24 Articulatory Phonology and Speech Impairment

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24.1 Introduction

In the field of Speech and Language Pathology, the distinction between "phonetics" and "phonology" has long been of interest, and much attention has been devoted to debating whether breakdown accounting for a variety of speech sound errors and disorders falls at one level or the other. In this chapter, we present accounts of speech impairment based on the theory of Articulatory Phonology (AP), which attempts to unify phonetics and phonology. As demonstrated in the following sections, Articulatory Phonology, in many cases, offers parsimonious account of impaired speech patterns based on principles of Task Dynamics (TD) and motor control, and, specifically, motor simplification, without the need to appeal to arbitrary rule-based processes.

24.2 Articulatory Phonology

Articulatory Phonology is a theoretical framework developed by Catherine Browman and Louis Goldstein beginning in 1986. AP aims to unify the physical and cognitive-linguistic levels of speech production (traditionally classified as "phonetic" and "phonological" levels, respectively), considering them to be low- and high-dimensional domains of a single system. The AP framework posits that the basic units of speech production are *gestures*, which serve both as units of lexical contrast (at the cognitive-linguistic level) and as units of articulatory movement (at the physical level) (Browman & Goldstein, 1989, 1992; Goldstein et al., 2006). These gestures consist of the formation and release of constrictions in the vocal tract and are described and modeled in terms of task dynamics and dynamical systems (Saltzman, 1986; Saltzman & Munhall, 1989). Dynamical systems are used to understand and model, using an equation or set of equations, quantitative changes in a given variable (e.g., position) over time, and can be characterized by the state of the system (e.g., tongue tip constriction degree) and a rule denoting how the state changes, depending on the current state. Within the AP framework, a gesture is defined as a dynamical system with set parameter values for defined vocal tract variables, such as *constriction location* and *constriction degree*. Both constriction location and degree can be conceptualized as the system's targets or end goals and are

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mathematically modeled as attractors in the system. Importantly, what such a system characterizes dynamically is *change* in vocal tract variables, such as constriction degree at a given constriction location, rather than the *motion* of individual articulators. In this way, given target attractors of the system, articulatory constriction formation can be modeled regardless of the start position of the articulators. A particular gesture is specified using one of the five possible sets of tract variables outlined in Table 24.1. The control regime for a given tract variable is comprised of the set of articulators used to form the constriction and release, as well as the parameter values in the dynamic equation that characterizes its movement and gives rise to the spatiotemporal unfolding of the constriction formation. Among these parameters are target (described above) and stiffness, which determines the rate at which the target is approached. The articulators in the control regime work synergistically toward the achievement of the specified parameter values, and are organized into a *coordinative structure* (Fowler et al., 1980; Turvey, 1977).

Given that gestures serve as basic units of phonological contrast, lexical items will contrast if they differ in gestural composition. These differences may involve (i) the presence or absence of a particular gesture; (ii) gestural parameters, such as target values for constriction degree; or (iii) the organization of the gestures. The organization and coordination of gestures within a particular lexical item, therefore, must be specified in critical ways to ensure perceptual recoverability. In this way, the relative timing of gestures that this organization gives rise to is information-bearing. It is this organization that AP posits comprises the phonological structure of speech.

Each gesture is associated with a planning oscillator, or clock, that is responsible for triggering its activation (Browman & Goldstein, 2000; Goldstein et al., 2006; Nam & Saltzman, 2003; Saltzman & Byrd, 2000). Articulatory studies have revealed that there are general principles that define how the activation of certain classes of gestures are organized or *phased* with respect to one another (Löfqvist & Gracco, 1999). As speech is being planned, each gesture's clock is set into motion at random phases and coupling forces specific to the gestural constellation at hand cause each gesture's clock to stabilize at specific relative phases before the triggering of each gesture's activation begins (Saltzman & Byrd, 2000).[1]

The *in-phase* mode of coupling is the most intrinsically simple and stable of all modes, and can be mastered with relative ease across modalities (e.g., drumming, speaking, etc.) (Haken et al., 1985). When coordinated *in-phase*, actions' activations are synchronous; one gesture's activation is triggered at 0° with respect to the other's activation. In CV sequences,

Table 24.1 Tract variable categories and articulators involved.

Tract variable	*Articulators involved*
Lip Aperture Lip Protrusion	Upper Lip Lower Lip Jaw
Tongue Tip Constriction Location Tongue Tip Constriction Degree	Tongue Tip Tongue Body Jaw
Tongue Body Constriction Location Tongue Body Constriction Degree	Tongue Body Jaw
Velic Aperture	Velum
Glottal Aperture	Glottis

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the gestures pertaining to the onset consonant and following vowel begin synchronously with one another (Browman & Goldstein, 2000; Goldstein et al., 2006; Nam, 2007), suggesting that the clocks associated with these gestures are coupled *in-phase*. Despite being triggered simultaneously, the gestures associated with CV syllables are recoverable due to differences in constriction degree, dynamic stiffness (causing the vocalic gesture to take longer to reach its target), and activation duration (allowing the vocalic gesture to remain active beyond the offset of the consonant gesture). The *in-phase* mode being the most intrinsically simple and stable is consistent with cross-linguistic data suggesting that CV sequences are the first to be mastered developmentally (Nam et al., 2009; Vihman & Ferguson, 1987).

The *anti-phase* mode of coupling is second most stable, and slightly less accessible than the *in-phase* mode (Haken et al., 1985). AP posits that the gestures involved in VC combinations are organized in the *anti-phase* mode, as the gesture(s) pertaining to the coda consonant begin later than the vocalic gestures. This is consistent with clocks associated with the gestures for the coda consonant being activated at 180º with respect to that of the vowel, resulting in sequential production. In accordance with the *anti-phase* mode being slightly less stable than the *in-phase* mode, consonants in coda position (i.e., VC) are developed by infants after those in onset position (i.e., CV) across languages (Vihman & Ferguson, 1987).

The aforementioned phase relations can be depicted using a *coupling graph* in which nodes represent the gestures and their respective planning oscillators and edges represent coupling relations between the pairs of planning oscillators. For example, in the word "mad" /mæd/, the labial closure gesture and the velic widening gesture corresponding to onset /m/ are coupled *in-phase* with each other and with the tongue body gesture corresponding to vowel nucleus /æ/, as represented by the solid connecting lines. The gesture corresponding to the vowel is coupled *anti-phase* with the tongue tip closure gesture corresponding to coda /d/, represented by the dashed line connecting them (Figure 24.1).

Coupling graphs give rise to *gestural scores*, which are used to generate motor commands for speech articulators. Gestural scores (Figure 24.2) display the activation duration of each gesture and therefore make observable any potential temporal overlap among them. The width of the box corresponding to a given gesture denotes the duration of time for which its set of values for the dynamic parameters are active. For example, in the word "mad" /mæd/, the lip closure gesture and the velic widening gesture corresponding to the onset consonant begin synchronously along with the tongue body gesture corresponding to the vowel. The activation duration for the lip closure gesture is shortest, while the velic widening gesture is slightly longer, and the activation duration of the tongue body gesture corresponding to the

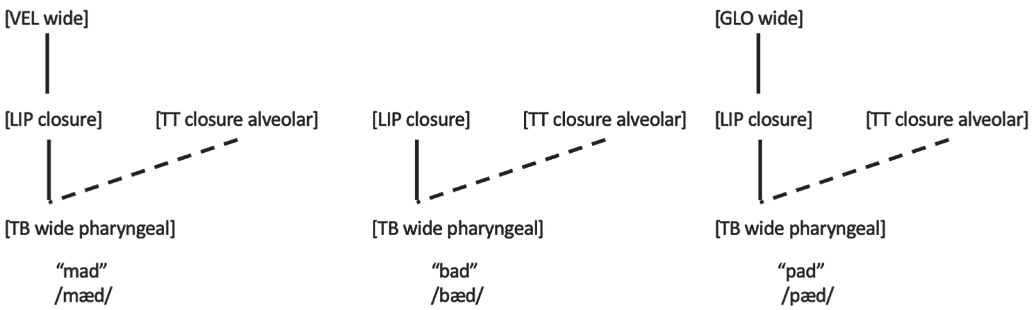

Figure 24.1 Coupling graph corresponding to the words "mad," "bad," and "pad." *In-phase* gestures are connected by solid lines whereas *anti-phase* gestures are connected by dashed lines.

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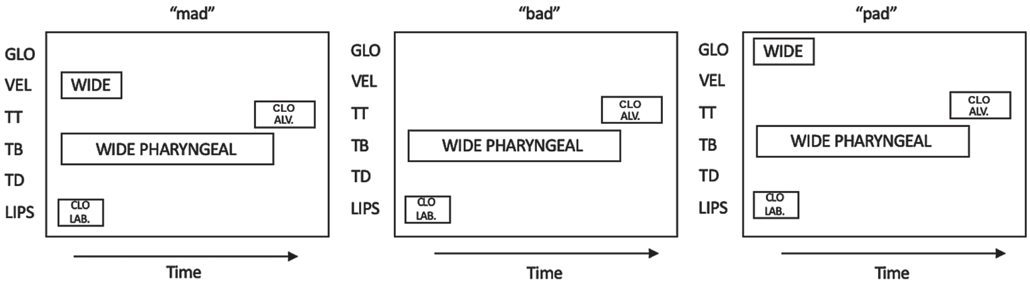

Figure 24.2 Gestural scores corresponding to the words "mad," "bad," and "pad."

vowel is longest. The tongue tip closure gesture, in its *anti-phase* relation to the tongue body gesture, is activated last in the sequence, overlapping only slightly in time with tongue body activation. The gestural scores for the words "mad" /mæd/ and "pad" /pæd/ are identical to the gestural score for "bad" /bæd/ except for the addition of the velic widening gesture and the addition of the laryngeal opening gesture, respectively.

These gestural scores exemplify how Articulatory Phonology is able to capture and unify both low-dimensional (e.g., phonological contrast) and high-dimensional (e.g., context-dependent variation) aspects of speech production that are otherwise attributed to "phonology" and "phonetics," respectively. The distinct gestural scores capture low-dimensional lexical contrast (i.e., between "mad," "bad," and "pad") based on the presence or absence of a single gesture (i.e., the velic widening gesture in "mad" and "bad" and the laryngeal opening gesture in "bad" and "pad"). Additionally, the relative timing of the laryngeal opening gesture, the labial closure gesture and the tongue body gesture in "pad" results in the well-attested aspiration of voiceless stops of English, a high-dimensional, context-dependent pattern (Goldstein & Fowler, 2003).

Tract variables specify goals of a gesture in terms of constriction location and constriction degree, hence controlling context-independent constriction trajectories. Gestural scores, together with their tract variable specifications (Table 24.1), are used to generate motor commands for speech articulators that work synergistically toward achievement of articulatory goals specified by those tract variables. These articulatory movements have aerodynamic and acoustic consequences.

In sum, AP posits that lexical items comprise gestures with intergestural coupling information. Tract variables specify goals of a gesture in terms of constriction location and constriction degree. The oscillators (clocks) associated with each gesture are coupled in a pairwise manner, are activated at random phases, and ultimately stabilize at their specified relative phases. The activation of these oscillators gives rise to gestural scores that represent sets of invariant gestures in the form of context-independent sets of dynamical parameter specifications, and specify temporal intervals during which constriction tasks actively control vocal tract articulators. These gestural scores are used to generate motor commands for speech articulators that work synergistically toward achievement of articulatory goals specified by tract variables. The resulting articulatory movements produce the aerodynamic and acoustic output ultimately perceived by listeners. *Interarticulator* coordination encompasses tract variable specification, which controls the context-independent constriction trajectories and the actual synergistic movements of articulators toward such goals. *Intergestural* coordination, on the other hand, is determined by the coupling information that yokes a set of gestures, determining the gestural score which specifies each gesture's activation interval and relative timing.

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24.3 Accounting for Patterns Exhibited in Developmental Speech of Typical Children and Those with Speech Delay or Impairment

While AP and TD have been used primarily to account for patterns in typical speech, recent work has demonstrated their utility also in accounting for patterns exhibited by individuals with speech impairment (Hagedorn et al., 2017, 2021, 2022; Namasivayam et al., 2020; van Lieshout et al., 2008). In the following sub-sections, we summarize how Articulatory Phonology and Task Dynamics can account for the atypical/developmental patterns observed and we identify the level(s) of the motor speech system at which the breakdown likely occurs, based on the existing evidence.

24.3.1 Weak Syllable Deletion

Weak syllable deletion refers to the omission of an unstressed syllable in speech (e.g., [ˈpju.ɾɚ] for /kʌm.ˈpju.ɾɚ/ "computer"). This can be accounted for by breakdown at the level of gestural planning oscillators corresponding to the gestures of the omitted syllable. If the gestural planning oscillators are absent or not appropriately activated, the triggering of the gestures which is dependent on those oscillators will also be absent.

24.3.2 Epenthesis

While epenthesis refers to the insertion of any non-target speech segment, neutral vowels are most frequently epenthesized, and tend to surface between consonants (e.g., [bə.ˈlæk] for /blæk/ "black") and word-finally, following coda consonants (e.g., [ˈbɔ.lə] for /bɔl/ "ball"). It is most likely that the percept of an epenthetic vowel surfaces due to erroneous relative timing among the target gestures. For example, complex phase patterns pertaining to consonant clusters (CCV) (specified at the levels of intergestural coupling and gestural planning oscillators) that are still being acquired and attuned in the child's system may be inaccurate or unstable. Children may consequently produce the gestures corresponding to consonants of a cluster with too great a lag (i.e., without sufficient temporal overlap) which will result in a perceptual and acoustic vocoid due to the absence of narrow vocal tract constriction during the period between the target consonantal constrictions. Similarly, it is possible that continued phonation beyond the offset of the final consonantal gesture(s) underlies vocoids that surface following voiced coda consonants. Such miscoordination between the laryngeal and supralaryngeal gestures' offsets would occur at the level of the gestural planning oscillators or mistiming of gestural scores.

24.3.3 Final Consonant Deletion

Final consonant deletion refers to the omission of coda consonants (e.g., [ɹɛ] for /ɹɛd/ "red"). While it is possible that all gestures corresponding to a particular segment are not entailed by a child's target representation of a particular lexical item,[2] in most cases, the pattern likely arises from motor simplification at a lower level.[3] At the level of intergestural coordination, failure of the oscillator(s) associated with the final consonant's gestures to be triggered would result in complete omission of the corresponding gestures. It is also possible that the gesture(s)' oscillators are triggered, but at an erroneous phase with respect to the preceding segments' gestures. Alternatively, the coda gestures' oscillators being triggered too early (e.g., between 0^{o} and 30^{o} with respect to the preceding onset consonant and vowel nucleus gestures) would likely result in erroneous co-production of the target coda gesture(s) with the target onset gesture(s). Depending on the timing of each gesture's formation and release, the coda gesture(s) may be covert, or not detectable in the acoustic signal, resulting in the perception of its omission (Surprenant & Goldstein, 1998). Similarly, depending on the target constriction degree of the final consonant segment, it is possible that perception of final consonant deletion arises due to miscoordination of the supralaryngeal articulators with the laryngeal articulators that control phonation. It is also possible that breakdown occurs at the level of tract variable specification, and that the constriction degree tract variable specification of the final consonant is too wide. Finally, acoustic and perceptual omission of the final consonant could also arise from inaccuracies at the level of articulatory synergy; if one or all articulators do not create a sufficient constriction, no final consonant will be detected in the acoustic signal.

24.3.4 Cluster Reduction and Deletion

Cluster reduction refers to the elimination of a subset of the target segments in a consonant cluster (e.g., [pa] for /spa/ "spa"), while cluster deletion refers to the omission of all segments in a target cluster (e.g., [a] for /spa/ "spa"). Onset clusters pose a particular challenge because of the complex coordination patterns that underlie their target production; we refer the reader to Marin and Pouplier (2010) for detailed explanation of these *competitive coupling* patterns.

Given the complex intergestural coupling patterns required for consonant clusters, breakdown at the level of intergestural coordination (i.e., intergestural coupling information, gestural planning oscillators, and gestural score activation) is most likely. This would cause all or some of the target gestures' activations not to be triggered, resulting in complete or partial omission of the cluster. Similarly, this could cause gestures to be triggered at inappropriate phases, resulting in the perception of only a subset of the consonants in a cluster due to gestural overlap. Alternatively, a child's target not entailing all appropriate gestures will result in omission of all or some of the segments in the cluster. Breakdown at the level of tract variable specifications also may result in cluster omission or deletion. Alternatively, constriction degree specification of one or more gesture being too wide, or constrictions at the articulatory synergy level that are not sufficiently narrow to render an acoustic percept may result in the percept of cluster reduction or deletion.[4]

24.3.5 Voicing, Nasal, and Place Assimilation

Voicing, nasal, and place assimilation in atypical speech refers to segments being erroneously produced with specific attributes of nearby segments. Errors of assimilation can most be straightforwardly accounted for by simplification of the motor patterns produced (e.g., through deletion of gestures or shifting the phase relations of gestures to an intrinsically simpler, more stable mode).

The most prevalent voicing assimilation pattern observed in developmental speech is prevocalic voicing (e.g., [bat] for /pat/ "pot"), which refers to target voiceless consonants in onset position being produced with voicing by influence of the following vowel. Articulatory Phonology posits that since the resting state of the vocal folds is adduction, glottal gestures are required for the production of target voiceless segments but not target voiced segments (Goldstein & Browman, 1986). Prevocalic voicing can be accounted for by breakdown at the level of intergestural coordination (i.e., intergestural coupling information, gestural planning oscillators, and gestural score activation) which prevents the activation of the onset consonant's glottal opening gesture from being triggered altogether, or at the appropriate time. All gestures corresponding to the onset consonant and the vowel are coordinated in-phase, such that their activations are triggered synchronously. It may be that despite the in-phase mode being most accessible, the developing system is taxed by the presence of multiple gestures needing to be planned and executed synchronously.

Similarly, nasal assimilation, by which target oral segments are produced as nasal in the presence of a target nasal segment (e.g., [mæ̃n] for /mæd/ "mad"), likely arises due to breakdown at the level of intergestural coordination causing the onset or offset of a single, target velic gesture to be mistimed with respect to the other target oral gestures in the sequence. Conversely, denasalization (e.g., [bæd] for /mæd/ "mad") likely arises due to breakdown at the level of intergestural coordination which prevents the activation of the velic lowering gesture from being appropriately triggered.

Place assimilation refers to the constriction location of a target segment being influenced by the constriction location of a segment in the vicinity (e.g., [bɛb] for /dɛb/ "Deb"). While Articulatory Phonology and the Task Dynamics model do not have mechanisms by which long-distance anticipatory assimilation[5] can be straightforwardly accounted for, recent extensions to the model proposed by Tilsen et al. (2016, 2019a) do. In the selection-coordination framework, gestures associated with upcoming speech segments are sequenced through competitive queuing, in which motor plans associated with each target initially have stable relative levels of excitation which, over time, rise until one plan reaches a selection threshold and is therefore executed while its competitors' (plans for other segments in the vicinity) excitations are temporarily gated. Achievement of a particular target induces suppression of that plan and de-gating of competing plans, allowing the plan with the next highest excitation level to reach the selection threshold. This continues iteratively until all plans have been selected (Tilsen, 2019b). Plans being executed prematurely, as in cases of anticipatory place assimilation errors, could be caused by error in enforcing appropriate selection thresholds (i.e., setting the threshold too low) or by erroneous assignment of the relative activation level for a particular plan, itself. Alternatively, inappropriate specification of parameters defining the "leaky gating" function – the mechanism by which even gestures that are not selected can exert influence on vocal tract shaping – may account for certain plans exerting premature and excessive influence on the vocal tract.

24.3.6 "Substitution" Patterns: Stopping, Fronting, Backing, Deaffrication, Palatalization, Depalatalization, Gliding, and Vocalization

Several error patterns exist that have historically been categorized as "substitution" patterns. Such categorization reflects presumption that target segments are substituted with non-target segments that differ in terms of place or manner of articulation. Among these patterns are stopping, fronting, backing, deaffrication, palatalization, depalatalization, gliding, and vocalization. Based on the existing evidence and predictions made by Articulatory Phonology and Task Dynamics, we propose that these patterns most likely emerge due to breakdown at the level of inter-articulator coordination (i.e., tract variable specification and articulator movement and synergy) rather than due to substitution of targets with non-target segments at higher (i.e., gestural) levels.

Stopping refers to replacement of a target fricative segment with a homorganic oral stop (e.g., [tɪp] for /sɪp/ "sip"). Fricatives are a notoriously difficult class of speech segments to master, given that they require the articulators to form constrictions with very particular aperture specifications, necessitating meticulous articulatory control (Stevens, 1971, 1972) and it is suggested that constriction degree targets for fricatives are likely specified with more precision than for other sounds (MacNeilage, 1970; Saltzman & Byrd, 2000). Stopping can therefore be accounted for by breakdown at the level of tract variable specification, at the level of synergistic articulatory movement execution, or both.

Velar fronting refers to target velar segments being produced at more anterior constriction locations on the palate (e.g., [tæp] for /kæp/ "cap"). The converse, coronal backing, refers to target coronal segments being produced more posteriorly (e.g., [kæp] for /tæp/ "tap"). Several studies have revealed that children who exhibit these patterns produce *undifferentiated lingual gestures*, in which movement of the tongue tip, tongue body, tongue dorsum, and the lateral margins of the tongue are not independently controlled (Gibbon, 1999; Gibbon & Wood, 2002; Goozée et al., 2007). It has been speculated that this pattern is driven primarily by developmental constraints on the independent movement of the jaw and tongue (Byun, 2012; Cleland & Scobbie, 2021; Davis & MacNeilage, 1995; Green et al., 2002). Additionally, Gibbon and Wood (2002) observed that undifferentiated lingual gestures are unlikely to be completely released at any one moment in time, resulting in *articulatory drift*, the direction of which determines which percept is formed; if an anterior constriction is released before posterior constriction, a velar is likely to be perceived, while if a posterior constriction is released before an anterior constriction, an alveolar is likely to be perceived (Cleland & Scobbie, 2021). Additionally, studies have demonstrated that many children exhibit *covert contrast* for these segments, in which subtle acoustic or articulatory differences exist between speakers' attempts of each target even when no detectable perceptual differences exist, and that perceptually acceptable /k/ is acquired in a gradient manner (Cleland & Scobbie, 2021; McAllister Byun et al., 2016; Scobbie et al., 1996). These findings suggest that (i) fronting and backing patterns do not reflect selection errors at the planning stage involving substitutions of entire target segments, (ii) children do have distinct articulatory targets for the contrastive segments, and (iii) such errors arise from breakdown at lower levels affecting articulatory movement and synergies, in the case of undifferentiated lingual gestures, and/or at the level of intergestural coordination, in the case of mistimed release gestures.

Palatalization refers to target alveolar fricatives being produced at a post-alveolar constriction location (e.g., [ʃi] for /si/ "see"), while depalatalization refers to target post-alveolar fricatives or affricates being produced at a more anterior, alveolar constriction location (e.g., [si] for /ʃi/ "she"). It is possible that the acoustic percepts of palatalization and depalatalization arise due to undifferentiated lingual movement compromising constriction location accuracy, reflecting breakdown at the level of articulator synergy and movement. Given the complexity of articulation and the turbulent airflow necessary for sibilant production (Narayanan & Alwan, 2000; Narayanan et al., 1995; Proctor et al., 2010; Shadle et al., 1996; Stevens, 1971) the control of distinct lingual regions poses a substantial motoric challenge to the speech system which is apparent especially during development (Cheng et al., 2007; Denny & McGowan, 2012; Green et al., 2000). It is also possible that these patterns are caused by erroneous constriction location or constriction degree tract variable specification, or due to temporal miscoordination of the multiple lingual gestures required (i.e., breakdown at the levels of gestural planning oscillators or gestural score activation).

Deaffrication refers to target affricate segments (e.g., /tʃ/, /dʒ/) being produced as either fricative or stop segments (e.g., [wɪt] or [wɪʃ] for /wɪtʃ/). In the AP/TD framework, affricates are composed of a stop constriction with a fricative release. As described above, fricative production poses a challenge to the motor speech system due to the very narrow range of permissible aperture values involved. Cases of fricative release omission could be accounted for by erroneous specification of the constriction degree tract variable corresponding to the release of the stop, omission of the constriction release specifications altogether, or difficulty at the level of articulatory movement and synergy. Cases of stop constriction omission (in which only a fricative remains) could be accounted for by erroneous specification of the constriction degree tract variable.

Gliding refers to target liquids (e.g., /l/ and /ɹ/) being produced as glides (e.g., /j/, /w/) (e.g., [ˈjɛ.woʊ] for /jɛ.loʊ/ "yellow"; [wɛd] for /ɹɛd/ "red"), while vocalization refers to these same target segments being produced as vowels (e.g., [ˈsæ.dʊ] for /sæd.l̩/ ("saddle")). /l/ and /ɹ/ require multiple lingual constrictions which pose a motoric challenge for the developing motor speech system due to the requirement of lingual differentiation (Cheng et al., 2007; Gibbon, 1999; Green et al., 2000; Lin & Demuth, 2015; Studdert-Kennedy & Goldstein, 2003).

American English /l/ is produced with both anterior and posterior lingual constrictions, and possibly with active lateral channel formation (Browman & Goldstein, 1995; Ying et al., 2021). Prior to mastery of target /l/, individuals tend to simplify the production, omitting either the anterior or posterior constriction, resulting in percepts approximating /w/ if the anterior constriction is omitted, or /j/ if the posterior constriction is omitted (Lin & Demuth, 2015). Vocalization will arise if the constrictions formed are not sufficiently narrow.

American English /ɹ/ is also produced with multiple simultaneous lingual constrictions. Although /ɹ/ production varies substantially among typical speakers (Zhang et al., 2003), Preston et al. (2020) outlines five articulatory requirements for accurate production: oral constriction involving raising of some portion of the front half of the tongue, tongue root retraction to create a pharyngeal constriction, lowering the midline of the posterior tongue body, contact of the lateral margins of the tongue body with the back teeth or gums, and slight lip rounding. Like /l/, during development and in individuals with speech impairment, /ɹ/ may be typically produced with only a subset of the required gestures. These patterns give rise to the percepts of gliding (e.g., [w]) or general rhotic distortion.

The simplification of the complex target liquids described above may be caused by breakdown at one or more of the following levels: defining required gestures, intergestural coordination, specification of constriction location, and degree tract variables for all gestures, formation of articulatory synergies (including differential control of distinct parts of the tongue), and articulatory movement.

24.4 Accounting for Patterns Exhibited in Articulation Impairment

"Articulation impairment" typically refers to errors in the production of rhotics or sibilants (e.g., derhotacization, [hʌ] for /hɝ/ "her"; s-distortions [s̪i] or [ɬi] for /si/ "sea"), and is presumed to involve breakdown at the level of speech motor specification and implementation (McLeod & Baker, 2017; Namasivayam et al., 2020; Preston et al., 2013). Within the AP/TD framework, it likely involves breakdown at the levels of defining required gestures, specification of constriction location and degree tract variables for all gestures, relative timing of all gestures (intergestural coordination), and articulatory synergies (including differential control of distinct parts of the tongue).

24.5 Accounting for Patterns Exhibited in Childhood Apraxia of Speech (CAS)

Childhood Apraxia of Speech (CAS) is a developmental motor speech disorder associated with purported deficits in planning and programming of speech motor commands. CAS characteristics include (i) impaired movement transitions between articulatory configurations and in coarticulation, (ii) groping or trial-and-error behavior, (iii) vowel distortions, (iv) impaired prosody, (v) voicing errors, (vi) consonant distortions due to "blending" of manner, and (vii) inconsistent errors across repetitions of the same word or phrase (Shriberg et al., 2017; Strand et al., 2013). Several recent experimental studies have demonstrated that children with CAS exhibit increased articulatory movement variability as compared to both children with typically developing speech and children with other speech sound disorders (Case & Grigos, 2020; Grigos et al., 2015; Moss & Grigos, 2012; Terband et al., 2012). Moreover, they have been observed to produce longer articulatory movement durations and larger movement amplitudes (Case & Grigos, 2016, 2020; Grigos & Case, 2018) as well as atypical behavior of single articulatory movements, and atypical interarticulator and intergestural coordination (Grigos et al., 2015; Munson et al., 2003; Nijland et al., 2002; Terband et al., 2011). Within Articulatory Phonology and Task Dynamics, the speech motor *planning* presumed to be affected in CAS is associated with intergestural coupling information, planning oscillators, and gestural score activations. The speech motor *programming* affected corresponds to interarticulator coordination and encompasses tract variable specification and articulatory movement/synergy formation.

24.6 Accounting for Patterns Exhibited in Apraxia of Speech (AOS)

Apraxia of Speech (AOS) is a neurogenic motor speech disorder that oftentimes occurs concomitantly with aphasia. While the exact neural substrates of AOS have yet to be unequivocally identified, it has been traditionally assumed that lesions to the left posterior inferior frontal gyrus (Broca's Area (BA 44)) and the ventral premotor cortex (BA6) are implicated (Richardson et al., 2012; Ziegler et al., 2021). However, recent work suggests that the middle precentral gyrus plays a unique role in speech motor planning and execution and that injury to this area results in pure apraxia of speech (Silva et al., 2022). AOS is classically defined as a disorder affecting the spatial and temporal planning and programming of speech motor commands specified in a target sequence (Ballard et al., 2015; Ziegler et al., 2012) and is generally characterized by speech production errors, reduced rate of speech, increased segment durations, increased intersegment (i.e., transition) durations, and other prosodic difficulties (Duffy, 2019; McNeil, 2000; McNeil et al., 1997, 2009; Ogar et al., 2005; van Lieshout et al., 2007; Wambaugh et al., 2006). These difficulties may exist alongside behaviors including articulatory groping, attempts to repair errors, difficulty with speech initiation (Duffy, 2019; Wambaugh et al., 2006).

AOS has been evidenced to result in increased variability of individual articulators (Bartle-Meyer et al., 2009a, 2009b; Itoh et al., 1979; McNeil et al., 1989, 1991; Hoole et al., 1997) and impairment of interarticulator and intersegmental coordination (Itoh et al., 1980, 1982; van Lieshout et al., 2007; Ziegler & Von Cramon, 1985). Several studies have revealed that many errors in apraxic speech impressionistically characterized as "substitutions" can more accurately be described as intrusions, in which intrusive gestures are *coproduced* with gestures pertaining to the target segment (Bartle-Meyer et al., 2009a; Hagedorn et al., 2017; Hardcastle et al., 1985; Pouplier & Hardcastle, 2005; Sugishita et al., 1987).

Articulatory breakdown in AOS likely results from the loss of procedural memories required to produce individual gestures as well as gestural combinations of varying sizes (e.g., segments, clusters, syllables, etc.) (Ziegler, 2008; Ziegler et al., 2021). This "glue" has been proposed to serve as cohesion of gestural components, both within and across segments, specifying coordination patterns. When this "glue" is lost, the speaker must assemble all movement components a tabula rasa, giving rise to the many clinical manifestations of AOS (Ziegler et al., 2021). In AP and TD, this breakdown occurs at levels of intergestural coupling, planning oscillator activation, and gestural score activation, determining how gestures are coordinated with each other in space and time, as well as at the level of articulator movement and synergy, determining relative contribution of various articulators to a goal.

24.7 Accounting for Patterns Exhibited in Dysarthria

Dysarthria refers to a class of several neurogenic speech disorders that can be further characterized based on the physiological level of breakdown implicated and characteristics of the resulting movement disorder. The locus of pathophysiology may be the central or peripheral nervous system or the articulatory organ itself, and may be congenital, as in the case of Cerebral Palsy, or acquired, as in cases of Amyotrophic Lateral Sclerosis, Parkinson's Disease, demyelinating or inflammatory diseases, or surgical or radiological trauma as part of treatment for head and neck cancer.

The articulatory patterns observed in speakers with dysarthria tend to vary by dysarthria type, though some characteristics are shared. Individuals with Parkinson's Disease (PD), Multiple Sclerosis (MS), and Amyotrophic Lateral Sclerosis (ALS) have been observed to produce impaired segment duration, reduced movement amplitude, and reduced speed (Connor & Abbs, 1991; Forrest et al., 1989; Hirose et al., 1981; Liss et al., 2009; Mefferd et al., 2019; Yunusova et al., 2008). These patterns can be accounted straightforwardly by breakdown of the dynamical parameter specification for stiffness (see Kim et al. (2021) for evidence supporting lower articulatory stiffness in speakers with ALS and MS and Goozee et al. (2000) for evidence that control of articulatory speed is the locus of impairment in dysarthria secondary to traumatic brain injury (TBI)). Individuals with ALS, PD, and TBI also exhibit patterns consistent with impaired intergestural and intragestural coordination, including reduced spatiotemporal coupling between lingual regions (Kuruvilla et al., 2012) as well as different relative contributions of the jaw and tongue in lingual constrictions (Bartle et al., 2006; Mefferd & Dietrich, 2019; Mefferd et al., 2012; Rong & Green, 2019). Impairment of lingual flexibility observed in individuals Parkinson's Disease (Whalen et al., 2014) and following partial glossectomy (Hagedorn et al., 2021) may be attributable to breakdown at the level of interarticulator coordination or articulator movement.

24.8 Conclusion

In this chapter, we provide accounts of a number of speech error patterns from an Articulatory Phonology and Task Dynamics perspective. We demonstrate that error patterns that may be traditionally classified as "motoric" ("phonetic") or "phonological" in nature can be accounted for by positing breakdown or simplification at one or more levels of the Articulatory Phonology and Task Dynamics model, which reconciles the phonetics-phonology dichotomy.

Adopting this framework has the additional merits of enabling characterization of the disorders in a more fine-grained manner (for example, distinguishing between impairment in articulator movement speed and *control* of speed in certain sub-types of dysarthria) as well as offering explanation of error patterns using basic concepts in task dynamics and motor control which have also been used to account for numerous behavioral phenomena across fields. By approaching speech disorders and speech error patterns in such a way, not only can error patterns and the disorders by which they are underlain be more effectively characterized, but through such characterization, clinical intervention for these disorders can be better informed, and thus optimized.

While the Articulatory Phonology and Task Dynamics model offers new insight into speech error patterns, it does have limitations. For example, it does not include any mechanism by which auditory feedback can be incorporated, rendering it unable to account for errors based on impaired auditory feedback (e.g., Houde et al., 2019; Sangtian et al., 2021) or effects of perturbed feedback on the system's behavior (e.g., Niziolek & Parrell, 2021). And, unlike some other models of speech production (e.g., Tourville & Guenther, 2011), the Articulatory Phonology and Task Dynamics model does not explicitly specify neurological structures or neurophysiological processes involved in each component, though extensions of the model (e.g., Tilsen, 2016, 2019b) do so to some degree.

It is our intent that this chapter serve also to inspire future directions of research focused on testing theory-based hypotheses regarding speech impairment, which will ultimately give rise to more complete characterization of the disorders at hand, more refined treatment strategies, and possibly refinement and extensions of the theory, itself.

NOTES

1 Importantly, the relative phase of gestures' clocks which determines the time of each gesture's triggering is controlled by the coupling relations between the clocks of individual pairs of gestures rather than by a master clock. For evidence, see Byrd (1996).
2 Omission of the segment in the target form could result from the child never having perceived the segment in modeled productions, such as in cases of hearing loss.
3 Evidence that all target gestures are likely present in the lexical representations of children without hearing loss includes their ability to discriminate between adult target forms and forms attempted by the child as reproduced by adults.
4 Breakdown at the tract variable specification level would be expected to affect the same segments in simple onset and coda positions, as well.
5 Here, we refer to long-distance assimilation in which intervening segments are unaffected.

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