The Labial-Coronal effect and CVCV stability during reiterant speech production: An articulatory analysis

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Abstract

In a companion paper [1], we showed that CVCV utterances with a labial consonant followed by a coronal one (LC sequences) are more stable than reverse CL sequences in speeded reiterant speech. We proposed that this could explain why human languages select LC sequences more often than CL ones (the “LC effect”). We provide here articulatory data explaining where the greater LC stability could come from, by investigating inter-articulator coordination during LC and CL utterances at an increasing rate. Rate increase leads variegated CVCV (e.g. /pata/) to be produced in a single jaw cycle but this is not the case for duplicated CVCV (e.g. /papa/). Furthermore, LC and CL sequences both evolve towards the same cycle with a progressive phasing of lips and tongue close together in the jaw cycle. Taken together, these results provide new elements to argue for motor control constraints shaping phonological patterns from economy principles.

1. Introduction

1.1. Regularities in language patterns

Comparative studies of languages phonology and human infants’ first productions have shown the trends in the shaping of human languages mirror trends in the development of speech production [1][2]. Firstly, CV (C for consonant and V for vowel) is the predominant syllable type in both canonical babbling and language inventories [3]. Secondly, CV combinations with the same place of articulation for the vowel and the consonant are preferred in both cases [2][4]. Thirdly, languages prefer to alternate place of articulation for successive consonants in CVCV disyllables, and in these variegated forms, Labial-to-Coronal patterns (/pata/, LC structure) occur more frequently than reverse order items (/tapa/, CL structure) [2][4]. Similarly, after reduplicated babbling (e.g. /papa/) progressively evolves towards variegation, infants display the same preference for “anterior to posterior progression” in their first words [2][5].

1.2. The “Frame then Content” (FC) theory

These observations lead researchers to suspect a common basis linked with basic properties of the perceptuo-motor system in relation to its ontogeny and phylogeny. The FC theory was elaborated in this framework [6]. It postulates a neo-Darwinian perspective on the birth of orofacial communication in both development and evolution, in which speech would have been elaborated from jaw movements preexisting in ingestion mechanisms. Thus, sequences of opening and closing jaw movements would constitute the speech frames. Motor control of other articulators is later developed and evolves towards global coordination for the generation of contents.

1.3. Economy in substance-based phonological theories

The FC theory belongs to a general framework attempting to explain language universals from speech substance through general perceptuo-motor economy principles [7]. Focusing on the motor aspects, speech production requires energy; hence motor control programming should tend to select movement sequences limiting energy requirements. The first way to minimize the biomechanical cost of the articulatory system is to limit displacements of articulators. This could explain the CV co-occurrence patterns described above: sharing place of articulation for the consonant and the vowel would limit tongue displacements [2].

1.4. Economy, synergy and phase transitions in CVCV

Dynamic studies of motor systems have pointed out that rate increase may induce switches from one program to another. For example, minimizing energy consumption under velocity requirements may induce a horse to switch from alternating limb movements in trot to simultaneous movements in gallop [8]. Similar re-phasing between an organ and its counterpart in rate increase has been displayed for bimanual coordination [9].

Applying such principles of energy minimization, inter-articulator synergy, and phase transitions between various motor organizations could provide potential explanations for understanding the structure of CVCV sequences in the world’s languages. Indeed, repeated motion of a single organ might reach its limit more quickly – and need a higher energy consumption – than achieving the same rhythm by the alternation of cycles of two organs coupled in phase opposition. This could mean that producing repeated motion with the same articulator (/papa/) would be less efficient and more costly than alternating articulator motion as in variegated CVCV (/pata/). This principle constrains piano playing: the same finger is never used twice for two consecutive notes.

Furthermore, for variegated sequences, inter-articulator synergy could depend on the degree of anticipation and phasing between articulators. In a companion study [1], we suggested that this could provide the basis for the LC effect. Indeed, we showed that during reiterant production of LC or CL CVCV at an increasing rate, LC sequences are stable, while CL sequences often switch towards the inverse LC pattern (e.g. /bada/ or /daba/) evolves towards a common attractor /bada/ or /dada/). We interpreted this result as evidence for a greater stability of LC sequences compared with CL ones, possibly resulting from tongue-tip movement anticipation during the labial movement. This would allow a
better phasing of articulators for LC CVCV compare to CL
and their grouping in a single jaw opening gesture.

In summary, motor economy would provide the basis for the
LC effect. The present study tested this hypothesis. For this
aim, we analyzed tongue-tip (TT), inferior-lip (IL) and jaw
movement during reiterated utterances of LC and CL
sequences produced by French speakers with a varying rate.

2. Method

2.1. Speech material

The phonetic material consisted of eight CVCV disyllable: two
reduplicated ones: /papa/ and /tata/ and six variegated ones:
three LC structures, /pata/, /pasa/ and /fata/ and their CL
counterparts /tap/a/, /sapa/ and /tafa/. The vowel /a/ was selected
since it is a central unrounded vowel, requiring almost no active
tongue or lip gesture. The selected labial and coronal
consonants were varied in order to test the robustness of
articulatory patterns observed over various manner of
articulation.

2.2. Procedure

Five college-aged French speakers (three females and two
males) without any speech or hearing deficits participated in the
experiment. They were instructed to continuously repeat the
disyllable enounced by the experimenter starting at a slow rate
and then at an increasingly rapidly rate up to whatever rate was
possible. The speakers then had to progressively decrease rate
to return to the initial slow rate. As verbal transformations
(switch from one structure to another one [1][10]) could occur
during this task, speakers were encouraged not to stop their
productions even if they seemed different from the initial
sequence. The eight disyllables were repeated three times with
orders that varied from one subject to another.

Tongue-Tip (TT), Inferior-Lip (IL) and jaw displacements
were tracked over time at 500 Hz using a Cartens
Electromagnetic Articulograph. The acoustic signal was
simultaneously recorded by the way of a microphone fixed on
the articulograph helmet and then digitized at 20 kHz. This
resulted in 18 wave files per subject (three per sequence) and
the 18 associated articulatory binary files.

2.3. Data analysis: assumptions and measurements

The first hypothesis was that for slow rates, each CVCV
production would respect a general rule: one jaw cycle for one
syllable. Then, biomechanical properties would limit the
decrease of jaw cycle duration above a floor value [11].
Disyllable duration would not decrease under twice this value
for duplicated CVCV. However, shorter disyllable durations
should be reached for variegated CVCV, due to the possibility
of phasing both the labial and the coronal gesture in a single jaw
cycle. Finally, progressive rephasing would happen between the
labial and the coronal gesture (as observed before, [1]); hence
the interval from IL constriction to TT constriction might be
shorter than the one from TT constriction to the next IL one.

To test these hypotheses, the intensity curve computed
from the acoustic signal was first labeled in the same way as
in the companion study [1] in order to compare the intensity
of Vl (the vowel following the labial consonant) and Vc (the
vowel following the coronal consonant). This measure allows
us to track vowel overshoot and reduction and to infer
whether the speaker is evolving towards LC (/pat/a/→/pat/a/) or
CL (/tap/a/→/tap/a/); Vc is more intense than Vl in the first
case, and less so in the second one. Vowels were labeled as
energy maxima and consonants as minima. Syllable and
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• The duration of the mandible cycle,
• An indicator of phasing between TT and IL: the duration of the labial-to-coronal phase (time from IL constriction to TT constriction $D_{LC}$), normalized by the whole disyllable duration (time from IL constriction to the next one $D_{LL}$): 
  \[ \Delta_{LC/LL} = \frac{D_{LC}}{D_{LL}} \]
• The position of each constriction event relative to the jaw cycle expressed in percents of cycle (Fig. 2).

3. Results

Acoustic data were analyzed in the same way as in the companion study. The results are quite coherent for the five speakers of the present study, and the 22 speakers of the companion study. They display similar variability between speakers and sequences, together with greater stability of LC sequences as compared to CL ones. Due to space constraints, these results could not be presented here, and articulatory analysis will focus on /papa/, /tata/, /pata/ and /tapa/ CVCV, globally representative of results for other sequences.

3.1. Disyllable vs. jaw cycle duration

Jaw cycle duration and syllable duration plotted against time show that during the acceleration phase, durations progressively decrease together (Fig. 1, bottom row). Then, when the syllable rate reaches around 200 ms, the jaw cycle duration separates from the syllable duration, and rather suddenly doubles in length. This indicates that the two syllables are now realized in a single jaw cycle. The global analysis displayed on Fig.3 confirms this observation. Indeed, the plot of jaw cycle duration against disyllable duration shows that productions for duplicated CVCV are grouped around an $(x=2y)$ line, with two jaw cycles for one disyllable. However, variegated productions are distributed both around the $(x=2y)$ and $(x=y)$ lines. Values around the $(x=y)$ line indicate that there are a number of sequences with two syllables for only one jaw cycle (Fig. 3, top row). For all sequences, jaw cycle is almost never shorter than 100 ms. Therefore, durations of duplicated disyllables are never shorter than 200 ms and peaks around 300 ms. For variegated sequences, however, it can reach values under 200 ms, and peaks around 200-250 ms (Fig.3, middle row). Finally, the comparison of jaw cycle histograms for duplicated and variegated CVCV (Fig. 3, bottom row) shows that there are two peaks in both case, one around 125 ms, the other around 250 ms. However, the peak at 250 ms is larger for variegated than for duplicated sequences.

3.2. Phasing between jaw and constrictors

The switch from a one-to-one towards a one-to-two relation requires a reorganization of inter-articulator coordination. Indeed, when each syllable is realized in its own jaw cycle, TT and IL are both phased with the jaw, occurring at a high jaw position (Fig.1, top left). Then, with rate increase, the two constrictors may enter into a single jaw cycle. The plots in Fig.4 display how this reorganization occurs. It appears that for four out of five speakers (S1, S3, S4, and S5), the labial constriction position peaks at –37.5% for both /pata/ and /tapa/ (Fig.4, top), while the coronal constriction peaks around 0%. The result is different for speaker S2 who realizes /p/ around –12.5% and /t/ around 25%. Altogether, the labial occurs in the raising phase of the jaw cycle, and the coronal around the jaw peak or slightly after, with a temporal distance between the labial and the coronal constriction lower than half a jaw cycle. The synchrony of the coronal constriction with the high position of the jaw within its cycle is also observed for /pasa/, /sapa/, /fata/ and /tafa/ (not presented here).

3.3. Phasing between TT and IL

Table 1 presents statistics on the duration of the labial-to-coronal phase relative to the disyllable duration, $\Delta_{LC/LL}$. Values of $\Delta_{LC/LL}$ lower than 50% indicate that /p/ is closer to /t/ than /t/ is to the next /p/, hence a greater synchrony for /pt/ than for /tp/. Four out of five values are significantly lower than 50% for /pata/, and three out of five for /tapa/.
Table 1: Means, standard deviations and number of observations of $\Delta$(LC/LL) for /pata/ and /tapa/ per speaker when two syllables are grouped inside a single jaw cycle. Asterisks indicate means significantly different from 50% at the 0.01 level after Bonferroni correction ($p<0.015$).

<table>
<thead>
<tr>
<th>Speakers</th>
<th>/pata/ Mean</th>
<th>std</th>
<th>Nb</th>
<th>/tapa/ Mean</th>
<th>std</th>
<th>Nb</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>49.35</td>
<td>6.16</td>
<td>20</td>
<td>53.05</td>
<td>2.64</td>
<td>5</td>
</tr>
<tr>
<td>S2</td>
<td>36.32*</td>
<td>9.30</td>
<td>25</td>
<td>40.34*</td>
<td>11.26</td>
<td>21</td>
</tr>
<tr>
<td>S3</td>
<td>44.3*</td>
<td>5.70</td>
<td>19</td>
<td>38.61*</td>
<td>5.7</td>
<td>11</td>
</tr>
<tr>
<td>S4</td>
<td>45.41*</td>
<td>9.10</td>
<td>56</td>
<td>49.46</td>
<td>12.56</td>
<td>48</td>
</tr>
<tr>
<td>S5</td>
<td>42.08*</td>
<td>8.05</td>
<td>67</td>
<td>40.84*</td>
<td>8.64</td>
<td>58</td>
</tr>
</tbody>
</table>

4. Discussion

Taken together, the results are in line with our expectations. Furthermore, they agree with previous studies on jaw motion and provide new elements to argue for motor control constraints shaping phonological patterns due to economy principles.

4.1. Jaw saturation

Jaw cycle durations display two peaks around 125 ms and 250-300 ms (Fig.3, bottom). Similar durations were found by Nelson et al. [11] for "sa-sa" utterances. These authors pointed out that 50 ms is the minimum duration of jaw strokes (closing vs. opening movement, corresponding to half of our jaw cycle). This is compatible with the first peak at 125 ms and the duration floor at 100 ms in our data. Moreover, their results displayed a "resonance" phenomenon: maximum motion amplitude was observed for stroke durations around 125 ms with an acceleration peak lower than for smaller duration cycles. This indicates smaller energy consumption, and it could explain the second peak of jaw cycles around 250-300 ms in our results. To summarize, 100 ms cycle duration corresponds to the saturation of the jaw oscillatory system. Speakers can reach such rates for both variegated and reduplicated sequences but it is more costly in energy than the slower preferred rate around four cycles per second. This would lead speakers to switch their motor program for variegated utterances from one cycle per syllable to one cycle per disyllable. This shift induces increasing proximity of the lip and tongue constriction to allow fast utterances.

4.2. Alternated vs. reduplicated motions

Indeed, realization of two syllables on a single jaw cycle could be possible for variegated LC and CL CVCV because coronal constriction could be anticipated during labial constriction while the inverse tendency would be rarely observed. That suggests a progressive evolution from both LC and CL structures to the LC pattern with an undershoot of $V_L$. However, while a TT movement could be initiated during an IL one, such anticipation is impossible for reduplicated CVCV: a single articulator could not begin a new movement if it has not finish the preceding one. Thus, alternating movement of two different articulators allows the attainment of fast rate production with little energy consumption. Coupled with asymmetries in phasing between IL and TT, that provides an explanation of both the LC effect and the dominance of variegated forms in lexicons of world's languages in term of economy of energy.

5. Conclusions

The preference for variegated over reduplicated patterns and for LC over CL sequences seems to be possibly related to motor economy constraints. Nevertheless, the greater articulatory stability of LC sequences also has some perceptual counterparts, as shown by the greater stability of LC over CL sequences in verbal transformation experiments [12]. More generally, motor economy should be combined with perceptual stability and distinctiveness criteria [13] to progress towards a general substance-based theory of the patterning of sound systems in human languages.

6. Acknowledgements

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7. References