ASPECTS OF COARTICULATION

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Abstract
The paper provides a summary of various types and aspects of coarticulation. After setting a framework that includes general considerations such as biomechanical and language-specific issues, the distinction between anticipatory and carry-over coarticulation, the discussion of articulatory pressure/resistance and its scope, it analyzes different levels at which coarticulation occurs: lips, tongue, velum and larynx. The review of the most influential models and theories from the 1960s until the present reveals that a comprehensive explanation of coarticulation is yet to be offered. In terms of neuromotor control, it shows that very little research has been done specifically on coarticulation, so most conclusions in available literature are indirectly derived from studies of speech production in general. The paper also tries to shed some light on coarticulation in populations that have been studied less extensively, such as children and clinical cases. The goal of this review is to give a brief overview of the current 'state of affairs' in coarticulation studies and argue for the need to extend them to more languages, less than typical populations and to higher levels of processing.

Keywords: coarticulation, coarticulatory resistance, coarticulatory pressure, speech acquisition, impaired speech motor control.

1 Introduction

Speech consists of segmental and suprasegmental features. However, the term 'segmental' may be a little misleading. It refers to individual sounds (rather than superimposed or accompanying characteristics of the utterance, i.e., prosody = suprasegmentals) and it may be inferred that the segments follow each other in an orderly fashion – one appearing after another has been completed. This misconception is readily recognized when one attempts to analyze a sample of speech and, as a first step, tries to separate/distinguish the individual sounds. It becomes painfully obvious that it is very difficult (if not impossible) to decide with certainty where one segment ends and the following one begins. The culprit is coarticulation.

In most general terms, coarticulation is defined as the influence that speech sounds exert upon one another in running speech.

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Although the terms coarticulation and assimilation are frequently used interchangeably and they both occur as consequences of sound context, the distinction between them is commonly described as assimilation referring to audible change resulting in the perception of another phoneme and coarticulation being reserved for the physiological domain of speech organs coordination (Hardcastle & Tjaden, 2011). In terms of generative phonology, it can be said that assimilation belongs to the realm of linguistic competence and coarticulation to that of performance (Chomsky & Halle, 1968). The former is language-determined (i. e., governed by language-specific rules, e. g., phonological ones) while the latter is universal although it may appear to differ across languages, particularly in degree, and what is considered assimilation in one language may be described as coarticulation in another (e.g., vowel harmony vs., transconsonantal coarticulation) (Farnetani & Recasens, 2010; Volenec, 2015; Horga & Liker, 2016). There have been other attempts to define this distinction, including the suggestion of a listener-centered approach (Fowler, 1980), but the issue is far from being resolved and it involves the age-old discussion about the phonetics vs. phonology domains.

In the literature, there are a number of terms referring to what is called coarticulation in this text: coordination, gestural overlap, interarticulator timing, context effects, sound-transitional effects (to name just a few) (Hardcastle & Tjaden, 2011).

2 General aspects of coarticulation

Coarticulation has its biomechanical and language-specific aspects. The biomechanical aspect is supposedly universal, because it is in essence a manifestation or consequence of characteristics and functioning of our speech production system. It is not limited to inertia of articulators, but rather it involves continuous modifications/adjustments in line with communicative demands during speech (not necessarily dependent on speech tempo). On the other hand, language-specific aspects of coarticulation are apparent in the assumption that coarticulation is governed by language rules, and therefore not a mere consequence of what our speech organs can or cannot do. If coarticulation were JUST biomechanically determined, the levels of speech planning/programming and speech execution would be independent without the possibility of feedback and error management. It seems appropriate to view coarticulation as a combination of the two aspects at an undetermined ratio, and here is where the distinction between anticipatory and carry-over coarticulation solves at least part of the problem.

In **anticipatory** coarticulation (also called forward, regressive, right-to-left) the current sound is influenced by the one following it, i.e., its place of articulation is slightly modified and approximates the place of articulation of the succeeding sound (e.g., the /g/ in goon is produced with the tongue dorsum in a more backward position than in geek). It is considered to be a sign of speech (motor) planning, and language-determined. In other words, it is a higher level process whose patterns vary across languages (Keating & Lahiri, 1993). It is therefore susceptible to disruption in speech disorders characterized by impaired (speech) motor control. From the perceptual viewpoint it contributes to faster and more accurate perception due to the fact that acoustic cues of the incoming segment are present in the current one (e. g., Dahan et al., 2001; Salverda et al., 2014). Experiments combining eye-tracking with cross-splicing of initial CV + final C from minimal pairs differing in the final C (e.g., net vs. neck) revealed that about 200 ms after word onset, i. e., before the actual articulation of the final consonant, subjects relied on the information contained in the vowel which was actually derived from the spliced out consonant: when [t] from net was added onto [ne] from neck, the subjects favored the picture of a neck before the [t] was reached (Dahan et al., 2001). This impact of coarticulation in lexical decision tasks has been found in experiments with nasalization as well (Beddor et al., 2013).

In **carry-over** coarticulation (also referred to as perseverative, backward, left-to-right, retentive) the current sound influences production of the following one (e. g., in boots lip protrusion necessary for the production of /u/ carries over onto /t/ and /s/), and it is generally taken as a consequence of inertia of the speech production apparatus, i.e., it is biophysiologically determined, and thus universal, although it has been argued that it involves a certain degree of planning as well (Recasens, 1999).

One and the same sound in a sequence may have both anticipatory and carry-over effects. For example, in the word /ana/ the /n/ has anticipatory effect on the initial /a/ and carry-over effect on the final /a/, as suggested by acoustic record, oral and nasal flow curves, and synchronized EPG, corresponding to opening of the velopharyngeal port right after onset of the initial /a/ and its remaining open until the end of the final /a/ (Farnetani & Recasens, 2010).

The range/scope and direction of coarticulatory effects is determined by a set of constraints that may include physiological features of the articulators (→ resistance), suprasegmental features (stress patterns, prosodic and syntactic boundaries, syntactic structure, rate of articulation, clarity, speech style) and language specific constraints – phonological structure (Hardcastle & Tjaden, 2011).

Coarticulatory resistance and coarticulatory pressure (dominance, aggressiveness) are two properties of sounds that are positively correlated: phonetic segments that are especially resistant to coarticulatory effects from the adjacent segments exert maximal coarticulation on them.

There is general agreement among researchers that there are some parts of the speech signal that are more resistant to coarticulatory effects and exhibit a higher degree of invariance. Krull (1989) reported that labial consonants are more affected than dental ones by coarticulation, and that in CVC syllables the vowel exhibits greater anticipatory coarticulation on the preceding consonant than carry-over effect on the following one. Interestingly, in contrastive hyperarticulation voiced and voiceless stops are affected differently: in order to avoid ambiguity, speakers decrease VOT in voiced stops and increase it in voiceless ones (Mücke et al., 2017). Liker and Gibbon (2018) report the tendency of /z/ to be more resistant to coarticulation effects than /s/. The adaptation of tongue position in lingual consonants to the tongue position of an adjacent sound is constrained by intra-articulator coordination and coupling of tongue dorsum with its other parts (i.e., lamina and tip): for example, in the production of postalveolars, such as /ʃ/, the tongue dorsum is critical and this limits their potential for adaptation to the subsequent vowel because tongue dorsum is slow and inert, therefore more resistant to adaptation than e.g., /s/ where the tip of the tongue is active. Alveolars closely follow in the degree of constraint, and labials (e.g., /p/) are more affected than alveolars (Zharkova et al., 2015). Coarticulatory resistance and pressure are further discussed below, in the context of DAC model.

Iskarous et al. (2013) propose a coarticulation-invariance scale on which the amount of 'mutual information', i.e., information shared by candidates for coarticulation, is proportional to the degree of coarticulation. The amount of information is based on the measurements of physical positions of articulators during speech production and it is high in coarticulation and low in invariant condition. Testing their scale on American English, Catalan and German data revealed that it confirms the previous empirical studies of contextual (in)dependence of specific sound categories, i.e. articulatory resistance.

There have been claims that coarticulation spreads over up to 6 neighboring sounds, but the span of coarticulation is still an issue for debate (Kent & Minifie, 1977; Farnetani & Recasens, 2010). Also it has been suggested that it varies across coarticulatory systems, labial coarticulation having the largest span, followed by velar and lingual coarticulation (for review see Volenec, 2015). Bell-Berti and Harris (1975) suggested that carry-over effects are more extensive than the anticipatory ones. However, regardless of the actual numbers, the finding that several units are in various stages of planning, adjustment, execution and somatosensory feedback at the same time, has implications for understanding the system of motor control.

Coarticulation is not limited to word level – in connected speech it is present across word boundaries as well. For example, in producing the noun phrases lean bacon or green boat, the alveolar nasal place of articulation of /n/ moves toward the bilabial place of articulation in anticipation of the bilabial /b/. Salverda et al. (2014) have shown that listeners make immediate use of anticipatory coarticulation in the determiner to predict the initial sound(s) of the upcoming word (in a paradigm where the determiner the is followed by targets starting with different consonants), which can be explained by the finding that from its very onset, the neutral schwa [ə] exhibited strong influence of the following sound, as shown by F_1, F_2 and F_3 trajectories.

Recasens (2015) reports the effect of stress and speech-rate variations on overall vowel duration, second formant frequency and coarticulation size but not on the consonant-specific patterns of degree and direction of vowel coarticulation, and interprets these results as indication that coarticulatory changes caused by prosody conform to the basic principles of segmental coarticulatory organization. Cho et al. (2017) found that prominence enhanced nasality of the consonant and orality of the vowel (rather than nasality) showing the coarticulatory resistance to nasal effects, even when the focus was on the nasal. Boundary strength induced prosodic position-dependent contradictory patterns. They conclude that vowel nasalization is under speaker's control and take their results as evidence of close relationship between the dynamics of speech timing and (the need to preserve) linguistic contrasts.

3 Levels/systems of coarticulation

Most research focuses on tongue related coarticulation, but coarticulatory processes are present at the laryngeal, nasal and labial levels as well. In other words, articulators studied in coarticulation are lips, tongue, velum and larynx. Mandibular movements are typically observed together with lips and tongue because they are considered to be integral part of changes in the position of the two.

Processes associated with **lips** are usually referred to as lip rounding, spreading or protrusion (e.g., in the word choose under the influence of /u/ lip rounding will begin during production of /tʃ/, and in cheese lips will be spread during production of /tʃ/ under the influence of /i/) and their acoustic aspects are described in terms of formant changes. Full description of lip aperture requires both the horizontal and vertical axis specification: rounded sounds have smaller aperture along both axes. In languages in which both rounded and unrounded vowels are constituents of the phonemic repertoire (e.g., Swedish, German, French), roundedness is associated with more complex articulatory characteristics, it is less variable and more resistant to coarticulation than in languages in which it plays no phonologically distinctive role (Farnetani & Recasens, 2010; Horga & Liker, 2016). Labial coarticulation seems to have the largest scope - Swedish electromyographic data reveal lip rounding starting up to 600 ms before the actual rounded vowel (Lubker et al., 1975, as cited in Volenec, 2015).

Coarticulatory displacements of the **tongue** along the horizontal (front – back) and/or the vertical axis (high/close – low/open) also result in corresponding formant shifts (e.g., in /aga/ and /igi/, the tongue shape during the closure for the /g/ is a blend of the gestures for the vowels and the consonant). It is important to note that tongue tip and tongue body may be controlled independently. This is also one of developmental constraints of articulation, since it seems that children take longer to master this selective control and to replace movements of the tongue as a whole with independent control of its tip/blade and body. Zharkova et al. (2012) contribute absence of significant effects on /s/ by the following vowel (particularly /i/ and /u/) in children, compared with adults, to this lack of differential control. They also relate their interpretation to Cheng et al. (2007)'s study and conclude that such differential coordination occurs around 9 years of age and is further refined into late adolescence; according to Schötz et al. (2013) it may extend even into the late 20s.

Lowering of the **velum** (typically referred to as nasalization) has repercussions in changes of the oral formant structure and occurrence of nasal formants (e.g., in the word dance, the nasal /n/ may initiate velum lowering as early as the initial /d/, causing nasalization of the oral /æ/). Coarticulatory activity between nasal consonants and neighboring vowels is a two-way street, i.e., reciprocal: during vowel production the velum is in a lower position in the vicinity of nasal consonants than in the vicinity of the non-nasal ones, and during nasal consonant production, the vicinity of close vowels results in lower velum position than the vicinity of open ones (Farnetani & Recasens, 2010; Horga & Liker, 2016). Nasal coarticulation is both language-determined and physiological, its extent depends on the phonemic repertoire of the language, and Bouchard and Chang (2014) suggest it is under speaker's control.

Coarticulation at the level of **larynx** is associated with vocal fold activity and the presence or absence of periodicity, but it is also directly related to the levels above the larynx. The degree and duration of laryngeal coarticulation are affected by place and manner of articulation. For example, the opening of the glottis in the articulatory process of devoicing has been reported to start earlier in fricatives than in stops (Hoole, 1999) and VOT has been found to vary across places of occlusion (Bakran, 1993; Horga & Liker, 2016). Similarly, different consonantal contexts (i.e., fricatives vs. stops) affect laryngeal activity during vowel production in different ways, both with respect to variability and timing. Research into correlation between laryngeal and lingual places of articulation has yielded inconclusive and often contradictory results largely due to different research questions and methods (for a review, see Horga & Liker, 2016; Liker & Gibbon, 2018).

4 Models

Several models have been developed to account for coarticulation. They include the look-ahead, articulatory syllable, time-locked, window, coproduction and articulatory phonology models (for a more extensive discussion of these and other models, see Farnetani & Recasens, 2010; Volenec, 2015; Horga & Liker, 2016).

The target undershoot model (Lindblom, 1963), although not explicitly a model of coarticulation, posits that articulators frequently fall short of their target (hence, undershoot) due to responding to simultaneous articulatory commands, but the relationship between the target and its mental representation is not clearly defined. According to Lindblom, the degree of coarticulation is a manifestation of speech economy; however, it does not depend exclusively on speech rate (as posited in earlier works), but on the demands for perceptual contrast and style (Lindblom, 1990; Moon & Lindblom, 1994). The strategies speakers use are determined by duration, input articulatory force and time constant of the system. Lindblom (1963) also proposed an elegant tool for measuring coarticulation, locus equation, which has been shown across many languages to be a robust indicator of its degree (Sussman et al., 1993; Bakran & Mildner, 1995). Locus equations are linear regressions of the onset of F_2 transition on F_2 target (at the vowel nucleus). The calculated slope and intercept depend on the consonant place of articulation. In CV syllables, steeper slopes are indicative of higher degree of coarticulation. Based on her comparison of locus equation and EPG data for English CV syllables, Tabain (2000) also suggested that a distinction should be made among consonant categories. Namely, her data revealed that alveolar and velar stops and nasals exhibit a good correlation between locus equation and coarticulation, as opposed to fricatives (especially /z/ and /ð/), where the correlation between EPG and locus equation data was very poor (possibly due to fricative noise obscuring the F_2 transition, and/or locus equation being incapable of encoding the more subtle differences in the degree of coarticulation found in coronals. However, according to Löfqvist (1999), EMA data do not support the notion that the slope in locus equation approach is indicative of the degree of CV coarticulation.

In the articulatory syllable model (Kozhevnikov & Chistovich, 1965, as cited in Farnetani & Recasens, 2010) coarticulation is limited to within CV sequences, which in light of prevailing evidence from various languages is too limited a scope.

Feature-spreading (sharing) / look-ahead model: Henke (1966) proposed a computer model positing that a segment (i.e., input from the neural representation level) will have coarticulatory effects that start as early as possible if there are no contradictory specifications. Along these lines Daniloff and Hammarberg (1973) proposed that phonetic representation includes articulatory and coarticulatory specifications, and the model scans upcoming units (i.e., looks ahead) for specified feature values, all with the goal of achieving smooth transitions between segments. However, empirical data across various languages have shown that contradictorily specified adjoining segments may still be subject to coarticulation, and that unspecified segments may have some resistance to coarticulation and/or may behave differently in different contexts (Farnetani & Recasens, 2010). This indicates that phonological features and their specifications are too rough units and coarticulation needs to be defined in much finer terms that should include articulatory, aerodynamic, acoustic and perceptual constraints.

To account for the gradual changes in the process of coarticulation, Keating (1990) proposed the so-called window model of coarticulation, according to which spatial and temporal context-dependent variations are governed by phonetic rules of the grammar. A window is the point at which categorical phonological input is converted into non-binary phonetic description and its size for each feature is positively correlated with variation, and in turn, negatively with specificity, e.g., poorly specified features are associated with wide windows and are subject to a high degree of contextual variation, hence coarticulation. On the other hand, narrow windows correspond to greater coarticulatory resistance. Windows are connected by paths (interpolation curves) that reflect articulatory and/or acoustic variations over time. Window size and position taken together with the shape of the path (contour) determine coarticulation, governed by demands for smoothness and least articulatory effort. Languages differ in coarticulation due to differences in phonology or phonetics. Major arguments against the model are based on experimental findings that failed to corroborate (expected) direct interpolation in contexts of unspecified sounds and on claims that the model is too simplified and does not account for the complex nature of speech production (Farnetani & Recasens, 2010; Volenec, 2015; Horga & Liker, 2016, and references therein).

The concept of articulatory gestures (not to be confused with articulatory movement or articulatory target) is associated with the task-dynamic model of speech production, in which phonetic gestures rather than phonological features or segments are inputs to the process of production (and by extension, coarticulation) (Fowler, 1980; Fowler & Saltzman, 1993; for discussion, see Farnetani & Recasens, 2010; Volenec, 2015; Horga & Liker, 2016). Articulatory gestures are defined as target/goal-oriented, serially ordered planned actions (of all articulators involved in the production of a particular sound), with intrinsic temporal structure, and context-independent. The speed at which this internal (re)organization takes place in cases of changed circumstances (e.g., obstruction, damage to articulators) indicates that it is not centrally controlled (Löfqvist (2010) proposes brainstem as the crucial point of integration of incoming somatosensory feedback and motor control, see below). In this context, coarticulation is seen as coproduction of articulatory gestures, i.e. overlap of neighboring ones. The extent of overlap depends on speech tempo and articulatory conditions and is, as a rule, controlled at the level of planning. When two articulatory gestures 'compete' for involvement of the same articulators, the result will depend on the strength of the two gestures: when their strengths are similar their influence will average out, otherwise the stronger one will suppress the effect of the weaker one. In other words, the stronger one can be characterrized as having greater coarticulatory resistance and, accordingly, greater coarticulatory effect. Cross-linguistic differences can be attributed to different gestural organization.

One of the models relying on articulatory gestures is the so called time-locked model of anticipatory coarticulation, which posits that component gestures of a segment begin a fixed interval of time before the phonetic target is achieved. However, not all experimental data support this model and some lend preference to look-ahead models. Also, cross-linguistic comparisons reveal a great deal of variability among languages (for discussion, see Farnetani & Recasens, 2010).

Recasens et al. (1997) proposed the Degree of articulatory constraint (DAC) model, according to which coarticulation is a process that continuously involves more than one speech unit. The model is based on Catalan data and focuses on lingual coarticulation (which is its major limitation). It postulates that the three elements of coarticulation: degree, temporal extent and direction are determined by the requirements imposed on the tongue in the process of speech production. Vowels and consonants are assigned values – the higher the value (degree of articulatory constraint) the more resistant the sound is to coarticulatory effects and the greater its coarticulatory pressure with respect to adjacent segments. Consonants requiring a high degree of articulatory precision (e.g., alveolar trill) have the highest DAC value, and those that do not require a great amount of tongue body activity (e.g., labials) have the lowest. Similarly, within vowels, the ones requiring the greatest amount of tongue dorsum displacement (e.g., front vowels) have the highest DAC value as opposed to those with an unspecified target (e.g., [ə]). The temporal extent is determined by the articulatory constraint in such a way that anticipatory effects start earlier when the preceding sound is relatively unconstrained (suggesting that it is not exclusively a result of planning). Carry-over effects are more variable and may take longer. Within the model, vowels and consonants tend to favor anticipatory or carry-over direction (e.g., dark /l/ favors anticipation, /ɲ/ favors carry-over component) (more on this in Farnetani & Recasens, 2010). Additionally, highly constrained consonants do not exhibit coarticulatory effects determined by their position within the syllable.

Current theories and models fail to offer a comprehensive explanation of coarticulation (i.e., at all the levels it occurs), and to account for cross-linguistic differences. Moreover, they seem to base their assumptions on differently defined domain/origin, function and control of articulation (Farnetani & Recasens, 2010; Horga & Liker, 2016).

5 Neuromotor control

At the level of neuromotor planning and programs Gracco and Löfqvist (1994) suggest that speech movements are organized into aggregates consisting of several functionally related articulators. These aggregates correspond to articulatory gestures. Each sound has its neuromotor representation based on the muscles that need to be activated for its production and their spatial and temporal coordination. These structures correspond to neurobiological equivalents of the phoneme. Obviously, as summarized by Kent and Minifie (1977), in the process of turning phonemic representations into actual speech the mentally stored discrete and invariant units undergo modifications not only in their boundaries but in their acoustic and articulatory properties as well. Coarticulation requires / relies on additional adaptive processes (central neural mechanisms) associated with these representations which enable combinations into larger sequences, so that the underlying units are modified in actual production. This requires that neural control of the units be flexible enough to allow for contextual variations. At the speech perception end, this flexibility is manifested in the ability to process the message successfully in spite of the lack of invariance present in the speech signal, and the circle back to matching the 'ideal' representations is complete.

Cerebral areas involved in speech processes have been studied extensively for decades, but relatively recently have some areas other than the cortex been recognized as important in speech motor planning and execution, such as the left insula (Dronkers, 1996), cerebellum (Gordon, 1996; De Smet et al., 2007) and thalamus (for review, see Katz, 2000). Also, with the discovery in the 1990s and subsequent fruitful research of mirror neurons (Rizzolatti & Craighero, 2004) the cooperation of sensory and motor networks has received the attention it deserves because of its implications for understanding speech production and perception processes (among others) and language in general.

Based on fMRI data of eight healthy volunteers, Riecker et al. (2005) suggest two levels of speech motor control associated with motor preparation (medial and dorsolateral premotor cortex, anterior insula and superior cerebellum) and execution processes (sensorimotor cortex, basal ganglia and inferior cerebellum). Brendel et al. (2010) on the basis of clinical data further elaborate on this speech motor control network and suggest organization into (at least) three functional neuroanatomical subsystems: one devoted to planning of movement sequences (premotor ventrolateral-frontal cortex and/or anterior insula), one being activated in the process of preparing for or initiation of upcoming verbal utterances (supplementary motor area), and the third being in charge of execution (corticobulbar system, basal ganglia, cerebellum). An interesting finding of their fMRI study was that the timing of activation of these different neural circuits was not fixed, but changed as the task progressed and one might assume that this flexibility is advantageous to accommodating and adjusting accordingly to feedback information coming from somatosensory networks. Such fluctuations in alternately activating various language-associated areas (predominantly in the left hemisphere) were reported by Nakai et al. (2017) as well.

Löfqvist (2010) describes neural motor control of speech as a distributed network consisting of neuronal circuits and centers at different levels. Within the network there is communication between the periphery and a central/executive unit that receives and processes incoming information about the current situation/context, and based on that selects not only the appropriate muscles to be activated but also determines/adjusts the level of their involvement and spatio-temporal organization/coordination. As in gross motor activity, the brainstem seems to be crucial for such integration involved in articulation as well. The rapid, functional compensations following perturbations to articulators are in agreement with such a distributed system.

Sensorimotor integration is an important part of this process and the perceptual system has a crucial role in the self-monitoring of speech (Hickok et al., 2011; Bouchard & Chang, 2014). Consequently, speech production requires activation of internal representations of sensory speech targets in addition to motor speech representations. Error signals that are received in the process of speech may be dealt with in two ways: by modifying motor programs for immediate target attainment, or by modifying representations for future reference (Hickok et al., 2011). Bouchard & Chang (2014) found significant activity in the ventral sensorimotor cortex (vSMC) during production of CV syllables. This activity robustly predicted acoustic parameters across vowel categories and different renditions of the same vowel. They also found significant contextual effects on vSMC representations of produced phonemes, which they took as indication of active control of coarticulation. In terms of direction, they found that representations of vowels were biased toward the representations of the preceding consonant, and representations of consonants were biased toward subsequent vowels.

Broca's area (inferior frontal gyrus in the language-dominant, usually left, hemisphere) has of course been described as undisputed crucial area in speech production (and a number of other language-related functions). Consequences of damage to this area include impaired motor planning of speech articulation seen as unsuccessful attempts at reaching the target while producing polysyllabic words and maintenance of serial order of phonemes (Davis et al., 2008). Peeva et al. (2010) used fMRI to study representation of speech segments of varying complexity and found that the left medial premotor regions process phonemes (while syllables are processed in the left lateral premotor regions) and that these areas have projections to primary motor cortex along which representations are transformed into motor commands to the articulators, thus confirming the dominance of the left (pre)motor cortex in speech planning and initiation.

By recording the activity of the lateral superior temporal cortex, Leonard et al. (2015) examined auditory processing of sound sequences (words and nonwords) and reported data that support the interactive bottom-up and top-down processes, i.e. integration of physical stimulus characteristics (bottom-up) with their contextual sequential structure and subconscious phoneme sequence statistics and higher-order linguistic knowledge (top-down). Moreover, their subjects' neural responses revealed dynamical encoding of language-level probability of preceding and upcoming sounds, clearly showing correspondence with phoneme onsets and transitions. This may help explain how even high degrees of coarticulation do not cause perceptual break-down and confirms the importance of superior temporal cortex in processing language stimuli and sensorimotor integration.

6 Developmental aspects

Speech planning and production are governed by developmental processes. While it is clear that this is reflected in coarticulation, exactly how it is manifested is less unambiguous. Some authors suggest that children's linguistic units are larger and less specified than adults' (hence, characterized by more variation and coarticulation) and that they become less coarticulated as refinement of speech production proceeds throughout maturation and mastering the language (e.g., Kent et al., 1996; Nittrouer et al., 1996). Nittrouer and Whalen (1989) report greater evidence of coarticulation in the fricative-vowel syllables of children than in those of adults. This increased coarticulation led to improved vowel recognition from the fricative noise alone, indicating that the coarticulated sound can be identified without correct identification of the most prominently specified one.

On the other hand, some authors (e.g., Cheng et al., 2007; Zharkova et al., 2012) report vowel contexts of greater coarticulatory influence on speech production in adults than in children (with children having greater within-speaker variability in the degree of coarticulation) and attribute that to children's immature speech, characterized by insufficient coordination and motor control, which is particularly apparent in children younger than nine years.

Sereno et al. (1987) claim that both the acoustic and the perceptual data show strong anticipatory labial coarticulation for the adults and comparable, although less consistent, coarticulation in the speech stimuli of the children. Based on acoustic and video data, Katz et al. (1991) conclude that young children and adults produce similar labial and lingual (sV) anticipatory coarticulatory patterns, but also (based on perceptual data) that coarticulatory cues in the speech of their 3-year-olds are less perceptible than those of older children or adults. They attribute the latter finding to the possibility that, fricatives being (among) the most difficult sound categories to master, children as young as 3 years, have less precise articulation of

/s/. They also found that children show greater variability than adults, but not greater degree of intrasyllabic coarticulation.

At least some of the differences among studies may be attributable to different environments studied and methods applied. A clearer picture of developmental aspects of coarticulation emerges if a distinction is made among coarticulation contexts: e.g., labial coarticulation seems to mature earlier than lingual (Katz & Bharadwaj, 2001; Goffman et al., 2008). However, there appears to be general agreement that (co)articulation is more variable in children than in adults and that stability increases with age (Cheng et al., 2007; Zharkova et al., 2011, 2012, 2017). This can be explained by (at least) two factors: general cognitive maturation (which takes care of speech planning), and practice due to experience (which takes care of sensory-motor precision). However, Schötz et al. (2013) claim that age related changes in speech motor control may not be complete before the age 30.

7 Clinical aspects

Since coarticulation is a marker of fine motor control in speech production it is an important issue in studies of motor disorders that have consequences on speech output, primarily its intelligibility, e.g., apraxia of speech, dysarthria in Parkinson's disease (PD).

Less coarticulation in clinical populations may be a direct consequence of the disorder, but it may also be an indirect result of slower speech rates that are frequently found in such subjects. Additionally, many of these patients produce speech movements that are reduced in size or amplitude (Hardcastle & Tjaden, 2011). One such example is smaller area of the vowel space (as determined by F_1 & F_2 values) but also a trade-off between correctness and time necessary to produce affricates found in hearing impaired speakers (e.g., Liker et al., 2007; Mildner & Liker, 2008).

Tjaden (2000) compared speech rate effects on coarticulation in PD patients and healthy subjects and found that coarticulation tended to increase with faster rates and decrease with slower rates, but more systematically so in control speakers. Overall results suggest increased coarticulation in PD patients relative to control speakers. This effect was not entirely attributable to the more rapid speaking rates for speakers with PD.

Dysarthria is characterized by impaired speech production manifested as impaired rate, intonation, articulation, volume, voice quality and nasality, as a consequence of damage to basal ganglia, thalamus, cerebellum or cerebral cortex (Chang et al., 2009). It typically accompanies various neurological impairments such as ALS, PD or traumatic brain injury, but it does not necessarily cause perceptually meaningful deficits in articulation and coordination. Some studies report normal coarticulatory patterns, some reveal subtle changes (increase or decrease of context effects), and yet others suggest different patterns at different levels (e.g., normal supraglottal coordination but incoordination at the laryngeal-supralaryngeal interface/level causing difficulties in stopping vocal fold vibration at the transition from a voiced to a voiceless sound) (for discussion, see Hardcastle & Tjaden, 2011).

Deep brain stimulation (DBS) has been shown to improve articulation in dysarthric PD patients by inducing changes in fine motor control. Sauvageau et al. (2014) have examined the influence of bilateral subthalamic nucleus DBS on carry-over coarticulation in CV combinations. Even though the consonant context influenced vowel articulation, this coarticulatory phenomenon did not vary as a function of the DBS across their 8 PD patients. In a previous study Wang et al. (2006) found that the side of DBS had different effects on speech production – left-hemisphere stimulation altered articulation accuracy. With right-hemisphere stimulation it remained unchanged or improved. However, not all studies report speech improvement and there is great variability among studies and patients (Aldridge et al., 2016).

Apraxia of speech (AOS) is manifested as impaired speech motor planning (especially for complex syllables) and has been associated with damage to the left anterior insula (Dronkers, 1996) and with damage to the posterior inferior frontal gyrus (Hills et al., 2004). However, it must be stressed that a strictly localizationist approach is not justified. AOS is often, but not always associated with Broca's aphasia (Katz, 2000).

In AOS, VOT values for voiced and voiceless stops tend to overlap (even when consonants are perceived as correct), and there is great variability in VOT for the same stop. These two features are taken as evidence of poor coordination of laryngeal-supralaryngeal events, and in turn this is interpreted as AOS affecting timing or coordination between articulators. This is corroborated by studies of anticipatory coarticulation (Katz, 2000; Hardcastle & Tjaden, 2011) revealing great variability in timing (especially in labial and lingual coarticulation). In addition to increased variability, some studies report delays in coarticulation: Patients with AOS begin vowel gesture in CV syllables later than controls. Ziegler and von Cramon (1986) attribute lack of coarticulatory cohesion in the speech of a patient suffering from verbal apraxia to a consistent delay in the initiation of anticipatory vowel gestures.

Studies of coarticulation in AOS and cerebellar ataxia suggest that anticipatory coarticulation has a multifocal representation in the nervous system and perserveratory coarticulation is regulated, at least in part, by the cerebellum (Katz, 2000).

In fluent types of aphasia, e.g., Wernicke's, anticipatory coarticulation is preserved, as evidenced by perceptual-acoustic studies. However, not all inconsistencies in (co)articulation and coordination that are physically present are perceptually noticeable as revealed by EPG data of an anomic aphasic (Hardcastle & Tjaden, 2011). For example, abnormal prevoicing and nasalization have been reported in Wernicke's patients (Katz, 2000).

Common speech characteristics of childhood/developmental apraxia of speech (DAS) are numerous and inconsistent consonant errors and context-related substitutions, groping and overall poor intelligibility. On the basis of locus equation calculations Sussman et al. (2000) concluded that reduced intelligibility of children with childhood apraxia of speech may be attributed to their inability to sufficiently distinguish among stop place categories due to poor refinement of coarticulation levels. Studies of DAS have also revealed inconclusive results with respect to coarticulation – some report earlier and stronger anticipatory vowel effects, some just the opposite. Usually children with DAS exhibit more inter- and intra-subject variable patterns than children with typical speech acquisition, and their speech suggests deficits in motor planning as well as in syllabic programming. Apparently, the breakdown occurs during the transformation of phonological representation into articulatory (motor) program; however it seems to involve not just execution but also the acquisition and automatization of a speech production plan (Maasen et al., 2001). This is also supported by the study of Grigos and Case (2017) where the effect of practice was found in both typically developing children and children with DAS, but while the former improved overall speech production accuracy, positive effects in the latter group were found only for the practiced items.

Evidence indicates that developmental **stuttering** is associated with dysfunctional sensorimotor integration. Bihemispheric activation competing for control of the speech production mechanisms and atypical right-hemisphere dominance have been suggested as well (Hickok et al., 2011). More specifically, stuttering may be caused by difficulties in transitioning between sounds (Hardcastle & Tjaden, 2011), which obviously would affect coarticulation.

Studies of coarticulation in persons who stutter are inconclusive. Frisch et al. (2016) found (examining velar-vowel coarticulatory patterns) that people who stutter do not differ significantly in anticipatory coarticulation patterns from fluent speakers but that their speech stability is lower and overall variability greater, which places them at the "less skilled" end of the typical speech production range in terms of motor skill, but implies that their motor programming ability is intact. Similar conclusions were reached by Smith et al. (2010) in a study of lip aperture. They conclude that results of research into anticipatory coarticulation may have implications for intervention planning: significant differences in coarticulation patterns between fluent and stuttering output reveal higher (cognitive/linguistic) level of impairment, requiring phonologically founded treatment targeting phonological representations, whereas lack of such differences is more congruent with sensory-motor impairment that would benefit from articulatory training, which is in line with the notion that speech motor learning is comparable to motor learning in general (Maasen et al., 2004; Donnarumma, 2017).

Acoustic analyses (expressed in terms of locus equation) in many studies of speech production in persons who stutter report atypical (steeper or shallower) or absent F_2 transitions, but at least some studies suggest normal F2 transitions in (perceptually) fluent tokens. Comparison of locus equation slopes and y-intercepts of perceptually fluent tokens of speech of children who stutter with non-stuttering controls revealed no significant differences, but F_2 transition rate was different between the two groups (for discussion, see Hardcastle & Tjaden, 2011).

According to Löfqvist (2010, p. 355) "If an articulatory pattern is to be maintained and transmitted across generations of speakers, the pattern would have to either be recoverable by auditory or audiovisual means, or follow from general principles of biomechanics and motor control." For articulators that are not visible to the naked eye (e.g., the velum or the larynx) auditory control is necessary not only for hearing and comprehension but also for learning speech production patterns. In postlingually **hearing-impaired** individuals speech production patterns/programs are maintained due to the kinesthetic and proprioceptive 'imprints' (a sort of an internal model) and somatosensory feedback. The quality and duration of these imprints depend on a number of factors, e.g., the time (childhood or adulthood) and dynamics of onset (gradually or suddenly), shape of residual hearing (favoring low or high frequency range), etc.; but in congenitally or prelingually hearing impaired individuals there is a high correlation between the degree of hearing loss and severity of speech production impairment. Smaller context effects are typically found in these subjects in comparison with normally hearing or postlingually deafened ones, which is manifested as reduced coarticulation, both anticipatory and carry-over (see Hardcastle & Tjaden, 2011, for a review).

8 Conclusions

The aim of this paper was to present some of the commonly addressed facets of coarticulation and to expose its aspects that have not received the attention they deserve. The issue of universality (biomechanics) vs. language specificity is regularly discussed in relation to carry-over and anticipatory coarticulation, respectively, although there is evidence that correlations are not exclusive. The fact that the range and direction of coarticulation are affected by a number of constraints introduces a high amount of variability in results, which makes comparisons across studies very difficult. Equally problematic for the search for coarticulation patterns are the levels at which coarticulation can be expected (labial, lingual, velar and laryngeal) and correlations among them. Related to that, models and theories that have been proposed over the years (e.g., target undershoot, articulatory syllable, look-ahead, window, coproduction, DAC) have typically focused on only selected levels and based their assumptions on differently defined aspects of coarticulation. With the advancement of technology in the past 25 years, research into neural control of speech perception and production has progressed from speculation to actual recordings of intact central neural mechanisms at work, but reliable paradigms for studying neurophysiological bases of coarticulation have yet to be designed. Sensitive populations, such as children and individuals with various disorders (e.g., dysarthria, apraxia of speech, stuttering or hearing impairment) have so far provided inconclusive data on the nature of coarticulatory processes, apart from the general finding of greater variability than is found in the typical adult participants. Also, more research is necessary that would tie together perceptual and production results.

The issue of coarticulation is, obviously, far from being comprehensively described or defined. Approaching it from various directions: theoretical, developmental and clinical, taking into consideration its production and perception aspects, analyzing articulatory and acoustic data, using all available tools and methods (e.g., EPG, ultrasound, EMA, fMRI, locus equation, acoustic analysis), and sharing cross-linguistic data, may eventually offer converging evidence about its scope, function and control.

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