DOI: 10.17469/O2101AISV000003

MARIANNE POUPLIER[1]

Between 'whims of fashion' and 'phonetic law': Performance constraints in speech production in the face of linguistic diversity

There is a long tradition in the speech sciences seeking to trace the shaping force of physiological constraints in the world's languages. Particularly the syllable has been in the focus of biologically oriented approaches and has been seen as the primary locus for the manifestation of universal production constraints. We discuss how current research into patterns of articulatory coordination within the syllable has revealed that by hypothesis preferred patterns are across languages more varied than anticipated by these models. Data from Polish are used as a case in point to exemplify how trade-offs between different production constraints may condition a departure from a by hypothesis preferred pattern. We discuss the extent to which these trade-offs may be language specific and the ramifications for modelling speech production.

1. *Physiological preference and the limits of linguistic diversity*

It almost goes without saying that speech perception and production impose absolute limits on linguistic diversity in terms of hearing thresholds, just noticeable differences, anatomical limits on possible tongue shapes, and the like, even though it has not been trivial to identify those hard limits of speech (e.g. the discussion on the (im)possibility of nasalized fricatives, cf. recently Warner et al., 2015). There is less consensus regarding the question whether performance constraints shape sound patterns *within* the available space. Some have taken the view that spoken language is first and foremost to be understood as a cultural product. Ladefoged, for instance, maintained that differences between languages are due to "whims of fashion rather than the rule of phonetic law" (Ladefoged, 1983a: 2); see also Ladefoged (1983b). From such a stance statistical regularities in the languages of the world are primarily "matters of chance and custom" (Ladefoged, 1983a: 1), and so are the exceptions to these statistical tendencies. They arise from just-so stories rooted in each language's individual history and culture (Evans, Levinson, 2009).

Others have taken a different stance: Lindblom, MacNeilage & Studdert-Kennedy (1983), for instance, observed many years ago that the world's languages "fastidiously

[1] Work supported by the ERC under the EU's 7th Framework Programme (FP/2007-2013) / Grant Agreement n. 283349-SCSPL. I would like to thank the organizers and audience of AISV 2015 for valuable discussions and feedback. I am also greatly indebted to my collaborators Manfred Pastätter and Stefania Marin.

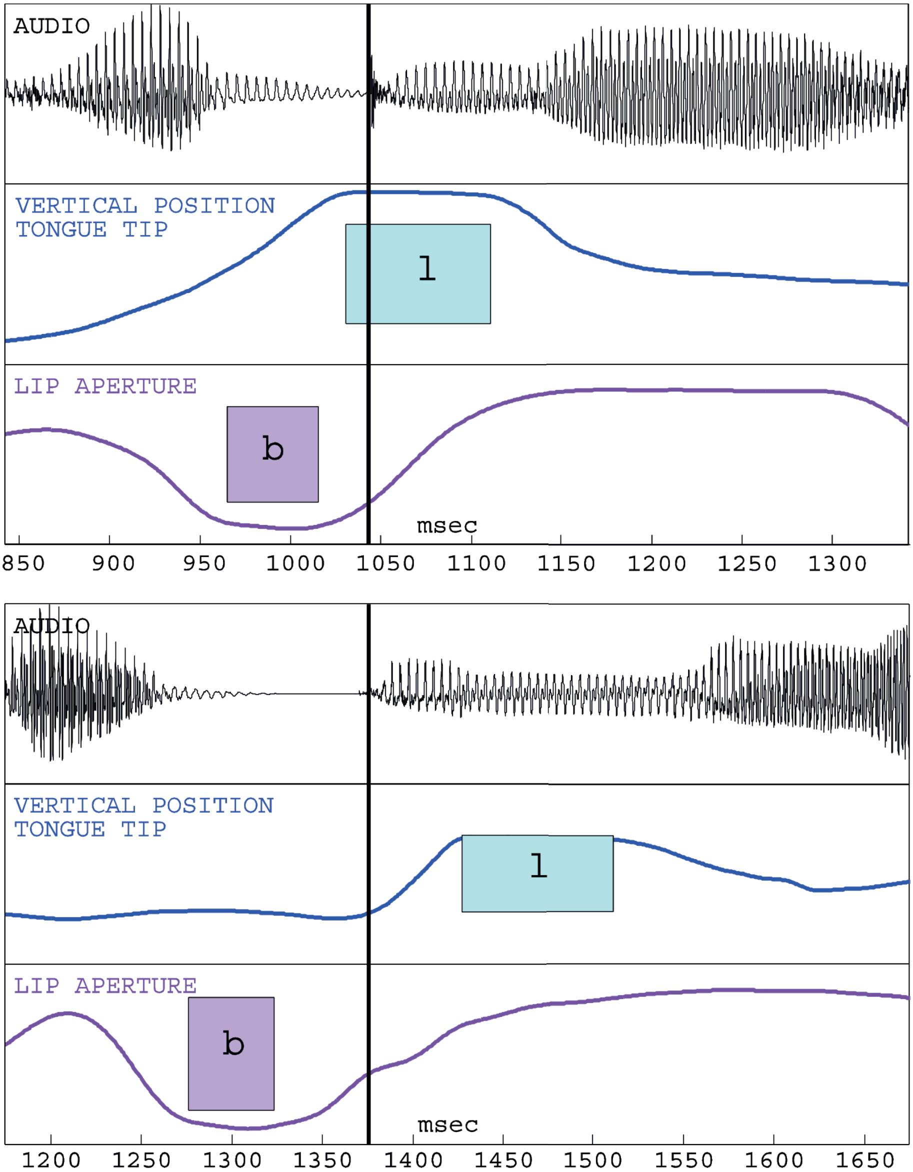
underexploit the full range of possibilities" (193). They argued that a random sampling of the possibilities of the universal phonetic space should make all possible sound patterns equally likely. Yet the phonologies the world's languages seem to defy the notion of random sampling. Performance constraints of the speech production and perception systems lead to structuration in a self-organizing system and thus effectively impose limits on linguistic diversity. The authors formulate performance constraints relevant for speech as sufficient perceptual distance at an acceptable articulatory cost (also known by the terms of hyper- and hypo-articulation (Lindblom, 1983b)). The impetus of the research program laid out by these and other authors in the 1980s and early 1990s was to understand spoken language primarily as biological behavior. The phonological and phonetic structure of spoken language is designed to ensure a highly efficient communication system; what efficiency means can only be understood with reference to the auditory and speech motor system. The latter is in turn nothing but a biological motion system – hence explicit parallels are sought between 'talking' and 'walking', posture control, reaching tasks, finger tapping and the laws of evolution (Grimme, Fuchs, Perrier & Schöner, 2011; Haken, Kelso & Bunz, 1985; Kelso, 1986; Lindblom, 1983a; Nelson, 1983; Ostry, Cooke & Munhall, 1987; Pouplier, 2012a). For instance, the wide preference for CV syllable structure or for mirroring consonant order between onset and coda (e.g., onset /bl/, coda /lb/) are argued to be deeply rooted in the physiology of speech production and perception (Browman, Goldstein, 1986; MacNeilage, 1998; MacNeilage, Davis, Kinney & Matyear, 2000; Redford, 1999; Vallée, Rossato & Rousset, 2009).

A lot of fruitful research has been informed by the research program looking for the biological foundations of language. Empirical efforts have been devoted to recreate in the laboratory distributional asymmetries in the world's languages in order to understand their conditions of emergence from a physiological viewpoint. A famous example is rate-induced resyllabification of VC to CV, first described by Stetson (1951), which has inspired an approach to spoken language from a dynamical systems perspective (Kelso, Saltzman & Tuller, 1986). Understanding preferred production patterns through rate-scaling is continued as a research paradigm until today (Goldstein, Pouplier, Chen, Saltzman & Byrd, 2007; Rochet-Capellan, Schwartz, 2007). Yet pinning down the relationship between (reflexes of) biological constraint in grammar and linguistic diversity has been very difficult. Languages continue to surprise us as to which sound patterns they incorporate into their grammars: much cited examples are languages like Tashlhiyt Berber or Georgian which in certain parts of their grammar seem to defy any notions of sonority in syllable phonotactics (Butskhrikidze, 2002; Dell, Elmedlaoui, 2002). Also many of the Slavic languages make pervasive use of phonotactic patterns that go against the grain of physiological preference. Languages also continue to surprise us with respect to the breadth of articulatory patterns they employ; the physical implementation of speech is more varied than often assumed, and it has been argued that there is a principled link between the phonotactic rules of a language and which general articulatory coordination pattern the language employs (Pouplier, Beňuš, 2011). In this paper, we will discuss a study on Polish as one instance of empirical evidence for ways in which languages may transgress hypothesized production preferences.

The syllable is by many seen as a primary domain within which production constraints operate, conditioning systematic phonotactic asymmetries. For instance, the jaw cycle has been proposed as the phylo- and ontogenetic basis for the syllable, and as a conditioning (albeit not a deterministic) factor in consonant phonotactics (MacNeilage, Davis, 2000; 2001; Redford, 1999; 2001). Since the 1980s and the rise of a dynamical systems approach to speech production which is deeply informed by a biological perspective on language, the role of in-phase coordination has received a lot of attention. The results of the above-mentioned experiment by Stetson (1951) in which speakers resyllabify VC under rate pressure to CV have been interpreted as evidence for a biologically preferred mode of speech motor coordination (synchrony) to be part of CV but not VC production (de Jong, 2001; Kelso et al., 1986): In a CV, but not a VC syllable, consonant and vowel are produced in-phase. Also work on speech errors (Goldstein, Pouplier et al., 2007; Pouplier, 2008) and the labial-coronal effect (Rochet-Capellan, Schwartz, 2007) have been linked to in-phase coordination and the jaw cycle. The labial-coronal effect appears in experimentally induced reorganization of CVCV to CCV (in a rate-scaling task). Specifically, both *pata* and *tapa* result in the labial-coronal sequence /pta/ (not /tpa/). The authors claim that this is due to /pta/ allowing for in-phase coordination with the jaw. They draw a direct connection between their experimental results and a statistical preference for labial-coronal phonotactics in the world's languages.

Despite this and similar evidence for the existence and the formative role of production constraints, languages have been known to differ systematically in their articulatory organization of the vowel cycle (vowel-to-vowel coarticulation (Beddor, Harnsberger & Lindemann, 2002; Manuel, 1990; Öhman, 1966)) as well as in consonant-consonant timing (Davidson, 2006; Kochetov, Pouplier & Son, 2007; Pouplier, Beňuš, 2011). This means for one that the same sequence of phonological symbols can be (co-)articulated very differently across languages. Figure 1 gives an illustrative example for such timing differences between German and Georgian for the syllable /ble/. In German (top panel of Figure 1), the /l/ has achieved its target plateau at the time of the release burst of the labial. In contrast, note how for Georgian (bottom panel) the constriction formation for /l/ only begins after the release of the labial, giving rise to an open transition. Secondly, also within a language place and manner differences are associated with significant differences in timing. For instance, Hoole and Bombien provided evidence for tautosyllabic stop-lateral sequences in German and French overlapping more in time than stop-nasal sequences (Bombien, Hoole, 2013; Hoole, Pouplier, Benus & Bombien, 2013). They attribute this to conflicting aerodynamic conditions for stops and nasals; a tight overlap between a stop and a nasal would obscure the burst and hence would make /kn/ perceptually unstable.

Figure 1 - *Illustration of timing differences between languages on the basis of kinematic data. The same segmental sequence, /bl/, is timed very differently in German (top) and Georgian (bottom). Top panel within each figure shows vertical tongue tip position over time, the bottom panel shows lip aperture. The rectangles indicate articulatory constriction plateaus for /b, l/. The black vertical line across panels marks the timepoint of the acoustic burst for /b/*



Many of the systematic articulatory timing differences reported in the literature are related to prosodic organization, i.e. syllable position and constituency. In an ideal case, we can distinguish by articulatory patterning a VC$CV from a V$CCV from a VCC$V sequence in terms of both consonant-vowel and consonant-consonant timing (Krakow, 1999). Since the syllable is also seen as a primary locus of physiological constraint manifestation, it constitutes an ideal testing ground for the interaction between language-specific and universal aspects of grammar and speech motor control. In the next section I will briefly introduce the coupled oscillator model of syllable structure as one particular suggestion of how 'naturally given' speech motor patterns are exploited by linguistic systems. I will then report on recent work on Polish which seeks to understand the conditions under which languages may diverge from these patterns, and explore the ramifications for modelling speech production.

2. *Coupled oscillator view of syllable structure*

Within their articulatory phonology framework, Browman and Goldstein (1985) and subsequent) have proposed to model syllable structure based on systems of coupled oscillators. A comprehensive overview of articulatory phonology is outside the scope of this paper; the interested reader is referred to recent publications (Gafos, Goldstein, 2012; Goldstein, Pouplier, 2014; Pouplier, 2011; 2012b). Articulatory phonology is a 'representational phonology' in the sense of Kisseberth (2011), characterized by laying emphasis on the predictive power of representations rather than on rules and constraints (for a combined articulatory phonology and OT approach see Gafos, 2002). Gestures, the basic representational units of the model, are conceptualized as linear second order mass-spring systems which enter into lexically specified coupling relations to form larger constituents such as segments and syllables. Syllables are seen as arising from characteristic patterns of temporal coordination among underlying gestures.

The gestural framework has relied to a large degree on the explanatory power of the relative phase values of 0° and 180° which have been identified in non-speech tasks as intrinsic modes of a system of coupled oscillators (Turvey, 1990). This means that these coordination patterns can be performed without learning and cannot be destabilized. Humans routinely learn and perform very complex coordination patterns, but when the learnt patterns can no longer be upheld due to e.g., rate pressure or disease, in-phase coordination is still retained. In-phase coordination is pervasive in biological systems (Strogatz, Stewart, 1993), and thus it is little surprising that frameworks that view speaking as a biological behavior seek to trace in-phase coordination in language. In this vein, articulatory phonology has proposed that the intrinsically stable modes are the basis of syllable structure. For instance, the near-simultaneous articulator movement onset of consonant and vowel in a CV syllable (Löfqvist, Gracco, 1999) has been interpreted as arising from an underlying in-phase coordination of syllable onset and vowel. Due to the greater temporal extent of the vowel (vowel articulations are intrinsically slower than consonantal articulations), the impression of serial order arises. Codas have been associated with an anti-phase or eccentric coordination mode (Goldstein, Pouplier, 2014; Krakow, 1999; Pouplier, 2012b). A rather direct link has been drawn between the basic stability of in-phase coordination and linguistic preference, i.e. statistical asymmetries in cross-linguistic patterns. Typological CV preference, the order of acquisition of onsets before codas, onsets having a greater resistance to sound change compared to codas and moraic weightlessness of onsets have all been linked to the hallmark stability of in-phase coordination (Nam, 2007; Nam, Goldstein & Saltzman, 2009).

In this model, onset clusters require more complex coordination patterns than singleton onsets: they are characterized by two competing phase relationships which prevent the multiple consonants from being produced on top of each other. All onset consonants are coupled in-phase to the vowel, but to ensure their recoverability, they are coupled anti-phase to each other. This underlying coupling topology gives rise to the so-called 'c-center effect' (Browman, Goldstein, 1995; 2000). The c-center simply denotes the surface correlate of articulator timing that the competing underlying coupling graphs give rise to. Specifically, the c-center provides evidence for the onset being coordinated at some level as a single entity to the vowel – while the timing of each individual consonant to the vowel changes with increasing onset complexity, the timing of the onset as whole (the c-center) does not. For example, when going from /**k**a/ to /s**k**a/, the timing of the /k/ to the vowel will differ in the two syllables, but the timing of the *entire onset* /**k**a/ and /**sk**a/ to the vowel will be the same. For the data we will consider below, it is important to point out that the c-center effect conditions increasing overlap of the vowel-adjacent consonant with the vowel as onset complexity increases: the /k/ in /s**k**a/ is more overlapped with the vowel compared to the /k/ in /**k**a/. For recent evidence on this matter see Peters and Kleber (2014).

Over the past decade, the model has been tested for a range of languages (Brunner, Geng, Sotiropoulou & Gafos, 2014; Gafos, Hoole, Roon & Zeroual, 2010; Goldstein, Chitoran & Selkirk, 2007; Hermes, Mücke & Grice, 2013; Marin, 2013; Marin, Pouplier, 2010; Pouplier, Beňuš, 2011). Results have supported the general idea that syllable constituency is articulatorily expressed in the relative timing of the consonants to each other and to the vowel. At the same time it has become clear that the basic gestural syllable model is not able to fully capture onset-vowel timing; a number of exceptions have been reported which are not straightforwardly accommodated by the model.

One specific exception to the patterns predicted by the gestural syllable model has been discussed in the context of obstruent clusters. We will report the relevant studies here as a case in point for languages stabilizing a greater range of patterns than anticipated by physiologically based syllable models. In particular, we focus on the role of coarticulation resistance. Coarticulation resistance is a concept in speech motor control that describes the differential contextual flexibility of sounds (Bladon, Al-Bamerni, 1976; Farnetani, Recasens, 2010; Iskarous, Mooshammer, Hoole & Recasens, 2013; Recasens, 2002): sounds with stringent aerodynamic production requirements or a high degree of dorsal control will resist coarticulation with neighboring consonants and vowels, for example, sibilants and the palatal vowel /i/ are highly ranked on the coarticulation resistance scale. Labials on the other hand, which require no lingual control at all, are among the least coarticulation resistant sounds: tongue shape during the production of a labial will be entirely dominated by the surrounding vowel context.

Complexity in the gestural model is defined as any deviation from the fundamental in-phase/anti-phase pattern and these deviations have often been motivated on perceptual grounds (Browman, Goldstein, 2000; Chitoran, Goldstein & Byrd, 2002). If coarticulation resistance interacts with syllable-level timing, this provides evidence that different gestural coordination patterns may be stabilized by languages on grounds of speech motor control, i.e. there may be trade-offs in speech motor control itself which lead to a contextual conditioned redefinition of preferred articulatory coordination patterns without necessarily implying a lesser stability thereof (Pouplier, 2012a). This in turn would invite us to take a broader view of what are deemed to be preferred articulatory patterns across languages.

3. *Onset-vowel timing and coarticulation resistance in Polish*

Marin (2013) reported for an articulography (EMA)[2] study on Romanian that consonant order interacts with the c-center effect. In particular, the onset clusters /sp-, sk-, sm-/ patterned as expected by the gestural model, showing an increase in consonant-vowel overlap between singleton and corresponding cluster condition (i.e., the /p/ in /**p**alə/ overlapped less with the vowel than the /p/ in /s**p**alə/). Stop-initial clusters /ps-, ks-, kt-, kn-/ failed to exhibit a c-center effect, there was no increase in C-V overlap between /**s**alt/ and /p**s**alm/. She attributed the lack of a c-center effect for the second cluster group to C1 being a stop, also discussing the possible role of frequency (Marin, 2011). Pastätter and Pouplier (2014; 2015) recently followed up on Marin's results on the basis of Polish, pursuing in particular the possibility that it is less manner of C1, but rather the coarticulation resistance of C2 that conditioned her results. Increasing consonant-vowel overlap with increasing onset complexity may not be a viable pattern for highly coarticulation resistant consonants such as sibilants.

Polish is a Slavic language featuring an unusual range of consonant clusters (Rochon, 2000). In particular, for a set of CC clusters the consonant members can appear in either order in both onset and coda, thereby allowing us to study the effect of order reversal in a systematic fashion within the same syllable position. By means of articulography (EMA) data from 6 Polish speakers were recorded by Pastätter and Pouplier (2014; 2015). The aim of the study was to test the hypothesis that increasing onset-vowel overlap conditioned by increasing onset complexity as predicted by the gestural syllable model is in an inverse relationship with the coarticulation resistance of the vowel-adjacent consonant (C_2). A highly coarticulation resistant

[2] Electromagnetic Articulography (EMA) is a recording technique that tracks the position of receiver coils attached to a speaker's articulators within a magnetic field (for an introductory overview see Stone, 2010).

consonant is expected to block increasing vowel-consonant overlap and no c-center effect will be observed. Sibilants are known to be among the most coarticulation resistant consonants both in terms of lingual and jaw position (Recasens, Espinosa, 2009), therefore the study in first instance focused on SCV and CSV onset clusters, where S stands for /s, ʃ/. Polish allows for a range of symmetrical SCV and CSV clusters all of which were included in our study: /ks-, sk-; mʃ-, ʃm-; ps-, sp-; pʃ-, ʃp-/; corresponding singleton conditions were also recorded (e.g., ***mʃalik*** *–* ***ʃalik;*** ***ʃmata*** *–* ***mata***). As an index of onset-vowel overlap, the temporal distance between the vowel-adjacent consonant of the cluster and a constant reference measurement point (a following word-medial consonant) was calculated for singleton-cluster stimulus pairs. For instance, the temporal lag of /ʃ/ in ***ʃalik*** to the word-internal /l/ was compared to to the same lag in *mʃalik*. The gestural syllable model predicts a decrease in this distance measure as going from singleton to cluster. The zero centered cluster:singleton ratio served as dependent variable. On this ratio, values <0 indicate an increase in onset-vowel overlap between singleton and cluster condition. Results confirmed the predicted significant main effect of sibilant position (vowel adjacent vs. vowel remote) on onset-vowel timing (Figure 2). For the CSV condition, there was no change in onset-vowel overlap as onset complexity increased from SV to CSV. For SCV conditions, on the other hand, such an increase in overlap was observed between CV => SCV, in accordance with the gestural model (Figure 2)[3]. That is, SCV clusters conformed to the preferred onset-vowel coordination pattern, while CSV clusters did not.

Coarticulation resistance is also known to hold for the jaw. The content-frame model of speech production (MacNeilage, 1998) has also drawn a strong link between the biological givens of speech production and linguistic structure, in particular syllable phonotactics. The framework ascribes a central role to the jaw cycle and predicts that languages will preferably arrange their CV phonotactics in accordance with the jaw cycle (MacNeilage, Davis, 2000). Frame-content theory has also been applied to consonant phonotactics within the syllable, deducing the typical reversal of consonant order between onset and coda from an interaction of consonantal jaw position requirements and the jaw cycle: for instance, /l/ requires an open jaw position, hence the 'natural' consonant order from a jaw perspective is /bl/ in onset but /lb/ in coda (Redford, 1999). Sibilants are produced by tunneling a jet of air against the front teeth and thus require a high jaw position and allow for little context-conditioned variability. We now take a look at jaw position in the Pastätter & Pouplier data. Figure 3 shows representative data from one speaker. Here for the same clusters that have entered into Figure 2, we see averaged jaw position at the temporal constriction midpoint of each segment of the (C)CVC syllable separately for the two onset types. The singleton condition is on the right in each graph. The relevant point here is the relative position differences between C1 and C2 for the

[3] Some approaches have argued, mostly on theory-internal grounds, for a 'special' status of obstruent-obstruent onset clusters in Polish and, for SCV clusters, an extrasyllabic status of /s/. We note that s-initial clusters show canonical syllable organization in our articulatory data (see also Rochon, 2000).

two cluster types. SC clusters show a monotonic lowering of the jaw throughout the cluster into the vowel. For CS clusters, on the other hand, we see a higher jaw position during C2 than during C1, i.e. the sibilant enforces a reversal of the jaw cycle during the onset for CS but not for SC clusters[4].

Figure 2 - *Cluster: singleton onset-vowel overlap ratio (zero-centered) as a function of sibilant position in the cluster. Negative values mean increasing C_2-vowel overlap with increasing onset complexity, a value of zero means no change in overlap between singleton and cluster conditions*

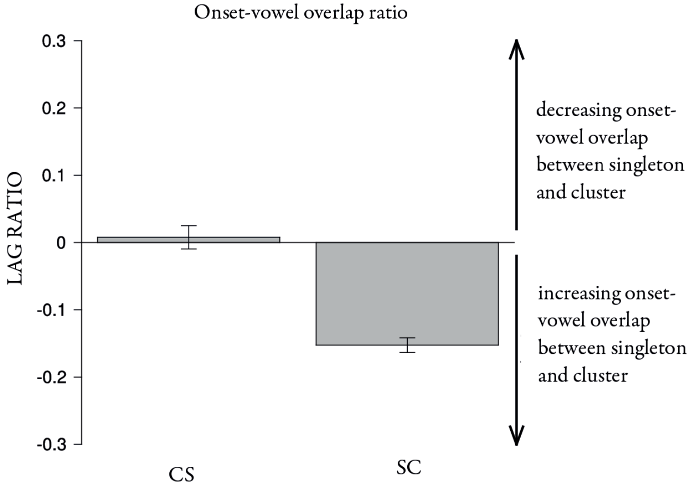
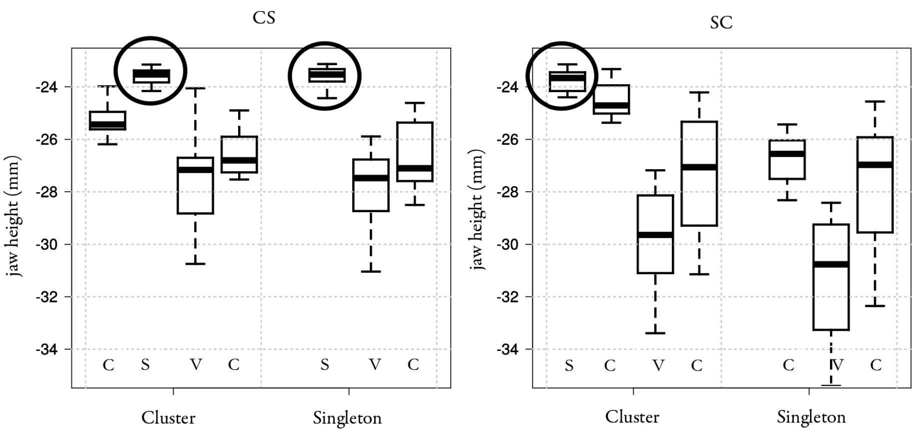


Figure 3 - *Average jaw position for each segment of the (C)CVC syllable for the two cluster types. CS clusters on the left, SC clusters on the right. Within each graph, the singleton condition is on the right, the cluster condition on the left. The sibilant is circled in each graph*

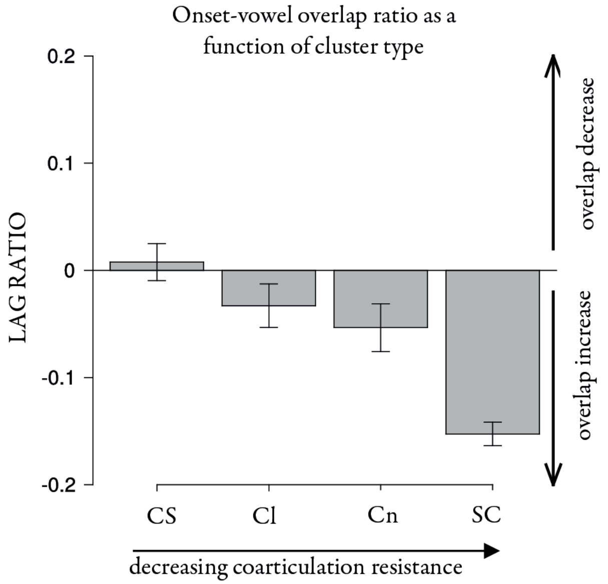


[4] Jaw coarticulation resistance may also explain why in the Marin data /kt/ patterned with /ks, ps/: While lingually among the lesser coarticulation resistant consonants, /t/ is for aerodynamic reasons quite stringent on jaw position requirements (Mooshammer, Hoole & Geumann, 2007).

Having identified differences in onset-vowel combination in SC vs. CS clusters which seem to be conditioned with differences in coarticulation resistance, we take an initial look at whether this would imply a difference in stability. In terms of token-to-token variability of the lag values, we find a significant difference in standard deviations SC: SD = .098; CS: SD = .134. A mixed model on these standard deviations was significant (dependent variable: standard deviations of onset-vowel overlap measure; fixed factor: Sibilant Position, random factors: Repetition, Cluster; $X^2[1] = 4.69$; $p < .05$). This suggests, against expectations, a lesser stability of CSV clusters.

The role of coarticulation resistance could be further substantiated by expanding the range of clusters beyond sibilants. Pastätter and Pouplier (2015) also included Cn (/kn-, pn-/) and Cl clusters (/kl-, pl-, ml-, vl-/). While Polish phonotactics does not allow us to systematically study the effect of order reversal for these clusters, they can be used to vary the coarticulation resistance of C_2. Results are given in Figure 4: Onset-vowel overlap increases linearly with decreasing coarticulation resistance of the vowel-adjacent consonant.

Figure 4 - *Cluster:singleton lag ratios as a function of coarticulation resistance of the vowel-adjacent consonant (decreasing from left to right). Negative values mean increasing C_2-vowel overlap with increasing onset complexity, a value of zero means no change in overlap between singleton and cluster conditions. Adapted from Pastätter and Pouplier (2015)*



Overall, the Polish data exhibit a systematic variation in onset-vowel timing as a function of manner of C_2, in accordance with the independently established coarticulation resistance hierarchy (Recasens, 1999; 2012; Recasens, Pallarès & Fontdevila, 1997). From the view of the gestural syllable model this means that a general, by hypothesis preferred pattern of temporal onset-vowel coordination may be overridden by other, spatial factors such as coarticulation resistance. The significant difference in standard deviations evidence a greater token-to-token variability in lag ratios for the CS compared to SC conditions. More sophisticated probing of the production system in terms of flexibility under prosodic variation or in the speech error probability should render a more complete picture of a possible differential plasticity of these patterns.

4. *Conclusions*

The issue we have laid out at the beginning of this paper was how frameworks which have made rather strong claims about syllable structure being rooted in, and ultimately epiphenomenal to biologically preferred movement coordination patterns may negotiate unexpected diversity in movement coordination. We have used data from Polish to trace a particular instance in which presumably preferred production pattern (the c-center, expression of underlying in-phase coordination) can be overridden by another production constraint, coarticulation resistance. The Polish data show that syllable-level timing preferences interact with a spatial factor – coarticulation resistance. The data show some indication for a lesser stability, providing initial evidence that this comes at a cost. To the extent that further analyses confirm the asymmetrical token-to-token variability between CS and SC cluster, this would in turn reinforce biologically oriented models of the syllable which have made rather strong claims about the foundational role of preferred timing patterns for the syllable, and have implicitly defined complexity as any deviation from the preferred timing pattern.

The Polish data are, however, only a first step in gaining a deeper understanding of the full range of production patterns that we may find across languages. Goldstein et al. (Goldstein, Nam, Saltzman & Chitoran, 2009) have proposed, comparing syllable onset data from English and Georgian, to increase the degrees of freedom for onset clusters by recognizing closure formation and release of each consonant as independent gestures (Browman, 1994; Nam, 2007). For the syllable model this means that the closure and release gestures of each consonant can independently participate in coupling relations to each other and to the vowel, exponentially increasing the number of possible coupling graphs for onset clusters with a corresponding loss of predictive power. This idea mainly served to capture language-specific differences in the behavior of C_1 in a C_1C_2 cluster in terms of C-C and C_1-V timing. This idea cannot be expanded to the Polish data in the current context, since coarticulation resistance is predominantly a spatial effect.

For the current data, a question to ask is how we can model the interaction between coarticulation resistance and timing, and whether we expect coarticulation resistance to differ between languages. At first blush, the answer to the latter question may be 'no' for sounds that are produced in the same fashion, i.e. using the same articulator synergies. /l/ for instance, can be produced with quite different synergies in terms of dorsal configurations giving rise to the well-known 'clear' vs. 'dark' continuum, which links correspondingly to the degree of dorsal control to differences in coarticulatory resistance (Recasens, Fontdevila & Pallarès, 1996). Yet for sibilants there have to my knowledge been no reports of a differential coarticulation resistance across languages. Velars are quite instructive to consider in this context. Velars exert a high degree of control on the tongue dorsum and hence should be coarticulation resistant on that count, but the well-known effect of velar fronting shows that velars in fact do allow for an adjacent vowel to exert considerable influence on the velar's place of articulation (Öhman, 1967). Iskarous et al. (2012) present a novel analysis of how language-specific effects in coarticulation can be modelled, using allophony in Navajo velar fricatives as case study: they argue for a language-specific element in parameter blending in the gestural model. Parameter blending is an element of the task dynamic (Saltzman, Munhall, 1989) model designed to capture dominance relations in cases of conflicting demands on the same articulator, i.e. it effectively models coarticulation resistance (Fowler, Brancazio, 2000; Fowler, Saltzman, 1993). Iskarous et al. are the first to discuss how language-specific effects in coarticulation resistance can be captured in a principled fashion using the blending parameter and by recognizing the independence of constriction location and degree in this respect: languages may differ on whether blending averages both constriction location and degree of the conflicting articulations (Navajo), or whether averaging occurs in only one of the parameters (English: constriction location allows for averaging, constriction degree is entirely dominated by the consonant). While this account elegantly captures the known language-specific spatial effects in velar-vowel coarticulation, the Polish data go further in suggesting that there is an interaction between syllable-level timing and coarticulation resistance, i.e. between spatial and temporal parameters, blocking increasing onset-vowel overlap with increasing coarticulation resistance. Further modelling work will have to be carried out in order to understand how to appropriately capture the Polish data, and cross-linguistic work will help pinning down how languages may negotiate different spatial and temporal demands of the speech motor system.

The existing work on articulatory coordination cited in this paper suggests that both spatial and temporal aspects of spoken language may carry a language specific component, and the range patterns languages allow for is currently not well understood. The biologically oriented models of speech production have tremendously contributed to our understanding of speech motor control and spoken language as a behavioral system. There is however a general tension between the models and linguistic diversity which we encounter not only in terms of phonological inventories and phonological rules, but also in terms of the articulatory implementation of speech. It is only if we increase our knowledge of how exactly and under which circumstances languages may go beyond a presumably 'naturally given' pattern, that we can achieve a deeper understanding of how languages oscillate between being both a cultural and a biological behavior.

References

Beddor, P.S., Harnsberger, J.D. & Lindemann, S. (2002). Language-specific patterns of vowel-to-vowel coarticulation: Acoustic structures and their perceptual correlates. In *Journal of Phonetics*, 30, 591-627.

Bladon, R.A.W., Al-Bamerni, A. (1976). Coarticulation resistance in English /l/. In *Journal of Phonetics*, 4, 137-150.

Bombien, L., Hoole, P. (2013). Articulatory overlap as a function of voicing in French and German consonant clusters. In *Journal of the Acoustical Society of America*, 134 (1), 539-550.

Browman, C. (1994). Lip aperture and consonant releases. In Keating, P. (Ed.), *Phonological Structure and Phonetic Form. Papers in Laboratory Phonology III*. Cambridge: Cambridge University Press, 331-353.

Browman, C., Goldstein, L. (1985). Dynamic modeling of phonetic structure. In Fromkin, V. (Ed.), *Phonetic Linguistics. Essays in Honor of Peter Ladefoged*. Orlando: Academic Press, 35-53.

Browman, C., Goldstein, L. (1986). Towards an articulatory phonology. In *Phonology Yearbook*, 3, 219-252.

Browman, C., Goldstein, L. (1995). Gestural syllable position effects in American English. In Bell-Berti, F., Raphael, L.J. (Eds.), *Producing Speech: Contemporary Issues.* Woodbury, NY: American Institute of Physics Press, 19-33.

Browman, C., Goldstein, L. (2000). Competing constraints on intergestural coordination and self-organization of phonological structures. In *Bulletin de la Communication Parlée*, 5, 25-34.

Brunner, J., Geng, C., Sotiropoulou, S. & Gafos, A. (2014). Timing of German onset and word boundary clusters. In *Laboratory Phonology*, 5 (4), 403-454.

Butskhrikidze, M. (2002). *The Consonant Phonotactics of Georgian*. Utrecht: LOT Dissertation Series.

Chitoran, I., Goldstein, L. & Byrd, D. (2002). Gestural overlap and recoverability: Articulatory evidence from Georgian. In Gussenhoven, C., Rietveld, T. & Warner, N. (Eds.), *Papers in Laboratory Phonology 7*. Berlin: Mouton de Gruyter, 419-448.

Davidson, L. (2006). Phonotactics and articulatory coordination interact in phonology: evidence from non-native production. In *Cognitive Science*, 30 (5), 837-862.

de Jong, K. (2001). Rate-induced resyllabification revisited. In *Language and Speech*, 20, 197-216.

Dell, F., Elmedlaoui, M. (2002). *Syllables in Tashlhiyt Berber and in Moroccan Arabic*. Dordrecht: Kluwer.

Evans, N., Levinson, S.C. (2009). The myth of language universals: Language diversity and its importance for cognitive science. In *Behavioral and Brain Sciences*, 32, 429-492.

Farnetani, E., Recasens, D. (2010). Coarticulation and connected speech processes. In Hardcastle, W.J., Laver, J. & Gibbon, F.E. (Eds.), *The Handbook of Phonetic Sciences*, 2nd ed. Wiley-Blackwell, 316-352.

Fowler, C., Brancazio, L. (2000). Coarticulation resistance of American English consonants and its effects on transconsonantal vowel-to-vowel articulation. In *Language and Speech*, 43 (1), 1-41.

Fowler, C., Saltzman, E. (1993). Coordination and coarticulation in speech production. In *Language and Speech*, 36, 171-195.

Gafos, A. (2002). A grammar of gestural coordination. In *Natural Language & Linguistic Theory*, 20, 269-337.

Gafos, A., Goldstein, L. (2012). Articulatory representation and organization. In Cohn, A., Fougeron, C. & Huffman, M. (Eds.), *The Oxford Handbook of Laboratory Phonology*. Oxford: Oxford University Press.

Gafos, A., Hoole, P., Roon, K. & Zeroual, C. (2010). Variation in timing and phonological grammar in Moroccan Arabic clusters. In Fougeron, C., Kühnert, B., D'Imperio, M. & Vallée, N. (Eds.), *Laboratory Phonology 10. Variation, Detail and Representation*. Berlin: Mouton de Gruyter, 657-698.

Goldstein, L., Chitoran, I. & Selkirk, E. (2007). Syllable structure as coupled oscillator modes: Evidence from Georgian vs. Tashlhiyt Berber. In *Proceedings of the XVI International Congress of Phonetic Sciences, Saarbrücken*, 241-244.

Goldstein, L., Nam, H., Saltzman, E. & Chitoran, I. (2009). Coupled oscillator planning model of speech timing and syllable structure. In *Proceedings of the 8th Phonetic Conference of China and the International Symposium on Phonetic Frontiers, Beijing, April 18-20, 2008*, CD-ROM.

Goldstein, L., Pouplier, M. (2014). The temporal organization of speech. In Goldrick, M., Ferreira, V. & Miozzo, M. (Eds.), *The Oxford Handbook of Language Production*. Oxford: Oxford University Press, 210-227.

Goldstein, L., Pouplier, M., Chen, L., Saltzman, E. & Byrd, D. (2007). Dynamic action units slip in speech production errors. In *Cognition*, 103 (3), 386-412.

Grimme, B., Fuchs, S., Perrier, P. & Schöner, G. (2011). Limb versus speech motor control: a conceptual review. In *Motor Control*, 15 (1), 5-33.

Haken, H., Kelso, J.A.S. & Bunz, H. (1985). A theoretical model of phase transitions in human hand movements. In *Biological Cybernetics* (51), 347-356.

Hermes, A., Mücke, D. & Grice, M. (2013). Gestural coordination of Italian word initial clusters - the case of 'impure s'. In *Phonology*, 30 (1), 1-25.

Hoole, P., Pouplier, M., Benus, S. & Bombien, L. (2013). Articulatory coordination in obstruent-sonorant clusters and syllabic consonants: data and modelling. In Spreafico, L., Vietti, A. (Eds.), *Rhotics. New Data and Perspectives*. Bolzano: Bolzano University Press, 81-97.

Iskarous, K., McDonough, J. & Whalen, D. (2012). A gestural account of the velar fricative in Navajo. In *Laboratory Phonology*, 3 (1), 195-210.

Iskarous, K., Mooshammer, C., Hoole, P., Recasens, D., Shadle, C., Salzman, E. & Whalen, D. (2013). The coarticulation/invariance scale: Mutual information as a measure of coarticulation resistance, motor synergy, and articulatory invariance. In *Journal of the Acoustical Society of America*, 134 (2), 1271-1282.

Kelso, J.A.S. (1986). Pattern formation in speech and limb movements involving many degrees of freedom. In Heuer, H., Fromm, C. (Eds.), *Generation and modulation of action patterns*. Berlin: Springer, 105-128.

Kelso, J.A.S., Saltzman, E.L. & Tuller, B. (1986). The dynamical perspective on speech production: Data and theory. In *Journal of Phonetics*, 14, 29-59.

Kisseberth, C. (2011). Conspiracies. In van Oostendorp, M., Ewen, C.J., Hume, E. & Rice, K. (Eds.), *The Blackwell Companion to Phonology.* Wiley-Blackwell, 1644-1665.

Kochetov, A., Pouplier, M. & Son, M. (2007). Cross-language differences in overlap and assimilation patterns in Korean and Russian. In *Proceedings of the XVI International Congress of Phonetic Sciences, Saarbrücken*, 1361-1364.

Krakow, R.A. (1999). Physiological organization of syllables: A review. In *Journal of Phonetics*, 27, 23-54.

Ladefoged, P. (1983a). The limits of biological explanations in phonetics. In *UCLA Working Papers in Phonetics*, 57, 1-10.

Ladefoged, P. (1983b). 'Out of chaos come order'; phsyical biological, and structural patterns in phonetics. In van den Broecke, M.P.R., Cohen, A. (Eds.), *Proceedings of the Xth International Congress of the Phonetic Sciences, Utrecht*. Dordrecht: Foris, 83-95.

Lindblom, B. (1983a). Can the models of evolutionary biology be applied to phonetic problems?. In van den Broecke, M., Cohen, A. (Eds.), *Proceedings of the Xth International Congress of the Phonetic Sciences, Utrecht.* Dordrecht: Foris, 67-81.

Lindblom, B. (1983b). Economy of speech gestures. In MacNeilage, P.F. (Ed.), *The Production of Speech.* New York: Springer, 217-246.

Lindblom, B., MacNeilage, P.F. & Studdert-Kennedy, M. (1983). Self-organizing processes and the explanation of phonological universals. In Butterworth, B., Comrie, B. & Dahl, B. (Eds.), *Explanations of Linguistic Universals*. The Hague: Mouton, 181-203.

Löfqvist, A., Gracco, V.L. (1999). Interarticulator programming in VCV sequences: Lip and tongue movements. In *Journal of the Acoustical Society of America*, 105 (3), 1864-1876.

MacNeilage, P.F. (1998). The frame/content theory of evolution of speech production. In *Behavioral and Brain Sciences*, 21, 499-546.

MacNeilage, P.F., Davis, B.L. (2000). On the origin of internal structure of words. In *Science*, 2888 (April), 527-531.

MacNeilage, P.F., Davis, B.L. (2001). Motor mechanisms in speech ontogeny: phylogenetic, neurobiological and linguistic implications. In *Current Opinion in Neurobiology*, 11, 696-700.

MacNeilage, P.F., Davis, B.L., Kinney, A. & Matyear, C. (2000). The motor core of speech: A comparison of serial organization patterns in infants and languages. In *Child Development*, 71 (1), 153-163.

Manuel, S. (1990). The role of contrast in limiting vowel-to-vowel coarticulation in different languages. In *Journal of the Acoustical Society of America*, 88 (3), 1286-1298.

Marin, S. (2011). *Organization of complex onsets in Romanian.* Paper presented at the Proceedings of the 9th International Seminar on Speech Production, Montréal, June 20-23, 2011.

Marin, S. (2013). Organization of Complex Onsets and Codas in Romanian: A gestural approach. In *Journal of Phonetics*, 41, 211-227.

Marin, S., Pouplier, M. (2010), Temporal organization of complex onsets and codas in American English: Testing the predictions of a gestural coupling model. In *Motor Control*, 14 (3), 380-407.

Mooshammer, C., Hoole, P. & Geumann, A. (2007). Jaw and order. In *Language and Speech*, 50 (2), 145-176.

Nam, H. (2007). Syllable-level intergestural timing model: Split-gesture dynamics focusing on positional asymmetry and moraic structure. In Cole, J., Hualde, J.I. (Eds.), *Papers in Laboratory Phonology 9*. Berlin: Mouton de Gruyter, 483-506.

Nam, H., Goldstein, L. & Saltzman, E. (2009). Self-organization of syllable structure: A coupled oscillator model. In Pellegrino, F., Marisco, E., Chitoran, I. & Coupé, C. (Eds.), *Approaches to Phonological complexity.* Berlin: Mouton de Gruyter, 299-328.

Nelson, W.L. (1983). Physical principles for economy of skilled movements. In *Biological Cybernetics*, 46, 135-147.

Öhman, S.E. (1966). Coarticulation in VCV utterances: Spectrographic measurements. In *Journal of the Acoustical Society of America*, 39 (1), 151-168.

Öhman, S.E. (1967). Numerical model of coarticulation. In *Journal of the Acoustical Society of America*, 41, 310-320.

Ostry, D., Cooke, J.D. & Munhall, K. (1987). Velocity curves of human arm and speech movements. In *Experimental Brain Research*, 68, 37-46.

Pastätter, M., Pouplier, M. (2014). The temporal coordination of Polish onset and coda clusters containing sibilants. In *Proceedings of the 10th International Seminar on Speech Production, Cologne, Germany, 5-8 May 2014*, 312-315.

Pastätter, M., Pouplier, M. (2015). Onset-vowel timing as a function of coarticulation resistance: Evidence from articulatory data. *Proceedings of the 18th International Congress of Phonetic Sciences, Glasgow*.

Peters, S., Kleber, F. (2014). Articulatory mechanisms underlying incremental compensatory vowel shortening in German. In *Proceedings of the 10th International Seminar on Speech Production, Cologne, Germany, 5-8 May 2014*, 316-319.

Pouplier, M. (2008). The role of a coda consonant as error trigger in repetition tasks. In *Journal of Phonetics*, 36, 114-140.

Pouplier, M. (2011). The atoms of phonological representations. In van Oostendorp, M., Ewen, C.J., Hume, E. & Rice, K. (Eds.), *The Blackwell Companion to Phonology*. Malden, MA: Wiley-Blackwell, 107-129.

Pouplier, M. (2012a). The gaits of speech: re-examining the role of articulatory effort in spoken language. In Solé, M.-J., Recasens, D. (Eds.), *Sound Change*. John Benjamins, 147-164.

Pouplier, M. (2012b). The gestural approach to syllable structure: Universal, language- and cluster-specific aspects. In Fuchs, S., Weirich, M., Pape, D. & Perrier, P. (Eds.), *Speech Planning and Dynamics.* Berlin: Peter Lang, 63-96.

Pouplier, M., Beňuš, Š. (2011). On the phonetic status of syllabic consonants: Evidence from Slovak. In *Journal of Laboratory Phonology*, 2 (2), 243-273.

Recasens, D. (1999). Lingual coarticulation. In Hardcastle, W., Hewlett, N. (Eds.), *Coarticulation: theory, data, and techniques.* Cambridge: CUP, 80-104.

Recasens, D. (2002). An EMA study of VCV coarticulatory direction. In *Journal of the Acoustical Society of America*, 111, 2828-2841.

Recasens, D. (2012). A study of jaw coarticulatory resistance and aggressiveness for Catalan consonants and vowels. *Journal of the Acoustical Society of America*, 132 (1), 412-420.

Recasens, D., Espinosa, A. (2009). An articulatory investigation of lingual coarticulatory resistance and aggressiveness for consonants and vowels in Catalan. In *Journal of the Acoustical Society of America*, 125 (4), 2288-2298.

Recasens, D., Fontdevila, J. & Pallarès, M.D. (1996). Linguopalatal coarticulation and alveolar-palatal correlations for velarized and non-velarized /l/. In *Journal of Phonetics*, 24, 165-185.

Recasens, D., Pallarès, M.D. & Fontdevila, J. (1997). A model of lingual coarticulation based on articulatory constraints. In *Journal of the Acoustical Society of America*, 102 (1), 544-561.

Redford, M. (1999). *An articulatory basis for the syllable.* PhD dissertation, University of Texas, Austin.

Redford, M. (2001). Constrained emergence of universals and variation in syllable systems. In *Language and Speech*, 44 (1), 27-56.

Rochet-Capellan, A., Schwartz, J.-L. (2007). An articulatory basis for the labial-coronal effect: /pata/ seems a more stable articulatory pattern than /tapa/. In *Journal of the Acoustical Society of America*, 121 (6), 3740-3754.

Rochon, M. (2000). Optimality in complexity: The case of Polish consonant clusters. Berlin: Akademie Verlag.

Saltzman, E., Munhall, K.G. (1989). A dynamical approach to gestural patterning in speech production. In *Ecological Psychology*, 1, 333-382.

Stetson, R.H. (1951). *Motor phonetics: A study of speech movements in action*. Amsterdam: North-Holland.

Stone, M. (2010). Laboratory techniques for investigating speech articulation. In Hardcastle, W.J., Laver, J. & Gibbon, F.E. (Eds.), *The Handbook of Phonetic Sciences*, 2nd ed. Malden, MA: Wiley-Blackwell, 9-38.

Strogatz, S.H., Stewart, I. (1993). Coupled oscillators and biological synchronization. In *Scientific American*, Dec., 102-109.

Turvey, M.T. (1990). Coordination. In *American Psychologist*, 45 (8), 938-953.

Vallée, N., Rossato, S. & Rousset, I. (2009). Favoured syllabic patterns in the world's languages and sensorimotor constraints. In Pellegrino, F., Marisco, E., Chitoran, I. & Coupé, C. (Eds.), *Approaches to Phonological Complexity.* Berlin: Mouton de Gruyter, 111-139.

Warner, N., Brenner, D., Schertz, J., Carnie, A., Fisher, M. & Hammond, M. (2015). The aerodynamic puzzle of nasalized fricatives: Aerodynamic and perceptual evidence from Scottish Gaelic. In *Laboratory Phonology*, 6 (2), 197-241.