

PROSODY IN ARTICULATORY PHONOLOGY

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1. Introduction

The linguistic term “prosody” has been conceived of as the structure of the utterance encoding prominence and hierarchical structure at the lexical and phrasal level (e.g., Beckman 1996, Ladd 1996/2008, 2001, Shattuck-Hufnagel & Turk 1996, Jun 2005). Prominence indicates a prominent syllable in a word or prominent word in a phrase. The hierarchical structure groups gestures or segments into larger prosodic units, ranging from the smallest (e.g., the syllable in English) to the largest (e.g. the Intonation Phrase in English). This chapter examines phrase-level prosody as it is understood in the framework of Articulatory Phonology (Browman & Goldstein 1992, Browman & Goldstein 1995, Goldstein, Byrd, & Saltzman 2006) and implemented in the Task Dynamics computational model (Saltzman & Munhall 1989, Saltzman 1995, Nam & Saltzman 2003, Saltzman, Nam, Krivokapić & Goldstein 2008). This is a relatively recent model of prosodic structure, with its first developments in Byrd et al. (2000). I start with a brief introduction to Articulatory Phonology¹.

Articulatory Phonology posits that phonological representations and speech production events are isomorphic. The motivation for this approach is to overcome the division that is traditionally made between cognitive and physical aspects of speech (Fowler 1980, Browman & Goldstein 1995) by viewing these two aspects of speech not just as compatible, but as the macroscopic and microscopic aspect of the same representation, where microscopic properties refer to the physical characteristics (articulatory, acoustic) of the macroscopic cognitive units (the combinatorial units of speech). Importantly in this characterization, the microscopic and macroscopic properties of a system are expected to interact and inform each other (Browman & Goldstein 1990b). The basic unit of speech is a gesture, a linguistically relevant constriction of the vocal tract, which is both an abstract, cognitive unit and at the same time allows for deriving the physical properties of speech. In other words, gestures are simultaneously cognitive units and “units of action” (Browman & Goldstein 1989).

Gestures are modeled as dynamical systems (specifically, constriction gestures are modeled as critically damped mass-spring systems).² The articulatory trajectories are

¹ For overviews of the model the reader is referred to Browman & Goldstein (1989, 1990a,b, 1991, 1992), Goldstein, Byrd, & Saltzman (2006), Pouplier 2011, Gafos & Goldstein (2011) and the Haskins website <http://www.haskins.yale.edu/research/gestural.html>; for an introduction to Task Dynamics see Hawkins (1992), and for an overview of the application of dynamical systems theory to speech see Van Lieshout (2004).

² A dynamical system is a system in which future states of the system are determined by its present state and a set of laws that specify the forces changing the system (Saltzman & Kelso 1987, Saltzman 1995). The computational model is named “Task Dynamic” to capture that “(a) it deals with the performance of well-learned skilled movements or

lawfully derived by the dynamical systems of the cognitive units (gestures). Another fundamental characteristic of the model is that cognitive processes of speech are understood as dynamical: “Thus, a dynamical perspective on coordinated movement not only reduces the conceptual distance between cognition on the one hand and mere bodily movement on the other, it forces reconceptualization of the nature of the inner cognitive processes themselves in dynamical terms. It thus turns out that cognition is not best thought of as something fundamentally distinct from movements of the body; rather, bodily coordination (and thereby interaction with the world) is really part of cognition itself” (Port & van Gelder 1995:159).

Each gesture is specified by a set of spatial and temporal parameters (target, stiffness, and damping, where the target corresponds to the linguistic task) and is implemented by the coordinated movements of the articulators associated with each gesture. The gestural score, which represents the spatio-temporal properties of gestures in an utterance and their relative timing (which will be discussed shortly), drives the movements of the articulators.³

It needs to be pointed out that gestures are defined in terms of abstract linguistic tasks (for example, a lip aperture constriction for [m]), rather than the specific movements of lips) and realized through coordinative structures—functional groupings of specific articulators that perform the task (e.g., upper and lower lip, and jaw for bilabial constrictions). As cognitive units, gestures are also contrastive, and the contrast can be 1) that gestures can be present or absent, 2) in terms of their spatio-temporal properties (e.g., gestures using the same articulator can differ in constriction location), and 3) determined through the temporal organization with other gestures.

Gestures are thus discrete units, specifying a task, but they result in continuous gesture trajectories, which in turn result in continuous movement of the vocal tract articulators. Since gestures are specified for both phonological and phonetic information, there is no need for a component mediating between phonology and phonetics.

Each gesture has associated with it a planning oscillator, or clock, that triggers the activation of that gesture (see Saltzman & Byrd 2000, Nam & Saltzman 2003, Nam, Goldstein, & Saltzman 2009). Thus the timing between two gestures is controlled by the coupling of their planning oscillators (note that the coupling specification is part of the lexical entry). The model makes use of two prevalent modes of coupling in skilled action, namely in-phase (simultaneous) and anti-phase (sequential) coupling. Both modes are available to humans spontaneously and require no learning, with the in-phase mode being the preferred, more stable mode (Haken, Kelso, & Bunz 1985, Turvey 1990). These two modes have been shown in experimental and modeling work to give rise to syllable structure (Browman & Goldstein 2000, Nam & Saltzman 2003, Goldstein et al. 2006, Nam 2007). When the planning oscillators are in-phase (as in C and V gestures in a CV syllable) the associated gestures will be triggered simultaneously and when the planning oscillators

gestures designed to accomplish real-world tasks; and (b) it is defined with respect to the dynamics that underlie a given action's kinematics. Note that kinematics refers to a gesture's observable spatiotemporal properties (e.g., its position, velocity, and acceleration trajectories over time), while dynamics refers to the pattern of the underlying field of forces that gives rise to these kinematics” (Saltzman 1986:130).

³ Note that this view of phonology and phonetics does not lend itself to easy transcription, and this applies to the model of prosody as well.

are anti-phase, as in the coda V and C gesture in a CVC syllable, the V and the coda consonant gesture are triggered sequentially. In complex syllable onsets (but not in codas), e.g., CCV syllables, the planning oscillators for each consonant are in-phase coupled to the vowel and anti-phase coupled to each other (Figure 1). This leads to competitive coupling which results in the first C starting earlier and the second starting later (when compared to the CV timing) capturing the *c-center* effect, whereby the midpoint of the onset consonants has a stable temporal relationship to the vowel, regardless of the complexity of the onset sequence (Browman & Goldstein 1988, 2000, Goldstein, Nam, Saltzman, & Chitoran 2009). In syllable codas, consonants are timed anti-phase to each other, and the first consonant is timed anti-phase to the vowel. Since there is only one type of coupling involved, there is no competitive coupling and consequently no c-center effect.

INSERT FIGURE 1 HERE

In the Articulatory Phonology framework intergestural timing thus emerges from the dynamics of the planning oscillator ensemble and syllable structure is the result of temporal coordination among the gestures comprising the syllable. The two coupling modes have been shown to provide a good account for empirically observed gestural timing in syllables (Browman & Goldstein 1988, Sproat & Fujimura 1993, Krakow 1999, Byrd et al. 2009), although there are cross-linguistic differences and exceptions, and the results are overall less consistent for codas than for onsets (see for example Goldstein et al. 2009, Marin & Pouplier 2010, Hermes 2013, Brunner et al. 2014 and discussion in Pouplier 2011). This conceptualization of the syllable can also help explain a wide range of phenomena, such as typological properties of syllable structure and their acquisition (Goldstein et al. 2006, Nam et al. 2010) and speech errors (Goldstein et al. 2007); see overview in Goldstein et al. (2006), Gafos & Goldstein (2011), and Pouplier (2011).

Finally, it should be mentioned that the specific predictions the model makes about articulation can be tested through the software implementation of the model, TADA (Task Dynamics Application; Nam, Goldstein, Saltzman, & Byrd 2004). TADA, which also incorporates the Haskins articulatory synthesizer CASY (Configurable Articulatory Synthesis), takes a text string as the input and generates an intergestural coupling graph (which specifies the gestures of the utterance and the coupling between the planning oscillators of the gestures), the gestural score, the movements of the articulators, and a timevarying vocal tract shape and area function. TADA can be combined with the synthesizer Hlsyn™ (Hanson & Stevens 2002) to synthesize the full acoustic signal. It can also be used without Hlsyn™ but it will not generate the full acoustic signal of the utterance, only its resonance pattern. For examples of use of TADA, see Gao 2008, Proctor 2009, Mücke, Nam, Hermes, & Goldstein 2012 who used it to verify their predictions for tones in Mandarin, for liquids, and for pitch accent alignment respectively. TADA can be downloaded at: http://www.haskins.yale.edu/tada_download/index.php and the manual for the model (Nam & Goldstein 2007) is available at http://www.haskins.yale.edu/tada_download/doc/TADA_manual_v09.pdf

Building on the outlined assumptions and foundations, prosodic structure is understood within Articulatory Phonology as arising through the coordination of a set of prosodic gestures. Like constriction gestures, these gestures present cognitive units and characterize the physical properties of speech. The prosodic gestures are temporal or clock-slowness gestures and tone gestures. We discuss these in sections 2 and 3, respectively, and prosodic gesture coordination in section 4. We turn to polysyllabic shortening and rhythm in section 5 and provide a summary and outlook in section 6.

2. Temporal modulation gestures and the π -gesture model

Byrd & Saltzman (2003; see also Byrd et al. 2000 for an earlier version of the model) extend the Articulatory Phonology approach to prosodic boundaries and propose that prosodic boundaries are viewed as prosodic gestures (π -gestures). Note that the π -gesture is the cognitive representation of the prosodic boundary, not just its phonetic implementation, in the same spirit that constriction gestures are simultaneously units of representation and units of action. Like constriction gestures, the π -gesture extends in time. It is coordinated with other gestures, and it has a target.⁴ Unlike constriction gestures, it does not have a constriction target however, but instead, it has a temporal target. The goal of the π -gesture is to locally slow the utterance clock which controls the time course of the constriction gestures. The effect of the π -gesture is to slow the time course of the constriction gestures that are active at the same time as the π -gesture. A slower course of activation leads to gestures being temporally longer⁵. **Due to the slowdown of the clock, constriction gestures co-active with the π -gesture will also start temporally later compared to the same sequence of gestures without the π -gesture.** As a consequence, gestures at boundaries become temporally longer and less overlapped. Both of these effects have been documented in the literature (less overlap: McClean 1973, Hardcastle 1985, Jun 1993, Byrd et al. 2000, Bombien et al. 2010, 2013, Byrd & Choi 2010; lengthening in articulatory studies: e.g., Fougeron & Keating 1997, Byrd & Saltzman 1998, Byrd 2000, Keating, Cho, Fougeron, & Hsu 2004, Cho 2006, Tabain 2003; in acoustic studies: e.g., Oller 1973, Wightman, Shattuck-Hufnagel, Ostendorf, & Price 1992, Shattuck-Hufnagel & Turk 1998).

The strength of activation of the π -gesture (indicated by the arrow in Figure 2) determines how strong the boundary effects are. Hierarchically higher boundaries will have stronger activations and consequently there will be more lengthening and less overlap than at lower boundaries, thus accounting for the empirical findings that boundary lengthening is cumulative. Whether the π -gesture also differs in scope at different boundaries is an empirical question, but the default assumption is that it does not (Byrd & Saltzman 2003, see also Byrd et al. 2006). Note that the π -gesture extends both phrase finally and phrase-initially, in other words, it accounts for both phrase-final and phrase-initial lengthening.

⁴ Note that the π -gesture has not been integrated in the coupled oscillator model at this point, but the coordination of the π -gesture to constriction gestures is a central question of the theory and we will discuss approaches to this question in section 4.

⁵ Gestures also become slower (with lower peak velocities) but this interacts with gesture displacement (or amplitude), which means that the change in peak velocity might not always be observable. See Byrd & Saltzman (2003).

INSERT FIGURE 2 HERE

A potential consequence of the temporal effects are changes in the spatial properties of gestures⁶. Specifically, some of the phrase initial articulatory effects that have been reported in the literature, for example the increase in gestural amplitude in phrase initial positions, could be a consequence of the temporal properties (see for an overview of initial strengthening phenomena Fougeron & Keating 1997, Fougeron 2001, Byrd & Saltzman 2003). One possibility for this effect to arise is when two gestures share the same articulator and are both affected by the π -gesture. Due to the effect of the π -gesture, the two gestures are less overlapped, and there will be more time for the first gesture to reach its target (i.e., there will be de-truncation), leading to larger amplitude of that gesture. In that case, the spatial changes can be understood as a consequence of the temporal changes, not as a main effect of prosodic structure. Note however that the π -gesture is not meant to capture all the effects of prosodic boundaries, only the temporal effects. For example, while VOT increases at prosodic boundaries in Korean (Cho & Keating 2001), which could be understood as the result of a π -gesture induced decrease in gestural overlap (as discussed in Byrd & Saltzman 2003), in Dutch the effect is opposite (VOT decreases at boundaries; Cho & McQueen 2005) indicating that processes other than lengthening take place at prosodic boundaries, and interact with the lengthening processes.

We now turn to some of the predictions of the π -gesture model (as developed in Byrd & Saltzman 2003). Like constriction gestures, π -gestures extend over a certain period, and consequently the boundary effects are expected to *extend over a certain period*. The scope of the effect has not been fully established yet (we will return to this question), but the prediction of the model is that the effect will be *local*, since only gestures co-active with the π -gesture will be affected. A related prediction is that there will not be gestures that are ‘skipped’ in the lengthening process. A further prediction of the model is that the boundary effect is strongest at the boundary and will *decrease with distance from it*, as the strength of activation of the π -gesture decreases (see Figure 2). Thus gestures (and acoustic segments) closest to the boundary will lengthen most, and gestures further away from the boundary less, regardless of the specific gestures (and acoustic segments) involved. These predictions have been born out in a number of articulatory (Byrd, Krivokapić, & Lee 2006, Krivokapić 2007, Katsika 2012 for Greek) and acoustic studies (e.g., Berkovits 1993a,b, for Hebrew, Cambier-Langeveld 1997 for Dutch).

An effect of the π -gesture is that gestures co-active with it are less overlapped. As mentioned above, this is due to the assumption that gestures co-active with a π -gesture have a delayed activation in comparison to phrase medial gestures. The prediction that arises is that the stronger the boundary, the less the gestural overlap will be. This prediction has been borne out so far (Byrd & Choi 2010, Bombien et al. 2010).

⁶ A spatial-modulation gesture, which modifies the spatial extents of constriction gestures, is discussed in Saltzman et al. (2008). At this point, however, it has not been used extensively in the model since it is not yet clear whether a separate spatial-modulation gesture is necessary to alter spatial extent, or whether such effects can be derived indirectly via the truncation/de-truncation effects that are direct outcomes of applying a temporal modulation gesture (E. Saltzman, personal communication 2015, see also Byrd & Saltzman 2003).

It should be pointed out that the effects of the boundary also depend on the shape of the π -gesture. That is, the strongest effects are predicted to be at the point where the activation of the π -gesture is strongest. In Byrd & Saltzman (2003) it was assumed that the strongest activation of the π -gesture is at the center, between two prosodic phrases. A different shape of the gesture would give different predictions as to where the temporal effects are the strongest. For example, if the shape of the π -gesture is skewed to the left, the effect would be strongest phrase-finally (see discussion and computational simulations in Byrd & Saltzman 2003). The shape of the π -gesture is at this point an empirical question.

It is expected that any type of gestures co-active with the π -gesture will lengthen, but the possibility cannot be excluded that lengthening could interact with other factors (such as perceptibility or coarticulatory resistance for example). This prediction has not been extensively investigated, but research so far suggests that all gestures examined lengthen, even though there are some differences between them regarding the extent of lengthening. Thus Fougeron (2001) finds, for French, post-boundary lengthening for a whole range of consonants (/t, n, k, l, s/) and two different vowels, and similarly Cho & McQueen (2005) find final lengthening for /t, d, s, z/ for Dutch. Both velar and bilabial consonants have been found to lengthen as well in German (Bombien et al. 2013). On the other hand, Fougeron (2001) finds less lengthening on /s/ than for other consonants and, as mentioned above, Cho & McQueen (2005) find that VOT in Dutch is shorter at higher prosodic boundaries than at lower boundaries (the opposite holds for e.g., Korean (cf. Cho & Keating 2001, Jun 1993). These might be examples of how lengthening effects interact with other aspects of speech production.

A further prediction of the π -gesture model is that there is no qualitative difference between phrase-final and phrase initial lengthening. In principle, there might be a difference in the *amount* of lengthening between phrase-final and phrase-initial position. As mentioned earlier, the amount of lengthening depends on the strength of activation of the π -gesture and therefore where the effect is strongest (phrase-finally, phrase-initially, or distributed symmetrically) depends on the shape of the π -gesture and, as will be discussed in section 4, its coordination with other gestures. The shape of the π -gesture is still an open empirical question, but importantly, there is no systematic, categorical, linguistically relevant difference between phrase-final and phrase-initial lengthening. Of course, listeners might be exploiting the lengthening arising from the π -gesture in different manners depending on whether the lengthening occurs at the beginning of a phrase or at the end of a phrase; for example, phrase initial lengthening might be more used for word recognition and phrase-final lengthening for syntactic disambiguation. Speakers also might use prosodic boundaries to plan the upcoming utterance and the planning might be differently distributed across the boundary. But the phonetic and phonological characteristics of the boundary are not specified separately for phrase initial and phrase final lengthening.

Within this model, boundaries of different strength also do not differ in a linguistically relevant manner. In other words, there are no different types of π -gestures for different prosodic categories (e.g., for the intermediate or Intonation Phrase in Beckman & Pierrehumbert's 1986 model), **the π -gestures only differ in strength**, i.e., in the amount of effect. A related issue is whether boundaries can be conceived of as being categorically different, reflecting a prosodic hierarchy with a small number of distinct categories, or whether boundaries are gradient, reflecting a more gradient view of the prosodic hierarchy.

The dynamic specification of the π -gesture allows for a structurally gradient or categorical prosodic hierarchy (Byrd 2006). As discussed in Byrd (2006), within Articulatory Phonology, a gradient structure would arise if the π -gesture has a continuum of activation strength values, while a categorical structure could arise by specifying a small number of attractors for the activation strength of the π -gesture. Another way a categorical structure could arise is if the π -gesture has a continuum of activation strength values, but different prosodic categories are distinguished through tone gestures, such as phrase accents and boundary tones (see Byrd 2006, Krivokapić 2007). This is a fundamental question for prosodic theory, but it has not been addressed thoroughly and is in need of extensive research. Phonetic evidence for a categorical view of prosodic boundaries would include the existence of specific phonetic properties marking each category. For example, the intermediate phrase (ip) and Intonation Phrase (IP) categories in Beckman & Pierrehumbert's (1986) model are distinguished by the presence of a boundary tone at the IP but not at the ip level (the increase in lengthening between ip and IP does not distinguish them, as this is a gradient, rather than a categorical difference; see also Frota 2000 on this point). Thus in Beckman & Pierrehumbert's (1986) model, phonetic properties give rise to the hierarchy of word, ip, and IP. However, studies examining the production and perception of boundaries indicate that the boundary values form a continuum, not a small number of clusters that would be expected if the hierarchy consists of categorically distinct phrases (Ladd 1988, de Pijper & Sanderman 1996, Swerts 1997, Krivokapić 2007, Krivokapić & Byrd 2012, see also arguments in Ladd 1996/2008, Frota 2000, Wagner 2005). Importantly, evidence suggests that the continuum is driven by structural properties of the hierarchy (Ladd 1988, Frota 2000, Krivokapić 2007, Krivokapić & Byrd 2012, Ladd 1996/2008, Wagner 2005). A second way to establish categorical differences between prosodic categories would be to show that different prosodic categories have different cognitive functions (similarly to phonemic contrasts, which distinguish lexical items). At this point, no evidence of such different functions exists. For example, prosodic phrases are known to disambiguate syntactically ambiguous utterances, but both ip and IP categories do that (e.g., Carlson, Clifton, & Frazier 2001, Clifton, Carlson, & Frazier 2002, Snedeker & Casserly 2010). A third way that a particular category could be justified is the existence of phonological rules that apply only at that specific level of the prosodic hierarchy. However, claims about such rules have been made based on impressionistic evaluations, rather than on experimental evidence (as pointed out in Byrd 2006, Wagner 2005). The few studies that have examined these rules have found that they apply in a gradient manner (see discussion in Byrd 2006, Wagner 2005, Krivokapić & Byrd 2012). Thus questions about the structural properties of the prosodic hierarchy, specifically whether it is gradient or categorical, and if categorical, how many categories exist, remain open. Importantly however, the dynamic view of prosodic boundaries allows us to conceive of a different type of prosodic hierarchy, one which would possibly better fit the empirical evidence to date.

A question related to the structure of the prosodic hierarchy that has not been addressed directly in this model is the relationship between syntactic and prosodic structure. In general, there are two types of approaches to the prosody-syntax interface: In one, phonological and phonetic phenomena associated with the phrase-level are mediated by prosodic structure (e.g., Nespor & Vogel 1986/2007, Selkirk 1984, 2011), while in the other they are defined directly over syntactic structure, rendering a separate prosodic

structure unnecessary (Cooper & Paccia-Cooper 1980, Wagner 2005; see discussion of the approaches in Selkirk 2011). The relationship between syntax and prosody in the Articulatory Phonology model has largely been unexplored, and there is no theoretical reason for the model to prefer one or the other approach (for a brief exploration of how the mapping between syntactic structure and prosodic structure could be approached within the model, see Krivokapić 2007).

It has been suggested that the π -gesture model could be extended to account for lengthening in prominence (Byrd & Saltzman 2003, see also Bombien et al. 2013) and recent work has modeled lexical stress using a clock-slowness gesture, namely the μ -gesture (Saltzman et al. 2008).⁷ Before the dynamics of the μ -gesture can be fully developed, a clearer understanding of the gestural timing and the kinematic properties of gestures in prominent syllables is needed. One difference between the μ -gesture and the π -gesture that can be expected lies in the coordination of the temporal modulation gesture to the constriction gestures. The evidence so far indicates that the strongest effect of the boundary is between two phrases and decreases with distance from that point, indicating that the strongest activation of the π -gesture is between two phrases. Prominence on the other hand seems to exert the strongest influence on the vowel of the prominent syllable (Cho & Keating 2009, Bombien et al. 2010, 2013), indicating that the strongest activation of the temporal modulation gesture in prominence is at the vowel. This difference does not imply that the temporal modulation gestures differ qualitatively for boundaries and for prominence, just that their coordination with constriction gestures is likely to be different.

To summarize: The π -gesture model, which extends the gestural account of Articulatory Phonology to prosodic boundaries and to prominence, conceptualizes prosodic boundaries in a fundamentally different way from other models. Boundaries are understood to be gestures, they are inherently temporal, the effect of the boundary is to slow down gestures that are co-active with it, in this way increasing their duration (and in some cases their spatial extent) and reducing gestural overlap; the effect is local, continuous, and gradually decreases with the distance from the strongest activation point of the π -gesture. From this model a set of specific predictions about the temporal properties of prosodic boundaries emerges and the model has been tested in a large number of studies. These studies overall indicate that the gestural approach is a good way to systematically capture properties of boundaries. The model also raises questions about critical aspects of the prosodic hierarchy. A number of questions related to the properties of the π -gesture have been mentioned that still remain to be explored (see Byrd & Saltzman 2003 for additional questions).

3. Tone gestures

Gao (2008, see also Gao 2009) further develops the gestural approach to prosodic structure and extends it to lexical tones. In her approach, tones are gestures which are, like other

⁷ The π -gesture and the μ -gesture are conceptually similar, but the π -gesture has not yet been implemented in the coupled planning oscillator network. They both locally modulate the temporal properties of an utterance. For a further discussion of the entailed differences, see Saltzman et al. (2008). For lengthening under prominence see e.g., Turk & Sawusch (1997), Turk & White (1999), Cho & Keating (2009), Mücke & Grice (2014) and the overview in Fletcher (2010).

gestures, specified as dynamical systems (Saltzman 1986, Saltzman & Kelso 1987, Saltzman & Munhall 1989), extend in time, have targets, and are coordinated with other gestures. Gestures generally have specific articulators associated with them, but, as Gao (2008) points out, at this point it is not possible to model the articulators involved in the production of F0 due to a lack of understanding of all physiological processes involved in its production (see Hirose 2010 for an overview of the production of F0). However, the *abstract linguistic tasks* of tone gestures can be specified at the level of F0 and in that sense F0 is an appropriate task variable, just like lip aperture for example.

Tone gestures have as their goal linguistically relevant variations in fundamental frequency (Gao 2008, McGowan & Saltzman 1995). In modeling the four tones of Mandarin, Gao posits two tone gestures (with an H and with an L target). Tones 1 and 3 have a single gesture (tone 1 has an H target, tone 3 an L target), while tones 2 and 4 arise from a combination of two tonal targets. Tones, like constriction gestures, have planning oscillators associated with them, and the coordination of tones is determined by general coupling mechanisms. In tone 2, the L and H gesture are coordinated in-phase and the L gesture has a shorter activation interval than the H gesture, while in tone 4, the H and L gesture are coordinated anti-phase. For tone 2, the in-phase coordination results in an overlap of the L gesture with the H gesture while both gestures are active. This overlap results in the mid-level F0 in the first part of tone 2, followed by the rise to H. For tone 4, the anti-phase coordination results in the H tone followed by the L tone, i.e., the falling contour of tone 4. Gao's computational implementation of these gestural representations in TADA (Nam, Goldstein, Saltzman, & Byrd 2004) showed that these gestural scores yield F0 contours that match contours obtained in speech (Gao 2008:44, Xu 1997:67).

Starting from this view of tones, Gao examines tonal alignment in syllables with different syllable structures (CV and CVC) and with different onset consonants. Kinematic data analysis showed two different coordination patterns of the four tones but they could both be explained by positing that the tone gestures behave like consonant gestures in their coordination patterns, i.e., that they are coordinated to vowel and consonant gestures like onset consonants are. For example, for tones 1 and 3, the onset consonant and the vowel are in-phase coupled and the tone and the vowel gesture are also in-phase coupled, while the consonant and the tone are anti-phase coupled. The multiple coupling specifications give rise to competitive coupling, like for onset consonant gestures, and consequently to the c-center effect. Thus in tones 1 and 3, the order of the gesture onsets is consonant, vowel, tone, indicating that the consonant gesture shifted leftwards and the tone gesture rightwards from the vowel onset, like in onset consonant clusters. As Gao points out, the specified coupling relations for tones 1 and 3 are like the ones observed for the onset consonants in English *spin* where the two supralaryngeal consonant gestures (tongue tip and lip aperture) are in-phase coupled to the vowel and anti-phase coupled to each other (see Figure 1). In Gao's analysis then, tones pattern with consonants in how they are coordinated, and they affect the gestural timing of consonant and vowel gestures. Note that the view that tones pattern with consonants fits well with theories of tonogenesis arguing that at least some tones have their historic origin in consonants (e.g., Hombert, Ohala, & Ewan 1979).

In addition to the observed in-phase coordination of vowel and tone gestures, anti-phase coordinations of the tone with the vowel (patterning like coda consonants) have also been suggested. Thus Hsieh suggests that tone 3 consists of an L tone coordinated in-phase

with the vowel and anti-phase with the onset consonant and an H tone gesture which is coordinated anti-phase with the vowel, accounting in this way for the behavior of tone 3 in different contexts (Hsieh 2011; Gao 2008 discusses tone 3 in sentence-medial positions only, a context also captured by Hsieh 2011; for another account of tone 3 see Yi & Tilsen 2014).

Gao's approach to tones has been used to investigate the coordination of tones with constriction gestures in pitch accents (this is referred to as "tonal alignment" in the autosegmental-metrical approach to intonation) in Catalan and Standard German (Mücke, Nam, Hermes, & Goldstein 2012), and Italian and Viennese German (Niemann, Mücke, Nam, Goldstein, & Grice 2011). These studies find that differences and similarities between languages arise from the specification of the coordination patterns of tone and vowel gestures, in other words, they are the result of phonological structure. For example, in a kinematic, acoustic, and modeling study examining pitch accent coordination with vowel and consonant gestures in a variety of syllable structures, Mücke et al. (2012) show that in Viennese German an L and an H tone are coordinated anti-phase to each other and in-phase to the V gesture of the accented syllable. This leads to competitive coupling which in turn gives rise to the H gesture shifting rightwards, and the L gesture shifting leftwards (like for onset consonant clusters, Figure 1). In Catalan on the other hand, Mücke et al. (2012) show that L and H are also coupled anti-phase to each other, but only the H gesture is coupled in-phase with the vowel. The result is that there is no competitive coupling and that the H gesture starts simultaneously with the V gesture. Importantly, as argued in Mücke et al. (2012), these results could be described as the tone gesture being aligned to "the left edge of the onset consonant" (in Catalan) as opposed to the "middle of the onset consonant" in German (Mücke et al. 2012:221), but an examination of this question that leverages the gestural approach and the coupling oscillator model can account for the observed differences between languages in a precise manner. Similarly, Nieman et al. (2011) argue that German and Italian differ in the gestures comprising rising tones and in the coupling of gestures. Thus the rising tone in Italian is comprised of one gesture (with an H target) that is in-phase coordinated with the vowel gesture, but in German, the rising tone is comprised of two gestures (with an L and an H target) which are in-phase coordinated to the vowel gesture and anti-phase to each other. This difference in coupling in the two languages leads to different F0 realizations. Nieman et al. (2011) also find that pitch accent tone gestures do not affect the lexically specified CV coordination patterns.

Mücke et al. (2012) observe an important distinction between lexical tone gestures and pitch accent tone gestures: Tone gestures in lexical tones, but not in pitch accents affect the lexically specified CV coordination patterns (cf. the effects of tone on coordination reported in Gao 2008 for Mandarin lexical tone and Nieman et al. 2011 for German and Italian pitch accents). They hypothesize that this could be due to the coupling of tone gestures for pitch accents not being specified lexically, but post lexically, and therefore not being fully integrated into the coupling model, as opposed to the coupling of tone gestures in tone languages, where tones are part of the lexical representation, and therefore integrated into the coupling model. Thus whether tone gesture coupling is specified at the lexical or at the post-lexical level could reflect and lead to typological differences.⁸

⁸ While the typological predictions of the prosodic model in Articulatory Phonology have not been much discussed, the coordination between gestures can be expected to be a major

Tonal alignment has been the subject of extensive research (for an overview see Ladd 2008). So far, consistent alignment between tonal landmarks (such as dips and peaks) and acoustic events have not been found. Lack of consistent alignment could be due to the relevant alignment landmarks being articulatory rather than acoustic in nature (as suggested in D'Imperio et al. 2007, Gao 2008) but more importantly, the search for alignment points has often focused on surface rather than on structural properties (as discussed in Ladd 2006, Gao 2008). To account for tonal alignment, Gao (2008) has taken as the starting point of her examination the assumption that the relevant domain of examination of timing is in terms of the structural properties of speech and that tones are gestures (see Ladd 2006 and Prieto & Torreira 2007 who also suggest that gestures in the sense of Articulatory Phonology might provide a better account of alignment). Much more work remains to be done in order to understand how the Articulatory Phonology model can account for different languages and the various factors affecting tonal alignment, such as e.g., phonological vowel length (Ladd et al. 2000), syllable structure (e.g., Prieto & Torreira 2007), speech rate (e.g., Prieto & Torreira 2007, Hsieh 2011), upcoming word boundary/prosodic environment (D'Imperio 2001, Prieto et al. 1995, Silverman & Pierrehumbert 1990). However, the results so far indicate that systematic phonological differences between languages and dialects, exhibited in different tonal composition and different coupling graphs, can account for surface variability in F0 alignment. Viewing tones as gestures within Articulatory Phonology also has the advantage of presenting tonal information in the same manner as constriction and prosodic information, thus allowing for an integrated investigation of prosodic phenomena. The approach has recently been extended to boundary tones in Greek (Katsika 2012, Katsika, Krivokapić, Mooshammer, Tiede, & Goldstein 2014), which will be discussed in the next section.

4. The coordination of prosodic events

The coordination of gestures is part of the phonological structure in Articulatory Phonology and is specified by the coupled oscillator model. This model has reconceptualized the notion of the syllable, and has been shown to account for timing of lexical tones and pitch accents. The π -gesture has not yet been integrated into the coupled oscillator model, but the coordination of the π -gesture to constriction gestures and other prosodic gestures is critical for understanding prosodic structure within Articulatory Phonology and recent work has been exploring this question.

One of the predictions of the π -gesture model is that lengthening is continuous (it does not skip any segments or gestures). A related question is how the onset of the boundary (specifically, the π -gesture) is determined. This question is of interest for any theory of prosodic structure but Articulatory Phonology has a consistent way of framing it, namely in terms of onset of the π -gesture and its coordination with other gestures.

These issues have been examined in a number of recent studies, and a specific focus has been placed on how pre-boundary prominence interacts with lengthening (e.g., Turk & Shattuck-Hufnagel 2007, Byrd & Riggs 2008, Katsika 2012, Katsika et al. 2014, Katsika 2016). In an acoustic study of English, Turk & Shattuck-Hufnagel (2007; see also Rusaw

source of typological variation. See discussions about typology of syllable structure, and how it relates to coupling graphs, in Nam, Goldstein, & Saltzman (2009).

2013 who replicated these findings) examined the effect of stress on the onset of final lengthening testing words with final, penultimate, and antepenultimate lexical stress. They found that final lengthening started earlier in the word when the stressed syllable was further away from the boundary, indicating that the boundary effects shift leftwards towards the stressed syllable. However, unstressed syllables between the stressed and the final syllable were not always lengthened, or were lengthened less than the stressed syllable. White (2002) also finds that the scope of lengthening extends from the end of the stressed syllable (in antepenultimate, penultimate, or ultimate position) to the boundary, but that the intervening unstressed syllables lengthen as well, contrary to Turk & Shattuck-Hufnagel (2007) and Rusaw (2013). Evidence for an interaction of boundary and prominence also comes from an articulatory magnetometry study by Byrd & Riggs (2008) who find that the onset of final lengthening can be attracted to the prominent syllable (but the results are speaker specific). Byrd & Riggs (2008) suggest two possible accounts, namely that the π -gesture either *shifts* towards the prominent syllable, thus keeping the scope of lengthening constant, or that the π -gesture *extends* towards the prominent syllable, thus increasing the scope of the π -gesture. Crucially, both accounts specifically link the onset of the boundary to another prosodic event (see also Byrd 2006, Krivokapić 2007), capturing the interdependence of boundaries and prominence that many studies have shown.

For Greek, Katsika (2012, 2016) found in an articulatory magnetometer study that the onset of final lengthening occurred during the final syllable in words with final stress, but that it started earlier when the stressed syllable occurred earlier (consistent with White 2002, Turk & Shattuck-Hufnagel 2007, Byrd & Riggs 2008, Rusaw 2013). Like White (2002) she found that lengthening is continuous (once it starts does not skip any gestures), as predicted by the π -gesture model. Katsika (2012, Katsika et al. 2014) combined this examination of temporal properties of prosodic boundaries with the examination of the onset of the boundary tone in IP boundaries. The onset of the boundary tone was always during the final vowel, but it occurred earlier within the vowel when the stressed syllable occurred earlier, in other words, it shifted towards the stressed syllable.

Katsika (2012, Katsika et al. 2014) suggests that this interdependency of prominence and boundary arises through the coordination of the μ -gesture, the boundary tone gesture, and the π -gesture. The π -gesture has a dual coordination. It is coordinated with the phrase-final vowel gesture and with the μ -gesture (the temporal modulation gesture on the stressed syllable) of the phrase-final word. The coordination with the μ -gesture is weaker, thus affecting the onset of the π -gesture less than the π -gesture's coordination with the phrase-final vowel gesture. In this way, the onset of lengthening will depend on the position of the stressed syllable, i.e., the onset will shift slightly, in a gradient manner, towards the stressed syllable. Thus the flexible scope of lengthening is accounted for by these two coordinations.⁹ Katsika also suggests that the variability in the alignment of the boundary tone can be accounted for if it is assumed that the boundary tone gesture is activated when the π -gesture reaches a certain, high level of activation (see also Byrd 2006 on this relationship between π -gesture strength of activation and boundary tone). When lexical

⁹ For a related approach see Rusaw (2013), who modeled the interaction between boundary and prominence lengthening, as found in Turk & Shattuck-Hufnagel 2007 and replicated in Rusaw 2013, with an artificial central pattern generator neural network model.

stress of the phrase final word is earlier in the word, the π -gesture will start earlier, and it will reach the level of activation that triggers the boundary tone earlier, thus triggering the boundary tone earlier. This means that, like the π -gesture, the onset of the boundary tone will shift slightly towards the stressed syllable (see Katsika 2012, Katsika et al. 2014 for further discussion). Thus the variability in the onset of lengthening and onset of the boundary tone gesture arise from the coordination of the π -gesture and the μ -gesture. This account also indicates a further interdependency of boundary properties, namely that between the temporal and tonal properties. Note that the coordination of prosodic gestures (which gestures are coordinated, what the strength of the coordination is, what type of coordination) can be expected to be a source of cross-linguistic variation

Katsika (2012, Katsika et al. 2014) further identifies pause postures, which are specific configurations of the vocal tract occurring at IP boundaries. She argues that pause postures are triggered by a very high activation of the π -gesture (higher than needed for the activation of the boundary tone gesture, thus achieving that only very strong boundaries have pause postures). While pause postures need to be further examined, some corroborating evidence for pauses as linguistic entities comes from the studies of Ramarayanan et al. (2009, 2010, 2013). These studies show that grammatical pauses, defined there as pauses between syntactic constituents, have specific kinematic properties, namely, they exhibit less variability and a decrease in velocity of articulators in comparison to other types of silent intervals. The observation of these pause specific configurations also indicates the need for further exploration of the relationship between final lengthening, pauses, and initial lengthening (see also discussions in Byrd & Saltzman 2003, Krivokapić 2014, Katsika et al. 2014).

To summarize: A number of recent studies (Byrd 2006, Byrd & Riggs 2008, Katsika 2012, Katsika et al. 2014) argue that prosodic boundaries arise through a set of temporally specified prosodic gestures that interact in a dynamic way. This view allows for a characterization of the tonal and temporal properties of prosodic structure, including an account of the gradient effects prosodic structure gives rise to. Recent work on articulation during pauses has revealed further aspects of prosodic boundaries.

5. Polysyllabic shortening, rhythm and the prosodic hierarchy

A recent extension of the theory is the modeling of polysyllabic shortening and rhythm. Early researchers (Pike 1945, Abercrombie 1967) have developed the notions of stress-timing and syllable-timing, and proposed that all languages are stress-timed or syllable-timed. The phonetic correlates of these two rhythm types were suggested to be foot and syllable isochrony. Since then, a large body of research has examined rhythmic properties of languages but has not found evidence for isochrony in either production or perception (e.g., Bolinger 1965, Huggins 1972, Lehiste 1972, 1977, Nakatani, O'Connor, & Aston 1981) and it is by now abundantly clear that strict isochrony does not exist (see the overview in Arvaniti 2012).

However, despite the clear evidence against strict isochrony, it is not disputed that there are temporal regularities as evidenced in durational aspects of speech, although it is likely that other aspects of speech, such as the timing of pitch accents and phrasal boundaries, are also relevant for characterizing rhythm (as argued for in Jun 2014). Specifically, there is evidence of polysyllabic shortening—the shortening of stressed syllables with the addition of unstressed syllables to a word or a foot—which can be seen

as a tendency towards foot isochrony (e.g., Lehiste 1972, Klatt 1973, Port 1981, Rakerd, Sennett, & Fowler 1987, Kim & Cole 2005, White & Turk 2010, Shattuck-Hufnagel & Turk 2011). Kim and Cole (2005), for example, find that the duration of the foot (defined in the Abercrombian sense of extending from one stressed syllable to the next) increases with the addition of unstressed syllables. In the process, the unstressed syllables do not shorten, but the stressed syllable does. In this way, the duration of the foot is somewhat constrained.

Within Articulatory Phonology, rhythmic properties are understood to emerge through the coupling of the foot oscillator, the syllable oscillator, and the temporal modulation gesture μ (Saltzman et al. 2008, Nam et al. 2008). The μ -gesture, which is associated with stressed syllables, slows the gestural activation of co-active gestures. As a consequence, stressed syllables are longer than unstressed syllables. The foot and the syllable oscillator (and, similarly, phrase level oscillators although this part of the model is not fully developed yet) extend the model of planning oscillators for gestures to prosodic structure. As stated in Saltzman et al. 2008 “the foot oscillator attempts to keep the duration of the foot constant, while the syllable oscillator attempts to keep the duration of the syllable constant” (Saltzman et al. 2008:180). These opposite goals of the oscillators, and the resulting competition, are modeled via interoscillator coupling functions, where the foot and syllable oscillators are coupled to each other bidirectionally, and each oscillator has a weighting which specifies the influence of the oscillator in the function. Depending on which oscillator’s weighting is stronger, the foot or the syllable will be the more dominant oscillator and the language will display a tendency towards foot or syllable isochrony. In the case of foot-dominance, an increase in the number of syllables in the foot will lead to the shortening of syllables (the syllables are “squeezed” in the foot), leading to polysyllabic shortening (the approach discussed so far is based on O’Dell and Nieminen 1999; see also Barbosa 2002, Cummins & Port 1998, and Tilsen 2009 for related approaches). In order to account for the fact that only the stressed but not the unstressed syllable shortens (as found in Kim & Cole 2005), the foot oscillator’s strength (weight) in the interoscillator coupling function is modeled to be weaker during the unstressed than during the stressed syllables. Thus the syllable oscillator is dominant during the unstressed syllables. This leads to the foot oscillator’s squeezing being weaker during the unstressed than during the stressed syllables which results in shortening of the stressed but not of the unstressed syllables.

The model of Saltzman et al. (2008; see also Nam, Saltzman, Krivokapić, and Goldstein 2008, O’Dell and Nieminen 1999) does not predict strict isochrony, but it captures polysyllabic shortening and the *tendencies* towards isochrony, thus allowing both the empirical facts and the hard to capture division between stress-timed and syllable-timed languages to be accounted for. Typological differences between languages can be understood as the difference in the dominance of the foot and syllable oscillator (compatible with a gradiently varying scale of stress-timedness, as suggested in Dauer 1983).

Extending the planning oscillators to prosodic structure provides the possibility of understanding the prosodic hierarchy as a network of oscillators, where oscillators with higher frequencies (for lower prosodic phrases) are embedded into oscillators of lower frequencies (higher prosodic phrases), as discussed in Saltzman et al. (2008; see also Cummins & Port 1998, Goldstein 2012). This approach has not been fully implemented

within the Task Dynamics model of Articulatory Phonology (but see Tilsen's 2009 dynamical model for this type of approach). The integration of this hierarchy of oscillators with other aspects of prosodic structure (such as temporal and tonal boundary events) is also a matter of future research. One immediately obvious consequence of this conceptualization of the prosodic hierarchy is that, like in the π -gesture approach, prosodic phrases based on the planning oscillators do not differ qualitatively, corresponding to the evidence outlined in Section 2, they only differ in oscillator frequencies.

Note that two possible views of prosodic structure have been outlined: The prosodic hierarchy can be understood as arising from a hierarchy of nested planning oscillators or as arising through the coordination of the π -gesture (which can have a categorical or a gradient activation), other prosodic gestures, and constriction gestures. These approaches also entail two distinct views of prosodic boundaries. In one view (the π -gesture view), the boundary is a phonological unit, and in the other, the boundary is a consequence of phrases, without a separate phonological status. Future research will determine which of these directions represents a more accurate way of conceptualizing the prosodic hierarchy.

6. Summary and Outlook

Within Articulatory Phonology, prosodic structure is understood in a gestural manner. Prosodic boundaries are viewed as arising through the coordination of temporal, tonal, and constriction gestures. Rhythmic structure is determined by the μ -gesture and the coupling between foot and syllable oscillators.

Within this model, and as opposed to other prosodic models, temporal information is part of the linguistic representation, and the coordination of gestures is guided by general principles of coupling. The clear, predictive nature of this model has sparked numerous studies. In particular, it has allowed the question of the scope of effect of the boundary and of gestural coordination to be formulated precisely and has led to a number of studies examining the temporal properties of boundaries and the relationship between temporal properties of boundaries, tonal gestures, and prominence. The dynamical nature of the model also makes it possible to account for both gradient and categorical prosodic phenomena (as shown, for example, in the examination of boundary strength or in the properties of the foot) in a manner that would be difficult to capture in other models. Furthermore, the simultaneous examination of temporal and tonal prosodic events is crucial for any model of prosodic theory, but is facilitated in Articulatory Phonology by the understanding that all prosodic phenomena are gestures that can be coordinated to each other and in that way can influence one another. This view also suggests an extension of the model to integrate body gestures. Recent studies have found strong evidence that body gestures are timed to prosodic structure (e.g., Kraemer & Swerts 2007, Esteve-Givert & Prieto 2013, Rochet-Capellan et al. 2008). Speech production models, and models of prosodic structure in particular, need to uncover the principles of this coordination. Within the Articulatory Phonology model body gestures could be understood as gestures, for example a hand or head gesture. These would be associated, like constriction gestures, with planning oscillators, and coordinated with constriction and prosodic gestures following the same principles of coordination as other gestures.

Many aspects of the model remain to be developed, among them many that are not well understood regardless of the theoretical framework. However, the basic assumption of the model—the dynamic, gestural approach, in which prosodic units have temporal

properties and are coordinated with each other via general coupling mechanisms—should continue to lead to fruitful research.

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Figures

Figure 1. Schematic representation of oscillator coupling and the associated gestural timing relationships. Competitive coupling (which exists in syllable onsets) is shown in the left part of the figure, and the gestural timing can be for example for the syllable onsets in “pin” and “spin”. The dashed line in the gestural timing of the onsets represents the c-center, which stands in a stable relationship to the vowel regardless of the number of consonants in the onset. The left part of the figure shows coupling in syllable codas, and the examples of words having this gestural timing could be “tip” and “tips”. Figure adapted from Marin & Pouplier (2010).

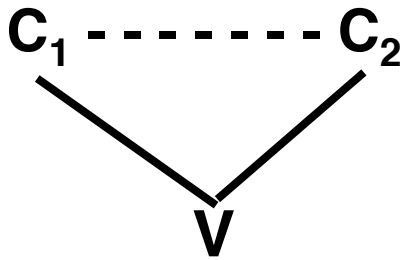
Figure 2. A schematic representation of the π -gesture model showing the overlap of the π -gesture and constriction gestures. The arrow indicates the strength of activation of the gesture, and the shading represents the scope of its effect, with darker shading indicating stronger activation. Figure adapted from Byrd, Krivokapić, & Lee (2006).



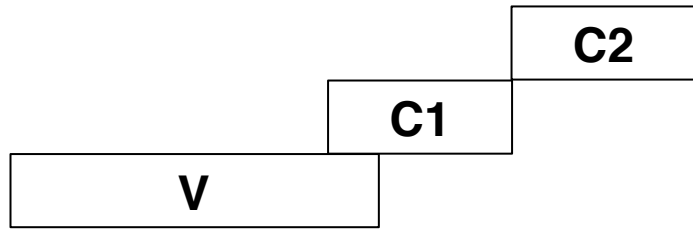
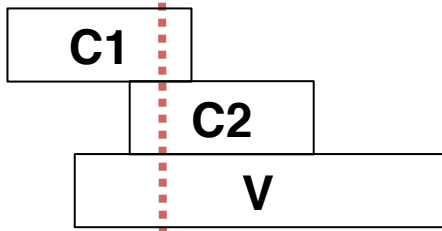
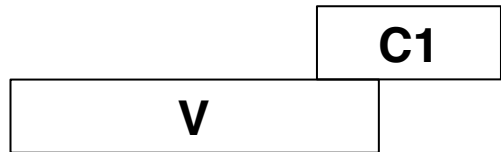
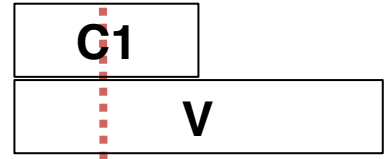
Competitive coupling (onset)

No competition (coda)

Oscillator coupling



Gestural timing



**Activation
strength**



Constriction

Constriction

Constriction

Scope of effect