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# Coarticulation

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## Summary and Keywords

The study of coarticulation—namely, the articulatory modification of a given speech sound arising from coproduction or overlap with neighboring sounds in the speech chain—has attracted the close attention of phonetic researchers for at least the last 60 years. Knowledge about coarticulatory patterns in speech should provide information about the planning mechanisms of consecutive consonants and vowels and the execution of coordinative articulatory structures during the production of those segmental units. Coarticulatory effects involve changes in articulatory displacement over time toward the left (anticipatory) or the right (carryover) of the trigger, and their typology and extent depend on the articulator under investigation (lip, velum, tongue, jaw, larynx) and the articulatory characteristics of the individual consonants and vowels, as well as nonsegmental factors such as speech rate, stress, and language. A challenge for studying coarticulation is that different speakers may use different coarticulatory mechanisms when producing a given phonemic sequence and they also use coarticulatory information differently for phonemic identification in perception. More knowledge about all these research issues should contribute to a deeper understanding of coarticulation deficits in speakers with speech disorders, how the ability to coarticulate develops from childhood to adulthood, and the extent to which the failure to compensate for coarticulatory effects may give rise to sound change.

Keywords: coarticulatory resistance, spatiotemporal coarticulatory effects, assimilation, anticipatory and carryover coarticulation, long-range coarticulation, gestural blending

# 1. General Concepts and Methods

Coarticulation can be characterized as changes in articulation and in the acoustic signal induced by one phonetic segment (the trigger) during another one (the target) due to overlap between their articulatory gestures. Examples of coarticulation are anticipatory velar lowering during a vowel preceding a syllable-final nasal consonant (*s**e**nd*) and tongue body raising and fronting during a schwa placed next to the palatoalveolar consonant /ʃ/ (*th**e** shore*, ***a**shamed*). Coarticulatory effects may involve several articulatory structures (velum, lips, tongue tip, tongue body, jaw, larynx) and acoustic properties (e.g., second formant frequency, segmental duration). They may result from the activation of a single articulatory gesture (as in ***a****shamed*), or from the interaction among articulatory gestures for different segments (as in the cluster /sk/ in the Spanish word *a****sc****o* 'nausea,' where /s/ is front lingual and /k/ a dorsal consonant).

Coarticulation may be measured in space and time. Thus, for example, tongue dorsum raising and fronting effects exerted by /ʃ/ on an immediately preceding schwa, which has no obvious lingual constriction, are predicted to be larger in terms of spatial displacement and start earlier than those occurring during a preceding vowel exhibiting a lingual constriction, such as /i/ or /a/. Moreover, the spatiotemporal effects in question may differ in direction: they may be anticipatory, and thus proceed leftwards toward the preceding segment(s) (as in *it is* ***a*** *shame*), or carryover, and thus proceed rightwards toward the following segment(s) (as in *mash* ***a*** *potato*). It is commonly accepted that anticipatory effects reflect phonemic planning in so far as they correspond to articulatory characteristics of phonemes which are yet to be produced (Whalen, 1990); carryover effects, on the other hand, depend on the ongoing state of the articulatory structures to a larger extent, which may account for why their offset is more variable (see sections 2.1 and 2.3.1.2). As pointed out for lingual coarticulation in section 2.3, the magnitude, temporal extent, and direction of the coarticulatory effects are conditioned by the place and manner of articulation characteristics of the triggering and target consonants and vowels, as well as by the articulatory subsystem which is involved in closure or constriction formation. Other factors affecting coarticulation are segmental position within the word and the utterance; the stress level of the segment; whether it occurs in a VCV (vowel-consonant-vowel), CC (consonant-consonant), or other sequence structure; speech rate; speaker; and language.

The study of coarticulation provides information about phonological assimilatory processes and sound change patterns. It has been traditionally assumed that coarticulatory effects are phonetic and thus gradual, variable, and universal, while assimilations are phonological and thus categorical, systematic, and language-specific. For example, tongue body raising and fronting effects from a palatal consonant during a schwa occur to a greater or lesser extent in any speech production event, but may only be labeled assimilatory if there is a sound change by which the coarticulatory effects in question give rise to a higher and fronter vowel such as /e/ or /i/ in a subset of lexical items or across the entire lexicon of a given language. Experimental evidence reveals, however, that the division between coarticulation and assimilation is not so straightforward. Indeed, coarticulatory effects may exhibit language-dependent differences (e.g., languages may differ regarding the degree of anticipatory vowel nasalization triggered by a syllable-final nasal consonant; see section 2.1), while processes which have been traditionally considered to be assimilatory may not apply categorically and systematically (e.g., in English or German, syllable-final /n/ assimilates completely or partially to the place of articulation of a following consonant, and more or less often depending on the consonant trigger, speaker, prosodic factors, and speech rate; see section 2.3.2).

There has been a substantial improvement of our knowledge of coarticulatory patterns in speech owing to an increasing number of large-scale phonetic experiments which have been carried out using several acoustic and articulatory recording and analysis techniques. Acoustic analysis provides information about spectral coarticulatory characteristics (also about coarticulatory effects in duration and intensity) associated mostly with tongue movement, nasality, and voicing. As for the articulation side, lingual coarticulatory effects in tongue-to-palate contact and tongue spatial configuration and kinematics have been investigated, respectively, with electropalatography and with ultrasound and electromagnetic articulometry. Electromagnetic articulometry also allows measuring coarticulation in lip and jaw displacement, while voicing coarticulation may be analyzed with electroglottographic data and anticipatory and carryover velar lowering with the help of a velotrace.

The present article is structured as follows. Section 2.1 reviews coarticulatory data in velar lowering and lip protrusion, which are expected to exhibit comparable patterns of overlap in so far as the two articulatory structures move independently of the tongue. Section 2.2 deals with voicing coarticulation, which differs from velar and labial coarticulation in that the glottal activity is heavily influenced by the intraoral pressure and airflow volume characteristics of the phonetic segments being produced. Tone coarticulation is reviewed in this same section, since it depends on laryngeal adjustments as well. Lingual and jaw coarticulation patterns, examined in sections 2.3 and 2.4, offer a rich scenario in so far as they are heavily determined by the specific consonant-vowel and consonant-consonant combinations available. Section 3 reviews briefly coarticulatory effects in the acoustic signal. Sections 4, 5, and 6 deal with how the degree of coarticulation varies with segmental position, stress, and speech rate; with the perception of coarticulatory effects and its relevance for sound change inception; with the acquisition of coarticulation in children; and with coarticulation in speakers with speech disorders. Coarticulation theories are referred to with reference to the coarticulation data for different articulators in each relevant section and also in the closing section 7, which also considers several aspects for future research.

# 2. Articulatory Structures

## 2.1 Velum and Lips

Experimental findings conducted in languages where vowel nasalization is not distinctive, such as English, reveal that, as stated by the time-locked model of coarticulation (Bell-Berti & Harris, 1981), the onset of anticipatory velar lowering associated with the nasal consonant trigger occurs at a fixed time before its acoustic onset independently of preceding phone string length as long as there is no articulatory conflict with a contextual phonetic segment. Consistently with the time-locked coarticulation model, in a

CVN sequence, where N stands for a nasal consonant and C for an oral consonant, the event in question takes place at about vowel onset but not earlier, since the velum must stay high during the production of the oral consonant. Also in agreement with the model, velar lowering has been shown to often proceed in two stages in a CVVN sequence: (a) a slow-moving action whose onset is aligned with the first vowel and represents its characteristic velar position, and (b) a subsequent higher-velocity movement, which is directly coordinated with the nasal consonant and begins at about V2 onset and thus at a comparable time to velar lowering onset in a CVN sequence (Bell-Berti, 1993). The two stages may overlap as the number of contextual vowels decreases and speech rate increases. The time-locked model of coarticulation was formulated as an alternative to the look-ahead model according to which nasal consonant-dependent velar lowering should extend over the maximal number of vowel segments preceding the trigger and thus start at the onset of the only vowel available in CVN sequences and at V1 onset in CVVN sequences (Moll & Daniloff, 1971).

In parallel to velar lowering, two separate stages of lip-rounding anticipation associated with /u/ have also been identified in /i$C_n$u/ sequences, where $C_n$ stands for a variable number of consonants and /i/ conflicts with lip rounding (see Boyce et al., 1990 and Perkell & Matthies, 1992 for English): (a) a gradual onset of lip protrusion occurring toward V1 offset, which is related to the consonant (consonants like /s/ have their own lip target position); (b) a subsequent faster second phase from acceleration maximum to protrusion maximum, which is closely linked to /u/ and may remain temporally fixed or else expand with the duration of the consonant interval and thus is not time-locked to the rounded vowel. The onset time of phase (b) depends greatly on the speaker, as confirmed by data on the extent of anticipatory labial constriction for /u/ in French and English showing a speaker-specific linear expansion rate of this phase as the consonant interval increases (Abry & Lallouache, 1995; Noiray et al., 2011).

Velar lowering anticipation may vary in time and amplitude across languages (Clumeck, 1976). Solé (2007) found that the vowel nasalization span in VC sequences with a nasal stop produced by Spanish and English speakers differs as a function of language: in Spanish, it is relatively short and constant across rates and is thus associated with the necessary time required by the velum to lower for the production of the nasal consonant; in English, it is longer and timed relative to vowel duration (planned), i.e., longer if the vowel lengthens as slower speech rates and shorter if the vowel shortens at faster rates. As to lip rounding, the onset time and amplitude of the anticipatory lip protrusion movement appear to be greater in Swedish than in English and thus to increase with the number of rounded vowels available in the language so that they can become sufficiently perceptually contrastive (Lubker & Gay, 1982). Extensive coarticulatory effects may have given rise to new phonemic units, for example, distinctive nasal vowels like those existing in present-day French, Hindi, and Portuguese, and phonological processes, for example, rounding harmony in Turkish, where a rounding plateau instead of a rounding trough has been reported to occur systematically in /uCu/ sequences (Boyce, 1990).

Both velar lowering and labial coarticulation may also exhibit carryover effects on the following vowel(s). There is some evidence that carryover nasalization is determined by the time needed to close the velopharyngeal port and thus by the inertial properties of the speech production system (Flege, 1988).

## 2.2 Larynx

### 2.2.1 Voicing

The extent to which voicing is transmitted from an underlyingly voiced obstruent (the trigger) to one or more adjacent obstruents (the target) in heterosyllabic consonant sequences depends, among other factors, on how the voiced/voiceless distinction is implemented for single obstruents in a given language. On the one hand, languages such as Russian or Catalan with active prevoicing in underlyingly voiced stops and unaspirated voiceless stops favor regressive voicing assimilation resulting from voicing anticipation in voiceless+voiced clusters (e.g., in Catalan, /kb/ > [gb] in *sac buit* 'empty sack'). On the other hand, in languages such as English and German, where voiced stops are implemented through a short voicing lead or lag and voiceless stops are aspirated, voiceless+voiced sequences may be realized phonetically as voiceless-voiced or else exhibit progressive devoicing yielding an entirely voiceless C2 realization (Westbury & Keating, 1986; Docherty, 1992).

Experimental data reveal that regressive voicing in heterosyllabic voiceless-voiced sequences in languages of the former group is phonetically gradient and strongly conditioned by the aerodynamic requirement for the trigger and target consonants. Thus, according to electroglottographic data for Catalan, where the voiced consonant trigger may also be a sonorant, regressive voicing is less when the syllable-final target consonant is a fricative versus a stop and, among stops, a velar versus a bilabial or a dental, the extent to which it applies tends to vary positively with degree of voicing in the syllable-initial consonant trigger, and triggering nasals and the alveolar trill /r/ disfavor the presence of voicing in the preceding obstruent due to aerodynamic factors; moreover, aerodynamic requirements may also account for the presence of less regressive voicing in CC#C versus C#C sequences and of greater devoicing of a syllable-onset voiced obstruent after a fricative than after a stop (Recasens & Mira, 2012; Ohala & Solé, 2010). Other characteristics besides vocal-fold vibration, such as the duration of the preceding vowel and of the target coda consonant, may act as regressive voicing cues, mostly in languages like English and German where vocal-fold vibration in underlying voiced obstruents is often completely or partially absent (Docherty, 1992).

Available data suggest that languages said to have a phonological regressive voicing assimilation process such as Russian, Hungarian, or Catalan may differ regarding the voicing ratio over the overall duration of the coda obstruent period; that is, the ratio in question is higher in Russian than in Hungarian and Catalan. In spite of this language-dependent difference, regressive voicing assimilation may be considered to apply systematically in all these languages, since in C#C and CC#C sequences the syllable-final obstruent phase shows voicing throughout or else a voicing period at its onset which must be attributed to the syllable-onset consonant trigger rather than to the vowel preceding the consonant cluster, for example, /a/ in the Catalan example *sac buit* mentioned above, since it is longer than this vowel voicing lag (see, e.g., Hallé & Adda-Decker, 2011 for French). On the other hand, there is an interesting interplay between the phonetic implementation of the regressive voicing assimilation rule and whether the underlying obstruent voicing distinction is maintained (as in French and Hungarian) or neutralized in favor of the voiceless cognate (as in Russian and Catalan) in syllable-final position.

Voicing coarticulatory effects may also be observed in tautosyllabic syllable-onset clusters, as for English sequences composed of a voiceless stop or fricative C1 and a sonorant C2 (*prayed*, *plead*, *smell*), which show obstruent shortening and sonorant devoicing resulting from the way the laryngeal and supralaryngeal components are temporally coordinated (Hoole, 1999). Languages may also differ regarding the effect that obstruents have on the voicing state at the edges of the adjacent vowels (Gobl & Ní Chasaide, 1999).

### 2.2.2 Tone

Tone languages distinguish words by their pitch (fundamental frequency, or $F_0$), either at static levels or in a particular contour (dynamic tones). Fundamental frequency ($F_0$) coarticulation may occur when tones are placed next to other tones in tone languages. Coarticulation data for Thai static and dynamic tones in succession reveal that, while their general $F_0$ excursion in isolated monosyllables is preserved, they adapt to the adjacent tone mostly at their edges (Abramson, 1979). Other studies reveal greater coarticulatory changes in $F_0$ shape in sequences of conflicting or antagonistic tones than in those of more compatible ones, despite which subjects are generally able to identify the coarticulated tones properly when presented in the original tone context condition (Mandarin Chinese; Xu, 1994). The degree of spatiotemporal tone adaptation varies with coarticulatory direction; a trend has been reported for carryover effects from a given tone on a following tone to be more prominent than anticipatory effects onto the preceding tone (Gandour et al., 1994, Xu, 1997). Moreover, though often less prominent than carryover effects, anticipatory tone effects may be more fixed and extend until vowel onset as a general rule (Vietnamese; Brunelle, 2009). The phonologization of tone coarticulation may give rise to tone sandhi.

## 2.3 Tongue

### 2.3.1 Sequences With Consonants and Vowels

#### 2.3.1.1 Coarticulatory Resistance

Consonants and vowels may be classified depending on lingual coarticulatory resistance, namely, the degree to which they block lingual coarticulatory effects from the adjacent phonetic segments. Thus, for example, in comparison to /p/ or /t/, /ʃ/ is more resistant to lingual coarticulatory effects from vowels (e.g., in tongue body height and fronting from /i/ versus /a/) in so far as the palatoalveolar fricative requires the tongue body for its production while the labial and dentoalveolar stops do not. Coarticulation occurs most often at those lingual regions which are not involved in closure/constriction formation and at flexible versus sluggish primary lingual articulators. Many of the coarticulatory characteristics for consonants and vowels presented below and in section 2.3.1.2 may be found in Recasens (1999).

Coarticulatory resistance in lingual activity for consonants varies with place and manner of articulation, as acknowledged by the degree of articulatory constraint (DAC) model of coarticulation (Recasens et al., 1997; Iskarous et al., 2013). Labials allow maximal lingual coarticulation from vowels, since the tongue body does not take part in their production. Consonants produced with a raised and fronted tongue dorsum—alveolopalatals, palatoalveolars, and palatals—exhibit minimal vowel coarticulation from low and back rounded vowels, since contracting the genioglossus muscle causes the entire tongue body to become highly constrained. Dentals and alveolars such as /d/ or /n/ exhibit intermediate degrees of vowel coarticulation and differ among themselves regarding the extent to which they allow effects in closure/constriction and tongue body fronting and in tongue dorsum height. Thus, consonants such as /s/ and the apical trill /r/, which occurs in Spanish and Italian, are maximally resistant due to the precise demands involved in the formation of a central slit for the passage of airflow (lingual fricatives), and in assigning enough tension to the tongue tip articulator and placing the tongue body in a relatively low and back position for the performance of a successful apical vibration (trill) (Solé, 2002). As for /l/, coarticulatory resistance increases with darkness degree and therefore is high for strongly dark varieties of the consonant such as those (existing in Portuguese and American English dialects) which, like the alveolar trill, are produced with tongue predorsum lowering and considerable tongue body retraction toward the velar region or pharyngeal wall. Velars differ from consonants of other places of articulation in that they blend with the following vowel and are thus articulated at about the postpalatal zone before front vowels and the velar zone before low and back vowels (Frisch, 2016). Russian palatalized dentoalveolars resemble (alveolo)palatal consonants in that they are highly resistant to lingual effects from vowels, and a similar relationship holds between Arabic pharyngealized dentoalveolars and strongly dark /l/ and the alveolar trill.

As for vowels, the schwa /ə/ behaves like labial consonants in being least resistant to consonant effects, and the dorsopalatals /i, e/ to (alveolo)palatal consonants in being most resistant. The back vowels /a, o, u/ exhibit consonant-dependent coarticulation mostly at the tongue front and predorsum, since these tongue regions are not primarily involved in back vowel constriction formation (/a/ is lower pharyngeal, /o/ is upper pharyngeal, and /u/ is dorsovelar; Wood, 1979). Coarticulatory effects on palatal vowels are exerted mostly by highly constrained consonants articulated with tongue dorsum lowering and tongue body backing such as the trill /r/ and dark /l/, while effects on back vowels are mostly associated with contextual (alveolo)palatal and palatoalveolar consonants.

### 2.3.1.2 Temporal Effects

Depending on their place and manner characteristics, vowels and consonants may differ not only in coarticulatory resistance but also in coarticulatory aggressiveness, namely, in the degree to which they modify the articulatory characteristics of other phonetic segments in the speech chain. It has been shown in this respect that coarticulatory resistance and coarticulatory aggressiveness are often positively correlated (Fowler & Saltzman, 1993). Thus, in a sequences like /əʃə/, the palatoalveolar fricative segment is both more coarticulation-resistant and more aggressive than the schwa.

By virtue of their production characteristics, consonants and vowels may favor right-to-left (anticipatory) or left-to-right (carryover) coarticulatory effects. Thus, strongly dark /l/ and to a large extent the trill /r/ favor anticipatory tongue body lowering and backing on preceding front vowels; i.e., the tongue has to lower and back in anticipation to the tongue-tip raising gesture for the successful execution of trilling (/r/) and in order to achieve a /u/-like configuration (dark /l/). C-to-V effects exerted by several dentoalveolar consonants mostly on low and back rounded vowels tend to also be anticipatory rather than carryover in so far as they are associated with the motion of the flexible tongue tip/blade articulator. On the other hand, spatiotemporal effects from (alveolo)palatal consonants on low and back rounded vowels may be more extensive if carryover than anticipatory, which is consistent with the fact that in a sequence like /aɲa/ the tongue dorsum lowering motion after consonantal release during V2 proceeds more slowly and is more /j/-like than the tongue dorsum raising movement during V1 before closure is achieved.

Vowel coarticulation in lingual activity may also proceed in the anticipatory and carryover directions, as found for transconsonantal vowel-to-vowel effects in Swedish and American English VCV sequences with a stop consonant (Öhman, 1966). In order to determine the relative strength of the anticipatory and carryover effects for the vowel trigger in VCV sequences, the principle should be taken into consideration that the strength of the vowel-dependent effects is inversely related to the strength of the consonantal effects at the temporal site where the two coarticulation types conflict with each other. Therefore, the prominence of vowel anticipation is expected to decrease with an increase in the degree of consonantal carryover (e.g., V2-to-V1 anticipation in a VCV sequence is less when the intervocalic consonant is /ɲ/ or /ʃ/ than when it is /d/), while the strength of vowel carryover ought to vary inversely with the salience of consonant anticipation (e.g., V1-to-V2 carryover in a VCV sequence should be less when the intervocalic consonant is dark /l/ than when it is /d/).

Taking the indications about coarticulatory resistance, aggressiveness, and direction given in section 2.3.1.1 and in the present section, it may be concluded that the temporal extent of V2-dependent anticipatory coarticulation in VCV sequences is not fixed (as advocated by Fowler & Saltzman, 1993) but conditioned by the degree of coarticulatory resistance for V1 and C. Thus, tongue body coarticulatory effects associated with the triggering vowel begin earlier when the immediately preceding consonant and/or the transconsonantal vowel are relatively unconstrained than when they are highly constrained, for example, when V1 is /ə/ and the consonant is labial or an alveolar such as /t/ or /n/ than when V1 is /i/ and the consonant is (alveolo)palatal or palatoalveolar. Moreover, it is also the case that, as found in some studies (see Recasens, 1999 for a review), though influenced by the articulatory requirements for the contextual segments, the onset of the V2-dependent anticipatory effects in VCV sequences is less context-dependent and thus more fixed than the offset of the V1-dependent carryover effects, which follows from the fact that only the former are associated with phonemic planning, while the latter depend mostly on the ongoing state of the articulators and their biomechanical characteristics.

Weak long-range anticipatory and/or carryover coarticulation effects extending more than two segments away from the target have been reported to occur both for vowel effects in VC[ə]CV sequences (Magen, 1997) and for /l/ and /r/ (West, 2000) in English. Also Arabic pharyngealized dentoalveolars trigger long-range effects extending at least three syllables with no clear prevalence of the anticipatory or carryover direction (Zawaydeh & de Jong, 2014).

An effect of language on degree V-to-V coarticulation has been shown to occur in several cases, the general hypothesis being that languages with more vowels should exhibit less transconsonantal coarticulation than those with fewer vowels, since contrast preservation restricts variability; in other words, the former tend to avoid coarticulation because vowels are more likely to be misperceived as a different vowel. This relationship has been reported to hold in English versus the five-vowel system languages Shona and Swahili (Manuel, 1990, though see Beddor et al., 2002). These studies also report language-dependent differences in vowel coarticulatory direction, namely, more extensive anticipatory versus carryover effects in Swahili and the opposite in English. Other languages may also differ regarding the degree of vowel anticipation in VCV sequences (French > Mandarin; Perrier & Ma, 2008).

### 2.3.2 Consonant Sequences

Consonants are subject to stricter production demands in consonant sequences than when they are adjacent to vowels due to the high requirements involved in the implementation of two closure or constriction places in succession. In parallel to sequences made of consecutive consonants and vowels, consonant sequences exhibit coarticulatory effects at unconstrained tongue regions such as anticipatory tongue dorsum raising during C1=/n/ in the case of /nʃ/ (*eleve**n sh**oes*) and anticipatory tongue front raising during C1=/k/ in the sequence /kt/ (*expe**ct**ing*).

A challenging research issue is to ascertain how the primary lingual gestures for the two consonants in a heterosyllabic consonant cluster interact with each other and whether this interaction may result in place assimilation. To a large extent, the articulatory outcome for heterosyllabic consonant sequences may be predicted from the degree of articulatory constraint for the two successive consonants, as shown next for Catalan clusters composed of front lingual consonants articulated at the dental, alveolar, and (alveolo)palatal/palatoalveolar zones (see Recasens, 2006 for most aspects referred to in this paragraph). EPG data reveal that regressive assimilation operates in sequences where C2 is more constrained than C1, i.e., /t, n/ + /r, s, ʃ/, as shown by the fact that dental /t/ becomes alveolar in this C2 context condition. On the other hand, sequences of consonants other than front lingual fricatives and rhotics, which therefore are subject to less strict manner of articulation demands, e.g., /nʎ, ʎn, ɲt/ and even /nt, lt/, are resolved through gestural blending and thus a single compromise articulation whose contact area at closure location encompasses generally that for the two individual consonants in succession. The alveolar lateral /l/, mostly if dark, tends not to assimilate or blend, which reveals that laterality may also contribute to an increase in articulatory constraint. In other cases, the degree of articulatory constraint does not account for the production mechanisms at work. Thus, instead of undergoing progressive assimilation, constrained+unconstrained consonant sequences, i.e., /r, s, ʃ/ + /t, n/, are implemented through gradual closure fronting from C1 to C2 and thus two separate consonant targets, which appears to be in support of the notion that categorical assimilations operate leftwards rather than rightwards and thus reflect the planning component of speech. Progressive assimilation processes are uncommon and may be exemplified with the change of /s/ into [ʃ] after /ʃ, ɲ, ʎ, j/ in Catalan dialects (/ɲs/ *any*s "years", /ʎs/ *alls* "garlics"), which should be attributed to the mechanico-inertial properties associated with the tongue dorsum fronting/raising gesture for (alveolo)palatal and palatoalveolar consonants.

As to sequences composed of heterorganic consonants produced with overlapping articulators, there is evidence from a large number of languages that regressive place assimilation is triggered by velars and labials rather than by front linguals, while front linguals are more prone to assimilate than labials and velars least prone to assimilate (Jun, 2004). Thus, the chances that assimilation occurs are, for example, greater for /tk/ than for /kt/ and for /nk/ versus /kn/ (also for /sʃ/ versus /ʃs/). A reason why /k/ is not likely to overlap with the following front lingual consonant may lie in the high demands associated with the tongue dorsum raising gesture and also in the fact that the tongue needs to be repositioned for producing the second consonant in sequences like /kt/ or /kn/. Blending may take place in clusters composed of heterorganic consonants, provided that their closure or constriction locations approach each other spatially as well as temporally; thus, /n/ (also /t, d, l, s/) may blend with the dorsopalatal approximant /j/ into a single alveolopalatal realization [ɲ] in the case of the English word *onion*.

Manner of articulation requirements play a highly relevant role in patterns of gestural overlap. Indeed, heterosyllabic sequences with a fricative and a stop overlap less than stop-stop sequences (Byrd, 1996). There is also a well-known trend for syllable-final /n/ to assimilate in place to the following syllable-initial consonant, more often so than /t, d/, since, in comparison to the dentoalveolar oral stops, the production of the alveolar nasal involves a lower intraoral pressure level and the generation of a burst of little acoustic salience which renders the consonant less prominent articulatorily and less perceptible (Kochetov & Colantoni, 2011). Moreover, patterns of regressive place assimilation in two-consonant consonant sequences with C1=/t, d, n/ may differ from one language to another; English and German speakers often exhibit cases of a residual C1 gesture as well as instances of regressive assimilation or of no assimilation, while regressive place assimilation appears to be the rule at least regarding the /nC/ sequences in syllable-timed languages like Italian and Spanish and also in Japanese.

Differences in gestural overlap may also take place in tautosyllabic consonant sequences. Little gestural overlap has been reported to occur in word-initial stop + fricative and stop + nasal sequences such as Romanian /ps/ and /kn/ due, among other possible factors, to aerodynamic and perceptual constraints (Pastätter & Pouplier, 2015). There is also less overlap in C*r* than in C*l* clusters (as in *crowd* and *cloud*; Hoole et al., 2013), which accounts for the possible insertion of a short intrusive vowel segment in the former consonant sequence in languages where the rhotic is realized as tap.

Homorganicity may facilitate manner assimilation and thus whether the two consonants in a cluster become fully assimilated if differing in manner of articulation originally, as for /tl/ > [ll] in the realization *se*[l l]*àmines* of *set làmines* “seven blades” in Catalan. Indeed, descriptive data gathered from phonological processes and sound change (Rice & Avery, 1991) suggest that regressive and even progressive manner assimilations should be easier to perform if the two consonants share the same closure/constriction location—for example, when the two are dentoalveolar, as in the above manner assimilation process—than if they do not.

### 2.4 Jaw

Jaw height is correlated with tongue dorsum height for vowels and is thus greater for high than for low vowels. Among consonants, jaw height is conditioned by manner and place of articulation requirements; thus, the lingual fricatives /s, ʃ/ and (alveolo)palatal consonants exhibit a high jaw, /l/ (mostly if dark) and possibly the trill /r/ and /n/ show a relatively low jaw position, and jaw height for stops varies in the progression /t, d/ > /p, b/ > /k, g/ (Mooshammer et al., 2007; Keating et al., 1994; Tabain, 2009).

The studies just cited (also Fletcher & Harrington, 1999) also dealt with differences in jaw height for consonants as a function of contextual vowels and for vowels as a function of adjacent consonants. Results reveal that consonants produced with a high jaw are more resistant to vowel-dependent effects than those articulated with a low jaw, and therefore that several consonants which exhibit little changes in tongue body position as a function of the contextual vowels also show little jaw coarticulation (lingual fricatives, (alveolo)palatals). This principle also holds for vowels to a great extent: in comparison to low vowels, high vowels are at the same time articulated with a high jaw position and are more resistant to consonantal effects in jaw height.

## 3. Acoustics

Coarticulatory effects may also be observed in the acoustic signal by means of spectrographic analysis. Consonantal effects on vowels measured at the vowel stationary part (if any) are generally positively related to effects in tongue body fronting/raising in the case of F2 and in oral opening in the case of F1. Thus, a higher and more anterior tongue body position during the production of schwa next to an (alveolo)palatal versus a labial consonant is associated with F2 differences ranging from 1,500 Hz in the labial context to 2,000 Hz in the (alveolo)palatal context.

Regarding consonants, vowel coarticulatory effects may be observed at the endpoint and in the trajectory shape of the vowel formant transitions, as well as in the frequency characteristics of the burst for stops, the fricative noise for fricatives, and the formant structure for sonorants (Kewley-Port, 1982; Jongman et al., 2000). The prominence of these spectral cues for segment identification in perception depends greatly on their acoustic salience, which may vary from one context to another (Dorman et al., 1977). Thus, for example, the F2 vowel transitions play a major role in the identification of consonant place of articulation in sequences such as /ɲa/ and /ɲu/, since they rise by about 500 Hz from the vowel to the consonant. Whenever the vowel transitions are less noticeable, the transitions and the nasal murmur are both taken into account by listeners for the nasal place identification. As for the effect of vowel context on place identification of the frication noise for the lingual fricatives /s/ and /ʃ/, see section 5.

# 4. Segmental Position, Stress, Speech Rate, and Lexical Factors

The prominence of intersegmental coarticulatory effects is conditioned by nonsegmental factors, for example, variations in speech rate, the position that consonants and vowels occupy within the syllable, word, and utterance and with respect to stress, as well as the frequency of occurrence of the words involved.

Whether bearing lexical or sentence stress, stressed vowels are encroached on less by coarticulatory effects from transconsonantal vowels than are unstressed, more reduced vowels (Fowler, 1981). Regarding the effect of segmental position, consonants are expected to allow more contextual coarticulation in syllable-final than syllable-initial position in line with the fact that they generally undergo more articulatory reduction in the former position than in the latter. Exceptions to this trend may be associated with the consonant allophonic characteristics; thus, in languages/dialects where coda /l/ is darker than onset /l/, such as several English varieties and Dutch, the former variety of the alveolar lateral should resist coarticulation to a larger extent than the latter. Also, highly constrained consonants such as the lingual fricatives /s/ and /ʃ/ may resist coarticulation in coda position as much they do in onset position. It is also the case that consonants overlap less in word-initial clusters than in clusters occurring across a word boundary and exhibit maximal superposition in word-medial clusters, which is consistent with a trend for regressive place assimilations to operate word medially rather than in C#C sequences. Coarticulatory effects also vary inversely with morphological boundary strength and thus are greater across a word boundary than across an intonational phrase boundary (Cho, 2004).

An increase in speech rate causes phonetic segments to shorten, undergo articulatory undershoot and overlap to a greater extent with other segments. An increase in coarticulation under these circumstances has been shown to occur both in consonant-vowel sequences (Gay, 1981) and in consonant clusters (/kl/, Hardcastle, 1985; obstruent sequences, Byrd & Tan, 1996). Interestingly enough, specific aspects of VCV coarticulation do not seem to be affected by an increase in speech rate, such as differences in coarticulatory resistance among the intervocalic consonants and the patterns of coarticulatory direction of the vowel effects (Recasens, 2015).

The degree of articulatory accommodation between the coda and onset consonants is also conditioned by the frequency of occurrence of the lexical item containing the former and/or latter phonetic segments (Bybee, 2001). Thus, coronal palatalization in English /C#j/ sequences is more liable to apply when /j/ belongs to a highly frequent than a less frequent word (*you* versus *union*, *unit*; Shi et al., 2005).

# 5. Perception and Sound Change

There is much evidence that listeners compensate for coarticulation by factoring out the coarticulatory effects and attributing them to their source. Thus, for example, listeners hear more /s/ tokens when presented a /ʃ/-/s/ noise continuum in the vicinity of /u/ than next to /a/ because they have some intrinsic knowledge that the spectral frequency of the fricative should become more /ʃ/-like in the /u/ context than in the /a/ context condition (Mann & Repp, 1980). Comparable results have been reported in studies on nasal coarticulation in VCN sequences (where N = nasal) and on V-to-V coarticulation in VCV sequences (Fowler, 1981; Beddor, 2016).

Failure to compensate for coarticulation may give rise to sound changes (Ohala, 1981). A fundamental aspect of the causes of sound change is the relation between the patterns of production and perception of coarticulated speech in individual language users. In this respect, there is conflicting evidence as to whether those individuals who exhibit more coarticulation in production are also more perceptually sensitive to coarticulation (Grosvald & Corina, 2012; Beddor, 2016). Different sensitivities to perceived coarticulation depending on production differences have been shown to occur in ongoing sound changes; thus, in comparison to younger subjects, older subjects of Standard British English appear to exhibit more contextual coarticulation on /u/ and compensate more for these coarticulatory effects (Harrington et al., 2008).

# 6. Acquisition and Speech Disorders

A research area which has attracted increasing attention in recent years is how coarticulatory abilities develop with age. Lingual configuration data collected with ultrasound (Zharkova et al., 2011, 2012) have been taken to confirm the hypothesis formulated in earlier acoustic studies that children show greater vowel-to-consonant coarticulation than adults because they use more global, less differentiated movements of individual articulators extending over a syllable-size temporal unit (Nittrouer et al., 1996; Sussman et al., 1999). This claim has been made in spite of the fact that, as reported by Zharkova and colleagues, in comparison to adults, six- to nine-year-old children show more vowel coarticulation on /ʃ/ and less vowel coarticulation on /s/, the argument being that independence between tongue front and tongue body is necessary for the coarticulation of /s/ but not for that of /ʃ/, since contextual adaptability for the palatoalveolar fricative relies basically on shifts in the forward part of the tongue. On the other hand, using ultrasound and acoustic data, Noiray et al. (2013) have found however that four- to five-year-old children exhibit comparable degrees of vowel coarticulation on /t/ to adults, which suggests that they have already learned the motor synergy between tongue front and tongue body, as well as greater vowel effects on /p/ and /k/ than on /t/, which also parallels the coarticulation scenario for adult speakers. Along the same lines, four- to five-year-old children and adults have been reported to exhibit a similar extent of anticipatory lip rounding during the phonetic segments preceding /u:/ in the sentence (Goffman et al., 2008). In spite of these conflicting results, most studies agree in that there is more within-speaker coarticulatory variability and thus less articulatory consistency in the speech of young children than in that of older subjects.

Much empirical and theoretical work is needed in order to ascertain whether coarticulation deficits in subjects with speech disorders and in hearing impaired subjects belong to the planning and/or execution speech components (Weismer & Green, 2015). Work on stuttering shows that stutterers coarticulate differently from normal speakers because they are motorically slower (e.g., they may show longer lip anticipation in $VC_nV$ sequences; Almé & McAllister, 1987). A recent ultrasound study on velar stop production in different vowel contexts show less articulatory stability in a subset of adults who stutter than in fluent ones, which may be taken to indicate that the former have less accuracy of articulatory control (Frisch et al., 2016). Loss of the ability to perform movement coordination successfully in apraxic subjects results in reduced coarticulation, as shown by little or no overlap between the dorsal and apical gestures in clusters like /kt, ks, kl/ (Gibbon, 2003; Ingram & Hardcastle, 1990; Maassen et al., 2010, pp. 247–248).

# 7. Theoretical Implications and Future Research

The coarticulation data reviewed in this article suggest that considerations about the production requirements for individual consonants and vowels need to be invoked in order to explain lingual, jaw, and voicing coarticulatory patterns in speech. The DAC model makes some correct predictions about the patterns of lingual and jaw coarticulation based on some crucial aspects about the articulatory constraints for the phonetic segments involved. Thus, for example, gestural overlap is generally more extensive and subject to lower production constraints in consonant-vowel sequences than in consonant clusters, where assimilation and blending may occur. Moreover, the direction of the intersegmental coarticulatory effects is conditioned by the spatiotemporal characteristics of the articulatory gesture(s) both for the trigger and target segment(s) in ways which can be predicted by the model, at least for those segments which are highly resistant to coarticulation; also for these segments, coarticulatory resistance and coarticulatory aggressiveness tend to be positively correlated. In many respects, the DAC model parallels the window model proposed by Keating (1990), which uses narrower or wider articulator-specific windows for vowels and consonants depending on how resistant they are to contextual articulation (e.g., the jaw height window is high and narrow for /s/ and low and wide for /æ/). As regards other articulatory structures, anticipatory effects in lip coarticulation are somewhat adaptable to context, while those involving the velum are more temporally fixed. A robust principle which appears to hold across articulatory structures and segmental units to a large extent is that the onset of anticipatory effects is more fixed in time than the offset of carryover effects, essentially because the former reflect the planning component of speech, while the latter are more dependent on peripheral constraints.

Coarticulatory patterns vary with speech rate, stress, segmental position, speaker, lexical frequency, and language. Language-dependent differences in the number of vowels or consonants may play a role on degree of coarticulation at least in some cases, and languages have been shown to also differ regarding the direction of the vowel coarticulatory effects and as to whether assimilatory phenomena such those occurring in /nC/ sequences may apply gradually or categorically and take place more or less frequently.

As for future research, data are lacking on jaw coarticulation in consonant clusters and on lingual coarticulation for consonants produced at the back of the vocal tract such as uvulars and pharyngeals. At a less specific level, information is needed about how coarticulatory patterns arise from patterns of interarticulatory movement, and on speaker- and language-dependent differences in coarticulation and in the frequency of occurrence of related assimilatory processes. There is also a need for experiments on the perception of coarticulation and in particular on how long-distance coarticulatory effects may give rise to long-distance assimilatory processes such as vowel harmony, as well as on the coarticulatory behavior of children and of speakers exhibiting speech disorders. These and other research issues will have to be addressed using additional experimental techniques to the ones available, such as high-speed magnetic resonance imaging.

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