

Title: *Acoustic and kinematic correlates of heterosyllabicity in different phonological contexts*

*Abstract:* We investigate the temporal and kinematic properties of consonant gemination and heterosyllabic clusters as opposed to singletons and tautosyllabic clusters in Italian. The data show that the singleton **vs.** geminate contrast is conveyed by specific kinematic properties in addition to systematic durational differences in both the consonantal and vocalic intervals; by contrast, tauto- and heterosyllabic clusters differ significantly for the duration of the consonantal interval but do not vary systematically with respect to the vocalic interval and cannot be consistently differentiated at the kinematic level. We conclude that systematic variations in acoustic vowel duration and in the kinematics of tongue tip gestures represent the phonetic correlates of the segmental phonological contrast between short and long consonants, rather than of syllable structure. Data are only partly consistent with the predictions of both moraic and gesture-based models of the syllable about the effects of syllable structure on speech production dynamics, and call for a more gradient view of syllabification.<sup>1</sup>

*Keywords:* Gemination, consonant clusters, syllable, gestural coordination, vowel duration, ultrasound tongue imaging (UTI), Italian phonology.

## 1. *Introduction*

### 1.1. *Heterosyllabicity in Italian*

In Italian, paroxytone disyllables containing a geminate consonant show a significantly shorter stressed vowel than disyllables containing a **singleton** (e.g. Fava & Magno Caldognetto 1976, Vogel 1982, D'Imperio

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& Rosenthal 1999, Vayra et al. 1999, McCrary 2004, Mairano & De Iacovo 2020). This timing characteristics has made Italian a good example of a language in which a vowel-to-vowel coordination pattern applies (that is, where the interval between the targets of two consecutive vocalic gestures does not depend on the intervening ‘amount’ of consonantal gesture; Fowler 1983, Smith 1992). Conversely, in canonical phonological accounts, this coordination is reflected in the generalization that a stressed penultimate syllable in standard Italian is bimoraic (e.g. Krämer 2009, Gordon 2016). Besides the singleton **vs.** geminate distinction, the duration of preceding stressed vowels is considered among the factors that are used to parse Italian consonant clusters into tauto- and heterosyllabic categories (e.g. Vogel 1982, Maddieson 1984, Kenstowicz 2017). Based on the view that the syllable with its moraic structure determines the phonetic duration of the segments, it is assumed that stressed vowels before tautosyllabic onset clusters (stop-liquid clusters, also called *muta cum liquida*) are long as they are the nucleus of an open syllable, whereas vowels before heterosyllabic clusters (sonorant-stop and stop-stop clusters) are short as they pertain to closed syllables. However, Italian phonotactics constrains the phonetic shape of clusters in such a way that only a reduced set of consonant combinations produce tautosyllabic clusters, compared to heterosyllabic ones that are more varied. For this reasons, as it will be shown below, directly comparing the singleton/geminate alternation with the tauto-/heterosyllabic cluster alternation is far from being a straightforward operation. Capitalizing on this structural observation, and providing detailed acoustic and articulatory data on the temporal organization of vowel-consonant sequences, the current study questions that the same timing patterns are at the origin of the vowel shortenings that can be observed before geminates and before heterosyllabic clusters (compared to, respectively, singletons and tauto-syllabic clusters). **We explore** an alternative view, according to which vowel shortenings, showing different acoustic and articulatory characteristics in the two contexts, should be interpreted as separate phenomena, bearing different functions in the phonology of the language and indexing the phonological length feature in the specific case of gemination.

It is well known from previous studies that besides syllable parsing, other factors also play a role in shaping the timing relationships between consecutive vowels and consonants. For instance, Farnetani & Kori (1986) found that if a cluster contained a voiceless plosive, the preceding vowel was shorter than when the cluster contained a voiced plosive, probably to compensate the increased duration of the consonantal interval.

Interestingly, the effect was present irrespective of whether the cluster was phonologically tauto- (stop-liquid, e.g. /tr/ vs /dr/) or heterosyllabic (sonorant-stop, e.g. /rt/ vs /rd/). These findings show that syllables in a word interact with each other, at least at the temporal level: vowel duration may be predicted by the phonological characteristics of segments pertaining to the *following* syllable. Evidence of cross-syllable effects in segments' duration can be found even elsewhere **in Italian**. For instance, the effect of stop voicing on the duration of vowels followed by nasal-stop clusters spans syllable boundaries (VNCV sequences, with C varying for voicing; Calamai & Celata 2011). However, in that case, subphonemic vowel variation could also be said to depend on the **nasal which** also varies, being longer before a /t/ than before a /d/. By contrast, in the /tr/-/dr/ and /rt/-/rd/ examples mentioned above, the temporal effect occurs unquestionably across syllables. Farnetani & Kori (1986) additionally reported that vowels preceding palatals /ʃ ɲ ʎ/ were significantly longer than vowels preceding geminates /s: l: n:/, but shorter than vowels preceding singletons /s l n/. This was explained as a consequence of the fact that palatals, in spite of behaving phonologically like geminates and thus closing the syllable, are considerably shorter than geminates. Similar patterns of gradual variation were found in laboratory speech (e.g. Vayra et al. 1999, McCrary 2004) as well as spoken colloquial Italian (Celata & Mairano 2004).

Since geminates have a significantly greater duration compared to singletons, vowel shortening has been viewed as a phenomenon of compensatory variation (or complementarity), although imperfect (e.g. Fowler 1981, Marotta 1985, D'Imperio & Rosenthal 1999). Thus compensation would imply a cross-syllable account of vowel durational variations: intervocalic geminates, which span a syllable boundary, are longer than intervocalic singletons and *therefore* induce a shortening of the preceding vowel. This view is incompatible with any theory (either moraic, or gesture-based) that looks at syllable constituency as the predictor of durational-rhythmical variations. On the one hand, mora theory is not designed to model gradual lengthening or shortening phenomena. On the other hand, gesture-based approaches do account for gradual compression effects, but only within syllables (see below, §1.2) **or across-syllable in the case of prosodic juncture effects** (e.g. Byrd & Saltzman's 2003  $\pi$ -gesture hypothesis); cross-syllable **morpheme-internal** effects would not qualify for gesture-based explanations and should therefore be explained in another way (Browman & Goldstein 1992). Interpretations of these facts have therefore varied from strong to mild rejection of a strictly moraic account (without, however, bolstering the case of gesture-based explanations).

Among the strongest rejections was McCrary's (2004: 263) conclusion that "the standard syllable-based analyses of [...] segment duration are not supported by experimental evidence. Instead, the conditioning factors [...] are segmental, contrast-based conditions. Syllable structure is not implicated in these phenomena". Less extreme positions can also be found. For instance Farnetani & Kori (1986) assumed that, although "the syllable is a base speech unit" in Italian, temporal compensations may also occur cross-syllable inasmuch as "two adjacent syllables are not temporally independent"; the conclusion is that "the unit which tends to be constant in duration is the entire V-to-V temporal interval", that the authors call the "rhythmical syllable" (p. 27) (cf. Fowler 1983).

All these studies further attest that much of the observed graduality is due to clusters. The validity of this statement is also confirmed on both a **diachronic** and a typological level. Stop-liquid clusters are tautosyllabic in many languages including Italian, but allow heterosyllabic parsing in some other languages and have allowed an oscillation between the two parsing solutions in diachrony. The most famous example is Latin, for which a stage with heterosyllabic *muta cum liquida* clusters has been reconstructed, for at least some words (e.g. Timpanaro 1965: 1090); other examples come from southern Italian dialects (Loporcaro 2005). By contrast, intervocalic geminates only allow heterosyllabic parsing.

So the question arises of why different consonantal sequences show different degrees of tolerance with respect to oscillation in syllable parsing. According to Venneman (2012: 21), historical descriptions are not themselves explanations and the latter have to be sought "by establishing phonetic correlates of speech sounds in context and generalizing over those correlates". More specifically, in the case of variable vowel shortenings and syllabification in Italian, we hypothesise, based on the literature reviewed below, that articulatory-kinematic correlates, besides acoustic ones, may be relevant to correctly understand variation and should therefore be investigated.

## 1.2. *Heterosyllabicity in articulation*

Vowel shortening in closed syllables has been related to a specific articulatory dynamics, according to which the aperture gesture for the vowel is truncated earlier and the subsequent closing gesture is anticipated,

compared to when a vowel is in an open syllable (Munhall *et al.* 1992). However, most of the studies have dealt with either codas of monosyllables (e.g. Shaiman 2001, Avesani *et al.* 2009, Marin & Pouplier 2010, Pastätter & Pouplier 2014) or, when heterosyllabicity is considered, syllables closed by geminates (an exception is Smith 1992, showing data on the /mp/ heterosyllabic cluster as produced by one Italian and three Japanese speakers). From the studies on geminates, we know that phonological length in consonants is not only conveyed by increased acoustic duration (associated *with* an increased duration of the jaw opening gesture), but also by specific articulatory and kinematic characteristics, among which are a more extended linguopalatal contact and a longer, spatially larger and sometimes slower gestures. Moreover, the consonantal gesture for an intervocalic geminate is reported to start earlier than the gesture for the corresponding singleton (e.g. Löfqvist 2005, 2006 and 2007 for Japanese and Swedish, Šimko *et al.* 2014 for Finnish bilabial stops, Türk *et al.* 2017 for Estonian bilabial stops, Ridouane & Hallé 2017 for Tashlhiyt Berber).<sup>2</sup> However, there are also studies reporting no or little kinematic difference for increased duration of consonants and vowels. For instance, Zeroual *et al.*'s (2008) EMA study of /t t: d d:/ in Moroccan Arabic notably reports that the only characteristics that consistently differentiate geminates from singleton is acoustic closure, which is reflected in a longer tongue tip contact; among the voiceless consonants only, the opening gesture is also faster for the geminate than the singleton. By contrast, the position of the articulatory target, the velocity of the closing gesture, the acoustic duration of the preceding vowel and the gestural anticipation of the consonant during the preceding vowel do not change across length categories. In a similar way, Löfqvist (2017) reports no statistically significant effect of consonant length in Japanese and Italian as far as the relative timing of the lip gesture for /m/ and the tongue body gesture for the following vowel (/a/ or /i/) is concerned.<sup>3</sup>

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<sup>2</sup> For the sake of completeness, it should be recalled that phonological length has articulatory correlates also in the case of vowels: gestures have been shown to be longer, faster and spatially more extended in long vs short vowels (e.g. Beňuš 2010 for Slovak, Türk *et al.* 2017 for Estonian).

<sup>3</sup> Again to be complete, there are mixed results also for vowels: for instance, German show little or *no* effect of quantity on the gesture velocity to the following consonantal constriction (although gestures are overall longer for tense/long vowels than for lax/short ones; Hertrich & Ackermann 1997).

The articulatory and kinematic studies on Italian geminates are not many. As for the articulatory correlates of increased duration, they have shown extended linguopalatal contact (Payne 2006) and higher tongue dorsum and predorsum (Dipino & Celata 2018). As for gestural timing, Smith (1992, 1995) showed that in non-word production of intervocalic /m:/ and /p:/, the interval between the articulatory target of the preceding vowel and that of the consonant was shorter, and the consonantal gesture started earlier and ended later with respect to the vowel-to-vowel transition gesture, compared to the production of intervocalic /m/ and /p/. According to the authors, these changes in both closing and release gestures would help accommodating longer constriction duration with an ideally equivalent vowel-to-vowel temporal interval (Öhman 1967). The same effects were found in the production of the intervocalic cluster /mp/, which was not different, in articulatory timing, from geminates /m:/ and /p:/.<sup>4</sup> Zmarich et al. (2007) measured the vertical displacement of the lower lip in the production of /p: b: m: f: v:/ included in pseudo words with preceding and following /a/, and found that for only one of the two subjects the velocity of the closing gesture (that is, at consonantal onset) was higher than for the corresponding singletons, although no difference was found in the amplitude of the gesture; more differences in both velocity and amplitude were found at the release of the consonant. In a similar study, Gili Fivela et al. (2007) analyzed the movements of lower lip, tongue tip and tongue dorsum during the production of the disyllables /im:a/, /al:a/ and /ad:a/. They found that, in the case of the geminate bilabial, the lip gesture started earlier with respect to the preceding /i/ in comparison to when the consonant was a singleton, but the release of the gesture toward the following /a/ was not different in singletons and geminates, which apparently contradicts the data in Zmarich et al. (2007). In the case of coronal laterals and stops, no differences between singletons and geminates were found in the closing gesture (onset of the geminate) whereas the gestures differed significantly at the consonantal release.

Taken together, these studies suggest that kinematic correlates of phonological length can be measured for geminates in various languages, although the effects are evanescent and potentially variable on a cross-linguistic base. For Italian, the available evidence is quantitatively limited, and sometimes contradictory.

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<sup>4</sup> Löfqvist (2017) failed at replicating the findings in Smith (1995) for Italian intervocalic /m/ and /m:/, showing that the interval between the lip release for the consonant and the tongue movement for the vowel did not change as a function of phonological length.

Coupled with studies of intra-syllabic gestural coordination (since Munhall et al. 1992), they suggest that the gesture for a coda consonant, be it the beginning of a geminate or the coda in a monosyllabic word, starts earlier with respect to the preceding vowel than the gesture for a non-coda consonant. The constriction gesture for a geminate is sometimes found to be slower, other times faster than for a singleton. Such variability in the literature is probably due to language-specific strategies and/or to methodological choices (consonant class, phonetic context, etc.).

## 2. Aims of the current study

The current study aims at investigating the motivations of variable vowel shortening and variable kinematics in Italian heterosyllabic sequences. We ask two major questions. The first is whether there are specific kinematic properties that, in addition to the temporal ones, convey the singleton vs geminate contrast in Italian. Based on the evidence reviewed above, we hypothesise that intervocalic geminates are produced with an anticipation of the beginning of the consonantal gesture, compared to intervocalic singletons. We investigate this issue with respect to four anterior coronal consonants, two stops /t t: d d:/ and two sonorants /n n: l l:/, considering that most of the existing evidence on Italian is rather limited to *(bi)labial* consonants and geminates. The second question is whether the temporal and kinematic properties of the singleton **vs.** geminate contrast can also be found in the contrast between an intervocalic tautosyllabic onset cluster and a heterosyllabic one (both beginning with the same consonant). According to a canonical moraic view of syllabic organization, in both cases the contrast is between an open and a closed syllable. If vowel shortening and kinematic variation are explained by the fact that there is a coda in the closed syllable, then the two types of contrasts should not diverge for their temporal and kinematic properties.

To answer these questions, we compared disyllables containing medial singletons (CVCV) and geminates (CVC:V), and disyllables containing medial stop-liquid onset clusters (CVCRV) and medial heterosyllabic clusters (either liquid-stop, CVRCV, or stop-stop, CVCCV)<sup>5</sup>. As already anticipated, the phonotactics of

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<sup>5</sup> C stands for plosive or nasal consonant, R for liquid, V for vowel. Note that some of our stimuli were vowel-initial disyllables, so the structures in those cases would be VCV vs. VC:V and VCRV vs. VRCV/VCCV.

Italian does not allow alternative syllable parsing in clusters: a stop-liquid cluster **can only be tautosyllabic**, and a sonorant-stop or a stop-stop cluster **can only be heterosyllabic**. Heterosyllabic clusters are phonologically more varied than tautosyllabic ones, whose C1 cannot be but a stop. By contrast, all stop and sonorant consonants (and fricatives as well) may occur as both singletons and geminates in the language. This aspect is of crucial importance because it shows that there are structural asymmetries in the language between the singleton **vs.** geminate alternation, on the one hand, and tauto- **vs.** heterosyllabic clusters alternation, on the other, the latter being phonotactically more constrained and phonetically less varied; moreover, within clusters, an additional asymmetry holds between heterosyllabic clusters (whose C1 may be a stop or a sonorant) and tautosyllabic clusters (whose C1 can only be a stop and C2 can only be a liquid). Speech timing (or more generally, prosody) and phonotactics strongly interact. The distributional differences between the two types of tauto-/heterosyllabic sequences are part of the Italian phonological grammar and should be taken into account when we investigate about heterosyllabicity and its temporal consequences on vowel-consonant organization.

Based on this observation, and on all previous knowledge of the phonetics and phonology of geminates and clusters reviewed above, the current study investigates whether the two types of alternation also have different acoustic and articulatory characteristics. More specifically, the hypothesis is that acoustic vowel shortenings and gestural anticipations of the post-vocalic consonant will be found to be more regular in the case of the singleton **vs.** geminate alternation, where they act as secondary phonetic cues of the phonological feature of consonant length, than in the case of clusters, where heterosyllabicity alone is not a sufficient predictor of systematic phonetic variation.

Before describing the experiment, we conclude this section by shortly reviewing three additional issues that we took into account in order to determine the number of syllables, the amount of segmental variation and the lexical frequency of the experimental stimuli.

We know from the literature that stressed antepenult and stressed final syllables behave differently from stressed penults in Italian (D'Imperio & Rosenthal 1999, Hayes 1995). For this reason, we limited our study to paroxytone disyllables. The implications that will be derived from the experimental results will consequently be relevant limited to this kind of phonological structure.



Individual segments and sound sequences are known to be more or less variable in duration on a language specific basis. For instance, languages without phonemic vowel length, like Italian, have been shown to display greater durational differences between vowels of different qualities, compared to languages with phonemic vowel length (e.g. Gordon 2006: 182). Context-sensitivity is an important issue also in articulatory-kinematic studies. For instance, Šimko et al. (2014) reported that the anticipation of the lip closing gesture for /p:/ in Finnish occurred in the /ap:i/ context more than in the /ip:a/ context and when the preceding consonant was /t/ more than when it was /p/; similar effects were found by Türk et al. (2017) in Estonian. Features of the consonant are relevant also in Zeroual et al.'s (2008) and Ridouane & Hallé's (2017) studies, according to which linguopalatal contact and gestural velocity differences are significant for voiceless plosives but not for their voiced cognates. Based on this literature, in this study we introduced some degree of contextual variation. More specifically, the stimuli included two different preceding vowels, i.e. low central /a/ or low-mid back /ɔ/. High or mid-high vowels were not used because their tongue configuration would have made the tracking of the tongue tip movement for the apical consonant too difficult. Moreover, the stimuli included three different phonetic conditions in the context that followed the target consonants: there could either be an /a/ vowel, or a sound articulated with a back constriction (a vowel such as /o/ or a consonant such as /k/ in a /dk/ cluster), or even a sound articulated with the anterior part of the tongue (a vowel such as /i/ or /e/ or a consonant such as /r/ in a /tr/ cluster).

We opted for real words, instead of purpose-made zero-frequency stimuli, under the hypothesis that a more ecologically valid elicitation paradigm will prevent the speakers from establishing articulatory routines that might differ from those of real speech production (e.g., McMillan et al. 2009). This however had a negative impact on the number of available test items, as our phonetic control parameters had to be very strict and not very many Italian words could finally meet those requirements. We also know that words differing for their frequency of occurrence may differ in how individual articulatory movements are produced; for instance, alveolar gestures may be reduced or even deleted in high frequency words (e.g., Bybee 2000, Lin et al. 2014) while studies on vowels have reported more anticipatory coarticulation in high frequency words and more extreme articulatory trajectories in low frequency words (e.g., Tomaschek et al. 2018). For this reason, we calculated the frequency of our word stimuli with respect to a reference corpus and entered this factor into the analysis. However, as it will be explained below, no effect of frequency was found on any of the

experimental variables.

### 3. Method

#### 3.1. Speech materials

Twenty-eight paroxytone disyllables with target consonants /t/, /d/, /l/ or /n/ were used for the experiment. These were all real Italian words, including toponyms (e.g. *Adria*), names of renowned commercial companies (e.g. *Bata*), proper names (e.g. *Batman*) or common abbreviations used in everyday language (e.g. *admin*). These items were organised in series of four (for /t/, /d/) or three items (for /l/, /n/) as shown in Table 1. In each series, the target obstruent occurred intervocally as a singleton (e.g. /'bata/), geminate (e.g. /'bat:a/), first consonant of an onset cluster (tautosyllabic cluster, e.g. /'patron/) or coda (heterosyllabic cluster, e.g. /'batman/). Stop-initial heterosyllabic clusters are not frequent in the Italian lexicon, particularly if compared to sonorant-initial ones; most often, they are included in words of foreign origin. Nevertheless, they do represent a possible option for Italian speakers, and for this reason they were included in the corpus. Since sonorants are not allowed as initial segments of a tautosyllabic cluster in Italian, target /l/ and /n/ only occurred intervocally as singletons and geminates (e.g. /'pala/, /'pal:a/) or as initial consonants of a heterosyllabic cluster (e.g. /'baltsa/)<sup>6</sup>. The unbalance of the speech corpus therefore reflects directly the asymmetry of the Italian phonotactics: both stops and liquids may occur as first member of a heterosyllabic clusters (V-stop-stop-V, V-liquid-stop-V), but only a stop can occur as first member of a tautosyllabic cluster (stop-liquid-V). Gaps in the corpus correspond to gaps in the phonological competence of the speakers.

Word-initial consonants did not change within each series, except for voicing distinctions in some of the series, which was judged irrelevant to the purposes of the current investigation. The vowel of the first syllable was always lexically stressed and could be /a/ (in six series) or /ɔ/ (in 2 series); the vowel did not change within each series. As anticipated in §2, some variation was also introduced in the articulatory

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<sup>6</sup> /ts/ and /dz/ represent the alveodental affricates, respectively voiceless and voiced. **The distribution of voicing varies across regional varieties of Italian (Meluzzi 2016); the form in which they appear in Table 1 corresponds to the Tuscan Italian pronunciation norm, as uttered by the subjects of the experiment.**

characteristics of the segment that followed the medial consonant. We controlled statistically for the effects of the segments that followed the target consonant, as well as of those that preceded, by including two independent factors, respectively for the preceding and the following phonetic context, in the analysis (see below, §3.4). Our kinematic analysis was limited to the timing and velocity of the cluster-initial apical gesture; we leave the question of cluster-internal gestural organization (which could also be relevant for the purposes of the current investigation) to future and more focused analyses.

The frequency of each word form (number of tokens and number of occurrences for millions of words) was calculated from the itTenTen16 web corpus (5.9 billion tokens; Jakubiček et al. 2013) and included in the random part of the two models that were run for the articulatory variable Ant (§3.4). Since however, the proportion of the random variance did not change when this factor was included with respect to when it was not, we concluded that the item frequency was not a relevant factor in our dataset and we therefore excluded it from further analyses.

	<i>target C</i>	<i>singleton</i>	<i>geminate</i>	<i>tautosyllabic cluster</i>	<i>heterosyllabic cluster</i>
s t o p s	/t/	/ˈbata/ <i>Bata</i> (1010; 0.17)	/ˈbat:a/ <i>batta</i> 'tap (subjunctive)' (3462; 0.59)	/ˈpatron/ <i>Pàtron</i> (442; 0.08)	/ˈbatman/ <i>Batman</i> (20793; 3.55)
		/ˈmɔta/ <i>mota</i> 'mud' (762; 0.13)	/ˈmɔt:o/ <i>motto</i> 'motto' (44669; 7.62)	/ˈbɔtro/ <i>botro</i> 'pond' (434; 0.07)	/ˈbɔtman/ <i>Botman</i> (27; 0.005)
	/d/	/ˈada/ <i>Ada</i> (21006; 3.58)	/ˈad:a/ <i>Adda</i> (24816; 4.23)	/ˈadria/ <i>Adria</i> (14486; 2.47)	/ˈadmin/ <i>admin</i> 'admin' (25599; 4.37)
		/ˈbɔdi/ <i>body</i> 'small suit for babies' (32294; 5.51)	/ˈbɔd:a/ <i>bodda</i> 'fatso (feminine)' (98; 0.02)	/ˈbɔdrum/ <i>Bodrum</i> (1337; 0.23)	/ˈpɔdkast/ <i>podcast</i> 'podcast' (13141; 2.24)
s o n o r a n t s	/l/	/ˈpala/ <i>pala</i> 'shovel' (36314; 6.19)	/ˈpal:a/ <i>palla</i> 'ball' (159925; 27.27)	impossible	/ˈbaltsa/ <i>balza</i> 'flounce' (9222; 1.57)
		/ˈkalo/ <i>calo</i> 'drop' (146356; 24.96)	/ˈkal:o/ <i>callo</i> 'foot corn' (2590; 0.44)	impossible	/ˈkaltsa/ <i>calza</i> 'sock' (14712; 2.51)
	/n/	/ˈvano/ <i>vano</i> 'room' (65047; 11.09)	/ˈvan:o/ <i>vanno</i> 'they go' (635328; 88.01)	impossible	/ˈvanto/ <i>vanto</i> 'pride' (18197; 3.1)
		/ˈgana/ <i>Ghana</i> (565, 0.1)	/ˈkan:e/ <i>canne</i> 'reeds' (37180; 6.34)	impossible	/ˈgandze/ <i>ganze</i> 'clever (fem. pl.)' (202; 0.03)

Table 1. Materials of the experiment: phonological transcriptions followed by orthographic transcriptions and English glosses. When gloss is absent, the word is a proper noun. Numbers in brackets: lexical frequencies, expressed as number of occurrences in the corpus and occurrences per million of words.

### *3.2. Speakers, equipment, recording procedure*

Ten native Italian speakers, 5 males and 5 females, aged 24-35 and reporting no speech or hearing deficit were recorded according to the following procedure. They were speakers of a Tuscan variety of Italian, in which gemination and vowel shortening before geminates are said to show up maximally as far as consonant duration ratios are concerned (Mairano & De Iacovo 2019). The task was a self-paced word reading of isolated target words and was run in an anechoic chamber. Synchronous audio and UTI data were collected at 60 Hz via a Mindray ultrasound machine equipped with a microconvex probe (Mindray 65EC10EA 6.5 MHz) and a stabilization headset (Articulate Instruments Ltd, 2008). The position of the probe was supposed to be orthogonal to the tongue surface so that the ultrasonic wave emitted from the probe was able to catch the entire lingual configuration during the speech movements. The acquisition platform was based on the AAA software, version 2.14 (Articulate Instruments Ltd, 2012). During the recording session, the speaker read the prompt items one by one, as they appeared in the AAA window on the computer screen in front of her/him. Three repetitions of the prompt list were recorded, except for one participant who repeated the prompt list four times. The order of the prompts was randomised across participants. The total duration of each recording session varied between 25 and 30 minutes.

### *3.3. Phonetic analysis and annotation*

Once completed, the recordings were exported from AAA into \*.wav format and imported into Praat, version 6.0.37 (Boersma & Weenink 2018) for manual segmentation and annotation. For each stimulus, the target consonant and the preceding vowel were segmented. The annotated acoustic signal was then reimported into

AAA for the semi-automatic tracing of the mid-sagittal tongue profiles (see below).

For each item, four phonetic measures were taken; two were acoustic measures and two were articulatory-kinematic.

In the acoustic domain, the duration of the stressed vowel and that of the following consonantal interval were measured. The onset and offset of the stressed vowel were established as the onset and offset, respectively, of higher frequency components (typically, F2). In particular, vowel onset was identified as the zero crossing of the first positive peak in the digitised waveform, alongside clearly visible formant patterns in the spectrogram. Vowel offset, in turn, was defined as the last well-formed period with a visible F2. Where the flanking consonants were nasals or laterals, intensity curves were examined alongside changes in F2 trajectories. The following consonantal interval was the target consonant (singleton or geminate) in some stimuli and a cluster formed by the target consonant and a following consonant in other stimuli. The onset of the consonantal interval coincided with the offset of the stressed vowel. When the consonantal interval corresponded to or ended in a plosive, its offset was established as the zero crossing of the first positive peak in the digitised waveform of the following unstressed vowel, alongside clearly visible formant patterns in the spectrogram. When the consonantal interval corresponded to or ended in a nasal, lateral or rhotic consonant, intensity curves were examined alongside changes in F2 trajectories to determine the boundary between the consonantal interval and the following unstressed vowel. Affricates were treated as contour segments and therefore included as such in the consonantal interval.

In the articulatory-kinematic domain, peak velocity of tongue tip gestures (henceforth: MaxVel) and the degree of anticipation of the apical gesture during the production of the preceding vowel (henceforth: Ant) were measured, based on UTI data. The procedure was inspired by Zeroual et al. (2008), who measured the gestural anticipation of alveolar plosives as the distance from the acoustic onset of the preceding /a/ to the onset of the tongue tip closing gesture. We replicated the procedure described in Strycharczuk & Scobbie (2015) for extracting dynamic information from midsagittal ultrasound images of tongue shape and location.

More specifically, UTI data were processed as follows. The fan set up (i.e., the search area within which the software operates the first gross tongue profile tracking) was customised for each speaker. **Tongue splines (i.e., tongue surface contours)** in each UTI frame included in the acoustically annotated intervals were traced

according to a semi-automatic procedure: **first**, a gross recognition of the brightest points **in each** ultrasound **frame**, potentially corresponding to **the 42 points composing the** tongue profile, was automatically run **by** the AAA **software**; then, careful manual correction was carried out, **again** frame by frame. The hard palate of each speaker was also tracked and then superimposed to the lingual profiles for reference; the palate images were obtained from the ultrasound frames relative to the moment of swallowing some water. Once **tongue** splines were **traced in the acoustically annotated intervals**, we first identified the relevant fan radials for tongue vertical displacement measurement (Figure 1, left). The fan is the coordinate frame, centred at the origin of the ultrasound signal (the probe) and consisting of 42 equidistant radials. Depending on the different articulatory properties of consonants and phonetic contexts, one of the fan lines between the 7th and the 12th from the right was selected to maximally capture the articulatory differences between the vocalic and the consonantal gesture in terms of tongue vertical displacement in the specific region of interest (tongue tip / blade). **The procedure was entirely manual and qualitative, that is, based on observation of concrete articulatory gestures, on a speaker-specific basis.** As a second step, we extracted tongue displacement and absolute velocity values along the selected fan (Figure 1, center). Peak velocity was the maximum velocity positive value of the tongue tip raising towards the palate. In the third step, we determined the instant at which the alveolar gesture for the post-vocalic consonant began (Figure 1, right). The articulatory maximum for the alveolar gesture occurs where the tongue tip velocity reaches its minimum (**velocity = 0 cm/sec; the tongue is steady against the palate**); this is preceded by a velocity peak that identifies the movement towards the target. We defined the articulatory beginning of the alveolar gesture as the point before the peak where the velocity reached at least 20% of the peak velocity. We then measured the duration of the interval from the onset of the vowel and the beginning of the alveolar gesture (“gestural delay” in Figure 1, right). As a fourth and final step, we divided this interval by the duration of the vowel, thus resulting in the proportional measure of how much of the vowel is produced before the gesture for the post-vocalic consonant begins (Ant). Smaller Ant values thus indicated stronger anticipation of the consonant with respect to the beginning of the vowel.

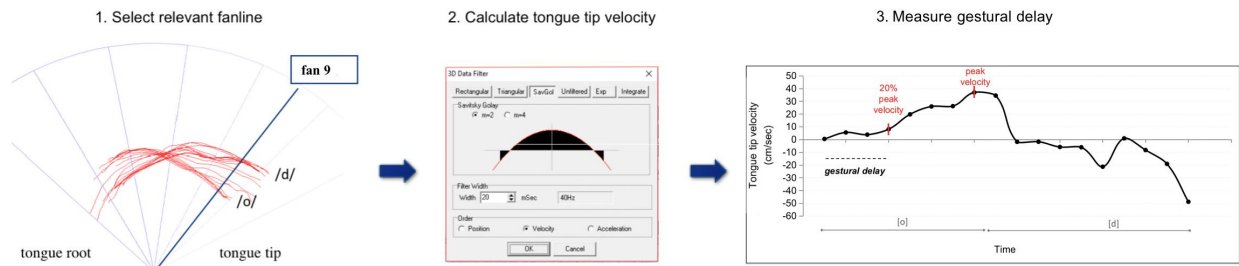


Figure 1. Schematisation of the procedure for the extraction of the kinematic-articulatory measures MaxVel and Ant from the stimulus *body*. See text for details.

### 3.4. Statistics

Linear mixed models were calculated using R (version 3.5.0; R Core Team 2018) with the lme4 package (Bates et al. 2015) fit by restricted maximum likelihood (REML). We estimated the best fitting model performing likelihood ratio tests between nested models: starting from the most general model and removing the redundant factors via a back-forward procedure. The analysis was split in two parts: in the first part, we analysed singletons and geminates, and in the second, tauto- and heterosyllabic clusters. In both parts, the four dependent variables mentioned in §3.3 were analysed, and namely, the duration of the stressed vowel (henceforth: V), the duration of the consonantal interval (henceforth: C), MaxVel and Ant.

Each variable was independently modelled. The factors which were supposed to influence the results were the following: Phonology (singleton vs geminate, in the first analysis; tauto- vs heterosyllabic cluster, in the second); Constriction (plosives vs sonorants); PrecedingV (/a/ vs /ɔ/); FollowingGesture (three levels: open, when the phoneme which followed the target consonant was /a/, tongue body constriction, when the following phoneme was /o/ or /k/, and tongue **front** constriction - when the following phoneme was /i/ or /e/). Speaker, Item, and Repetition were included as random factors. As mentioned above (§3.1), the Frequency of the items was initially included among the random factors in the models with MaxVel and Ant as the dependent variables, but in no case it proved to account for any part of the random variation component; therefore, it was subsequently excluded from the statistics. Observations over and above the standard deviation multiplied by 2.5 were considered outliers and therefore excluded from the statistics: this led to the

exclusion of a few items, as summarized in Table 2.

	<i>C</i>	<i>V</i>	<i>MaxVel</i>	Ant
Singletons - geminates (N = 490)	10 (2%)	9 (1.8%)	15 (3%)	11 (2.2%)
Tautos. - heterosyllabic clusters (N = 370)	6 (1.6%)	8 (2.2%)	10 (2.7%)	8 (2.2%)

Table 2. Number (and percentage) of outliers in the datasets.

The most general model included all the independent factors as predictors as well as the interactions between Phonology and Constriction, Phonology and PrecedingV, and Phonology and FollowingGesture; the model also included by-Speaker and by-Item random intercepts in its random part as well as by-Speaker random slopes for Phonology and Constriction and by-Item random slopes for Phonology and Repetition, to account for the effects of random variance in these predictors (Baayen et al. 2008). In the case of the cluster dataset, it proved impossible to start from the most general model including all independent factors and interactions as this raised problems of non-convergence, partly related to the unbalance of the experimental conditions across the dataset. Therefore, we ran a general model that was equivalent to that of the singleton/geminate dataset with the exception of the interactions, which were not included. Then, in order to verify whether the difference between tauto- and heterosyllabicity was shaped by the other predictors, we ran post-hoc comparisons (independent sample t-tests, or Wilcoxon Paired Signed-rank Test when the normality assumption was not met) crossing Phonology with either Constriction, PrecedingV or FollowingGesture.

The degree of correlation between C and V was calculated using the Kendall rank correlation test.

## 4. Results

### 4.1. Singletons and geminates



#### 4.1.1. Acoustics

The difference in duration between singletons and geminates was extremely robust, as expected, both over the entire dataset (singletons:  $N = 243$ ,  $\mu = 0.081$  s,  $\sigma = 23$ ; geminates:  $N = 247$ ,  $\mu = 0.185$  s,  $\sigma = 29$ ) and in the speech of each participant. The linear model that best accounted for the data, calculated according to the procedure in §2.4, included only two predictors, i.e. Phonology and Constriction. The output of the model is shown in Table 3 (deviation coding). The factor Phonology accounted for a difference of  $0.103$  s between singletons and geminates; in addition, plosives were overall  $0.020$  s longer than sonorants. No significant interactions were found, which meant that the difference between singletons and geminates was equally represented among plosives and sonorants; at the same time, plosives were longer than sonorants both when singletons and when geminates.

	Estimate	Std. Error	t value	Pr(> t )	
(Intercept)	0.1325	0.0059	22.336	< 0.001	***
Phonology	-0.1034	0.0090	-11.485	0.0005	***
Constriction	0.0204	0.0086	-2.379	0.0307	*

Table 3. Optimised linear mixed model for the variable C. Data subset: singletons and geminates. Number of observations: 480; speakers: 10; items: 16. Correlation between Phonology and Constriction: 0.035.

The difference between singletons and geminates was also evident in the acoustic duration of the preceding vowel, with geminates showing shorter vowels ( $N = 247$ ,  $\mu = 0.151$  s,  $\sigma = 30$ ) than singletons ( $N = 243$ ,  $\mu = 0.188$  s,  $\sigma = 29$ ). The model that best accounted for the data included the two predictors Phonology and Constriction (Table 4). The factor Phonology accounted for a difference of  $0.037$  s (recall that the difference was over  $0.100$  s for the variable C); by contrast, the effect of Constriction on vowel duration was approximately of the same magnitude as for consonant duration, vowels before plosives being on average  $0.019$  s shorter than before sonorant (recall that plosives were estimated  $0.020$  s longer than sonorants in the

C model). No significant interaction was found.

Kendall's correlation test showed that V was inversely correlated with C ( $\tau = -0.338$ ,  $p < .001$ ). This indicated that, in the acoustic dimension, the longer the consonant, the shorter the preceding vowel.

	Estimate	Std. Error	t value	Pr(> t )	
(Intercept)	0.1701	0.0074	22.857	< 0.001	***
Phonology	0.0373	0.0066	5.617	0.0009	***
Constriction	0.0194	0.0065	2.959	0.0076	**

Table 4. Optimised linear mixed model for the variable V. Data subset: singletons and geminates. Number of observations: 480; speakers: 10; items: 16. Correlation between Phonology and Constriction: 0.090.

#### 4.1.2. Tongue tip kinematics

MaxVel was higher in geminates ( $N = 243$ ,  $\mu = 38.8$  cm/sec,  $\sigma = 10.5$ ) than in singletons ( $N = 247$ ,  $\mu = 32.1$  cm/sec,  $\sigma = 8.6$ ), which suggested that the apical gesture is faster in the realization of geminate constriction, compared to singletons. The statistics confirmed that the only significant predictor was Phonology (Table 5), which accounted for a difference of 6.2 cm/sec. The velocity of the apical gesture appeared not to be influenced by phonetic factors such as the following articulatory gesture; there was a statistically non-significant tendency for consonants preceded by /ɔ/ to be initiated with a faster movement compared to consonants preceded by /a/.

	Estimate	Std. Error	t value	Pr(> t )	
(Intercept)	0.958	0.0544	22.112	< 0.001	***
Phonology	-0.6218	0.1033	3.617	0.0085	**
PrecedingV	-0.0985	0.0376	-1.034	0.0581	ns

Table 5. Optimised linear mixed model for the variable MaxVel. Data subset: singletons and geminates.

Number of observations: 475; speakers: 10; items: 16. Correlation between Phonology and PrecedingV: 0.127.

Average Ant values were found to be higher in singletons ( $N = 247$ ,  $\mu = 0.656$ ,  $\sigma = 0.145$ ) than in geminates ( $N = 243$ ,  $\mu = 0.530$ ,  $\sigma = 0.178$ ), suggesting that the anticipation of the apical gesture occurred proportionally earlier in geminates than in singletons. The model that best accounted for the data included three predictors, i.e. Phonology, Constriction and PrecedingV. Thus, compared to the acoustic variables of C and V and the kinematic variable of MaxVel, Ant appeared to be influenced by the shape assumed by the oral cavity during the production of the preceding vowel. The output of the model is shown in Table 6. In addition to the singleton *vs.* geminate distinction, Ant was longer for sonorants than for plosives, thus suggesting that the apical gesture began comparatively earlier when the consonant was a plosive with respect to a sonorant. Recall that Ant is a proportional estimation uninfluenced by the absolute duration of the vowel. Moreover, the apical gesture began comparatively earlier when the vowel was /ɔ/ than when it was /a/, indicating that, all other things being equal, the tongue tip started earlier its raising gesture when the preceding articulation involved a raised posterior tongue than when the preceding vowel was articulated with a flattened tongue dorsum and a lowered jaw. No significant interactions among any of these factors were found.

	Estimate	Std. Error	t value	Pr(> t )	
(Intercept)	0.5614	0.0244	22.973	< 0.001	***
Phonology	0.1207	0.0274	4.394	0.0004	***
Constriction	0.0917	0.0380	-2.414	0.0280	*
PrecedingV	-0.1344	0.0269	4.992	0.0003	***

Table 6. Optimised linear mixed model for the variable Ant. Data subset: singletons and geminates. Number

of observations: 479; speakers: 10; items: 16. Maximum correlation between variables: 0.258.

## 4.2. Tauto- and heterosyllabic clusters

### 4.2.1. Acoustics

The difference in duration between tauto- and heterosyllabic clusters was robust (tautosyllabic:  $N = 125$ ,  $\mu = 0.148$  s,  $\sigma = 24$ ; heterosyllabic:  $N = 245$ ,  $\mu = 0.213$  s,  $\sigma = 28$ ). The linear model that best accounted for the data included only two predictors, i.e. Phonology and FollowingGesture (Table 7). The factor Phonology accounted for a difference of  $0.060$  s; in addition, clusters followed by high vowel (i.e. those in /admin/, /adria/ and /gandze/) were  $0.010$  s shorter than clusters followed by /a/ (i.e. those in /baltsa/, /kaltsa/, /batman/ and /botman/).

	Estimate	Std. Error	t value	Pr(> t )	
(Intercept)	0.2170	0.0059	36.341	< 0.001	***
Phonology	-0.0603	0.0041	-14.597	< 0.001	***
FollowingGesture (tfront)	-0.0183	0.0038	-4.721	< 0.050	**
FollowingGesture (tbody)	-0.0078	0.0038	-2.032	> 0.050	ns

Table 7. Optimised linear mixed model for the variable C. Data subset: clusters. Number of observations: 364; speakers: 10; items: 12. Correlation between Phonology and FollowingGesture: -0.26.

Comparing tauto- and heterosyllabic clusters within subsets of data defined by the other predictors, all comparisons turned out to be significant. We found a significant difference between tautosyllabic and stop-initial heterosyllabic clusters ( $t = -13.208$ ,  $df = 78$ ,  $p < .001$ ) as well as between tautosyllabic and sonorant-initial heterosyllabic clusters ( $W = 14$ ,  $p < .001$ ); the difference was equally significant within the group of items with a preceding /a/ ( $W = 7$ ,  $p < .001$ ) as well as for those with a preceding /o/ ( $t = 9.6646$ ,  $df = 38$ ,  $p$

< .001); finally, the difference was significant for items defined by both a tongue body ( $t = -10.606$ ,  $df = 48$ ,  $p < .001$ ) and a tongue front ( $W = 2$ ,  $p < .001$ ) following gesture. These data confirmed that the C durational difference between tauto- and heterosyllabic clusters was strong and consistently represented across the dataset.

The difference between tauto- and heterosyllabic clusters was also evident in the acoustic duration of the preceding vowel, with heterosyllabic clusters showing shorter vowels ( $N = 245$ ,  $\mu = 0.151$  s,  $\sigma = 23$ ) than tautosyllabic ones ( $N = 125$ ,  $\mu = 0.172$  s,  $\sigma = 25$ ). The model that best accounted for the data included three predictors, i.e. Phonology, Constriction and FollowingGesture (Table 8). The factor Phonology accounted for a difference of 0.033 s (recall that the difference was of 0.060 s for the variable C); there was an additional effect of Constriction, showing that vowels before clusters beginning with plosives (/dm/, /tm/, /dr/, /tr/, /dk/) were estimated 0.033 s shorter than before clusters beginning with a sonorant (/nt/, /nts/, /lts/); recall that the two groups of clusters were not found to differ significantly for C. Finally, as a mirror image of what was found in C, vowels before clusters followed by high vowels (i.e. those in /admin/, /adria/ and /gandze/) were estimated 0.015 s longer than vowels before clusters followed by /a/ (i.e. those in /baltsa/, /kaltsa/, /batman/ and /botman/).

	Estimate	Std. Error	t value	Pr(> t )	
(Intercept)	0.1651	0.0069	23.694	< 0.001	***
Phonology	0.0333	0.0048	6.918	< 0.001	***
Constriction	-0.0334	0.0048	-6.933	< 0.001	***
FollowingGesture (tfront)	0.0147	0.0034	4.250	< 0.050	**
FollowingGesture (tbody)	0.0065	0.0034	1.903	> 0.050	ns

Table 8. Optimised linear mixed model for the variable V. Data subset: clusters. Number of observations:

362; speakers: 10; items: 12. Maximum correlation between factors: -0.566.

Independent sample t-tests showed that, when the dataset was split by Constriction (stop vs sonorant), vowels were significantly shorter before stop-initial heterosyllabic clusters /dm/, /tm/ and /dk/ than before stop-initial tautosyllabic clusters /dr/ and /tr/ ( $t = 8.5695$ ,  $df = 78$ ,  $p < .001$ ) but, interestingly, vowels before sonorant-initial heterosyllabic clusters /nt/, /nts/ and /lts/ were not different from vowels before stop-initial tautosyllabic clusters ( $t = 0.41876$ ,  $df = 78$ ,  $p = 0.6765$ ). This is illustrated in Figure 2. The hetero- vs tautosyllabic difference in V duration was significant within the subset of items with a preceding /a/ ( $t = 2.1276$ ,  $df = 78$ ,  $p < .05$ ) as well as within the subset of items with a preceding /o/ ( $t = 6.699$ ,  $df = 38$ ,  $p < .001$ ). Finally, concerning the following articulatory gesture, the difference was significant when the following gesture involved the tongue body (/patron/, /bɔtro/, /bɔdrum/ as opposed to /pɔdkast/, /vanto/;  $t = 2.8202$ ,  $df = 48$ ,  $p < .05$ ) but not when the following gesture involved the tongue front (/adria/ as opposed to /gandze/, /admin/).

Altogether, these data suggested that, as far as V was concerned, the difference between the two types of clusters disappeared in selected data subsets. In particular, vowels before heterosyllabic sonorant clusters showed the same duration than before tautosyllabic clusters.

Kendall's correlation test showed that V was significantly but mildly correlated inversely with C ( $\tau = -0.11$ ,  $p < .050$ ).

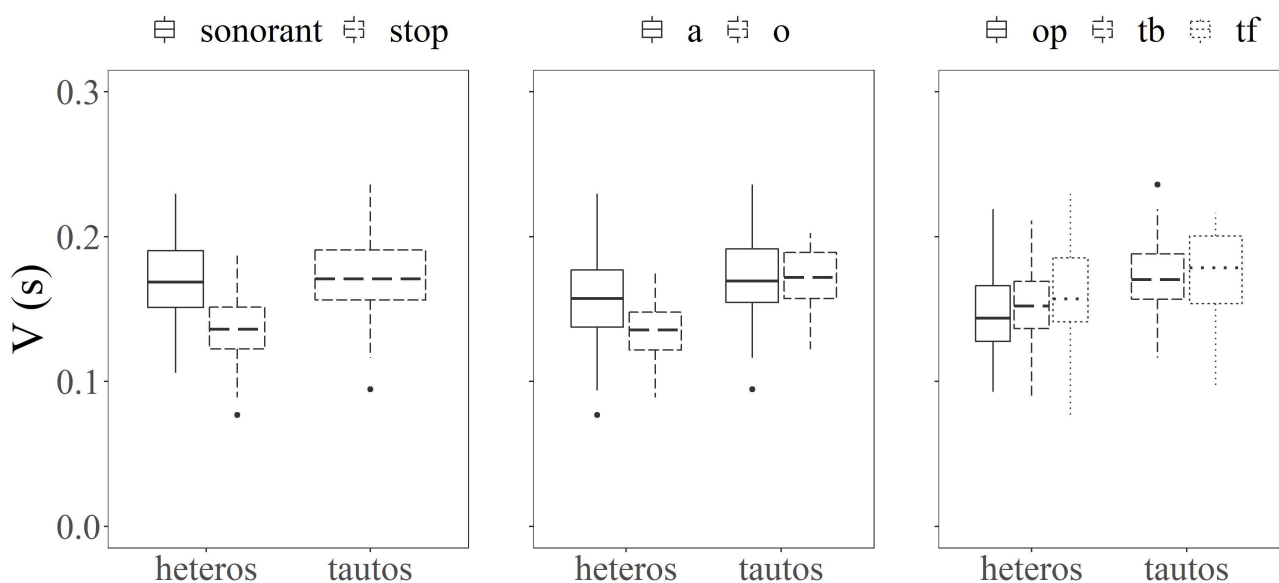


Figure 2. V duration in tauto- and heterosyllabic clusters, as a function of Constriction (sonorant vs. stop),

PrecedingV (/a/ vs. /o/) and FollowingGesture (opening v.s tongue body constriction vs. tongue fronting).

Data subset: clusters.

#### 4.2.2. Tongue tip kinematics

MaxVel was on average higher in tautosyllabic clusters ( $N = 125$ ,  $\mu = 34.3$  cm/sec,  $\sigma = 14.3$ ) than in heterosyllabic ones ( $N = 245$ ,  $\mu = 32.8$  cm/sec,  $\sigma = 9.9$ ). However, the difference was not statistically significant. As illustrated in Table 9, there was no effect of Phonology on MaxVel variation in clusters. The model that best accounted for the data included PrecedingV as the only significant predictor, which accounted for the fact that consonants preceded by /ɔ/ were initiated with a faster apical movement than consonants preceded by /a/; the estimated effect amounted to 8.5 cm/sec.

	Estimate	Std. Error	t value	Pr(> t )	
(Intercept)	0.888	0.0544	20.012	< 0.001	***
PrecedingV	-0.0854	0.0116	-4.034	0.0431	*

Table 9. Optimised linear mixed model for the variable MaxVel. Data subset: clusters. Number of observations: 360; speakers: 10; items: 12.

Comparing tauto- and heterosyllabic clusters within subsets of data defined by the other predictors, no comparison turned out to be significant. This confirmed that the MaxVel difference between tauto- and heterosyllabic clusters was absent from the whole dataset, as well as from its subparts defined by Constriction, PrecedingV and FollowingGesture.

Coming now to the second kinematic measure, Average Ant values were found to be higher in tautosyllabic ( $N = 125$ ,  $\mu = 0.496$ ,  $\sigma = 0.118$ ) than in heterosyllabic clusters ( $N = 245$ ,  $\mu = 0.463$ ,  $\sigma = 0.131$ ). However, the model that best accounted for the data was one in which none of the predictors were found to be significant

(Table 10). Thus, compared to the two acoustic variables and MaxVel, Ant appeared not to be influenced by any of the factors that were taken into consideration. The difference between tauto- and heterosyllabic clusters depicted above for the average Ant values was therefore irrelevant at the statistical level when the whole group of data was considered.

	Estimate	Std. Error	t value	Pr(> t )	
(Intercept)	0.4702	0.0191	24.68	< 0.001	***

Table 10. Optimised linear mixed model for the variable Ant. Data subset: clusters. Number of observations: 363; speakers: 10; items: 12.

When we looked at subsets of data defined by the factors Constriction, Preceding V and FollowingGesture, we found that Ant was significantly different in tauto- vs heterosyllabic clusters when stop-initial clusters were considered ( $t = 2.1299$ ,  $df = 71.036$ ,  $p < .05$ ), but not when sonorant-initial heterosyllabic clusters were compared to stop-initial tautosyllabic clusters ( $t = 0.45135$ ,  $df = 70.785$ ,  $p = 0.6531$ ), a pattern which closely resembled the one found for V (§4.2.3) and which is represented in Figure 3. Also similar to V was the fact that the difference between clusters was significant when the following gesture involved the tongue body (patron/, /bɔtro/, /bɔdrum/ as opposed to /pɔdkast/, /vanto/;  $t = 2.1391$ ,  $df = 48$ ,  $p < .05$ ) but not when the gesture involved the tongue front (/adria/ as opposed to /gandze/, /admin/). Finally, Ant differences were not significant in either subset of items with a preceding /a/ or /ɔ/.



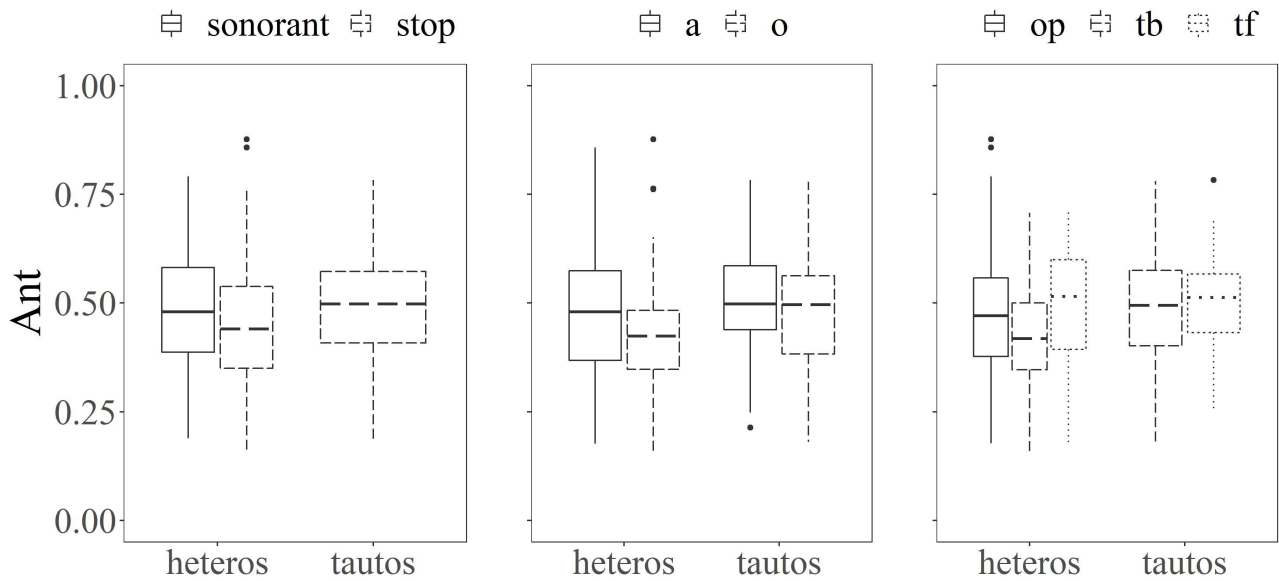


Figure 3. Ant values in tauto- and heterosyllabic clusters, as a function of Constriction (sonorant vs. stop), PrecedingV (/a/ vs. /o/) and FollowingGesture (opening vs. tongue body constriction vs. tongue fronting).

Data subset: clusters.

## 5. Discussion

This study had two principal purposes: one was that of determining if the singleton **vs.** geminate contrast in the case of selected Italian apical consonants showed specific articulatory-kinematic correlates, and the other was that of verifying if syllables closed by heterosyllabic clusters showed similar or different temporal and kinematic characteristics compared to syllables closed by geminates. Concerning the first point, we could document specific kinematic correlates that suggest a different timing of the tongue tip raising gesture in intervocalic geminates as opposed to singletons; by contrast, the difference between tautosyllabic and heterosyllabic clusters was not clearly indexed by different kinematic correlates. We will now itemise and discuss the specific findings starting from the singleton **vs.** geminate contrast and then coming to clusters.

### §5.1 Singletons and geminates

Our experiment has confirmed that, when gemination is investigated in isolated target disyllables, vowels before geminates are significantly shorter, compared to when they are before singletons. Unsurprisingly, the durational difference between singleton and geminate consonants was much bigger (estimated around 0.100 s) than the difference between the preceding vowels (0.037 s). The significant negative correlation between C and V additionally suggested that there is complementarity between the two, that is, the duration of the vowel is partly predicted by the duration of the entire consonantal interval, including when, as in the case of geminates, it spans a syllable boundary (cross-syllable compensation as a result of increased duration). The correlation coefficient was equal to -0.34, thus similar to what was found in bigger corpora of spoken Italian including clusters (e.g. Celata & Mairano 2014 reported -0.36 as the maximal by-speaker value, -0.39 as the maximal by-context value and -0.42 for the singleton/geminate subset). The absence of strict isochrony in languages is generally attributed to phonetic arguments such as the fact that vowels are incompressible beyond an absolute minimum duration in order to maintain the word's perceptual identity (since Klatt 1976). However, there may be additional aspects to be considered, such as data distribution.

In this respect, Figure 4 shows that C is bimodally distributed, with one frequency peak at 0.0715 s and a second peak at 0.1765, whereas V is normally distributed ( $W = 0.99788$ ,  $p = 0.8052$ ), with values centred around one peak at 0.1618 s. Gemination is a categorical phenomenon: this is evidenced by the bimodal distribution of singletons and geminates found in the data. By contrast, vowel shortening is not categorical; rather, it is gradient, as evidenced by the non-bimodal distribution of values. This difference can already be seen as an indirect piece of evidence against a strictly moraic account of vowel duration in Italian, because moraicity predicts categoricity (vowels are either “short” or “long” if they appear in closed or open syllables, respectively), whereas vowel differences are actually gradual in the language. Moreover, the distributional characteristics of vowels and consonants directly reflect their functional difference: phonological distinction in consonants, non-phonological variation in vowels. Therefore, the data suggests that the production of the consonantal (i.e., segmental) phonological contrast is anchored to specific production dynamics that include a principle of cross-syllable compensation of the durations of vocalic and consonantal intervals.

An additional finding also pointed towards the existence of durational compensations in the data. Sonorants (both singletons and geminates) were shorter than stops (Table 3); symmetrically, vowels before sonorants

were longer than before stops (Table 4). In both cases, the difference was about **0.020 s**, thus confirming that temporal compensation was pervasive in this dataset.

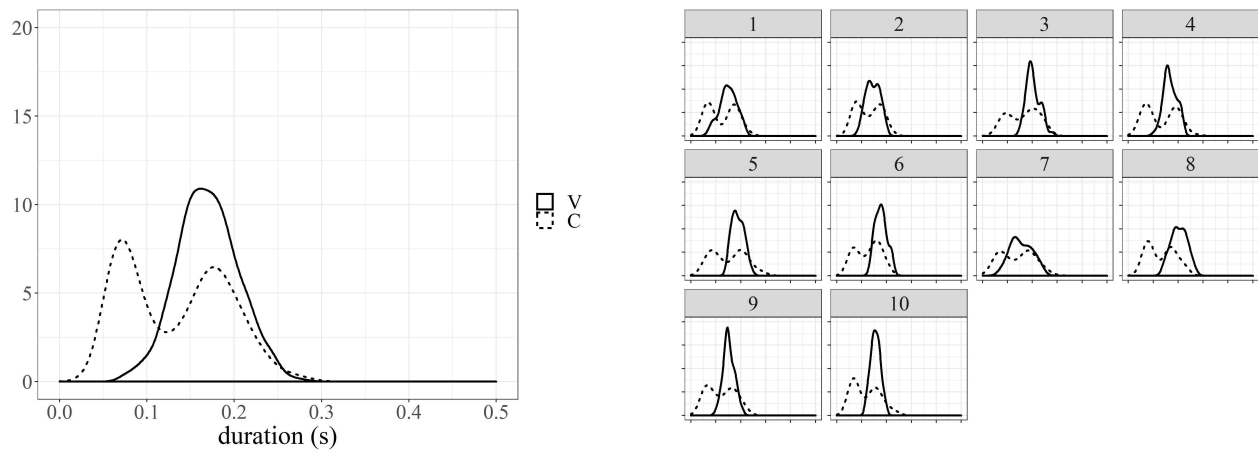


Figure 4. Density curves for variables V and C, overall (left) and split by subjects (right). Data subset: singletons and geminates.

In the kinematic domain, the apical gesture for a geminate was faster and began comparatively earlier **during the acoustic vowel** than the gesture for a singleton, indicating an increased anticipation between the nucleus and the following consonantal gesture in the case of geminates. (Recall that the Ant variable was normalized over vowel duration and therefore this effect cannot be seen as an artefact of having acoustically shorter vowels before geminates).

This finding was consistent with data from various languages that suggested that the closing gesture for a geminate consonant starts earlier than for a singleton (e.g. Šimko et al. 2014 for Finnish, Türk et al. 2017 for Estonian, Ridouane & Hallé 2017 for Tashlhiyt Berber; see review in §1). However, in other languages no effect of gemination on articulatory timing was found (e.g. Moroccan Arabic, according to Zeroual et al. 2008). This suggests that the length contrasts may be differently implemented across languages not only at the level of segments' duration but also at the level of gestural organization, which has an impact on the degree of cohesion of adjacent segments (and therefore, of consecutive syllables). Moreover, our kinematic

data are only partly consistent with previous findings on Italian (§1.2). In particular, the current results are consistent with the data for the bilabial nasals and stops reported in Gili Fivela et al. (2007), Smith (1995) and Zmarich et al. (2007, one subject), but they are not consistent with the data for apical /l:/ and /n:/ in Gili Fivela et al. (2007), for various bilabial and labiodental consonants in Zmarich et al. (2007) and for /m:/ in Löfqvist (2017). As anticipated in §1, inconsistencies in the results may be due to methodological differences across studies; see for instance the arguments by Löfqvist (2017) about the way of quantifying the synchronization of lower lip and tongue movements in the production of /m:/. Another complication in the case of (bilabial) nasals might be related to the presence of a velum gesture, which is not necessarily synchronous with the oral constriction gesture but nevertheless ensures the realization of acoustically prominent resonances. In this respect, our UTI-based analysis being focused on apical stops and sonorants (preceded by low or mid-low vowels) could rather easily track tongue tip movements, as opposed to dorsal movements required for the preceding vowels.

Both kinematic effects of gemination (increased closure velocity and increased temporal anticipation) were extremely robust in our data, as they appeared to be consistently present across consonants (sonorants, stops) and phonetic contexts.

Apart from correlating to the singleton *vs.* geminate distinction, Ant was also found to vary significantly as a function of vowel quality and consonantal constriction. Stops, which were overall acoustically longer than sonorants, were preceded by acoustically shorter vowels and articulated with a proportionally greater anticipation of the constriction gesture, compared to sonorants. Although both stops and sonorants in our dataset were anterior coronals, their manner distinction turned out to be consistently manifested by acoustic as well as kinematic differences. Concerning vowel variations, when the vowel involved a posterior tongue movement, the tongue tip for the consonant started raising earlier (and tended to move faster, Table 5) than when the vowel was produced with a low, flat tongue dorsum. Such contextual variation suggests that apical consonants are differently timed depending on the articulatory nature of the adjacent segments, even if - as in the case of vowels - the tongue tip is not actively involved. Our findings are therefore consistent with previous knowledge of apicals' sensitivity to contextual variations documented in the acoustic and articulatory domains (since e.g. Keating 1991, Recasens et al. 1997), furthermore providing new evidence in

the kinematic domain.

### §5.2. *Clusters*

We compared intervocalic tauto- and heterosyllabic clusters to see if the temporal and kinematic characteristics defining the singleton *vs.* geminate contrast also held for the cluster contrast, under the assumption that in both cases there was an opposition between an open and a closed syllable. There is a substantial asymmetry in Italian as far as heterosyllabic clusters are phonetically more varied (both stop-stop and sonorant-stop clusters) than tautosyllabic clusters (only stop-liquid clusters), and this asymmetry was directly reflected in the choice of the materials for the current experiment. These distributional differences between different types of clusters make the cluster alternation phonetically and phonotactically less regular than the singleton *vs.* geminate alternation. Assuming that they are part of the phonological grammar of the language, we hypothesized that acoustic vowel shortenings and gestural anticipations of the post-vocalic consonant were less regular in the case of the cluster alternation, compared to the singleton *vs.* geminate alternation, in spite of the fact that traditional moraic accounts treat both alternations as a contrast between an open and a closed syllables.

A first result in the domain of acoustic measurements concerned the fact that, like geminates were significantly longer than singletons, so heterosyllabic clusters were significantly longer than tautosyllabic ones; moreover, vowels before heterosyllabic clusters were significantly shorter. The difference between clusters was estimated around **0.060 s**, thus lower than between singletons and geminates, but still relevant<sup>7</sup> and statistically significant. By contrast, the difference between the preceding vowels amounted to **0.033 s**, i.e. somehow smaller than in the singleton *vs.* geminate contrast (where it amounted to **0.037 s**). Then at the group level, we can conclude that the temporal properties of the singleton *vs.* geminate contrast were also present in the tauto- *vs.* heterosyllabic cluster comparison. Figure 5 additionally shows that data distribution is also similar at the group level: C shows a non-normal distribution ( $W = 0.97527$ ,  $p < 0.001$ , with a main

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<sup>7</sup> Consider that the just noticeable difference (JND) for consonants is considered by Lehiste (1970: 13) to be 10 to 40 ms.

peak at 0.2081 s and a secondary lower peak at 0.1523 s), and V is normally distributed ( $W = 0.99492$ ,  $p = 0.2649$ ). However, there was much more individual variation, with plots on the right of Figure 5 showing inconsistent evidence of a bimodal distribution in the C variable and inconsistent evidence of a normal distribution in the V variable.

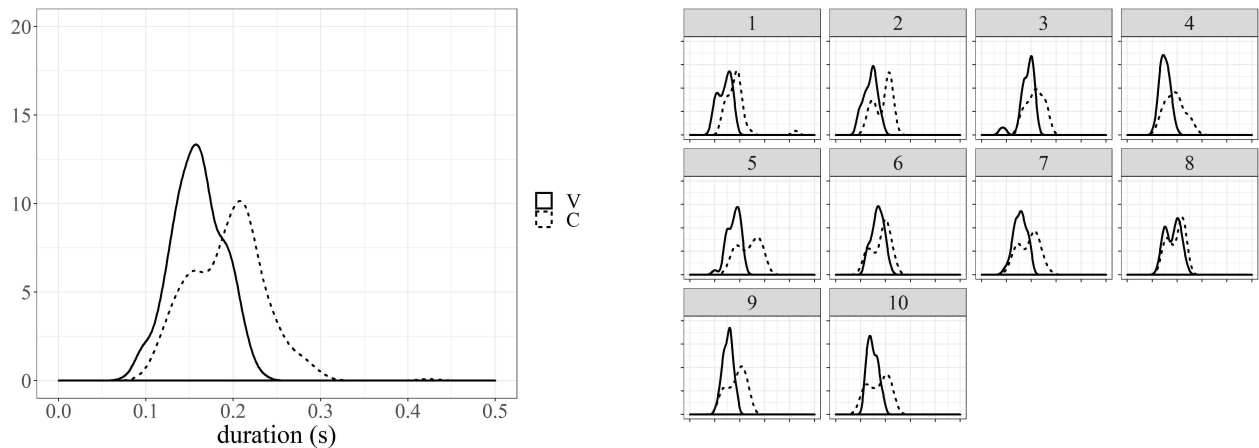


Figure 5. Density curves for variables V and C, overall (left) and split by subjects (right). Data subset: clusters.

A second relevant aspect concerns the difference between stop-initial and sonorant-initial clusters. While the two groups did not differ as far as the duration of the consonantal interval was concerned (Table 7), V was significantly different, with vowels before stop-initial clusters showing a shorter duration than vowels before sonorant-initial clusters (Table 8). This result suggests that vowel variations before clusters may be determined by factors that are unrelated to the cluster's tauto- vs. heterosyllabicity. Vowel duration varied according to the sonorant vs. stop distinction also in the singleton/geminate dataset (see above, §5.1). However, in that case the consonants also varied, consistently with the principle of durational compensation that we found in that dataset. By contrast, in the cluster dataset which is at issue here, only vowels vary, whereas stop-initial and sonorant-initial clusters show the same average duration. In this respect, then, the cluster dataset shows evidence of vowel variation which is less predictable and apparently irreducible to heterosyllabicity.

A third source of evidence for the rhythmical difference between pre-geminates and pre-cluster vowels is

that the difference between tauto- and heterosyllabicity had an impact on the duration of the preceding vowel only when stop-initial clusters were taken into account (Figure 2). Finally, the fact that the inverse correlation between cluster and vowel duration was very low ( $\tau = -0.11$ ) further suggests that another characteristic of the singleton *vs.* geminate contrast, that is, the tendency to distributing vocalic and consonantal intervals into slots of complementary duration, is not implemented in the sequences with clusters to the same extent. Recall that compensation is inherently cross-syllabic, as it presupposes that the duration of the entire consonantal interval, spanning from the coda of a syllable to the onset of the subsequent syllable, influences the duration of the nucleus of the first syllable (Fowler 1983, Farnetani & Kori 1986, Smith 1992). In our data, we can thus conclude that complementarity characterizes the segmental phonological contrast more clearly than the contrast between tauto- and heterosyllabic clusters.

The following phonetic context was found not to affect the duration of acoustic vowels and consonants in the singleton/geminate dataset, yet it did affect the duration of both consonants and vowels in the cluster dataset (Table 7 and 8): there was a symmetric effect of vowel shortening and cluster lengthening before /i/, whose motivation will not be investigated given that the clusters were composed of different segments. More importantly, there was no interaction between the effects of the phonetic context and the effects of the phonological contrast between tauto- and heterosyllabicity. It should therefore be concluded that in the cluster dataset, the effects of contextual variability were overall stronger than in the singleton/geminate dataset.

Concerning the kinematic findings, the models did not provide any statistical evidence of an effect of either MaxVel or Ant. Therefore, it should be concluded that, differently from singletons and geminates, tauto- and heterosyllabic clusters did not differ systematically for the kinematic properties investigated here.

There was, however, an important effect of the factor Constriction. Within stop-initial clusters, tautosyllabicity was manifested by less gestural anticipation (higher Ant values) and heterosyllabicity by increased gestural anticipation (lower Ant values) (Figure 3). Given that vowel duration also changed in the same way (Figure 2), we may conclude that, among stop-initial clusters, heterosyllabic clusters were preceded by shorter vowels and were produced with a proportionally greater anticipation of the consonantal gesture, compared to tautosyllabic clusters. However, when sonorant-initial heterosyllabic clusters were

considered, vowel duration and gestural anticipation did not differ from tauto-syllabic stop initial clusters. Moreover, Figure 3 shows that Ant distinguished between clusters only in the context of low vowels. Therefore, we should conclude that the contrast between tauto- and heterosyllabicity in clusters is manifested at the levels of vowel shortening and gestural anticipation in only a small subset of the data, which correspond to a small subset of the lexicon of the language. At the level of peak velocity, there is no significant difference between clusters.

## *6. Conclusions*

This study has shown that heterosyllabicity may be related to different properties in the speech signal and in speech articulation. This means that, in a phonetically-grounded view of phonological relations, the notion itself has to be specified in terms of the rhythmical and gestural consequences that it bears in the language. As a matter of facts, our results suggest that the contrast between tauto- and heterosyllabic clusters in Italian disyllables is much more weakly cued at the level of acoustic and articulatory correlates, especially if compared to the contrast between singletons and geminates. Gemination has robust correlates not only in the durational variations of the consonant and of the preceding vowel, but also in the velocity and the relative timing of the tongue tip constriction gesture, which occurs comparatively earlier than in intervocalic singletons. Robustness derives from systematicity across subjects and phonetic conditions. Peak velocity and gestural anticipation, besides vowel shortening, should all be considered as phonetic ways to enhance the contrast between phonologically long and short consonants. Contrast enhancing through systematic variation of production dynamics occurs frequently in languages and the speakers have an auditory advantage from that (e.g. Storme 2019, Dmitrieva 2019). All stops and sonorants (plus fricatives) can be geminated in Italian; to such widespread distribution of the phonological length feature correspond systematic acoustic and kinematic variations between singletons and geminates.

By contrast, heterosyllabic clusters show variable vowel shortening, with optionality at the level of individual subjects, and absent or weak kinematic correlates, with limitations related to the specific type of cluster and the quality of the surrounding phonetic context. In clusters, the phonetic context has a much stronger effect in modulating both acoustic durations and speech gesture timing relations. Clusters



themselves are complex phonetic objects, compared to geminates whose production differences with respect to the corresponding singletons are primarily related to the temporal extension of the constriction. Moreover, our dataset was asymmetric to the extent that it directly incorporated the asymmetry of the Italian phonotactic system which allows two types of heterosyllabic clusters (i.e. stop-initial and sonorant-initial clusters) and only one type of tautosyllabic clusters (stop-initial clusters), thus including a source of inescapable variability in the two groups of items. The phonetic complexity of clusters, alongside the asymmetric distribution of clusters in the dataset, can thus explain their variable behavior and the lack of articulatory routines related to cluster syllabification, as well as the weakness of the vowel duration effects. There is no kinematic and very little acoustic evidence of heterosyllabicity as such in clusters.

The compensatory mechanisms which makes vowels to shorten proportionally to the amount of lengthening in consonants (although strict isochrony is far to be reached) is also more effective in the case of intervocalic singletons and geminates than in the case of clusters, consistently with the primary role that the duration of the constriction gesture plays in the singleton vs. geminate distinction.

Taken together, these data suggest that, in the production of disyllables by Italian speakers, systematic variations in acoustic vowel duration and in the kinematics of tongue tip gestures represent the phonetic correlates of the segmental phonological contrast between short and long consonants, rather than of syllable structure. In order to be considered phonetic correlates of heterosyllabicity, the same systematic variations should have been found in vowel-cluster sequences, which was not the case in the current study. Stressed vowel shortening, showing different acoustic and articulatory characteristics before geminates and before heterosyllabic clusters, should be considered as bearing different functions in the phonology of the language and indexing the length feature in the case of gemination. This view is consistent with typological and historical data that establish a clear link between vowel shortening and gemination. For instance, in various languages contrastive vowel quantity arose as a reaction to the process of consonant degemination (e.g. in Breton, Bothorel 1982; in Northern Italian dialects, Loporcaro 2007). Similarly, typological surveys show that 26 languages have vowel shortening in the context of gemination but only 9 have vowel shortening in the context of a singleton syllable coda (Maddieson 1984).

Our data confirm Smith's (1992) and Farnetani & Kori's (1986) findings about the tendency for Italian to

show isochrony within the vowel-to-vowel interval, especially in disyllables with singletons and geminates. However, our data are only partly consistent with the predictions of both moraic and gesture-based models of the syllable. With respect to the moraic model, it may be problematic that not all types of closed syllables show the same rhythmic and kinematic correlates. In particular, the traditional assumption that the duration of the preceding stressed vowel can be directly predicted by syllabic constituency appears, in the light of the current data, inadequate to account for the entire picture of heterosyllabic consonantal sequences in Italian. Our kinematic data, in particular, show that no gestural timing routines can be established to account for the tauto- vs. heterosyllabicity contrast in clusters; in parallel, variation at the acoustic output is linked to various phonetic and contextual factors that are unrelated to syllabification. Moreover, the fact that heterosyllabic clusters do not necessarily imply vowel shortening might suggest that some of them give rise to extra-heavy syllables, something that is generally considered dispreferred in languages, although not impossible (Gordon 2006). For instance, Moosmüller & Brandstätter (2014) show that Middle Bavarian dialects, generally considered to exhibit a rigid pattern of durational compensation (short vowels before *fortis* stops, long vowels before *lenis* stops), do indeed include extra-heavy syllables with *fortis* stops preceded by long vowels; the authors derive from this data that a strictly moraic account is insufficient to describe the temporal organization of these dialects and that although “the quantity interaction [...] is [...] reflected in a strong correlation between vowel and consonants, [...] the type V:F is not integrated in this pattern, but takes an intermediate position” (Moosmüller & Brandstätter, 2014: 93).

By contrast, in the case of gestural models of syllable structure, the fact that the increased gestural anticipation of codas is variable in the phonological contexts (geminates vs. clusters) can only be accounted for if the timing relationships between gestures within the syllable are conceived of as very general templates over which language-, context- and possibly also speaker-specific constraints apply. As a matter of fact, this view is receiving increasing support from cross-linguistic investigation of a variety of phenomena related to the internal organization of syllables (e.g. Pouplier 2015, Chen et al. 2017, Pouplier et al. 2020), showing the role of phonetic segmental factors in shaping the articulatory cohesion within the syllable. Gestural cohesion effects spanning syllable boundaries also call for a more gradient view of articulatory syllabification.

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