An articulatory basis for the Labial-to-Coronal effect: /pata/ seems a more stable articulatory pattern than /tapa/

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1 An articulatory basis for the Labial-to-Coronal effect:

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This paper investigates the coordination between the jaw, the tongue tip and the lower lip during repetition with rate increase of Labial-to-Coronal (L_aC_o) Consonant-Vowel-Consonant-Vowel disyllables (e.g./pata/) and Coronal-to-Labial (C_oL_a) ones (e.g. /tapa/) by French speakers. For the two types of disyllables: (1) the speeding process induces a shift from two jaw cycles per disyllable to a single cycle; (2) this shift modifies the coordination between the jaw and the constrictors and (3) comes with a progression towards either a L_aC_o attractor (e.g. (/pata/ or /tapa/) $\rightarrow$ /patá/ $\rightarrow$ /ptá/) or a C_oL_a one (e.g. (/pata/ or /tapa/ $\rightarrow$ /tapá/ $\rightarrow$ /tpá/). Yet, (4) the L_aC_o attractor is clearly favored regardless of the initial sequencing. These results are interpreted as evidence that a L_aC_o CVCV disyllable could be a more stable coordinative pattern for the lip-tongue-jaw motor system than a C_oL_a one. They are discussed in relation with the so-called LC effect that is the preference for L_aC_o associations rather than C_oL_a ones in CV.CV disyllables in both world languages and infants' first words.

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1. Introduction

The analysis of CV.CV disyllables in world languages lexicons reveals that Labial-to-Coronal (L_aC_o) sequences (e.g. /pata/) are about 2.5 times more used than Coronal-to-Labial (C_oL_a) ones (e.g. /tapa/) (Locke, 1983; MacNeilage *et al.*, 2000a, 2000b; Rousset, 2003). This asymmetry, also displayed in infants' first words in the course of ontogeny (Ingram, 1974; Locke, 2000, MacNeilage *et al.*, 2000a, 2000b), is known as the "LC effect". The existence of the same trend in infant and adult speech lead MacNeilage and Davis (2000b) to propose a "substance-based" explanation of the LC effect in the framework of the "Frame-Content Theory" of speech development (MacNeilage, 1998). Yet, there are some problems with their explanation, letting space for further hypotheses. The present investigation is an attempt to test an original explanation of the LC effect, based on motor principles likely to intervene both in speech development and in on-line adult speech production.

1.1. The "simple first" hypothesis

MacNeilage and Davis (2000a, 2000b) proposed that the LC effect might result from the conjunction of two principles in the course of speech development: (1) labial proto-consonants (or closants in the Frame-Content terminology) would be easier to produce by infants than coronal ones, and (2) in order to deal with the complexity of the mental lexicon access required in the production of their first words, infants would focus on easier forms. Thus, they would select sequences of actions beginning by the simpler gesture, supposed to be the labial one. The preference for L_aC_o disyllables in development would then have been preserved in adults' languages.

64 The assumed greater simplicity of labial gestures is one component of the Frame-Content
65 theory of speech motor control development (MacNeilage, 1998; MacNeilage and Davis, 2000a,
66 2000b). This theory claims that speech production begins in babbling with phonation associated
67 with repeated vertical oscillations of the jaw. Apart from vocal tract pre-settings, the other
68 articulators would stay stable all along the jaw cycles. Thus, besides their alimentary function,
69 jaw cycles would induce alternation of closing and opening patterns (*closants* and *vocants*) and
70 constitute the *frame* of speech. Then, the speech segmental *content* (independent control of
71 consonants and vowels inside the frame) would progressively emerge from the development of
72 the central and peripheral motor control of the other articulators. According to MacNeilage and
73 Davis, for neutral vocal tract pre-setting, that is purely passive tongue and lips, jaw upwards
74 gestures would induce a labial closure of the vocal tract and so, the production of labial closants
75 (“pure frames”). On the contrary, coronal closants would require an active motion of the tongue
76 in pre-setting (“fronted frames”). Therefore, labial closures would be easier to realize than
77 coronal ones. However, the “simple first” explanation suffers in our view from several
78 weaknesses. Firstly, it is a bit ad hoc. Secondly, the “simpler” nature of labial closants in
79 babbling has been questioned by Vilain *et al.* (1999) in a study exploiting articulatory models of
80 the vocal tract. They compared three models with different morphologies – coming from the
81 statistical analysis of cineradiographic data recorded from three different adult speakers. They
82 simulated pure frames on the three models, by applying jaw upward commands, all other
83 articulators being kept passive, and they obtained different kinds of closures. In one model the
84 jaw raise resulted in closing the lips first, producing a labial contact, while in another one it first
85 resulted in a closure inside the vocal tract, producing a coronal contact. In the last model, a labial

and a coronal contact were obtained almost in synchrony. Therefore, both /ba/, /da/ and /bda/ could be pure frames according to the vocal tract morphology. This could explain why analyses of babbling inventories do not display a preference for labial patterns over coronal ones (Locke, 1983).

Another problem concerns the extrapolation from infants to adults. Indeed, there is no reason to believe that labial plosives would stay simpler than coronal ones in adult speech, both involving a specific articulatory control superimposed on the jaw, respectively for the lips in labials and for the tongue in coronals (Munhall and Jones, 1998). Finally, the “simple first” hypothesis tends to consider the articulatory control of L_aC_o and C_oL_a utterances as a sequence of independent phonetic segments while it might be better characterized as coordinative structures (Kelso *et al.*, 1986; Nitttrouer, 1991).

1.2. An alternative hypothesis based on jaw-tongue-lips coordination

It is widely assumed that some coordinative patterns are more stable and economic than others and that the repetition of a multi-effectors gesture with rate increase would attract the system toward its most stable coordinative mode. This has been first established for inter-limb coordination (Hoyt and Taylor, 1981; Haken *et al.*, 1985) and then, extended to articulators' coordination in speech production (Kelso *et al.*, 1986; Lindblom, 1990a; Kelso, 1995). Such criteria of stability and economy have been introduced in substance-based criteria shaping the sound systems of human languages (e.g. Stevens, 1989; Lindblom, 1990b). In this vein, it has been shown that rate increase induced repeated VC syllables to switch towards cycled CV ones (Stetson, 1951; Tuller and Kelso, 1991; de Jong, 2001). This led the authors to conclude that CV

sequences are more stable than VC ones, which could explain the preference for CV syllables over VC ones in language inventories (Redford and Diehl, 1999; Rousset, 2003).

These studies provide an interesting framework for attempting to anchor the LC effect in the properties of the articulatory motor system rather than in a pure developmental framework. More precisely, we assume that a labial constriction followed by a coronal one could be a better coordinative pattern for the lip-tongue-jaw system than the coronal-then-labial one. This assumption is inspired from Sato *et al.* (2006). The authors supposed that in CCV or CVC sequences involving a labial and a coronal consonant, there was a trend to anticipate the coronal constriction during the labial one, rather than the inverse. Hence, lips and tongue were more in-phase in /psə/ than in /spə/. The reason is that in /psə/, the tongue tip may be prepared for /s/ during the labial closure, so that the /p/ release is almost synchronous with the tongue-driven onset of the next /s/. On the contrary, in /spə/, the lips must stay open during the production of the /s/, before labial closure followed by the /p/ release, so that the tongue-lip synchrony is difficult to achieve (see also Byrd, 1996; Zsiga, 1996; Surprenant and Goldstein, 1998, for compatible data in English; and Chitoran *et al.*, 2002 for Georgian). This articulatory asymmetry between the two sequences of consonantal gestures could be a part of the LC effect explanation in both language development and world languages lexicons.

1.3. An experimental scenario

The presumed greater stability of the coordination in L_aC_o compared with C_oL_a could be investigated through the speeding paradigm. The slow regular repetition of C_1VC_2V disyllables should be characterized by a regular alternation of C_1 and C_2 gestures over time. On the contrary,

rate increase could lead to asymmetries, the C_2 constriction being either closer to the previous or to the next C_1 one. This would induce the reduction of either the vowel after C_1 or after C_2 . The French language, under study here, displays a stress on the word last syllable. Therefore, in the repetition with rate increase of a CVCV disyllable, French speakers should rather reduce the first vowel, and a CCV re-syllabification could be expected. Hence, two hypotheses may be contrasted. In a first one, there would be no asymmetry between L_aC_o and C_oL_a coordination, and the French speakers would preserve the original disyllable prosody through speeding. In this first hypothesis, L_aC_o CVCV sequences would evolve toward a L_aC_o attractor (e.g. /pata/ → /patá/ → /ptá/) while C_oL_a CVCV sequences would evolve toward a C_oL_a CCV attractor (e.g. /tapa/ → /tapá/ → /tpá/). Yet, if, as we expect, the L_aC_o coordination is more stable than the C_oL_a one, this would attract the system towards a L_aC_o attractor regardless of the initial CVCV sequence (e.g. (/pata/ or /tapa/) → /patá/ → /ptá/). Hence, in this second hypothesis, the repetition with rate increase of both L_aC_o and C_oL_a CVCV disyllables would evolve towards a L_aC_o attractor. The first experiment, based on acoustic measurements, aimed at selecting which of these two assumptions is true.

In a second experiment based on articulatory measurements, we studied how the articulatory coordination between jaw, tongue and lips would be reorganized in order to subtend the progression from one constriction per jaw cycle (e.g. /pata/) towards two constrictions per jaw cycle (e.g. /ptá/). A prediction was that the two constrictions would be realized on a single jaw cycle before the fading of the vowel was completed (e.g. /patá/). In other words, the variation of the articulation place between the first and the second constriction would allow the production of two syllables on a single jaw cycle, while most studies of jaw movements associate the jaw cycle

with the CV syllable (Nelson *et al.*, 1984; Ostry and Flanagan, 1989; Perkell and Zandipour, 2002; Perkell *et al.*, 2002).

2. An acoustic study of LC and CL stability

The aim of this first study is to test if L_aC_o sequences are more stable than C_oL_a ones in a speeding paradigm, using an acoustic measure of vowel reduction.

2.1. Method

2.1.1. *Speakers and phonetic material*

28 native French speakers with no speech or hearing problem and naive as to the purpose of the study participated in the experiment. The phonetic material consisted in six CVCV disyllables: three L_aC_o (/pata/, /pasa/ and /fata/) and their three C_oL_a counterparts (/tapa/, /sapa/ and /tafa/). This choice aimed at contrasting L_aC_o and C_oL_a sequences while controlling for a possible “plosive-to-fricative” effect. Indeed, in the framework of “sonority” principles (Selkirk, 1984; Clements, 1990) it could be supposed that utterances containing a fricative and a plosive would switch towards plosive-fricative attractors (e.g. /tfa/, /psa/), rather than the L_aC_o attractors /pta/, /psa/ and /fta/ expected in the framework of our basic assumptions. The /a/ vowel was selected to provide an open configuration, mainly involving the jaw, with basically no strong requirements on the lips and the tongue. The six disyllables were randomly arranged inside three lists. The three lists were presented to each speaker in different orders. Hence each disyllable was presented three times to each speaker. The test began with three items provided as training stimuli (/vada/, /daba/ and /dava/).

2.1.2. Procedure

In order to simplify post-treatments the experiment was assisted by a computer program that allowed to record utterances and to display a kind of visual metronome. The participants were sitting in front of a computer connected to a microphone. The instruction was to repeat the disyllable displayed on the screen at an increased and then decreased rate following as much as possible the rhythm of a visual flash. The aim of this flash was not to precisely control the speakers' rate but rather to give global timing marks in order to homogenize acceleration and deceleration phases between speakers and to attempt to drive the speakers to their limit rate. It was mentioned that the flash would reach rates impossible to follow and the instruction was to maintain a rate as high as possible during this period until the decelerating phase. Moreover, speakers were encouraged to go on without interruption even if they perceived any kind of transformation of the uttered sequence.

The experiment began by the three practice trials. Then, the three lists were successively displayed. Each trial started with the presentation of the CVCV sequence to repeat, displayed in the middle of the screen. Speakers initiated the flash pressing the "space" key. A blue square took the place of the disyllable on the screen for one second, followed by the flash. The flash was an alternation of a black and a white square. The instruction was to produce one syllable on the black flash and the other on the white one. Duration of each square presentation started at 300 ms and progressively decreased to reach 125 ms at the middle of the acceleration phase and 50 ms at the end of the acceleration phase (8 s). The progression was shaped in order to obtain a large amount of rapid productions. The timing of the deceleration phase was the symmetric of the acceleration one. Thus, each trial record lasted 16 s. Speakers sometimes took a breath inside the

whole acceleration-deceleration process, but this occurred seldom and at random positions inside the 16 s utterance. Then the speaker spontaneously resumed the process at about the same tempo he/she had reached before the breath.

2.1.3. *Hypotheses and measurements*

The working hypothesis is that both L_aC_o and C_oL_a repetitions would evolve towards a L_aC_o CVCV sequencing until eventually reaching a L_aC_o CCV consonantal cluster. For example, if /pata/ is indeed more stable than /tapa/, the speeding process should be: (/pata/ or /tapa/) → /patá/ → /ptá/. The contrasted prediction is that, if there were no asymmetry between L_aC_o and C_oL_a utterances in terms of coordinative structure, the French prosodic pattern with a stress on the final syllable of a word should drive the behavior with e.g. /pata/ → /patá/ → /ptá/ and /tapa/ → /tapá/ → /tpá/. Finally, both trends could be observed, with a L_aC_o vs. C_oL_a asymmetry, superimposed on an effect of the initial uttered sequence. These predictions were tested by prosodic measurements based on vowel intensity. Acoustic energy was continuously estimated, within the Praat software¹ using a 42.6 ms Kaiser-20 window (sidelobes below -190 dB). Maxima and minima of energy curves were automatically detected and then hand-selected as vowels and consonants (Figure 1). When a speaker's production evolved towards a single consonantal cluster (e.g. /ptá/), the labeling rule was to mark the “vanished” vowel and the two consonants around as a same event (e.g. Figure 1, right). Speakers' errors such as repetition of a single syllable or pauses were removed. From these data, two parameters were computed for each CVCV or CCV sequence correctly produced (now referred as “utterances”): (1) the utterance duration and (2) the variation of intensity between the two vowels, that is the difference between

the intensity of the vowel after the coronal consonant (V_{Co}) and the intensity of the vowel after the labial consonant (V_{La}):

$$\Delta I = I(V_{Co}) - I(V_{La})$$

The operational hypothesis was that ΔI would be positive for both the L_aC_o and the C_oL_a utterances for fast productions, with very high positive values indicating a shift towards a single L_aC_o CCV syllable (e.g. from /pata/ or /tapa/ to /ptá/, as in Figure 1).

---- Figure 1 ----

2.2. Results

The analyses excluded two speakers, one because he did not manage to alternate the labial and the coronal constrictions at a fast rate and the other for recording problems. Apart from local errors, all the 26 remaining speakers' utterances respected a "... $L_aV_{Co}V_{La}V_{Co}V$..." sequencing, L_a and C_o respectively being the labial and the coronal consonants of the target CVCV sequence, and "V" the vowel /a/ or nothing.

2.2.1. Evolution of ΔI across rate: global tendencies

The plot of ΔI values against utterance durations for all the speakers' L_aC_o and C_oL_a utterances shows very similar patterns for the three L_aC_o and C_oL_a pairs. Hence, only the graphs for /pasa/ and /sapa/ are displayed on Figure 2 (top), as a representative example. Globally and for both the L_aC_o (left) and C_oL_a (right) groups, utterance durations range from 100 to 700 ms. Furthermore, ΔI values are close to 0 for durations longer than about 300 ms whereas they vary from -40 to

40 dB for shorter durations. Actually, standard deviations of ΔI values (Figure 2, bottom) are small above 300 ms, and larger under 300 ms. The shift from small to large ΔI values is stable around 300 ms for all CVCV sequences, leading us to select this value as a limit for further analyses. Thus, for slow rates, the speakers keep a regular alternation of labial and coronal syllables without any strong reduction effect. Then, rate increase induces the reduction of either V_{La} (positive ΔI values) or V_{Co} (negative ΔI values). Hence, both the L_aC_o (/psá/) and the C_oL_a (/spá/) CCV clusters seem to constitute possible attractors for the repetition of either L_aC_o or C_oL_a CVCV logatoms. Yet, the graphs display more positive than negative ΔI values for the two types of disyllables. Therefore, the L_aC_o attractor seems to prevail over the C_oL_a one, particularly for the L_aC_o trials (Figure 2, top left).

---- Figure 2 ----

2.2.2. Detailed analysis according to the disyllables and to the speakers

In order to investigate more precisely possible reorganizations of productions in the speeding process, the analysis of ΔI was restricted to utterances with durations shorter than 300 ms. In spite of the flash, the utterance durations varied a lot according to the speaker and to the trial. Therefore, for the analysis, we kept only speakers achieving a sufficient amount of quick data with the following criterion: for each of the six CVCV logatoms, the speaker should have produced at least five quick utterances (durations shorter than 300 ms) for at least two of his/her three trials. Then, only the two trials with the largest number of quick utterances were analyzed. This criterion excluded five speakers. In the following, only the utterances with durations less than 300 ms are analyzed, for the two selected trials of the 21 remaining subjects.

Global means of the 42 trials are positive for all disyllables, and all significantly different from 0 except for /sapa/ (Table I, first row). Moreover, the distribution of the 42 means according to their sign (last four rows in Table I) shows that the ratio of positive means related to negative ones (rows 3 and 5) is 2.5 for /pata/ and /tapa/, 7.4 for /fata/, 3.6 for /tafa/ and 1.8 for /pasa/ whereas it is 1 for /sapa/. A Chi-square test shows significant difference between the frequencies of positive vs. negative means ($\chi^2(1) = 6.6$, $p < .001$). Restricted to means that significantly differ from 0 (rows 4 and 6) the prevalence of positive means over negative ones is even greater with a ratio of 4.75 for /pata/, 2.5 for /tapa/, 3 for /pasa/, 1.4 for /sapa/, 13 for /fata/ and 5.3 for /tafa/ (frequency of significant positive means significantly different from significant negative ones, $\chi^2(1) = 6.8$, $p < .001$). Hence, the speeded repetition of L_aC_o and C_oL_a CVCV disyllables more often evolves towards the corresponding L_aC_o attractor (eg. /pasá/ or /psá/) than the C_oL_a one (eg. /sapá/ or /spá/). However, C_oL_a forms appear in some cases for both L_aC_o and C_oL_a trials. Furthermore, two additional factors tend to emerge. Indeed, there is some trend that ΔI values are larger, and more systematically positive, for L_aC_o than for C_oL_a trials on one hand, and for /pata/-/tapa/ and /fata/-/tafa/ than for /pasa/-/sapa/ trials on the other hand.

---- Table I ----

Considering that two attractors seem to coexist, though with a preference for the L_aC_o one, we wondered whether they might coexist for a given speaker. For this aim, Figure 3 (left) displays the relation between mean ΔI values for the first and the second selected trial, for each speaker and for each CVCV sequence, provided that the two means significantly differed from 0.

It appears that mean ΔI values are both significantly positive for 41 cases, both significantly negative for 7 cases and have different signs in 5 cases. Therefore, the dominant behavior is to evolve towards the same attractor for the two trials with a large preference for the L_aC_o compared to the C_oL_a one. Yet, in some cases, the attractor differs from one trial to the other. Then, grouping all logatoms, it appears that some speakers tend to be “ L_aC_o stable” (e.g. S12, right part of the Figure 3) whereas others are, in a lower extend, rather “ C_oL_a stable” (e.g. S23). Finally, some speakers are “bi-stable”: the category of attractor they evolved towards changes according to the trial (S20) or to the logatom (S6).

---- Figure 3 ----

In summary, the speeded repetition of L_aC_o and C_oL_a logatoms could evolve both towards the L_aC_o or the C_oL_a attractor. Yet, and despite variability between disyllables and between speakers, the L_aC_o attractors are largely favored compared to the C_oL_a ones. Thus, /patá/-/ptá/ is the favorite attractor for /pata/ and /tapa/; /pasá/-/psá/ for /pasa/ and to a lower extend for /sapa/ and /fatá/-/ftá/ for both /fata/ and /tafa/.

3. An articulatory study of L_aC_o and C_oL_a stability

The main purpose of the second study is to understand from EMMA recordings how the articulatory system could evolve with rate increase from a L_aC_o or a C_oL_a CVCV disyllable towards either a L_aC_o or a C_oL_a attractor, with a preference for the first one.

3.1. Method

3.1.1. Speakers and phonetic material

The participants were five college-aged French speakers (three females - S1, S3 and S4 - and two males - S2 and S5), without any speech or hearing deficits. They did not participate in Experiment 1. The L_aC_o and C_oL_a disyllables were the same as in the acoustic study. Two duplicated CVCV logatoms (/papa/ and /tata/) were added as control items.

3.1.2. Procedure, data recording and processing

The instruction was to continuously repeat the disyllable enounced by the experimenter starting at a slow rate and then at an increasingly rapid rate up to the highest possible one. The speakers then had to progressively decrease the rate to return to the initial slow one. Contrary to the first experiment, no external tempo driver was used because of the already difficult conditions of EMMA recording. 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. The articulator motions were tracked over time at 500 Hz using a Cartens Electromagnetic Articulograph. Two reference transducers, one at the bridge of the nose and the other on the gums above the upper teeth allowed to correct the data for head movements. The three measurement points were: the jaw (transducer placed beneath the lower teeth); the Tongue Tip (TT, transducer placed at about 1 cm from the tip of the tongue) and the Lower Lip (LL, transducer just beneath the vermilion border of the lower lip). These raw measurements were then processed according to classical procedures (see Hoole P., 1996 for more details). These involved translation and rotation correcting for head movement, resulting in

setting the origin at the reference coil located on the upper incisors, the vertical axis as the line joining the reference coils on upper incisors and nose bridge, and the x-axis aligned with the occlusal plane. The acoustic signal was simultaneously recorded by the way of a microphone fixed on the articulograph helmet and then digitized at 20 kHz.

3.1.3. *Hypotheses*

The first hypothesis is that the mandible would evolve from a one-cycle-per-syllable relationship to a one-cycle-per-disyllable relationship when speeding L_aC_o or C_oL_a CVCV logatoms. However, duplicated L_aL_a (/papa/) or C_oC_o (/tata/) CVCV logatoms were expected not to display this behavior. The second hypothesis concerns the lips-tongue coordination inside a single jaw cycle at high rates. Two attractors were expected, either L_aC_o or C_oL_a . In the first case, the labial constriction and the next coronal constriction (respectively maximum values of LL and TT trajectories) should be close together. In the second case, the coronal constriction should be close to the next labial one. Considering the small number of speakers, and the variability observed in the first experiment, no strong claim was made about a preference for L_aC_o attractors. Instead, the hope was that inter-speaker variability would enable to observe both kinds of attractors, in order to be able to characterize them articulatorily.

---- Figure 4 ----

3.1.4. Measurements

Processing of acoustical data was the same as in Experiment 1. It led to computation of the duration and intensity variation between the two vowels (ΔI) for each utterance (CVCV or CCV items correctly produced). Articulatory analysis used articulator trajectories preprocessed by a low-pass Chebychev filter (cutting frequency at 15 Hz). Jaw maxima and minima (Figure 4, row 2) were automatically detected on the jaw trajectory, allowing its segmentation into closing and opening phases (up and down strokes). Post-processing discarded movements realized during pauses or errors (detected from the acoustical labeling). For the correct utterances, two criteria were used in order to discard productions subtended by too small jaw movements. Firstly, we checked for the regular alternation of opening and closing strokes; secondly, we removed strokes with an amplitude lower than 0.1 mm, which is the claimed precision of the EMMA system. Table II summarizes the total number of correct utterances and the number of correct utterances kept for further articulatory analysis. Then, TT and LL events were labeling on articulatory signals, with the help of acoustic events. TT constrictions were defined as the highest TT positions between the vowel after the labial consonant (V_{La}) and the vowel after the coronal consonant (V_{Co}) (Figure 4, row 3). Similarly, LL constrictions were defined as the highest LL positions between V_{Co} and V_{La} (Figure 4, row 4). This method (similar to Hertrich and Ackermann's one, 2000) discards secondary maxima due to passive motion induced by the jaw gesture that comes with the other constriction.

---- Table II ----

Then, jaw cycles were separated into an up stroke and its adjacent down stroke. The jaw cycle duration was the sum of its up and down stroke durations and the jaw cycle amplitude was the mean of its up and down stroke amplitudes (Figure 5.A). Each constriction event was assigned to the jaw cycle that temporally included it and positioned relatively to this jaw cycle (Figure 5B). This measure, expressed in percent of jaw cycle, constitutes an indicator of the phasing relationship between the jaw and constrictors. Finally, the coordination between TT and LL was characterized by the duration of the labial-to-coronal phase (time from LL constriction to TT constriction D_{LaCo}), normalized by the whole disyllable duration (time from a LL constriction to the next LL one D_{LaLa}):

$$\Delta_{(LaCo/LaLa)} = D_{LaCo} / D_{LaLa}$$

---- Figure 5 ----

3.2. Results

3.2.1. Acoustic analysis

The global pattern of ΔI against utterance duration for L_aC_o or C_oL_a sequences is very close to the pattern observed in the first experiment (compare Figure 6, right, with Figure 2). That is, ΔI values are close to 0 for durations longer than 300 ms whereas ΔI values far from 0 appear for shorter durations, with more positive than negative values. On the contrary, ΔI values are always close to 0 for duplicated L_aL_a or C_oC_o logatoms (Figure 6, left).

---- Figure 6 ----

Moreover, the mean values for utterances with durations shorter than 300 ms (Table III) represent the panel of behaviors observed in the first experiment. Indeed, as a subset of speakers of the acoustic study, S3 fails to produce enough rapid productions. This may indicate that this speaker rarely shifts towards a CCV structure. Then, S1 and S4 tend to favor the C_oL_a attractor (more negative than positive means) especially for /pasa/ and /sapa/ for S1 and for the three C_oL_a disyllables for S4. On the contrary S2 and S5 tend to favor the L_aC_o attractor for all disyllables except for S5's /sapa/ productions. Interestingly, these behaviors correspond to both the speakers' profiles and the variability between sequences observed in the first experiment.

---- Table III ----

3.2.2. *Global analysis of jaw cycles*

The /tapa/ utterance samples displayed on Figure 4 illustrate the speeding process generally observed for a L_aC_o or a C_oL_a trial. First, during the acceleration phase (left), each constriction comes with its own jaw gesture. Yet, the amplitude and the duration of the jaw cycle for the labial constrictions tend to be smaller than for the coronal constrictions. Then, rate increase induces the progressive fading of the jaw cycle that supports the labial constriction, resulting in a single jaw cycle for the two constrictions. For this example, the plot of the acoustic signal (top) shows that the speaker does not evolve towards a CCV syllable but produces two

syllables on a single jaw cycle (splitting phase, middle). Finally, the deceleration progressively brings the system back to its initial state with one jaw cycle per syllable (right).

Plots of jaw cycle durations (y) against CVCV durations (x) for all speakers' productions (Figure 7, first row) and separately for the duplicated (left) and variegated (right) CVCV sequences show that duplicated productions are grouped around the ($y=x/2$) line (i.e. two jaw cycles for one disyllable) whereas both L_aC_o and C_oL_a ones are distributed around the ($y=x/2$) and ($y=x$) lines (i.e. two vs. one jaw cycle per disyllable). This distribution splitting occurs for utterance durations less than about 400-450 ms. Analyses of ΔI in the acoustic study showed that the shift towards a CCV cluster, characterized by high ΔI values, occurs for durations shorter than 300 ms. Therefore, the shift towards a single cycle for two syllables occurs before the total suppression of one of the two vowels (that is, for longer utterance durations).

---- Figure 7 ----

The utterance duration histograms (Figure 7, second row) display similar values for the duplicated and the L_aC_o / C_oL_a group. Yet, the durations of duplicated utterances are never shorter than 225 ms and are mostly around 300 ms whereas around 15 % of L_aC_o / C_oL_a productions reach durations from 175 ms to 225 ms with a peak of distribution around 250-275 ms. On the contrary, the jaw cycle durations (Figure 7, third row) are clearly shorter for the duplicated productions (peak of distribution around 150 ms) than for L_aC_o / C_oL_a ones (peak of distribution around 225 ms). Finally, the jaw cycle duration is never shorter than 100 ms for all logatoms. Altogether, this portrait is coherent with the fact that at a fast rate L_aC_o / C_oL_a sequences can be

produced on one single jaw cycle. The progression towards a single cycle limits jaw motion and keeps it at a more comfortable duration for the fastest production rates. Thus, it probably limits the energy consumption.

In order to analyze the shift from two jaw cycles to a single one, the speaker's productions were classified into three periods (e.g. Figure 4). The "splitting" phase includes the utterances realized on a single jaw cycle. The "acceleration" and the "deceleration" phases include the utterances realized on two jaw cycles respectively before and after the splitting phase.

3.2.3. *Patterns of jaw motion in the acceleration phase*

The amplitude and duration of jaw opening and closing strokes in the acceleration phase are plotted on Figure 8, for each speaker, respectively for duplicated (left) and L_aC_o / C_oL_a (right) sequences. Strokes are seldom shorter than 50 ms, which agrees with the 100 ms threshold observed for the jaw cycle durations (Figure 7). Separate regression lines are superimposed for labial and coronal cycles. In their study of jaw motion for duplicated sequences (/sa/), Nelson *et al.* (1984) used the same kind of display. A theoretical analysis allowed the authors to define a limit parabolic curve, such that for a given value of the maximum acceleration during a jaw stroke, the corresponding amplitude vs. duration points were always on the right of the limit parabolic curve. Without entering their explanation in too many details, the principle is basically that to achieve a given trajectory extent in a given duration, the acceleration along the trajectory must achieve a sufficient maximum value. Reciprocally, for a given maximum acceleration value and a given trajectory extent, duration cannot be lower than a limit, specified by the parabolic curve. On the figure, we have superimposed three such limit curves, respectively corresponding to maximum acceleration values of 0.25 g, 0.50 g and 1.5 g (see also Nelson, 1983).

It appears that for duplicated utterances (Figure 8, left), speakers S3 and S4 follow a different pattern from speakers S1, S2 and S5. For S3 and S4, stroke amplitude decreases with duration for both the labials (in /papa/) and the coronals (in /tata/) cycles. Moreover, the distribution of amplitude vs. duration tends to follow the theoretical curve corresponding to an acceleration of 0.25 g. On the contrary, amplitude does not decrease with duration for S1, S2 and S5. Moreover, while S1 keeps a small amplitude for all durations, rate increase leads S2 and S5 beyond the 0.25 g limit curve, towards an acceleration up to 0.5 g. Therefore, to support rate increase, speakers either decrease the jaw stroke amplitude without increasing acceleration (S3 and S4) or increase acceleration without changing amplitude (S1, S2 and S5). These results agree with the study by Sonoda and Nakakido (1986). These authors observed that jaw motion speeding induced either an increase in velocity and little change in amplitude or little velocity change and a decrease in amplitude (see also Lindblom, 1990a for a link with phonetic variations; and Perkell et al. 2002 for a more detailed discussion of intersubject differences).

---- Figure 8 ----

The jaw behavior is more homogeneous for the L_aC_o / C_oL_a group. For all speakers, there is a global decrease of amplitude with duration (Figure 8, right) and the distributions more or less follow the 0.25 g curve. Furthermore, the means of amplitude and duration tend to be smaller for the strokes that subtend the labial constrictions as compared to the strokes that subtend the coronal constrictions, with significantly negative differences in a number of cases, and no significantly positive difference (Table IV). This pattern is modulated by two factors. Firstly,

there are individual differences, with, for example, larger differences between the labial and coronal jaw strokes for speaker S3, and smaller for speaker S2. Secondly, the labial to coronal difference is increased for /pasa/ and /sapa/ logatoms (for which the labial jaw cycle is of a significantly lower amplitude and duration for all speakers) and decreased for /fata/ and /tafa/ logatoms (for which the difference is significant only for Speaker 3). This portrait suggests that in the acceleration phase, the passage from two jaw cycles to a single one rather corresponds to a progressive removal of the “labial cycle”, as displayed in Figure 4. We shall now explore how the reorganization between jaw, tongue and lips occurs in the “splitting” phase.

---- Table IV ----

3.2.4. Coordination between jaw and constrictors in the acceleration, splitting and deceleration phases

For most of the productions realized on two jaw cycles (during the acceleration and the deceleration phases), the TT and LL constrictions are around 0% of the jaw trajectory (Figure 9, top and bottom). This indicates that each constriction occurs when the mandible is at its highest position. So, TT and LL successively move in phase with the jaw. Yet, distributions look less peaked at 0% for TT (Figure 9, right top and bottom) than for LL (Figure 9, left top and bottom) for both duplicated and L_aC_o / C_oL_a groups. Moreover, for L_aC_o and C_oL_a logatoms, there was some trend for more variations during the deceleration phase than during the acceleration phase. This could be interpreted as a sign of hysteresis, considering the much more complex portrait in the splitting phase.

In the splitting phase, the labial and coronal constrictions must reorganize within one jaw cycle. The basic trend for reorganization is clearly displayed in Figure 9: the tongue constriction is around the highest jaw position (phase 0%), while the labial constriction is around the lowest position (phase 50% or -50%). On this basic pattern, a global shift towards the right of the jaw cycle can appear, with a coronal constriction in the beginning of the opening phase (around 25%) and a labial constriction in the beginning of the closing phase (around -25%). Two factors seem to intervene in this possible shift. The first factor is speaker variability, with S2 more involved in the right shift than all other speakers. The second factor is the nature of the labial and coronal consonants. Thus, for /pasa/ and /sapa/, the coronal constriction is strictly located around the jaw highest position (0% phase) while for /fata/ and /tafa/ it is often shifted towards positive values. The correspondence with the predominance of the coronal jaw cycle upon the labial one in terms of amplitude and duration, displayed in the previous section, is obvious. It is rather straightforward. Indeed, the coronal fricative /s/ induces a specifically high jaw position, generally higher than all other phonemes, including the coronal plosive /t/ or /d/ (Keating, 1983; Lindblom, 1983; Keating *et al.*, 1994; Lindblad and Lundquist, 1999, see also data for French in Rhardisse and Abry, 1994). Hence the coronal jaw cycle is increased, and the coronal constriction is more strictly stuck on the highest jaw value. On the contrary, the labiodental /f/, also inducing a high jaw position, increases the labial jaw cycle, which induces the shift towards the right, with higher values of the labial constriction in the jaw trajectory. This global pattern is also modulated by the difference between L_aC_o and C_oL_a attractors.

---- Figure 9 ----

512

513 *3.2.5. Articulatory characterization of L_aC_o and C_oL_a attractors*

514 L_aC_o utterances should be characterized by both a higher intensity of the second vowel
515 over the first one (positive value of ΔI , Table III) and a proximity of the labial and next coronal
516 constrictions ($\Delta_{(LaCo/LaLa)}$ smaller than 50%, Table V). Notice however that data selection for
517 these two analyses satisfy different criteria, that is utterance duration less than 300 ms for the
518 acoustic analysis and utterances produced on a single jaw cycle for the articulatory analysis.
519 Despite these differences, the two analyses are relatively coherent.

520 Indeed, means of $\Delta_{(LaCo/LaLa)}$ tend to be higher than 50% for S1, which agrees with the
521 C_oL_a profile that characterizes this speaker in the acoustic space. On the contrary, all $\Delta_{(LaCo/LaLa)}$
522 means for S2 are smaller than 50%, which confirms the speaker's tendency to be L_aC_o -stable. For
523 S4, means of $\Delta_{(LaCo/LaLa)}$ are smaller than 50% for all L_aC_o sequences whereas they are greater
524 than 50% for /sapa/ and /tafa/, which agrees with acoustic data showing that this speaker tends to
525 be L_aC_o -stable for the L_aC_o logatoms and C_oL_a -stable for the C_oL_a ones. For S5, $\Delta_{(LaCo/LaLa)}$
526 means are smaller than 50% for all the sequences except /pasa/ and /sapa/, which confirms his
527 acoustic profile: L_aC_o for /pata/, /tapa/, /fata/ and /tafa/ but rather C_oL_a for /sapa/. Finally, results
528 for S3 show that though this speaker does not often reach utterance durations shorter than 300 ms
529 (Table III), she evolves towards a single jaw cycle for all sequences. Moreover, she tends to be
530 L_aC_o -stable with $\Delta_{(LaCo/LaLa)}$ values always significantly smaller than 50% except for /fata/.

531

532 ----- Table V -----

Therefore, quite logically the L_aC_o attractor corresponds to a decrease of the temporal distance between the labial and the next coronal constriction, while the C_oL_a attractor corresponds to a decrease of the temporal distance between the coronal and the next labial constriction. However, there is a clear predominance of switches towards the L_aC_o attractor (e.g. /patá/ or /ptá/) over the 21 speakers of the acoustic study (Experiment 1). This agrees with the hypothesis according to which the anticipation of the tongue gesture during the labial constriction, typical of L_aC_o CVCV' (e.g. /patá/) or CCV' (e.g. /ptá/) sequences, is much more likely than the anticipation of the labial gesture during the tongue constriction.

4. Discussion

The present work aimed at testing the hypothesis that the L_aC_o sequencing is a more stable articulatory pattern than the C_oL_a one. The results of Experiment 1 provide arguments for this hypothesis for French. Furthermore, the results of Experiment 2 allow to better describe the articulatory phenomena that subtend this asymmetry.

4.1. The L_aC_o / C_oL_a coordinative system “on line”

The results of the articulatory study confirm that rate increase could induce the repetition of L_aC_o and C_oL_a CVCV sequences to evolve from one jaw cycle per syllable towards a single jaw cycle for two syllables until a single CCV syllable is eventually achieved. This progression seems more economic regarding jaw motion. In this process, the determination of the attractor (L_aC_o vs. C_oL_a) may result from the interaction of several factors.

4.1.1. *The motor program shift*

At the beginning of the repetition process, the speakers produce one jaw cycle per syllable. During this period, each constriction occurs at the highest jaw position. Then, with rate increase, the amplitude and the duration of the jaw strokes decrease together until reaching a threshold value (near 50 ms for an opening or a closing gesture). Coupled with the anticipation of one constriction during the previous one, this induces the shift on a single cycle. This shift rests on the reorganization of the tongue-lip-jaw coordination. Globally, two coordinative patterns are displayed to achieve the two constrictions on a single jaw cycle (Figure 10, right), depending on the initial profile of jaw motions (Figure 10, left). Firstly, and in most of the cases, the jaw cycle that carries the labial constriction becomes shorter and smaller than the jaw cycle that carries the coronal constriction (Figure 10, top left). Hence, when rate increases, the labial cycle reaches the threshold duration earlier than the coronal one. This induces the preservation of the phasing between the jaw and the tongue tip highest positions, whereas the lower lip constriction occurs during the jaw closing gesture or at the end of the opening gesture (Figure 10, top right). This is typically the case for Speaker 3, and for /pasa/ and /sapa/ utterances. Secondly, when no asymmetry appears between the two cycles during the acceleration phase (Figure 10, bottom left), the tendency is to observe a dephasing of both TT and LL in reference to the jaw cycle. Thus, the LL and TT constrictions respectively occur during the closing gesture and during the opening gesture (Figure 10, bottom right). This is the trend for Speaker S2 and for /fata/ and /tafa/ utterances.

---- Figure 10 ----

These results are interesting in the context of previous articulatory studies (Nelson *et al.*, 1984; Kelso *et al.*, 1985; Hertrich and Ackermann, 2000), modeling works (Redford and Diehl, 1999; Redford *et al.*, 2001; Oudeyer, 2001) or theories (MacNeilage, 1998) that always associated the jaw cycle to the CV syllable. Moreover, patterns of mandible motions are close to data published in the literature and tend to confirm the general principle of economy of effort.

4.1.2. *Economy of effort*

Various possible indicators of economy of effort have been proposed in the literature, e.g. maximum speed or jerk that is acceleration derivative (Nelson, 1983). In their already mentioned study, Nelson *et al.* (1984) characterized jaw strokes by the maximum acceleration compatible with the observed movement, which is the indicator we used in Section 3. Furthermore, they showed that during the repetition of /sa/ with rate increase, the jaw motion progressed in a way that tended to minimize energy consumption. In their data, the durations of jaw opening and closing strokes were never shorter than 50 ms. Similar values appear in the present articulatory study. Then, for one of their three analyzed speakers, Nelson *et al.* observed “a maximum in the movement distance as the movement times decreased into the region of 125 ms”. According to the authors, this “resonance” effect shows that 125 ms could be the most economic duration for up and down jaw strokes. It would correspond to the “natural” rate of 3-4 cycles and so, 3-4 syllables per second. In our study (Experiment 2), durations of jaw cycles for L_aC_o and C_oL_a utterances are mainly around 225 ms (Figure 7), which corresponds to jaw stroke durations around 112.5 ms, close to the 125 ms value observed by Nelson *et al.* On the other hand, the production of duplicated CVCV sequences at very fast rates requires to decrease the jaw cycle

down to 150 ms and so, to stroke durations around 75 ms, close to the saturation value. Furthermore, estimation of the maximal acceleration value in Figure 8 indicates that it is generally smaller for the L_aC_o and C_oL_a sequences compared to the duplicated ones. Taken together, these results suggest that when rate increases, the coordination of the two constrictions on a single jaw cycle might be more economic for the jaw than the alternation of two jaw cycles.

4.1.3. *Multi-determinism of a bistable system*

The results show that with rate increase, the lips-tongue-jaw system could evolve either towards a L_aC_o attractor (e.g. /pata/→/patá/→/ptá/) or a C_oL_a one (e.g. /pata/→/tapá/→/tpá/). Thus, the coordinative system is bistable. Yet, according to the first study, the L_aC_o attractor prevails. On this basic pattern, a number of other additional factors are observed or could be assumed to play a role. Firstly, the initial coordination provides a bootstrap towards the corresponding attractor: the preference for the L_aC_o attractor is less marked for the repetition of C_oL_a CVCV sequences as compared to L_aC_o ones. This is particularly the case for /pasa/ and /sapa/, with /pasa/ more frequently evolving towards the L_aC_o attractor whereas /sapa/ often evolved towards the C_oL_a one. This is likely to be due to the fact that, in spite of the instruction to continue even if transformations occurred, some speakers tried to respect the initial structure and even tended to reduce the speed when they perceived a shift to the reverse sequencing. Secondly, the C_oL_a attractor was more often observed for /sapa/ as compared to /tapa/ and /tapa/. The difference between /sapa/ and the other C_oL_a disyllables could rest on articulatory factors. Indeed, analysis of the jaw cycles in the second experiment showed that in the acceleration phase, the asymmetry between the jaw cycles that come with the labial constriction and the jaw cycles that come with the coronal one are more systematic for /pasa/-/sapa/ than for the other sequences,

which was interpreted in terms of the need for a specific high jaw position for achieving /s/. This could favor the progression towards the C_oL_a attractor for /pasa/ and /sapa/. Thirdly, inter-speaker differences, which could come from specific individual patterns of coordination, lead to differences in the selection of one or the other attractor, as displayed in Section 2.2.2.

But a number of other factors, not studied in the present work, could also intervene in the selection of one or the other attractor. An obvious one is the selected language. Indeed, it is likely that the CCV re-syllabification process observed here results from the fact that these forms are possible in French and that the language stresses the last syllable of a word. Therefore, future experiments should be done to assess the L_aC_o greater stability in languages with other prosodic behaviors or phonological constraints. Other additional experiments should also be done on the role of the vowel context, the consonantal mode (e.g. voiced or nasal consonants), etc. Nevertheless, in spite of all these established or potential additional factors, the L_aC_o attractor is globally the dominant one over all speakers and disyllables in the present study, which suggests that it could indeed be the most stable and economic, at least in French.

4.2. Substance-based selection of phonological sequences

The underlying assumption of this work is that world languages inventories might be shaped by substance-based constraints such as properties of the motor control system. Thus, some sequencing of syllables might be preferred because they are easier to produce in the sense that they are more economic (less energy consuming) or more stable (easier to control). In this framework (Liljencrants and Lindblom, 1972; Lindblom *et al.*, 1984; Kelso., 1995; Davis *et al.* 2002), the present study brings at least two interesting contributions: (1) the production of duplicated CVCV sequences may be more costly than the production of CVCV sequences that

vary the constrictor from the first to the second consonant, and (2) the L_aC_o sequencing seems more stable than the reverse C_oL_a one.

4.2.1. Variegated rather than duplicated

Statistical analyzes of world languages lexical inventories show that in C_1VC_2V sequences, lexicons favor associations that vary the articulation places in C_1 and C_2 , rather than those that repeat the same constriction (MacNeilage and Davis, 2000a, 2000b; Rousset 2003). This means that languages prefer e.g. “pata” to “papa”. Yet, duplication could, a priori, be considered as simpler in terms of control, which could explain that it is the core behavior in canonical babbling (MacNeilage and Davis, 2000a, 2000b). However, the articulatory data obtained here lead to propose that the preference for variegated sequencing in world languages could result in part from the fact that the repetition of the same constriction is more costly for the jaw than the alternation of two different constrictions. Indeed, the comparison of the production of L_aC_o / C_oL_a and duplicated CVCV sequences shows that quicker production rates could be achieved for L_aC_o / C_oL_a sequences with less energy consumption for the jaw, since anticipation allows producing L_aC_o and C_oL_a CVCV utterances on a single jaw cycle whereas it is impossible for duplicated ones. Thus, without involving the extreme speeds obtained here at the end of the acceleration phase, it appears that the alternation of the movement of two constrictors is probably easier and more economic than the repetition of the movement of a single constrictor for the mature speech production system. Similar principles govern other synergies such as fingers in piano playing. This results from the fact that when two different organs are involved, the motion of one organ could be anticipated during the realization of the other one, which is not possible when a single organ realizes the two successive gestures. The possibility to produce two syllables

on a single jaw cycle might be generalized to other kinds of sequencing than L_aC_o and C_oL_a ones in further investigations. Moreover, the preference for the L_aC_o attractor in the two experiments shows that inside the preference for variegated forms, some associations might be more appropriate than others.

4.2.2. L_aC_o rather than C_oL_a

The results of Experiment 1 are in favor of the idea that L_aC_o sequences appear as a natural and coherent production unit, more stable and better “in-phase” than their C_oL_a inverse counterpart. This could explain the preference for L_aC_o utterances in infant production, rather than the “simple first” explanation previously proposed. There is actually no reason to believe that the greater stability of L_aC_o sequences in the present experiments on adults could be due to any “simple first” mechanism. Rather, articulatory coherence could provide a common basis to both infant data and our results. Of course, the fact that the C_oL_a structure may also be locally stable, though less often selected in the speeding process, is not incompatible with this reasoning. It just suggests that C_oL_a sequences are also viable, though suboptimal in comparison with L_aC_o ones, which agrees well with typological and developmental data.

5. Conclusion

The experimental data analyzed here point out a major difference between L_aC_o and C_oL_a sequences at the production level: L_aC_o sequences can be considered as a more stable coordinative pattern for the motor system than C_oL_a ones. Then, a causal relationship between this asymmetry and the universal “LC effect” has been advanced. Of course, such a claim has to be improved testing L_aC_o and C_oL_a sequences stability in both other languages and more directly

in infant' first words. To this aim, the paradigm and the acoustic analysis method proposed here could allow comparing L_aC_o and C_oL_a stability for speaker samples of different languages, which is necessary for generalization. Specific methodologies should be developed for studying stability in infant speech. Moreover, further articulatory investigations of jaw-tongue-lip coordination in the production of C_1VC_2V disyllables would be necessary to better understand the anticipation processes, and their link with the asymmetry in jaw cycles for different constriction places in C_1 and C_2 . It remains that the present study adds some new material to the already significant set of perceptuo-motor constraints likely to play a role in the shaping of phonological systems, hopefully taking substance-based approaches to language universals one step further.

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699 7. Notes

700 ¹The Praat software is developed by P. Boersma and D. Weenink, at the Institute of
701 Phonetic Sciences. It is available to free download on their web page
702 (<http://www.fon.hum.uva.nl/praat/>).

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8. References

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807 Tables

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Table I: Analysis of intensity variations between the vowel after the labial and the vowel after the coronal consonant for utterances shorter than 300 ms for the 42 analyzed trials (see text for the details about data selection). For each disyllable: means (dB) and are compared with 0 according to a two-tails t-test ($df = 41$) with Bonferroni correction ($ p \leq .01/6$); standard errors; repartition of the 42 means according to their sign: for all the means and for the means that significantly differ from 0 according to a two-tails t-test with Bonferroni correction ($p \leq .05/42$).*

		pata	tapa	pasa	sapa	fata	tafa
Means		6.6 *	7.0 *	7.5 *	3.8	8.9 *	8.6 *
Standard errors		1.9	1.9	1.7	1.7	1.7	2.1
Number of positive means	All	30	30	27	21	37	33
	Signif.	19	15	18	13	26	21
Number of negative means	All	12	12	15	21	5	9
	Signif.	4	6	6	9	2	4

817 *Tableau II: Number of CVCV or CCV utterances correctly produced (Tot.) and number of*
818 *utterances produced with sufficient jaw motion (see text) and kept for further articulatory*
819 *analysis (Ar.) for each speaker and each sequence.*

	papa		tata		pata		tapa		pasa		sapa		fata		tafa	
	Tot.	Ar.	Tot.	Ar.	Tot.	Ar.	Tot.	Ar.	Tot.	Ar.	Tot.	Ar.	Tot.	Ar.	Tot.	Ar.
S1	63	63	63	60	61	59	59	54	60	59	54	54	53	51	51	47
S2	51	49	53	52	58	47	52	48	62	43	59	43	65	59	58	49
S3	53	51	56	54	60	59	63	61	59	59	64	64	57	57	65	65
S4	66	63	68	60	76	52	73	55	74	73	62	60	69	64	71	53
S5	94	85	100	76	109	93	102	80	99	73	95	82	98	79	100	74

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Tableau III: Means (m) of intensity variation between the vowel after the coronal and the vowel after the labial consonant for utterances shorter than 300 ms for the three trials taken together, for each speaker and each disyllable (n is the number of observations for m computation). Thirty t-tests (df = n-1) with Bonferroni correction compare each mean to 0 ($^{\circ} p \leq .005$, $ p \leq .05/30$, $** p \leq .01/30$).*

	pata		tapa		pasa		sapa		fata		tafa	
	n	m	n	m	n	m	n	m	n	m	n	m
S1	31	0.8	29	-0.1	29	-1.4*	27	-2.9**	23	-0.2	24	-0.7
S2	25	23.2**	11	9.2	25	11.7*	20	5.5	30	20.3**	20	13.9**
S3	5	-0.8	9	-0.7	0	-	0	-	0	-	10	1.5
S4	43	-0.7	37	-4.7°	37	-0.1	30	-2.4**	28	0.3	29	-1.6°
S5	67	6.9**	59	4.7**	56	1.7°	45	-2.5**	54	7.6**	53	1.1

*Tableau IV: Means of amplitudes and durations for the jaw cycles that come with the labial and the coronal constrictions in the acceleration phase, for each speaker and each L_aC_o / C_oL_a pair (n is the number of observations for means computations). The significance of the difference between means was tested using t -tests ($df = n-1$) with Bonferroni corrections (** $p \leq .01/15$, * $p \leq .05/15$, NS : Not Significant).*

Speaker	Sequence	n	Amplitudes (mm)			Durations (ms)		
			labial	coronal	p	labial	coronal	p
s1	pata/tapa	47	0,58	0,91	**	163,6	198,6	**
	pasa/sapa	38	0,59	2,06	**	162,7	247,2	**
	fata/tafa	23	0,98	0,77	NS	272,6	222,1	NS
s2	pata/tapa	21	1,83	1,57	NS	231,9	244,0	NS
	pasa/sapa	28	1,07	1,48	**	209,1	285,2	**
	fata/tafa	23	1,00	0,83	NS	263,7	235,7	NS
s3	pata/tapa	59	1,17	2,75	**	178,3	229,7	**
	pasa/sapa	55	1,01	3,46	**	169,9	269,5	**
	fata/tafa	54	2,02	2,36	**	211,2	219,5	NS
s4	pata/tapa	23	1,16	2,67	**	174,7	247,0	**
	pasa/sapa	18	1,20	3,89	**	206,1	279,2	NS
	fata/tafa	33	1,57	1,34	NS	223,3	214,6	NS
s5	pata/tapa	35	0,85	2,53	**	204,7	268,0	**
	pasa/sapa	14	1,08	3,78	**	196,0	370,7	**
	fata/tafa	52	1,43	1,66	NS	267,8	247,0	NS

Tableau V: Labial-to-coronal duration means (m) normalized by the whole utterance duration $\Delta(L_aC_o/L_aL_a)$, expressed in percent, for each speaker and each disyllable (n is the number of utterances involved in computing m). Values smaller than 50% indicate that the duration from the labial constriction to the following coronal one is smaller than the duration from the coronal constriction to the following labial one, which signals an evolution towards the L_aC_o attractor. On the contrary, values higher than 50% signal an evolution towards the C_oL_a attractor. Thirty two-tails t-tests ($df = n-1$) with Bonferroni correction compare each mean to 50 ($p \leq .05/30$, ** $p \leq .01/30$).*

	pata		tapa		pasa		sapa		fata		tafa	
	n	m	n	m	n	m	n	m	n	m	n	m
S1	20	49,3	5	53,0	27	50,8	26	51,0	31	53,7**	32	52,0
S2	25	36,3**	21	40,3*	20	41,1	22	43,9	40	30,5**	36	36,1**
S3	19	44,3*	11	38,6**	22	41,5**	17	42,5**	10	44,8	23	43,7**
S4	56	45,4*	48	49,5	60	46,3**	44	52,0	38	42,8**	30	51,4
S5	67	42,1**	58	40,8**	67	51,8	71	53,5*	35	37,9**	41	44,9*

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