types. This lengthening was unexpected. The expectation had been that jaw opening for V2 would be lengthened to accommodate the articulation of a complex onset. It is difficult to attribute the effect to segmental duration, since total consonantal duration was not different for V.CCV and VC.CV stimuli. However if the slowing was due to segmental duration, then it would have to be due to differences in relative duration. C1 was longer and C2 was shorter in V.CCV stimuli than in VC.CV stimuli.

Although Experiment 2 provides little evidence for a functional relationship between the syllable and cycle in adult language, it also provides little evidence for the view that jaw movement is defined by segment-to-segment articulatory constraints. Consonant timing varies greatly with respect to maximal jaw closing, and this variation is not systematically related to any of the factors explored in the present Experiment. Because of variation in when the jaw peaks vis-à-vis consonant articulation, it is hard to imagine that jaw closure represents a well-defined consonantal target, as the segment-first view would seem to predict. Instead, consonants and vowels appear to be timed to coincide with spatial location on the cycle. Segments were initiated at similar jaw heights regardless of suprasegmental structure or other characteristics of the cycle.

General Discussion

In spite of the relationship between sonority and jaw height (e.g., Lindblom, 1983), the results from present study indicate that the relationship between the syllable and the jaw cycle may be fortuitous rather than functional. Segments usually appear to be initiated at the same spatial location in a jaw cycle, but the cycle appears not to impose a strict temporal constraint on segmental articulation. A consonant that is initiated at a particular height can be initiated either during the upward or downward trajectory of the cycle, depending on where there is enough room to articulated it. Our phenomenological sense of segment groupings therefore cannot be defined or clarified in terms of the cycle, at least for adult English. So, overall, the evidence disfavors the hypothesis argued for in Redford (2000), which pushes the Frame/Content mode of speech production into adult language to define the online production of syllables.

The alternative hypothesis, namely, that jaw movement follows segmental articulation, is not supported by the evidence either. There is a strong sense in which jaw movement appears to be independently specified, as suggested by the neurophysiological data reviewed in MacNeilage (1998). First, the maximal opening and closing movements do not seem to reflect segmental targets, as shown above. Second, a single jaw cycle can span one to many segments. So, the question remains, why does the jaw move during speech? And, does this movement reflect anything other than the vestiges of babbling or inaccurate target attainment and inertia on the part of a slow and massive articulator? Given (1) the role of the jaw during the development of speech production (viz. Davis & MacNeilage, 1990); (2) some correspondences between the cycle and adult syllables; and (3) the potential of jaw movement to help explain a variety of syllable-related patterns in language (see section 2 above), we continue to expect that the cycle organizes segments in adult speech at some level and/or under certain conditions. We will test this expectation in future research by moving away from the over-practiced utterances focused in the present study to measure jaw movement during sequence learning tasks, where the sequences will be highly novel sound combinations.

References

Bell, A., & Hooper, J.B. (1978). Issues and evidence in syllabic phonology. In A. Bell & J.B. Hooper (Eds.), *Syllables and segments* (pp. 3-22). Amsterdam: North Holland.

Butt, M. (1992). Sonority and the explanation of syllable structure. *Linguistische Berichte, 137*, 45-67.

Clements, G.N. (1990). The role of the sonority cycle in core syllabification. In J. Kingston & M. Beckman (Eds.), *Between the grammar and the physics of speech* (pp. 283-333). New York: Cambridge University Press.

Davis, B.L., & MacNeilage, P.F. (1995). The articulatory basis of babbling. *Journal of Speech and Hearing Research, 38*, 1199-1211.

Fitts, P.A. (1954). The information capacity of the human motor system in controlling the amplitude of movement. *Journal of Experimental Psychology, 47*, 381-391.

Fowler, C.A., & Saltzman, E. (1993). Coordination and coarticulation in speech production. *Language and Speech, 36*, 171-195.

Gracco, V.J. (1994). Some organizational characteristics of speech movement control. *Journal of Speech and Hearing Research, 37*, 4-27.

Haggard, M. (1973). Correlations between successive segment durations: Values in clusters. *Journal of Phonetics, 1*, 111-116.

Hooper, J.B. (1972). The syllable in phonological theory. *Language, 48*, 525-540.

Keating, P., Lindblom, B., Lubker, J., & Kreiman, J. (1994). Variability in jaw height for segments in English and Swedish VCVs. *Journal of Phonetics, 22*, 407-422.

Kelso, J.A.S., Vatikiotis-Bateson, E., & Kay, B. (1985). A qualitative dynamic analysis of reiterant speech production: Phase portraits, kinematics, and dynamic modeling. *Journal of the Acoustical Society of America, 77*, 266-280.

Kenstowitcz, M. (1994). *Phonology in generative grammar*. Cambridge, MA: Blackwell.

Klatt, D. (1976). Linguistic uses of segmental duration in English: Acoustic and perceptual evidence. *Journal of the Acoustical Society of America, 59*, 1208-1221.

Kuehn, D.P., & Moll, K.L. (1976). A cineradiographic study of VC and CV articulatory velocities. *Journal of Phonetics, 4*, 303-320.

Lindblom, B. (1983). Economy of speech gestures. In P. MacNeilage (Ed.), *The production of speech* (pp. 217-246). New York: Springer-Verlag.

MacNeilage, P.F. (1998). The frame/content theory of evolution of speech production. *Behavioral and Brain Sciences*, *21*, 499-546.

MacNeilage, P.F., & Davis, B.L. (2000). On the origin of internal structure of word forms. *Science, 288*, 527-531.

MacNeilage, P.F., Davis, B.L., & Matyear, C.L. (1997). Babbling and first words: Phonetic similarities and differences. *Speech Communication, 22*, 269-277.

MacNeilage, P.F., Davis, B.L., Matyear, C.L., & Kinney, A. (2000). The motor core of speech. *Child Development, 71*, 153-163.

Perkell, J. (1969). *Physiology of speech production: Results and implications of a quantitative cineradiographic study*. Cambridge, MA: MIT Press.

Redford, M.A. (2000). An articulatory basis for the syllable. Doctoral dissertation, University of Texas at Austin, 2000. *Dissertation Abstracts International, 61*, 1127.

Redford, M.A., & Diehl, R. (1999). The relative perceptual distinctiveness of initial and final consonants in CVC syllables. *Journal of the Acoustical Society of America, 106*, 1555-1565.

Selkirk, E. (1982). The syllable. In H. van der Hulst & N. Smith (Eds.), *The structure of phonological representation* (pp. 337-383). Dordrecht: Foris.

Stone, M., & Vatikiotis-Bateson, E. (1995). Trade-offs in tongue, jaw, and palate contributions to speech production. *Journal of Phonetics, 23*, 81-100.

Sussman, H.M., Bessell, N., Dalston, E., & Majors, T. (1997). An investigation of stop place articulation as a function of syllable position. *Journal of the Acoustical Society of America, 101*, 2826-2838.

Sussman, H.M., MacNeilage, P.F., & Hanson, R.J. (1973). Labial and mandibular dynamics during the production of bilabial consonants: Preliminary observations. *Journal Speech and Hearing Research, 16*, 385-396.