

**The A-map model: Articulatory reliability  
in child-specific phonology**

Tara McAllister Byun

Sharon Inkelas

Yvan Rose

Corresponding addresses:

Tara McAllister Byun

Department of Communicative Sciences and Disorders  
Steinhardt School of Culture, Education and Human Development  
New York University  
665 Broadway, 9th Floor  
New York, NY 10012  
USA  
tara.byun@nyu.edu

Sharon Inkelas

Department of Linguistics  
University of California  
Berkeley, CA 94720  
USA  
inkelas@berkeley.edu

Yvan Rose

Department of Linguistics  
Memorial University of Newfoundland  
St. John's, Newfoundland, A1B 3X9  
Canada  
yrose@mun.ca

**The A-map model: Articulatory reliability  
in child-specific phonology**

## Abstract

This paper addresses a phenomenon of longstanding interest: the existence of child-specific phonological patterns which are not attested in adult language. We propose a new theoretical approach, termed the A(rticulatory)-Map model, to account for the origin and elimination of child-specific phonological patterns. Due to the performance limitations imposed by structural and motor immaturity, children's outputs differ from adult target forms in both systematic and sporadic ways. The computations of the child's grammar are influenced by the distributional properties of motor-acoustic traces of previous productions, stored in episodic memory and indexed in the eponymous A-map. We propose that child phonological patterns are shaped by competition between two essential forces: the pressure to match adult productions of a given word (even if the attempt is likely to fail due to performance limitations), and the pressure to attempt a pronunciation that can be realized reliably (even if phonetically inaccurate). These forces are expressed in the grammar by two constraints that draw on the motor-acoustic detail stored in the A-map. These constraints are not child-specific, but remain present in the adult grammar, although their influence is greatly attenuated as a wide range of motor plans come to be realized with a similar degree of reliability. The A-map model thus not only offers an account of a problematic phenomenon in development, but also provides a mechanism to model motor-grammar interactions in adult speech, including in cases of acquired speech impairment.

**Keywords:** A-map, Phonology, Acquisition, Sensorimotor mapping, Speech articulation, Accuracy, Precision

## The A-map model: Articulatory reliability in child-specific phonology

### 1. Introduction

This paper proposes a new theoretical approach to account for the existence of *child-specific phonological patterns*, a phenomenon of longstanding interest in the literature on developmental phonology.<sup>1</sup> By child-specific phonological patterns, we refer to any systematic patterning of sounds found in the speech of children but not in adult typology. Some of these patterns are common among young children (e.g. Bernhardt & Stemberger 1998), while others are idiosyncratic and specific to certain individuals, especially in the earliest period of word productions (e.g. Ferguson & Farwell 1975; Macken 1979; Vihman & Croft 2007). The existence of child-specific phonological patterns is problematic for models that assume continuity between child and adult grammars (e.g. Macnamara 1982; Pinker 1984). The present work was undertaken with the goal of explaining child-specific phonology without abandoning the assumption that child grammars draw from the broad space of possible adult grammars.

Due to anatomical and motor control differences, children and adults are subject to distinct pressures in the physical act of producing speech.<sup>2</sup> We argue that child-specific patterns have transparent roots in these phonetic differences, yet they also have the systematic and categorical quality that is the hallmark of phonological grammar. This leads us to our core claim that child-specific phonological patterns constitute evidence for constraints that grammatically encode a substantive bias favoring the production of candidates whose associated motor-acoustic mappings are stable/reliable for a given speaker. To integrate motor pressures into the phonological grammar, we draw on the mechanism of an *internal model* representing a speaker's knowledge of mappings between motor plans and sensory outcomes (e.g. Wolpert, Ghahramani & Flanagan 2001), which we represent with an exemplar space of episodic traces encoding inputs perceived and outputs produced. The informational content of the internal model is distilled in a grammatical module that we term the A-MAP. We posit two constraints whose violation magnitudes are determined via reference to the A-map. The first, ACCURATE, penalizes a candidate in proportion to the distance in acoustic-perceptual space between the internal model's prediction of the child's output and the center of the cloud of traces representing the adult target. The second constraint, PRECISE, penalizes a candidate in proportion to the average distance between traces representing actual outputs and intended outputs (efference copies),

which can diverge in cases of performance error. Crucially, these constraints are not child-specific; they remain active in the grammar, albeit with diminishing influence as a wide range of speech targets become stable over the course of motor maturation. The A-map model thus is not only an account of developmental phenomena, but also offers a mechanism to model motor-grammar interactions in adult speech, including in cases of acquired speech impairment (e.g. Buchwald & Miozzo 2011).

The paper begins with a discussion of child-specific phonological patterns in section 2, followed in section 3 by a critique of models that have been proposed to capture them. In section 4, we explore the role of performance limitations in children's trajectories of speech development, emphasizing the intertwined nature of motor maturation and lexical-grammatical development. We introduce the A-Map model in sections 5-6, followed by an illustrative case study in section 7. In section 8, we focus on the A-map model's capacity to capture the elimination of child-specific phonological patterns, as well as the potential for reemergence in the context of acquired speech deficits. Section 9 offers a brief discussion of the novelty and broader implications of the A-map model, and section 10 concludes the paper.

## **2. Child-specific speech patterns as a challenge for formal models of phonology**

The phenomenon of child-specific phonological processes represents a longstanding challenge for phonological theories whose aim is to model all and only the phonological patterns that are found in human language. The processes in question are robustly attested in the speech of typically developing children, but lack counterparts in adult phonological typology (see overviews in Rose & Inkelas 2011; Vihman 2014). In some cases they diverge sufficiently from the norm in adult phonology to have been called “unnatural” or “crazy” (Buckley 2003). A well-known example is the phenomenon of positional velar fronting in English, in which velar consonants are realized with coronal place in word- or foot-initial but not foot-internal contexts (e.g. Ingram 1974; Chiat 1983; Stoel-Gammon & Stemberger 1994; Bills & Golston 2002; Inkelas & Rose 2003, 2007; Dinnsen 2008; Dinnsen et al. 2011; McAllister Byun 2012). In adult grammars, synchronic /k/ → [t] alternations<sup>3</sup> are attested marginally or not at all, whereas velar fronting is a commonly observed process in children up to three years, six months of age (Grunwell 1981). The positional character of some children's velar fronting is especially noteworthy. With a few well-understood exceptions (e.g. Steriade 1999; Steriade 2001), adult

languages follow an implicational generalization whereby the existence of a featural contrast in a prosodically weak position implies its presence in prosodically strong contexts. As the examples in (1) reveal, the child pattern of positional velar fronting shows precisely the opposite bias, neutralizing lingual place contrasts in strong position only:<sup>4</sup>

(1) Positional velar fronting (data from Inkelas & Rose 2007: 710-711)

a. Fronting of velars in prosodically strong positions

<u>Orthography</u>	<u>IPA Target</u>	<u>IPA Actual</u>	<u>Age</u>
<i>cup</i>	'kʰʌp	['tʰʌp]	1;09.23
<i>again</i>	ə'gɛn	[ə'dɪn]	1;10.25
<i>hexagon</i>	'hɛksə'gʌn	['hɛksə'dɔn]	2;02.22
<i>conductor</i>	kən'dʌktəɹ	[tʌn'dʌktə]	2;01.21

b. Absence of velar fronting in prosodically weak positions

<i>monkey</i>	'mʌŋki	['mʌŋki]	1;08.10
<i>bagel</i>	'beɪgəl	['beɪgu]	1;09.23
<i>octopus</i>	'ʌktəpʊs	['ʌktəpʊs]	2;04.09
<i>back</i>	'bæk	['bæk]	1;10.02

A superficially similar child-specific pattern is positional fricative neutralization, in which fricatives are replaced with stops or glides in prosodically strong positions (e.g. Chiat 1989; Rvachew & Andrews 2002; McAllister Byun 2011). For example, Chiat (1989) and Marshall & Chiat (2003) document an English-learning child, aged 4;7-4;10, who substituted stops for fricatives foot-initially (*sun* ['tʌn], *decide* [də'taid]) but not foot-medially (*person* ['pɜ:sən], *ozone* ['əʊzəʊn]) or foot-finally (*miss* ['mɪs]) (data adapted from Marshall & Chiat 2003:651–653). In section 7, we present a similar case study of positional fricative stopping attested in the productions of a Portuguese-acquiring child.

A third example of a child-specific pattern is major place assimilation of consonants to vowels. Bates, Watson & Scobbie (2002:152) cite Fudge's (1969) example of an English-learning child aged 1;4 whose realization of coronal, labial, and velar obstruent place was contingent on the place of the following vowel. Data are given in (2) below.<sup>5</sup> Target labial and

velar stops take on coronal place before a front vowel, while target coronals are realized with labial place before a back rounded vowel and with velar place before a back unrounded vowel. Note that in the examples in (2), the conditioning influence is exerted by the properties of the vowel as realized by the child, rather than the adult vowel target.

(2) Context-dependent realization of obstruent place (age 1;4)

a. Coronal place before a front vowel

<i>drink</i>	dɪŋk	[tɪ]
<i>again</i>	əgɛn	[dɛn]

b. Labial place before a back rounded vowel

<i>ball</i>	bəl	[bo]
<i>book</i>	bʊk	[bo]
<i>dog</i>	dɑg	[bobo]

c. Velar place before a back unrounded vowel

<i>truck</i>	tɹʌk	[kʌk]
<i>garden</i>	gɑɹdɛn	[gʌŋ]
<i>doggie</i>	dɑgi	[gʌgʊ]

Although adult phonologies do permit consonant-vowel interactions such as palatalization of velars before front vowels, and show a limited amount of vowel assimilation to the major place of consonants (e.g. Ní Chiosáin & Padgett 1993; Hume 1996), there is no adult phonological pattern comparable to the three-way neutralization across major place of articulation seen in (2).

A fourth, often-cited example of child-specific phonology is child consonant harmony (e.g. Smith 1973; Stoel-Gammon & Stemberger 1994; Goad 1997; Pater 1997; Pater 2002; Pater & Werle 2001; Pater & Werle 2003; Becker & Tessier 2011; McAllister Byun & Inkelas 2014). Although adult typology does include instances of nonlocal consonant assimilation (e.g. Shaw 1991; Hansson 2001; Rose & Walker 2004), child consonant harmony is unique in allowing assimilation for major place of articulation. The examples in (3) show that child consonant harmony can involve long-distance assimilation of coronal to labial or velar place and labial to velar place, among other attested patterns.

## (3) Child consonant harmony (Pater &amp; Werle 2001, citing Compton &amp; Streeter 1977)

## a. Regressive assimilation: Velar trigger, coronal or labial undergoer

<i>dog</i>	dɑg	[gɔg]	1;5.14
------------	-----	-------	--------

<i>bug</i>	bʌg	[gʌg]	1;5.18
------------	-----	-------	--------

## b. Regressive assimilation: Labial trigger, coronal undergoer

<i>top</i>	tɒp	[pʌp]	1;6.8
------------	-----	-------	-------

## c. Progressive assimilation: Velar trigger, coronal or labial undergoer

<i>coat</i>	kɒt	[kɒk]	1;5.18
-------------	-----	-------	--------

<i>cup</i>	kʌp	[kʌk]	1;5.13
------------	-----	-------	--------

**3. Approaches to child-specific phonology**

The existence of child-specific phonological patterns is problematic for ‘continuity’ models positing that child and adult grammars draw from the same grammatical primitives (e.g. Macnamara 1982; Pinker 1984). These include constraint-based models of grammar which assume that child and adult phonologies reflect different rankings of a shared set of universal constraints (e.g. Prince & Smolensky 1993/2004). If the constraints that drive child-specific patterns are part of a universal inventory, they should have some reflex in adult typology — contrary to the actual evidence from cross-linguistic surveys. Previous responses to this theoretical conundrum can be classified into three major categories.

**3.1. Pure performance**

The PURE PERFORMANCE school of thought (e.g. Hale & Reiss 1998, 2008) holds that child-specific patterns are strictly the product of performance limitations of young children and are unrelated to their grammatical competence. Hale & Reiss equate child-specific phonology with “pseudophonological” effects in adult speech for which a phonological explanation clearly is not appropriate. They give the example of the “intoxicated ... captain of the Exxon Valdez around the time of the accident at Prince William Sound,” which Johnson, Pisoni & Bernacki (1990) found to feature “misarticulation of /r/ and /l/, deaffrication, final devoicing” (Hale & Reiss 1998: 669). The pure performance approach makes it possible to maintain a strong version of the



continuity hypothesis: children are posited to have adult grammars, with any apparent deviations arising from their faulty production apparatus.

It is unquestioned that performance factors play a key role in the inception of child-specific phonological patterns. However, the pure performance view is inconsistent with a wealth of evidence that child-specific patterns can also exhibit all the characteristic hallmarks of phonological grammar (e.g. Rose 2000:15ff). One standard diagnostic for the grammatical status of a pattern pertains to the nature of conditioning factors. Phonetic processes below the threshold of grammaticality are typically gradient and conditioned by a variety of physical factors (e.g. closure duration, speech rate), whereas grammaticalized patterns apply systematically and can be conditioned by a closed set of discrete analytical units. In our previous example (1), the pattern of positional velar fronting exhibited by Inkelas & Rose's (2007) case study subject was conditioned by prosodically defined units—fronting occurred in foot-initial but not foot-medial contexts—with no apparent influence of other factors such as speech rate, VOT, vowel context, or vocal loudness. Many other examples of categorical, prosodically conditioned effects have been documented in early phonological development (e.g. Spencer 1986; Fikkert 1994; Freitas 1997; Barlow 1997; Rose 2000; Goad & Rose 2003, 2004).

Natural class effects can also act as a diagnostic for grammaticalized generalizations. For example, in many children the process of fricative stopping affects both labials and coronals, even though these two places of articulation involve largely distinct speech-motor structures. Longitudinal evidence shows that children tend to resolve fricative stopping across all places of articulation within the same developmental stage (e.g. Rose 2014; see also Levelt & van Oostendorp 2007). This convergence implies a generalization about fricative continuancy that transcends the individual speech-motor organs and associated gestures involved in the production of fricatives, and belies a pure performance account.

A final type of evidence for the grammatical status of child speech patterns comes from the existence of U-shaped learning curves, which have been reported in numerous case studies of phonological development (e.g. Leopold 1939; Leopold 1947; Ferguson & Farwell 1975; MacWhinney 1978; Bowerman 1982; Fikkert 1994; Freitas 1997; Bernhardt & Stemberger 1998; Inkelas & Rose 2003; Inkelas & Rose 2007; Becker & Tessier 2011; Rose & Brittain 2011; McAllister Byun 2012). In U-shaped learning, a child is observed to produce a sound with relatively high accuracy in early stages of development, then shift to patterns of

variable/incorrect productions, followed by increasing accuracy until adult or near-adult levels are reached. U-shaped learning represents a challenge for the pure performance approach because the children in question have previously shown themselves physically capable of approximating the adult target.

### **3.2. Nativism**

Diametrically opposed to the pure performance account is a competence-only, NATIVIST approach which holds that child phonological patterns are grammatical and can be framed in the same terms as adult grammars. In constraint-based approaches of this kind, both child and adult phonologies are characterized by the same constraint set, although rankings or weightings may differ. Thus, every discovery of a pattern in child speech that is not attested in adult language typology forces a new enrichment of universal grammar. For example, Morrisette, Dinnsen & Gierut (2003) and Dinnsen (2008) propose that the child-specific pattern of positional velar fronting illustrated in (1) is driven by a constraint \*#k (“No word-initial velars”), while Dinnsen et al. (2011) posit a constraint AGREE that requires all consonants in a word to share the same major place of articulation, accounting for child-specific consonant harmony, exemplified in (3). These authors argue that the constraints in question are high-ranked in child grammar but are demoted as the child is exposed to evidence from adult speech. However, if a constraint is part of the universal inventory, the principle of factorial typology inherent in Optimality Theory predicts that its effects should be attested somewhere in the range of adult grammars. Even a heavily demoted constraint might exert its influence under circumstances that promote the emergence of the unmarked (TETU), such as epenthetic or reduplicative contexts (McCarthy & Prince 1994; Alderete et al. 1999). Insofar as these predictions are not borne out, adoption of a nativist approach to child patterns weakens the capacity of the theory to generate a restrictive model of adult typology (see discussion in Inkelas & Rose 2007; McAllister Byun 2011).

### **3.3. Transient phonology**

The TRANSIENT PHONOLOGY approach, represented by e.g. Pater (1997, 2004); Hayes (1999); Rose (2003); Goad & Rose (2004); Becker & Tessier (2011), is a variant of the nativist approach. It assumes that children possess and utilize constraints shared with adult speakers, but differs in proposing that child patterns may also reflect the influence of immature

representations, or of constraints that are not part of the adult grammar. Child-specific constraints are assumed to be induced from the child's experience of the perceptual or distributional properties of the ambient language data, or from the child's generalizations over his/her own production experience. For example, Pater (1997) proposes a constraint REPEAT ("Successive consonants must agree in place specification") to capture the child-specific consonant harmony pattern illustrated in (3), and suggests that this constraint is a grammatical reflection of a motor-planning advantage for repeated gestures. Becker & Tessier adopt a similar approach in their more recent account of child consonant harmony, positing that the child "was driven by concerns of some articulatory nature to induce the constraint AGREE(KVT)" (Becker & Tessier 2011:182).

Implicit in the notion of child-specific constraints is the assumption that these constraints are eliminated or turned off at some point in the typical course of maturation (see, also, Levelt & van Oostendorp 2007; Veer 2015). By the same logic laid out in connection with nativist models in the previous section, it is not sufficient to suggest that these constraints are simply demoted or reduced to a low weight; if they remain part of the system, the model still predicts that child-specific constraints could still exert effects in adult language. To our knowledge, no model has explicitly proposed an update mechanism to explain how child-specific constraints can be completely eliminated over the course of maturation. In principle, the transient phonology approach offers increased flexibility to model child-specific phonological patterns without predicting their attestation in adult typology. In practice, however, it shares with nativist theories the difficult challenge of explaining why the constraints responsible for child-specific phonology disappear so absolutely that they never show effects in adult languages.

### **3.4. Transient phonetics: Between competence and performance**

The present paper fills a gap in our understanding of child-specific grammatical patterns by proposing that transient phonological patterns are directly rooted in the TRANSIENT PHONETICS of developing children. The A-map model, which we outline in detail below, assumes that child-specific patterns are the product of the child's phonological grammar. However, the A-map model departs from the nativist and transient phonology approaches by introducing a direct and sustained link between children's phonological patterns and functional pressures on production and/or perception. As child-specific functional pressures are resolved over the course of

maturation, the associated phonological patterns also fade, providing a natural account of both the origin and the cessation of child-specific phonology. The A-map model rests on the key assumption, familiar from exemplar models of memory and shared by the independently developed Linked-Attractor model (Menn, Schmidt & Nicholas 2009), that traces representing past productions are stored and made available to the grammar (see further in section 5.2). We propose that child-specific patterns can arise as a phonologically expressed reflex of previous error patterns, but unlike the transient phonology approach, we do not posit child-specific constraints like REPEAT or AGREE(KVT). Instead, the A-map model holds that child-specific phonological patterns arise through the influence of a universal mechanism, which we encode formally with PRECISE, a violable constraint which favors forms with a history of reliable articulatory execution. This constraint remains present in the adult grammar, but for a mature speaker, virtually all sounds/sequences can be realized with similarly high reliability, and the constraint's effect is minimal.

#### **4. Grammar-motor interactions in development**

##### **4.1 Anatomical and motor differences between child and adult speech production**

It is indisputable that children and adults differ in their experience of the physical act of producing speech. First, there are significant anatomical differences between child and adult speakers. Most notably, the child's tongue is larger in proportion to his/her vocal tract than the adult's (Fletcher 1973; Kent 1981; Crelin 1987), and it occupies a more anterior position in the oral cavity (Kent 1992). The palate of a child speaker is also narrower and lower than that of the adult. Thus, from infancy to around two years of age, the tongue fills the oral cavity almost completely (Crelin 1987). Second, children and adults differ in their motor planning capabilities. In early stages of development, children produce gross speech gestures in which multiple structures (e.g. jaw and tongue, jaw and lips) move together as a single unit. This 'linking' of distinct structures appears to simplify the motor control task by reducing the number of degrees of movement freedom involved (Green et al. 2000; Gick et al. 2008). Different structures pose differing demands on the developing motor system: controlling the bilaterally hinged mandible is motorically simple, whereas the tongue poses a uniquely challenging motor control task. Thus, child speakers typically go through a stage in which the tongue plays a passive role in articulation, borrowing its movements to some extent from the active jaw articulator (e.g.

MacNeilage & Davis 1990a,b; Green, Moore & Reilly 2002). A third and related difference pertains to the relative instability of speech-motor planning and execution in child speech production. While even skilled adult speakers produce speech errors, these performance errors occur with significantly greater frequency in language learners (e.g. Dell, Burger & Svec 1997). Studies of articulator movement kinematics (e.g. Smith & Goffman 1998) and patterns of linguo-palatal contact (e.g. Fletcher 1989) also show that children's speech gestures are more variable than those of mature speakers, even in the absence of overt errors.

#### **4.2 Anatomical and motor pressures at the root of child-specific phonological patterns**

The anatomical and motor-control differences detailed above are of particular interest because they have been invoked in the context of accounting for various child-specific phonological patterns. While an exhaustive review of links between performance pressures and developmental phonological patterns falls outside of the scope of the present paper, below we briefly review a sampling of such relationships that have been proposed in previous literature, and in section 7 we discuss a detailed account of performance pressures at the root of a pattern of positional fricative stopping.

*Velar fronting:* The larger size and more anterior placement of the child speaker's tongue has been identified as a major driving force behind child speech patterns involving substitution of a sound with a more anterior place of lingual articulation, as in the pattern of velar fronting. The positional variant of velar fronting, illustrated in (1), has been explained as the product of interacting anatomical, motoric, and phonological factors (Inkelas & Rose 2007). Children who apply fronting only in word- and foot-initial contexts are demonstrating knowledge of the prosodic structure of the target form, and they replicate the adult process of enhancement of consonants in prosodically strong positions. However, the larger gestural excursion needed for prosodic enhancement presents a more challenging motor control task, increasing the likelihood that the child will use a ballistic gesture that produces undifferentiated linguo-palatal contact (McAllister Byun 2012). In some children, this yields a systematic pattern of place substitution in the context(s) where gestures are largest (Inkelas & Rose 2003, 2007).

*Consonant-vowel interactions:* The consonant-vowel interactions depicted in (2) above have been analyzed as a consequence of the difficulty that young children experience in planning discrete gestures in which one articulator moves relatively independently of the others.

According to the FRAME-DOMINANCE hypothesis (MacNeilage & Davis 1990a,b), children's earliest syllables are characterized by open-close oscillations of the mandible in which the position of the tongue relative to the jaw remains more or less constant. Without independent movement of the tongue, the identity of the consonant is highly constrained by the vocalic context, explaining why very young children tend to produce babbled sequences and early words combining front vowels with coronal consonants or back vowels with velar consonants.

*Consonant harmony*: Even if a child can produce accurate gestures in simple contexts such as CV syllables, he/she may have difficulty combining multiple discrete gestures into a complex sequence. From a motor planning standpoint, producing a single gesture repeatedly is less challenging than planning and sequencing multiple distinct gestures (Pater 1997). As discussed above, this has given rise to accounts in which the child's limited motor planning capacity is invoked as the driving force behind the child-specific pattern of consonant harmony for major place of articulation. The same reasoning underlies characterizations of adult consonant harmony as a phonologized reflex of the processing or planning pressures that give rise to sporadic speech errors involving gestural repetition (Hansson 2001), although the more restricted nature of adult harmony processes points to a more limited influence of these pressures.

### **4.3 Early production experience shapes later output**

The above-described patterns are thought to reflect the interaction of phonological learning with anatomical and motor constraints that are broadly shared across child speakers. However, there is also evidence that a child's individual history of experience in the domain of production can have a systematic impact on what targets the child will attempt in subsequent stages of development, and how those targets will be realized. Some well-known evidence for this interaction comes from *lexical selection and avoidance* and *template effects* in child phonology.

Lexical selection and lexical avoidance refer to the observation that in early stages of lexical development, many children show systematic but idiosyncratic preferences to acquire words representing specific sounds, sound sequences, or word shapes (e.g. Ferguson & Farwell 1975; Schwartz & Leonard 1982; Menn 1983; Stoel-Gammon 2011; Vihman 2014). It is of particular interest that these patterns of selection have been found to reflect the influence of the child's previous history of pre-linguistic babbling. Infants may show individual preferences in

their babbling, producing a particular syllable shape or place or manner of articulation with relatively greater frequency than others. A number of studies demonstrate that children who favor a particular sound or syllable during babbling tend to carry this same preference into their early word productions (e.g. Stoel-Gammon & Cooper 1984; Vihman et al. 1985; Bernhardt & Stoel-Gammon 1994). For example, Stoel-Gammon & Cooper report the case of a child, Daniel, whose pre-linguistic babbling reflected a strong preference for CVC syllables with velar place. Their analysis indicates that 22% of Daniel's first 50 words had a final velar consonant; most of these were realized with the same syllable, [gak], that he favored most in babbling. For the other children in the study, words with final velars made up only 4-8% of the lexical repertoire.

Previous research points to a mechanism whereby early production experience, even outside of the context of meaningful speech, could give rise to systematic biases in the lexicon. Babbling is characterized as an exploratory process in which a child learns to associate vocal motor actions with their auditory and somatosensory consequences (e.g. Guenther 1994; Menn, Schmidt & Nicholas 2009, 2013; Stoel-Gammon 2011). At the same time, the child is becoming aware of similarities between his/her own perceptually encoded outputs (e.g. [ba]) and corresponding adult forms (e.g. *ball*). It has been proposed that possessing a stable motor-acoustic mapping for a particular syllable or speech string can facilitate acquisition of words incorporating those sounds (Locke 1983; Stoel-Gammon 2011; Vihman 2014). The hypothesis is supported by recent research indicating that both child and adult learners acquire new word-meaning mappings more quickly and accurately when they already possess the corresponding articulatory routine in memory (Storkel, Maekawa & Aschenbrenner 2013; Kan, Sadagopan, Janich & Andrade 2014). This effect also has a plausible neural basis in a model where auditory-motor transformations in the dorsal stream form the foundation for verbal working memory (Hickok & Poeppel 2007): a string that undergoes auditory-motor transformation is encoded more specifically and more robustly than a string processed at a purely auditory level in the ventral stream.

The influence of previous production experience on subsequent outputs extends beyond lexical selection and avoidance. Children may not only select forms that correspond with their preferred shapes for production, but also actively alter adult target forms to achieve a closer match with their preferred production patterns or 'templates' (Waterson 1971; Leonard & McGregor 1991; Macken 1996; Vihman & Velleman 2000; Vihman & Croft 2007; Menn,

Schmidt & Nicholas 2009, 2013; Vihman 2014). Classic template effects are described as whole-word patterns for which there is no readily identifiable segment-by-segment mapping between from the adult form and the child's output. Priestly's (1977) classic examples of template effects in the output of an English-acquiring boy aged 1;10-2;2 are listed in (4):

(4) Word-level templates (data from Priestly 1977)

basket	bæskət	[bajak]
blanket	blæŋkət	[bajak]
tiger	taɪgəɪ	[tajak]
turkey	tʌki	[tajak]
fountain	faʊntən	[fajan]
flannel	flænəl	[fajan]

Although template effects have much in common with lexical selection and avoidance, they require a more elaborated model than the simple notion of enhanced encoding via auditory-motor transformation. This is because template effects involve a tradeoff: by systematically substituting his/her preferred motor plan, the child speaker must accept a less-than-perfect match for the adult auditory target. Because the motor plan is preferred based on the child's own idiosyncratic experience, not universal markedness, existing phonological formalism does not supply a mechanism to model these substitutions. We take the view that standard approaches to phonological formalism, which have been highly successful in capturing regularities in adult speech codes, should be enhanced to accommodate template effects. To achieve this extension of the formalism, two prerequisites must be met, stated in (5). Our proposal addressing both of these goals is the A-map model, detailed below.

- (5) Extensions to phonological formalism needed to capture a preference for a candidate associated with a stable motor-acoustic mapping:
- a. A metric to represent the relative goodness of different motor-acoustic mappings.
  - b. A means of coding information about (a) that is legible to the grammar.

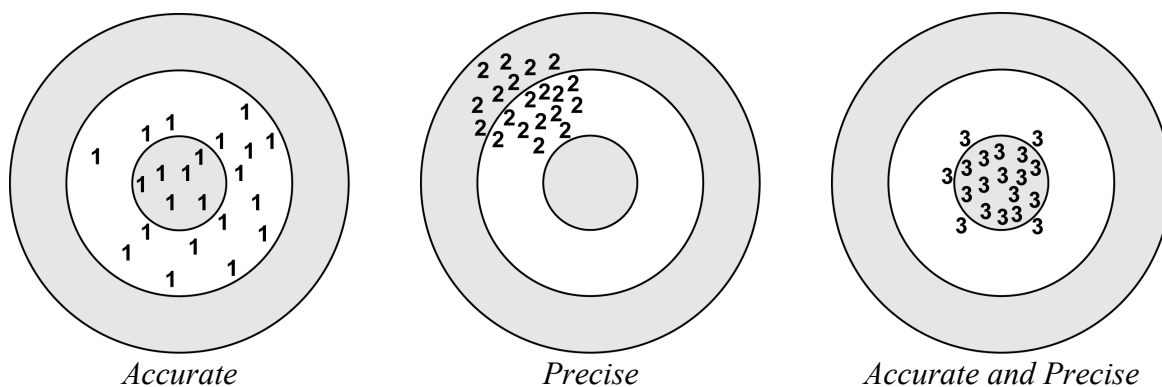


## 5. The A-map model: Grammatical knowledge of motor-acoustic mappings

### 5.1. Overview

We propose a new model of phonological learning in which children's phonology reflects the influence of two competing tensions. The first pressure is the child's desire to match adult productions of a given speech string, even if performance limitations are likely to cause the child to fall short of the intended target. The opposing pressure is a preference to use a stable, well-practiced motor plan that can be realized with few performance errors, even if the perceptual output associated with this motor plan is not a perfect phonetic match for the adult input. Similar tradeoffs have been documented in non-speech motor learning in humans (e.g. Phillips et al. 2011), as well as in birdsong (e.g. Kao, Doupe & Brainard 2005). We will describe these competing tensions in terms of ACCURACY and PRECISION in motor-acoustic mappings.

The conceptual distinction between accuracy and precision is schematized in Figure 1, which uses a dartboard metaphor to represent three possible scenarios for the relationship between a child's past productions of a given motor plan and the sensory target that executions of that motor plan are intended to achieve. The bull's-eye represents an adult acoustic-perceptual target, e.g. the phone |s|; the numerals represent traces of the child's previous attempts to match that target. On the first dartboard, the points labeled '1' are *accurate*, meaning that a measure of central tendency summarizing the points' location would coincide roughly with the bull's-eye. However, this collection of throws is not precise; there is considerable scatter in the location of individual points. On the second dartboard, the points labeled '2' are *precise*, meaning that the outputs of this dart cluster tightly around a single location, but they are not accurate, because the center of this distribution does not coincide with the bull's-eye. The points on the third dartboard are both accurate and precise.



**Figure 1: Accuracy and precision are distinct and potentially competing pressures**

We assume that child speakers are subject to both a pressure to be accurate (i.e. produce a form that is a good match for the adult input) and a pressure to be precise (i.e. produce a form that can be realized without an undue amount of performance error). Importantly, there is potential for competition between these two pressures. In some cases, closely approximating the acoustics of the adult target may require a high degree of articulatory control; for example, if the adult target is a sibilant, the tongue must be configured into a grooved shape that requires discrete control over different functional regions of the lingual musculature (e.g. Gibbon 1999). Based on developmental evidence such as U-shaped developmental curves (see section 3.1), we assume that the motor-acoustic mapping for a sibilant is typically not entirely unavailable to the child. For many speakers, however, these complex articulatory targets are not stable at an early stage in development. Thus, a child who strives to produce a close match for the adult phonetic target may succeed some of the time, but will also produce error forms that feature less complex tongue configurations (e.g. /θ/, /ʃ/, /t/). Under these circumstances, a child might instead opt for a production routine that is less accurate but more precise. This would involve selecting a motor plan whose auditory consequences fall in the neighborhood of the adult target without necessarily representing the closest possible match; its distinguishing characteristic is that the child can execute it in a reliable and consistent fashion.

We express these two pressures through grammatical constraints, ACCURATE and PRECISE. These constraints are evaluated with reference to exemplar clouds representing actual and intended consequences of past executions of the motor plan associated with a given candidate, distilled into a concise format in a grammatical module we term the A-map. The grammatical constraint ACCURATE penalizes a candidate in proportion to the distance between the adult

acoustic-perceptual target and the predicted outcome of executing the candidate's associated motor plan. The constraint *PRECISE* penalizes a candidate in proportion to the average distance between predicted and actual acoustic-perceptual outcomes in previous executions of the candidate's associated motor plan. In short, the A-Map model enriches a constraint-based grammar with episodic detail about motor-acoustic mappings in order to reflect an ongoing, grammatically governed competition between the pressures of motor plan reliability and auditory-perceptual accuracy.

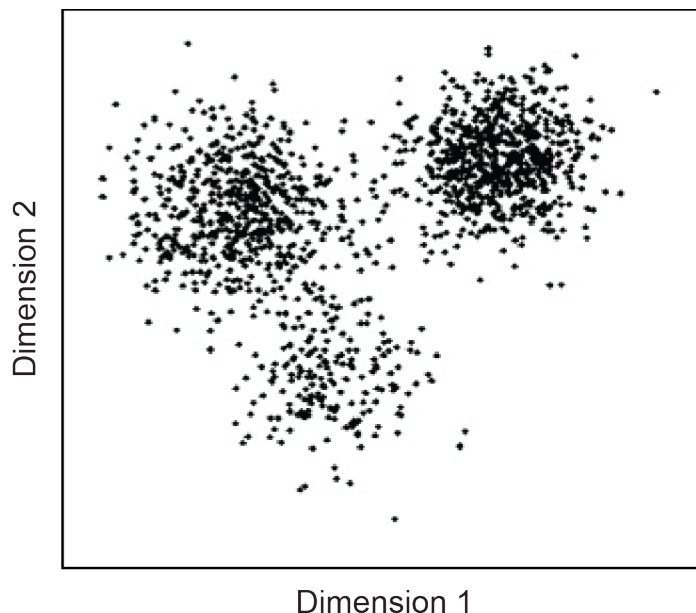
## **5.2. A hybrid grammar: Constraints and exemplars**

We formulate the A-map model of child phonology within a system of violable constraints, using the weighted-constraint framework of Harmonic Grammar (HG; Legendre, Miyata & Smolensky 1990; Smolensky & Legendre 2006; Pater 2009).<sup>6</sup> We make a number of assumptions that are standard for models of acquisition in such frameworks. First, we assume basic continuity between the constraint inventory accessible to the child speaker and that of the adult —or at least, our model does not crucially require the assumption of any differences between child and adult constraint sets. Second, we adopt the Gradual Learning Algorithm for Harmonic Grammar (HG-GLA; Boersma & Pater 2007) as a mechanism by which initial-state constraint weights can be transformed to an appropriate weighting for the adult grammar to which the child is exposed.

Our model also aims to place constraint-based formalism in a broader context. It has been amply demonstrated that speakers encode phonetic information with finer-grained detail than the phoneme or feature level, and that this detailed information may be retained even over an extended period of time (e.g. Pisoni 1997). In keeping with an episodic or exemplar-based model of phonology (e.g. Johnson 1997, 2006; Pierrehumbert 2001, 2002, 2003), we assume that phonetic forms experienced in the act of producing and perceiving speech are stored as detailed traces in a multi-dimensional map of the phonetic properties of speech. Because new traces are constantly being formed and old traces decay over time, the exemplar space is continuously evolving.

Studies of infant speech perception have established that infants are sensitive to the distributional properties of phonetic inputs (Maye, Werker & Gerken 2002). In exemplar-based models of phonology, categories can be characterized in terms of probability distributions over exemplar clouds: a region of high probability represents the center of a phoneme category, while

low-probability regions represent boundaries between categories (Pierrehumbert 2003; Munson, Edwards & Beckman 2005; see also Menn, Schmidt & Nicholas 2009, 2013). For very young children, exemplar memory may be organized primarily at a coarse-grained (e.g. word) level. As children identify meaningful regularities over the course of exposure to many linguistic inputs, their representations become more segmentalized (e.g. Munson, Kurtz & Windsor 2005; Werker & Curtin 2005; Fikkert & Levelt 2008; Curtin, Byers-Heinlein & Werker 2011). While it is difficult to graphically depict the episodic traces of entire words, they can be conceptualized as dynamic trajectories through multiple dimensions of acoustic space (e.g. Shiller, Rvachew & Brosseau-Lapr e 2010). Figure 2 is a common type of depiction of the episodic traces of phones, whose pattern of clustering reveals multiple distinct phoneme categories.



**Figure 2: Episodic traces in two arbitrary dimensions of phonetic space.  
[Based on figures from Scobbie (2007), Pierrehumbert & Gross (2003)]**

Our model takes a novel step by integrating the phonetic exemplar space with the concept of an INTERNAL MODEL (Wolpert & Kawato 1998; Wolpert, Ghahramani & Flanagan 2001; Shiller, Rvachew & Brosseau-Lapr e 2010; Tian & Poeppel 2010; Hickok 2012; Scott 2012; Guenther, Ghosh & Tourville 2006). The internal model represents an individual's knowledge of mappings between motor actions and their associated sensory consequences. In the context of speech, a motor plan has auditory as well as somatosensory correlates, learned implicitly through

the individual's experience of executing articulatory gestures and perceptually encoding the resulting speech output. The internal model can be used to map between motor plans and sensory consequences in either direction. The INTERNAL INVERSE MODEL estimates the motor plan most likely to produce a particular acoustic-perceptual output. We are especially interested in the direction that predicts the consequences of executing a motor plan, the INTERNAL FORWARD MODEL. In the forward direction, the model generates an EFFERENCE COPY simulating the sensory correlates of a planned motor action. If there is a mismatch between the predicted and actual sensory consequences of a planned movement, an error is detected, and a correction can be attempted or learning can occur. To implement the internal model in an exemplar-based grammar, we assume that the speaker stores not only the perceptually encoded traces of speech outputs—either his/her own or others'—but also traces of the efference copies representing the expected sensory consequences of a planned utterance.<sup>7</sup> We will use the term 'motor-acoustic exemplar space' to refer to our exemplar-based implementation of the internal model for speech.

The A-map model shares some important elements with the independently developed Linked-Attractor model of child phonology. Menn, Schmidt & Nicholas (2013) describe a 'phonological landscape' that closely resembles our motor-acoustic exemplar space: "The child is born with an initial phonological landscape: its topography represents the auditory-acoustic categorical perception boundaries present at birth, and the lip, tongue, and control capacities present at birth. This initial topography changes continuously with maturation and with experience" (Menn, Schmidt & Nicholas 2013:300). The focus of the Linked-Attractor model is on lexical and other structural frequency effects represented in the 'landscape' of sensory traces created by the child's previous experience, while the incorporation of the internal model into the A-map framework shifts the focus to motor planning and execution. However, the two models are inherently compatible, and their overlap reflects a growing consensus regarding the importance of appealing to exemplar-based memory in modeling linguistic competence and performance.

### **5.3. Accuracy and precision in motor-acoustic exemplar space**

The internal model is an important component of a production grammar, but it does not fully determine future phonological behavior. This is because of the competing roles of two grammatical pressures, accuracy and precision. In (5a) we identified the need for a metric

indexing the relative goodness or stability of motor-acoustic mappings, and in section 5.1 we introduced the metaphor of precision as a means of conceptualizing this property. In this section, we define the notions of accuracy and precision in relation to clouds of traces in motor-acoustic exemplar space. Section 6 discusses the reification of these notions as constraints in a phonological grammar.

In Figure 3, the letter T marks the center of a cloud representing the child's perceptually encoded traces of a speech target as it is realized in the adult input.<sup>8</sup> In simple terms, T is the target the child is attempting to match. To reproduce this target, the child consults the internal inverse model to identify motor plans whose predicted sensory consequences most closely coincide with this region of acoustic-perceptual space.<sup>9</sup> For a given motor plan, the letter E marks the center of the cloud of efference copies representing the sensory predictions generated in connection with the child's previous executions of the motor plan. Put simply, E is the sound that the speaker expects a given motor plan to produce. Finally, the letter A marks the center of the cloud representing the child's perceptually encoded traces of his/her own acoustic outputs when executing the same motor plan. Distances between clouds have been exaggerated for clarity in Figure 3.



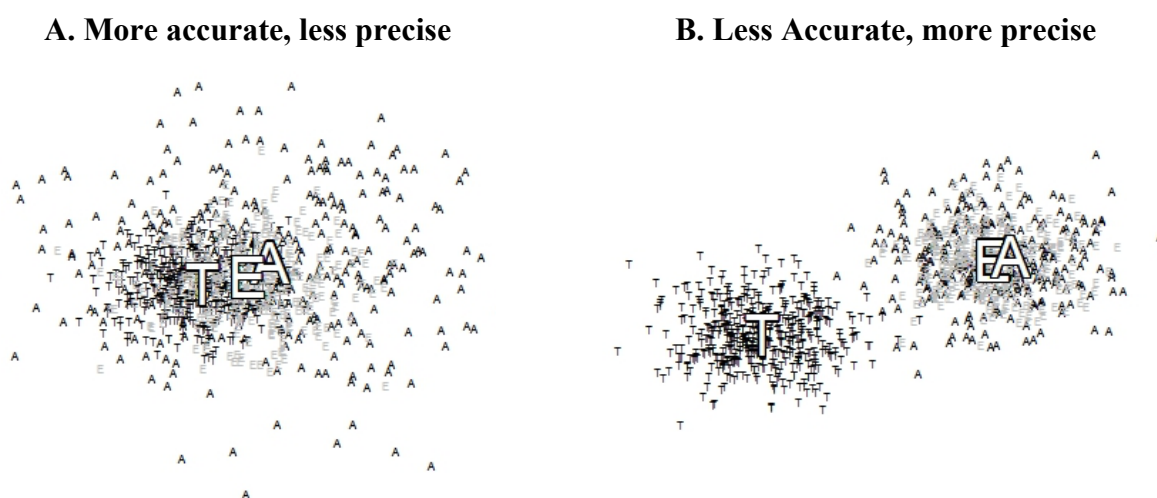
**Figure 3: Clouds in motor-acoustic exemplar space representing the adult target (T), the child’s actual outputs for an associated motor plan (A), and efference copies representing the expected sensory consequences of planned outputs of that motor plan (E)**

For a given pairing of motor plan and adult target, we define ACCURACY as the distance in phonetic space between T, the center of the cloud of traces of perceptually encoded adult inputs, and E, the center of the cloud of efference copies representing the predicted sensory consequences of executing that motor plan. The distance between these two points is expected to be nonzero, since anatomical and motor differences generally prevent child speakers from producing an exact match for an adult acoustic model. Nevertheless, the grammar can favor a motor-acoustic mapping that minimizes this distance.

We define PRECISION as the average distance in phonetic space between pairs of traces in clouds A and E—that is, the average distance, for any given motor plan, between a trace representing the child’s actual output and the trace of the concurrently generated efference copy representing the child’s intended output. In cases where a motor error occurs, the trace of the efference copy and the trace representing the speaker’s actual output occupy different locations. When the motor plan is novel or complex, frequent performance errors yield a larger mean difference between pairs of predicted and actual acoustic-perceptual consequences. By encoding how reliably the execution of a motor routine yields output forms that match the intended

sensory consequence, the notion of precision fills the need for a metric to represent the relative goodness of different motor-acoustic mappings, as identified in (5a).

Figure 4 illustrates the potential trade-off between the competing pressures of accuracy and precision. The motor-acoustic mapping in (A) illustrates accuracy; the child has selected a motor plan whose sensory consequences are, on average, close to his/her perceptual encoding of the adult model. Despite the overlap in acoustic-perceptual space between the child's productions and the adult target, however, there is considerable scatter in the cloud of forms produced, reflecting divergence from the intended outputs that are represented by traces of efference copies. While accurate on average, the motor plan illustrated in (A) is imprecise. In (B), the child selects a motor plan that he/she can execute consistently: the cloud of traces representing the actual consequence of executing the motor routine coincides closely with the cloud of efference copies generated in connection with the same motor plan. However, these outputs diverge to a considerable extent from the adult target T. Thus, the mapping depicted in (B) is more precise but less accurate than the mapping in (A).



**Figure 4: Accuracy and precision as competing pressures in the motor-acoustic exemplar space**

## 6. Formal implementation: The A-map

The preceding section addressed goal (5a) by defining the property of precision, which can act as an index of the relative goodness of different motor-acoustic mappings. We now turn to (5b), which identified the need for a means of coding this information that can be fed into the



computations of the grammar. To achieve this aim, we first provide operational definitions for the concepts set forth in the preceding sections.

### 6.1. The A-map

Section 5.3 identified several points in or measures of motor-acoustic exemplar space that will be relevant for the grammatical calculations to follow. We propose that this informational content is distilled in a grammatical module that we term the A(rticularity)-map; it contains the values defined in (6)-(10).<sup>10</sup> For clarity, each operational definition is also restated in an informal way; see text in brackets. (Note that although we use the index “ $i$ ” in each definition, the values of  $i$  vary independently across different definitions.)

- (6)  $T_{mean[i]}$ : The measure of central tendency of  $T_{[ij]}$ , the cloud of episodic traces of adult inputs associated with a particular speech target  $i$   
[T is the target the speaker is attempting to match]
- (7)  $MP_{[ij]}$ : The motor plan generated by the internal inverse model in connection with target  $i$   
[Among all the motor plans a speaker considers using,  $MP_{[ij]}$  is the particular motor plan whose predicted sensory consequences, on average, best approximate the target  $i$ ]
- (8)  $E_{mean[i]}$ : The measure of central tendency of  $E$ , the cloud of episodic traces of efference copies representing the predicted sensory consequences generated in connection with previous executions of a given motor plan,  $MP_{[ij]}$   
[E is the sound that the speaker expects a given motor plan to produce]
- (9)  $A_{mean[i]}$ : The measure of central tendency of  $A$ , the cloud of episodic traces of acoustic outcomes perceptually encoded in connection with previous executions of a given motor plan  $MP_{[ij]}$   
[A is the sound that the speaker has produced in the past for a particular motor plan]
- (10)  $Noise(MP_{[ij]})$ : The average distance between pairs of episodic traces—one efference copy and one perceptually encoded acoustic output— generated in connection with previous executions of a given motor plan,  $MP_{[ij]}$ . For the set of  $n$  pairs of traces associated with  $MP_{[ij]}$ , this measure is calculated as follows:

$$Noise(MP_{[ij]}): = \frac{\sum_1^n |E_j - A_j|}{n}$$

[*Noise* is a measure of error representing the distance between past expectation and past outcome of a particular motor plan]

## 6.2. Features and representations

How do motor plans and their associated acoustic-perceptual outputs relate to conventional phonological representations? This is not a novel type of problem; it is faced by any analysis that makes reference to both phonological generalizations and continuously-valued phonetic variation. One possible solution offered in the literature is to define two distinct modules of grammar, one ‘phonological’ module whose representations are categorical, followed by a ‘phonetic’ module with gradient representations (e.g. Keating 1988; Cohn 1990). Another possibility is to dispense with categorical representations altogether, reducing all ‘phonology’ to ‘phonetics’ (e.g. Flemming 2002). We take a different approach to this challenge. As stated above, our goal is not to replace formal categorical grammatical generalizations with calculations over continuously valued episodic traces in exemplar space, but rather to link the categorical grammar to this more detailed level of encoding. A precedent for transparently connecting exemplar distributions with abstract phonological representations is provided by Emergent Feature Theory (Mielke 2008), a framework in which distinctive features are induced from distributional regularities in both acoustic-perceptual and articulatory domains of phonetic space. This process can be likened to the emergence of patterns of clustering and separation in the multidimensional motor-acoustic exemplar space assumed in the present model. Mielke (2008) does not discuss whether emergent features retain a link to detailed phonetic data. We propose that they do, and that this link is instantiated via the internal model. Our view is consistent with Stevens’ (1972) Quantal Feature Theory, which characterizes features as mappings between a stable and identifiable dimension in acoustic-perceptual space, and the articulatory place or manner of articulation involved in the production of this acoustic dimension (see also, Halle & Stevens 1979; Stevens 1989; Keyser & Stevens 2006; Stevens & Keyser 2010). An explicit link between features and the internal model can be found in the theory of analysis by synthesis, which frames speech perception as a multistep process involving active prediction and hypothesis-testing (Halle & Stevens 1959; Halle & Stevens 1962; Poeppel, Idsardi & Wassenhove 2008; Poeppel & Monahan 2011; Kuhl et al. 2014). In this model, coarse-grained

perceptual processing of the input signal is used to generate a preliminary hypothesis regarding the featural identity of perceived phonemes. The features of the hypothesized phonemes are then used to synthesize an internal prediction of the acoustic-perceptual signal, which is compared against the actual input. In sum, work in the analysis by synthesis framework makes the case that features, while abstract, are also linked to specific knowledge about auditory and articulatory phonetics, and can serve as the basis for synthesis of detailed phonetic predictions.

Adopting this notion of the dual nature of features, we propose that the grammar can make reference to both abstract and phonetically detailed levels of representation. We will thus assume the existence of a class of constraints that refer to features in their abstract/categorical instantiation; these are the same as conventional markedness and faithfulness constraints used to capture patterns in Optimality Theory and related models. However, there exist some phenomena, such as language-specific differences in degree of co-articulatory overlap, that can be grammatically captured only through constraints that make reference to gradient phonetic detail (Flemming 2002). The present model will rely crucially on two constraints that make reference to the properties of motor-acoustic mappings in exemplar space, with features and the A-map acting as the intermediaries between the abstract representation and the episodic detail.

### 6.3. Constraints

The competing forces of precision and accuracy are formally implemented in our model by two grammatical constraints: *PRECISE* and *ACCURATE*. *PRECISE*, a phonetically-informed markedness constraint, is formally defined in (11). Constraint violations are calculated in reference to a candidate  $c_{[i,j]}$ , where  $[i]$  indexes the adult target  $i$ , and  $[j]$  indexes the production candidate (an association of motor plan and predicted acoustic-perceptual outcomes). Candidates in a given comparison set are all competing to realize the same adult target  $i$ .

(11) *PRECISE*:

For a candidate  $c_{[i,j]}$  with associated motor plan  $MP_{[j]}$ , assign a penalty in proportion to the magnitude of  $Noise(MP_{[j]})$ .

In a grammatical comparison of candidates, *PRECISE* will assign a greater penalty to a candidate whose motor plan  $MP$  is unstable, yielding a high average degree of separation between actual

and predicted acoustic-perceptual outcomes (large  $Noise(MP)$ ). A candidate whose motor plan is realized reliably, resulting in a compact cloud of traces that coincide with the simulations of the internal model (small  $Noise(MP)$ ), will violate PRECISE minimally. This was illustrated in Figure 4 (B).

By contrast, ACCURATE favors a candidate whose predicted acoustic-perceptual consequence is a close match for the adult target. For any given candidate  $c_{[i,j]}$  with associated  $MP_{[j]}$ , the penalty for violating ACCURATE is calculated in terms of  $T_{mean[i]}$  and  $E_{mean[j]}$ . Recall that  $T_{mean[i]}$  is the center of the cloud representing the child's perceptual encoding of adult productions of target  $i$ ;  $E_{mean[j]}$  is predicted acoustic-perceptual consequence of executing  $MP_{[j]}$ . ACCURATE assesses the distance between  $T_{mean[i]}$  and  $E_{mean[j]}$ , as in (12). By comparing  $T_{mean[i]}$  against  $E_{mean[j]}$  rather than against  $A_{mean[j]}$ , ACCURATE evaluates a candidate relative to its potential outcome under optimal circumstances. It does not factor in the likelihood of performance errors, because this role is filled independently by PRECISE.

(12) ACCURATE:

For a candidate  $c_{[i,j]}$  with associated motor plan  $MP_{[j]}$  that maps to a predicted acoustic-perceptual outcome  $E_{mean[j]}$ , assign a penalty in proportion to the distance in acoustic-perceptual space between  $E_{mean[j]}$  and the target  $T_{mean[i]}$ .

The interaction of PRECISE and ACCURATE is a crucial component in the A-map model of grammar. For a given adult target  $i$ , ACCURATE might favor one candidate, while PRECISE might favor another. The relative weighting of ACCURATE and PRECISE in the grammar, in interaction with any other relevant constraints, will determine the outcome in such a case. We will see this interaction at work in an actual example from child phonology in the next section.

Like other high-level constraints (e.g. MAX, IDENT; Prince & Smolensky 1993/2004), PRECISE and ACCURATE could be defined at any of several levels of granularity (e.g. word, syllable, phoneme), and in reality they may apply at multiple levels in an overlapping fashion. In a similar way, it is possible to define a class of ACCURATE sub-constraints, some focused on matching individual sounds, others on matching segment strings, features, or other possible aspects of the signal. Defining multiple levels of constraint application would give our model flexibility to deal with important phenomena such as lexical exceptions to phonological patterns

(lexical fossils and precocious lexical forms; see Becker & Tessier 2011; Tessier 2013).<sup>11</sup>

However, we defer exploration of this topic to future work. For the purpose of this preliminary exposition of our model, we will treat both PRECISE and ACCURATE as monolithic constraints that apply at the level of individual segments.

### **7. Case study: positional fricative stopping in the A-map model**

In this section, we apply the A-Map model to a case study of a child-specific substitution pattern: stopping of fricatives in word-initial but not word-final position. Positional fricative neutralization was discussed in sections 2 and 3 and in previous work by Edwards (1996), Marshall & Chiat (2003), Inkelas & Rose (2007), and McAllister Byun (2011). The phenomenon has received attention because it reverses a well-documented typological bias whereby the range of featural contrasts, including manner contrasts, is maximized in syllable-initial position (e.g. de Lacy 2002; Smith 2002; Barnes 2006 for recent overviews). A typical example of the adult pattern comes from Korean, where fricatives, stops, and affricates are contrasted in onset position, but all three neutralize to stop manner in coda position (Ahn 1998). In the child pattern, by contrast, stop and fricative manner are neutralized in onset position while remaining distinct in coda contexts. This discrepancy makes it difficult to capture the child pattern within the formalism developed for adult grammars. At the same time, positing constraints to capture stopping in initial position gives rise to the incorrect prediction that some reflex of the child pattern ought to be detectable in adult typology (see discussion in Inkelas & Rose 2007; McAllister Byun 2011).

We draw our data from a Portuguese-acquiring child named Inês, whose development was originally documented in the Portuguese-CCF corpus (Correia 2009; Correia, Costa & Freitas 2010; Costa 2010) available through CHILDES/PhonBank (<http://childes.talkbank.org/phon/>; Rose & MacWhinney 2014). Further descriptions of Inês's data can be found in Burkinshaw (2014) and (Rose 2014). We chose this example because positional fricative stopping has a well-studied articulatory basis and because the data from Inês provide a particularly compelling argument for the phonological character of this child-specific pattern. This section has the following structure: First, we review the previous literature on the articulatory motivation for the child-specific pattern of positional fricative neutralization. We then present data from Inês and make the case that this pattern, while rooted in articulatory pressures, requires modelling within

the context of a categorical phonological grammar. We subsequently model positional fricative stopping within the A-map framework and argue that this model achieves the appropriate balance of articulatory and grammatical factors. In the following section, we show that the A-map model, unlike competing models, can account for the absence of any reflex of positional fricative stopping in adult typology.

### **7.1. The A-map for coronal fricatives**

Behind the scenes of any A-map analysis is the speaker's history of stability and variability in executing associated speech targets; thus, we begin this example with a review of the motor control factors that affect children's performance during attempts to realize fricatives in initial and final position. While we limit ourselves to the consideration of extra-grammatical factors in this section, in the following sections we will see how these phonetic biases form the basis for a grammatical pattern of positional fricative stopping mediated by the constraints ACCURATE and PRECISE.

McAllister Byun (2011) analyzes the articulatory pressures that underlie the child-specific pattern of positional fricative neutralization, arguing that the major driving force is the child speaker's difficulty producing a coarticulated transition from an onset fricative to a vowel. In a typical, coarticulated fricative-vowel transition, the jaw lowers in anticipation of the vowel while the tongue remains high to maintain the correct aperture for friction (Mooshammer, Hoole & Geumann 2006). An extensive literature suggests that such dissociated movements of the tongue and jaw are problematic for child speakers, who favor ballistic movements of the entire tongue-jaw complex (MacNeilage & Davis 1990a; Kent 1992; Green, Moore & Reilly 2002). (Articulatorily simpler segments such as stops and glides can overlap with the vowel without requiring dissociated lingual control (e.g. Kent 1992).) The transition from a vowel to a fricative is less demanding than the reverse, in terms of jaw-independent tongue control, because of gestural timing differences across onset and coda positions (Krakow 1999). Converging experimental evidence indicates that the timing of the onset-vowel transition is tightly constrained, while the vowel-coda transition is more flexible (Tuller & Kelso 1990; Tuller & Kelso 1991; Nam, Goldstein & Saltzman 2009; Giulivi et al. 2011). McAllister Byun (2011) reports evidence that the loose timing of the vowel-to-coda-fricative transition is particularly pronounced in children with positional asymmetries in fricative production, who were found to

exhibit a prolonged vowel-fricative transition with a minimum of gestural overlap. When the tongue and jaw can move together toward the target constriction for the final fricative, there is a lower likelihood of error.

Fricatives in onset position are thus motorically more demanding than coda fricatives. Accordingly, we assume that a child speaker's attempts to produce a fricative-vowel sequence incur a larger number of performance errors than the child's attempts to produce the equivalent vowel-fricative sequence in coda position. Some of these errors may involve overshoot and yield stopping, but this is not a necessary assumption of our account; errors involving gestural deletion or substitution of other segments such as glides are also possible. Whatever the nature of the error, the key point is that the frequent performance errors incurred in connection with the onset fricative result in a high average divergence between efference copies and actual outputs produced, translating to a high *Noise(MP)* value.

## 7.2. Data from Inês

Portuguese is an example of a language whose fully-developed grammar permits a wider range of contrasts in onset than coda position: while onset position allows fricatives with labial, alveolar, postalveolar, and uvular place of articulation, in coda position only the postalveolar fricatives |ʃ| and |ʒ| are attested. Nevertheless, Portuguese learner Inês exhibited a pattern of positional fricative stopping similar to that described in previous literature for English-acquiring children by Edwards (1996), Chiat (1989) and Marshall & Chiat (2003).

(13) Positional fricative stopping in Portuguese (Inês, 2;07.16; Portuguese-CCF corpus data)

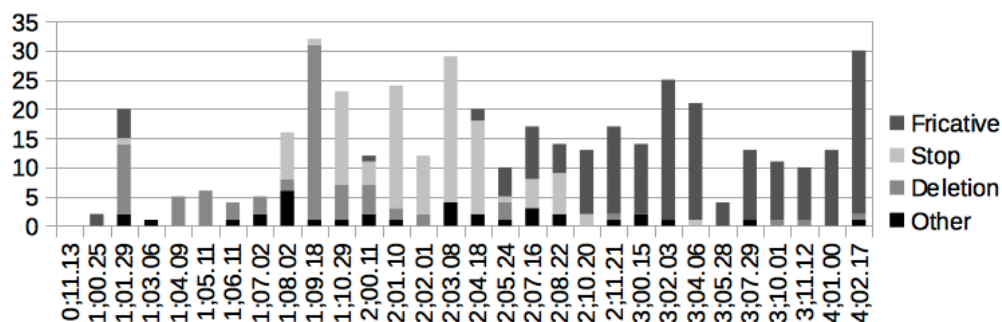
a. Stopping of fricatives in onset position

<i>já</i>	ʒa	[ˈda]
<i>sim</i>	sĩ	[ˈti]
<i>chega</i>	ʃegə	[ˈteɣə]
<i>sabes</i>	sabiʃ	[ˈtabʃ]

## b. Absence of stopping in coda position

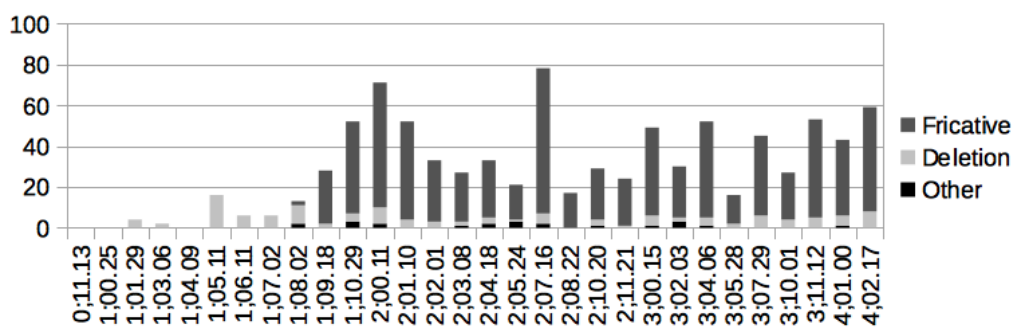
<i>canetas</i>	kɐ'netɐʃ	[kɐ'netɐʃ]
<i>papéis</i>	pɐ'pɛjʃ	[pɐ'pɛjʃ]
<i>compras</i>	['kõprɐʃ	['kɔpɐʃ]
<i>vais</i>	['vajʃ	['vajʃ]

The longitudinal corpus data available for Inês show that the pattern of positional fricative stopping both entered and was eliminated from her grammar in abrupt, categorical fashion. Figures 5 and 6 represent the frequency of occurrence (token counts) of different output categories in Inês's production of the postalveolar fricatives [ʃ, ʒ]. We focus on these targets for simplicity, as they are the only fricatives that are permitted in both onset and coda position in the adult phonology of Portuguese. As can be seen in Figure 5, Inês attempted few fricatives until around 1;08. By 1;09, fricatives emerged in coda position, where they were realized with virtually ceiling-level accuracy. At the same time that Inês began to produce coda fricatives accurately, however, she developed a systematic pattern of fricative stopping in onset position. This pattern remained stable for nearly a year before it was rapidly eliminated, resulting in accurate production of fricatives across all positions.



**Figure 5: Inês's productions of target postalveolar fricatives in syllable onsets**





**Figure 6: Inês's productions of target postalveolar fricatives in phrase-final syllable codas**

The case study of Inês is particularly apposite as an illustration of the A-Map model because her child-specific phonological pattern of positional fricative stopping engages with the phonology of the adult grammar in a significant way. Inês's positional stopping shows a systematic feeding relationship with a sandhi process, obligatory in the adult grammar, that yields resyllabification of a coda before a vowel-initial word. Additional examples from Inês's output are provided in (14), comparing the same lexical items as they appeared across the two relevant contexts within unique recording sessions. As these examples show, a word-final fricative is stopped when syllabified as the onset of the following word, but produced accurately in phrase-final position.

(14) Inês's stopping across words (through resyllabification; Rose 2013)

a.	<i>mais uma</i>	'majʃ'umə	['maj'dumə]	2;01.10
	cf. <i>Não há mais</i>	'nẽw̃'a'majʃ	['nu'a'majʃ]	2;01.10
b.	<i>dois anéis</i>	'dojʃ'e'nɛjʃ	['dod'e'nɛjʃ]	2;04.18
	cf. <i>não, dois</i>	'nẽw̃ 'dojʃ	['ɲo'dojʃ]	2;04.18
c.	<i>mais ele</i>	'majʃ'eli	['maj'deli]	2;08.22
	cf. <i>mais</i>	'majʃ	['majʃ]	2;08.22

The grammatical conditioning seen in (14) is the kind of evidence that makes it impossible to entertain a PURE PERFORMANCE account of child phonology (see section 3.1). While Inês's positional stopping pattern is motivated in part by articulatory factors, it is systematic and grammatically conditioned by a language-specific resyllabification process; it cannot be reduced to articulatory bumbling of the sort affecting the inebriated speech of the captain of the Exxon

Valdez (Hale & Reiss 1998). Because Inkelas & Rose (2003, 2007) and McAllister Byun (2011, 2012) invoke performance pressures at the root of child speech patterns, these accounts have in some instances been incorrectly characterized as belonging to the pure-performance category (Davis 2010; Dinnsen et al. 2011). The case study of Inês emphasizes the point that while child speech patterns may have transparent origins in phonetic performance pressures, they clearly belong to the domain of phonological grammar.

### 7.3. Modeling positional fricative stopping in the A-map framework

This section uses the A-map framework to model the behavior of initial and final fricatives in the phonology of Inês. Recall that the adult target  $i$  has both an abstract/featural representation and a phonetic representation consisting of a distribution of episodic traces in multidimensional acoustic-perceptual space, with a measure of central tendency  $T_{mean[i]}$ . As laid out above in section 6, each candidate  $c_{[i,j]}$  also has both an abstract representation in terms of distinctive features and an associated motor plan  $MP_{[j]}$ . The grammar can retrieve information stored in the A-map about the speaker's previous experiences of producing  $MP_{[j]}$ .  $E_{mean[j]}$ , the mean location of efference copies generated through previous executions of  $MP_{[j]}$ , is used to evaluate the constraint ACCURATE, while the mean distance between actual and expected sensory outcomes ( $Noise(MP_{[j]})$ ) determines the violation magnitude for the constraint PRECISE.

In example (15) we present a tableau following the conventions of Harmonic Grammar (HG), which relies on weighting of constraints to select the optimal output from a set of possible candidates (Legendre, Miyata & Smolensky 1990; Smolensky & Legendre 2006; Pater 2009). The constraints used in the tableau are ACCURATE and PRECISE; the candidates considered are /ʒa/ (15a) and /da/ (15b). The adult target that these candidates compete to match is |ʒa|.

IN HG, constraint violations are represented with negative numbers indicating the magnitude of the associated penalty. The  $H(armony)$  column on the right sums up the products, for each cell, of that cell's violations and the weight of the corresponding constraint; the candidate with the least negative  $H$  score is selected for production. The present account does not depend crucially on the relative weighting of constraints, so in tableau (15), both ACCURATE and PRECISE are given a weight of arbitrary magnitude 1.

The first candidate, /ʒa/, is maximally faithful with respect to the acoustic-perceptual properties of the target. The child's internal model includes a corresponding mapping from the

motor plan  $MP_{/z\alpha/}$  to a close approximation of the acoustic-perceptual properties of adult  $|z\alpha|$ . The efference copies ( $E_{mean}$ ) generated in connection with previous executions of this motor plan thus fall so close to the target ( $T_{mean}$ ) that violation of the constraint ACCURATE is minimal; we represent it here as magnitude 0. However, in this schematic example the child has demonstrated low past reliability in attaining the intended acoustic-perceptual target, with outputs reflecting frequent errors ranging from [ja] to [da] to [za]. The candidate is thus associated with a high  $Noise(MP)$  value, which translates to a large violation of the constraint PRECISE, represented here as -4.<sup>12</sup> The competing candidate, /da/, features a coronal stop in place of the target fricative. Because the child can execute this simpler motor routine with a high degree of reliability, it has a much lower  $Noise(MP)$  value than the faithful candidate and thus incurs a smaller PRECISE violation (shown here as -2). However, the cloud of efference copies generated in connection with executions of this target has a different central location than the target  $T_{mean}$ , incurring a modest violation (-1) of ACCURATE. In this illustrative tableau, the more stable candidate (15b) has the lowest negative  $H$  score and wins out over the more faithful candidate (15a).

(15) Comparison of candidates for target  $|z\alpha|$  (evaluation of onset position)

	dult target: $ z\alpha $	ACCURATE	PRECISE	$H$
		$w = 1$	$w = 1$	
a.	$ z\alpha $	0	-4	-4
☞ b.	$ d\alpha $	-1	-2	-3

A different result is obtained when the target fricative occurs in coda position, as illustrated in (16). In the preceding section, we presented arguments from the literature to the effect that the need to execute a jaw-independent lingual gesture is lower, and motoric demands correspondingly smaller, for a fricative in final rather than initial position. This difference is represented in (16) by decreasing by half the PRECISE violation incurred by the faithful fricative target. Because the coarticulatory transition is not problematic for ballistic gestures like stops, the difference in relative strength of the coupling of CV and VC sequences does not affect a stop target in the same way as a fricative. Therefore, we do not depict an asymmetry in the magnitude of PRECISE violations for onset versus coda stop targets. We do reduce (to -.5) the magnitude of the ACCURATE violation in (16b) to reflect the well-documented phenomenon whereby contrasts in postvocalic position have lower perceptual salience than prevocalic contrasts (e.g. Steriade

2001), although this is not a crucial assumption for the present calculation. Under these circumstances, it is faithful candidate (16a) that emerges as most harmonic:

(16) Comparison of candidates for target |maiʃ| (evaluation of coda position).

	Adult target:  maiʃ	ACCURATE	PRECISE	<i>H</i>
		$w = 1$	$w = 1$	
☞ a.	maiʃ	0	-2	-2
b.	mait	-.5	-2	-2.5

We recognize that the framework proposed here might be criticized as overly powerful, insofar as the user modeling a child phonological pattern is free to hand-specify both constraint weights and the magnitude of PRECISE violations incurred by competing candidates. In an ideal research situation, the analyst would have access to an actual child's lifetime production and perception experience in both motor and auditory/acoustic dimensions, and could then construct an actual exemplar space from which PRECISE and ACCURATE violations can be empirically established. A researcher with access to such data could also observe the probability distribution of the outputs the child has produced, and use a Maximum Entropy model (e.g. Hayes & Wilson 2008) to determine weightings for ACCURATE and PRECISE that will generate that observed distribution. As longitudinal studies and recorded corpora of children's speech and child-directed speech continue to multiply (Rose & MacWhinney 2014), there is reason for optimism regarding our ability to estimate the auditory-acoustic aspects of a child's speech experience. Large-scale or longitudinal measures of children's speech-motor experience are further in the future, but as models of motor control of oral structures become more sophisticated (e.g. Gick et al. 2014), computational simulations should become available for this aspect of the model. The approach taken in the present paper is offered as a necessary first step, laying out a general theoretical framework that makes it possible to integrate motor pressures into grammatical computations. We hope that future research will replace our hand-weights for ACCURATE and PRECISE with values that are derived empirically or computationally rather than schematically.

## 8. The A-map and the elimination of child-specific phonological patterns

One of our core goals in proposing a new model of developmental phonology was to explain the existence of phonological patterns that are unique to child speakers. Previous models have

proposed that child-specific constraints can be constructed in response to articulatory or perceptual pressures (e.g. Pater 1997; Becker & Tessier 2011). Since these constraints have no reflex in adult typology, models positing them must assume that the constraints are not merely demoted, but are actually eliminated from the grammar in the normal course of maturation. In our model, children's performance limitations take on grammatical expression through the intermediation of the A-map and the constraint PRECISE. As motor-acoustic mappings become increasingly reliable over the course of maturation and production experience, changes to the A-map, which dictates the magnitude of PRECISE violations, will result in complete elimination of child-specific patterns driven by PRECISE.

It is important to reiterate that ACCURATE and PRECISE themselves are not child-specific constraints. ACCURATE persists, as a highly ranked constraint, in adult grammars, where it could account for the type of imitation and accommodation phenomena that have been uncovered in sociophonetic research (e.g. Sumner & Samuel 2009; Babel 2012; see also Babel 2011 for a recent overview). PRECISE also remains present in the adult grammar, although its influence is greatly attenuated for reasons articulated below. Like any other constraints, these are subject to conventional mechanisms of phonological growth such as changes in constraint weighting. The A-map model requires the existence of a mechanism along the lines of the Gradual Learning Algorithm for Harmonic Grammar (HG-GLA; Boersma & Pater 2007) to do the primary work of determining the weights of conventional constraints. We assume that the weights assigned to ACCURATE and PRECISE can be adjusted in the same manner as other markedness and faithfulness constraints. Thus, in each cycle of evaluation in which the form favored by PRECISE differs from the adult acoustic target, the weight of PRECISE will decrease incrementally relative to the weight of ACCURATE.

However, we propose that this process coexists with a second type of learning in which changes in motor-acoustic mappings alter the topography of the A-map, which in turn tends to reduce the magnitude of the PRECISE violation incurred by a given target. (Recall that the A-map dictates the magnitude of PRECISE violations, but not the weight of the constraint itself.) The mapping from motor plan to acoustic space can be affected by substantive changes in articulatory anatomy that occur in infancy and early childhood (Bosma 1985; Fletcher 1992) as well as developmental advances in speech-motor control. As they mature, children exhibit increasingly refined movements of individual articulators, e.g. moving the tongue independently of the jaw

(Green et al. 2000). Once this process of speech-motor *differentiation* gives the child stable control of the tongue and jaw as independent articulators, it will no longer be the case that ballistic tongue-jaw gestures map more reliably to acoustic space than discrete lingual gestures. Targets like initial and final fricatives, which previously had very different values of *Noise(MP)*, will gradually converge on similar values. After this ‘flattening’ of peaks and troughs in the A-map, the constraint PRECISE will cease to exert a meaningful influence on the computations of the grammar. This constitutes the crucial explanation for why patterns such as positional fricative stopping are eliminated with no residual reflex in adult typology, even in contexts for the emergence of the unmarked (TETU).

Because PRECISE remains latent in the adult grammar, our model also makes the prediction that phonological patterns driven by motor pressures might reemerge in adult speakers with acquired deficits in speech-motor control. If a speaker loses the ability to execute certain motor plans or motor plan sequences reliably following a stroke or other brain injury, these performance failures will be encoded in the dynamically updated A-map. PRECISE could then drive systematic phonological repairs of the problematic sequences. This model is consistent with evidence that error patterns produced by adults with acquired speech deficits often do not have the unpredictable character of pure performance errors, but rather show regularities that are best captured through the formalism of constraint-based grammars (e.g. Buchwald 2009).

In fact, logic strikingly similar to the reasoning underlying the above analysis of positional fricative stopping in child phonology was invoked in a case study of two adults with impaired speech secondary to aphasia and apraxia of speech by Miozzo & Buchwald (2013). These authors provide extensive convergent evidence that one patient, DLE, had a deficit at a phonological level, while the other patient, HFL, was impaired at a more phonetic or articulatory level. However, both patients showed markedly similar patterns of cluster reduction. This suggests that cluster reduction is driven by a phonologically active articulatory pressure, readily captured in our model with the constraint PRECISE. While typical adult speakers of English have no trouble producing even complex sequences of consonants, an adult whose speech-motor control is compromised due to damage to motor regions of the brain may experience articulatory difficulty with these sequences. This difficulty would be manifested in the form of an increased rate of occurrence of performance errors, which would be encoded in the A-map in the form of an elevated value of *Noise(MP)*, which would in turn yield a larger PRECISE violation for

consonant clusters than singleton consonants. A sufficiently large PRECISE violation can outweigh the influence of the faithfulness constraint MAX-SEGMENT and drive a systematic phonological process of cluster reduction.

The parallel to the present account actually arises in connection with Miozzo & Buchwald's explanation of an apparent violation of sonority hierarchy and dispersion effects in the output of patients DLE and HFL. As Miozzo & Buchwald note, consonant clusters with greater sonority distance between margin and peak are preferred (less marked) relative to clusters with similar sonority (e.g. obstruent-obstruent or nasal-nasal). Similarly, low-sonority onsets are unmarked relative to high-sonority onsets, while high sonority is preferred in coda position. The sonority dispersion effect is observed in the data from DLE and HFL. In onset clusters, reduction (deletion) was more likely in similar-sonority clusters (e.g. /fl/) than in dispersed-sonority clusters (e.g. /pl/). However, onset reduction overall was much more likely to affect C1, preserving the higher-sonority C2, e.g. /fl/ → [l]. This reduction is not sonority-optimizing for onsets. By contrast, final clusters showed more variability. In an obstruent cluster, both positions were subject to error, while reduction in sonorant-obstruent clusters showed a strong tendency to optimize sonority, e.g. /lk/ → [l].

Miozzo & Buchwald explain the asymmetry between sonority-optimizing coda cluster reduction and non-sonority-optimizing onset cluster reduction in terms of the difference in relative strength of gestural coupling in onset-vowel and vowel-coda contexts, citing the same sources used here to account for positional asymmetries in children's fricative production (e.g. Nam, Goldstein & Saltzman 2009). Specifically, Miozzo & Buchwald make the assertion that onset clusters systematically reduced to the second consonant due to the particularly strong nature of the coupling between that consonant and the vowel. In coda position, the looser nature of the vowel-coda coupling allows for deletion of either consonant, permitting sonority effects to emerge. However, Miozzo & Buchwald do not specifically address how this motorically motivated pattern of cluster reduction made its way into the output of DLE, whose cluster reduction was revealed by several diagnostics to apply at a context-independent or phonological level. Our model offers a mechanism whereby these articulatory pressures, encoded in the A-map as a consequence of asymmetries in the nature and relative frequency of performance errors, can be expressed in the grammar and interact systematically with conventional markedness and faithfulness constraints responsible for sonority sequencing effects.

## 9. Discussion

In this final section, we summarize the aspects of the A-map model that make a novel contribution relative to previous literature. In particular, we emphasize that the A-map posits a specific mechanism by which motor influences can be incorporated into the computations of the phonological grammar, and that it offers a principled explanation for areas of divergence between child speech patterns and adult phonological typology. We conclude by commenting on several directions of investigation that could provide empirical evidence either for or against the A-map model. In cases where relevant data have already been collected, we incorporate the existing evidence into our discussion.

The inextricability of motor skill acquisition and phonological learning is a well-known puzzle in the study of child speech development ( see, e.g. Green, Moore & Reilly 2002; Vick et al. 2012; Vick et al. 2014). As we saw above, child speech errors often have identifiable roots in performance limitations, yet also show a categorical, systematic quality that is inconsistent with the character of true performance breakdowns. Such speech patterns may persist long after the elimination of the physical pressure that originally motivated the error. For example, children with a surgically repaired cleft palate may possess a fully functional articulatory mechanism, yet continue to exhibit speech patterns related to insufficient velopharyngeal closure over a period of years post-repair (Whitehill, Francis & Ching 2003). These cases can be contrasted with studies examining how speakers compensate for short-term perturbations such as bite blocks (Fowler & Turvey 1980). The bite block affects articulation, but we have no reason to suspect that it alters the speaker's phonological grammar; accordingly, its effects are only transient. The persistence of compensatory patterns in speakers with a history of cleft palate suggests that these performance pressures have been incorporated at a deeper, grammatical level.

Most existing proposals that overtly acknowledge the undeniably intertwined nature of development in speech-motor and phonological domains have taken one of two approaches: either they have stipulated that child speech processes are driven by factors distinct from the grammatical mechanisms conventionally posited to govern adult phonology (Hale & Reiss 1998, 2008), or they assert that motor pressures can be expressed in the grammar but decline to specify the mechanism by which these two domains interact (e.g. Pater 1997; Becker & Tessier 2011). To our knowledge, the present work is virtually unique as a formal model that includes a well-



specified mechanism for the incorporation of motor pressures into the computations of the grammar (but see Boersma 2011 and, for related discussion, Menn, Schmidt & Nicholas 2009).

We also regard it as a novel contribution that the A-map model incorporates an explicit explanation for the observed discontinuity between child phonological patterns and adult typology. In our review of previous literature in section 3, we noted that some of the most successful accounts to date invoke ‘transient’ phonology. By proposing constraints that are present in the child’s grammar but are eliminated from the inventory over the course of maturation, these models can capture both the systematic nature of child errors and the absence of counterparts of these patterns in adult typology. To our knowledge, though, no transient phonology account has included a specific proposal of how these child-specific constraints are deactivated or eliminated over the course of maturation. The A-map model aims to fill this gap in explanatory adequacy. Although the output patterns produced by the A-map and PRECISE are particular to child speakers, the PRECISE constraint itself is not child-specific. Once anatomical and motor maturation have run their full course, values of *Noise(MP)* will be similar across a wide range of target sounds and sound sequences, with the result that PRECISE will cease to have a meaningful impact on grammatical computations. Our model thus allows the assumption of continuity of the constraint set across child and adult speakers, yet it does so without generating the incorrect prediction that all phonological patterns observed in child speech should have some reflex in adult typology. It additionally predicts that phonological patterns driven by PRECISE could re-emerge in the speech of adults with acquired deficits in speech-motor control; this prediction is borne out in case studies of adults with aphasia and apraxia of speech (e.g. Buchwald 2009; Miozzo & Buchwald 2013).

The present paper has been largely concerned with synthesizing existing evidence that points to the need for a mechanism like the A-map, and laying out the specifics of the formal model. Follow-up work will focus on generating and testing specific predictions of the model. Several such predictions are laid out below; many other directions of inquiry could also profitably be entertained.

#### *1. Changes in variability over the course of acquisition of speech targets*

Within a child speaker, the A-map model predicts that variability should decrease as a child enters a stable error pattern favored by PRECISE. That is, the earliest error patterns should be characterized by low accuracy and high variability, since the child has no stable motor plan

(either accurate or inaccurate) to realize the target speech string. Our model predicts that it should be possible to observe children making a transition from this variable/inaccurate phase into a phase characterized by low accuracy and low variability. In this latter low-variability stage, the child is making use of a stable motor plan under the influence of PRECISE; the motor plan that produces a fully accurate adult target is not yet well established in the child's repertoire, and so PRECISE favor a different plan. As the child makes a transition from this stable error to a more accurate output, we predict at least a brief interval of heightened variability, followed by stabilized production of the correct target output.

This predicted trajectory was illustrated using consonant harmony data from the Trevor corpus in McAllister Byun & Inkelas (2014). However, the strength of the conclusions that could be drawn from that study was limited by the fact that only the transcribed record of the child's output was available. An improved experimental methodology would use instrumental measures (either acoustic or, ideally, articulatory; see e.g. Lin & Demuth 2015) to obtain finer-grained evidence about changes in variability over the course of speech acquisition. For example, a longitudinal study using optical kinematic tracking of articulator movements could show high motor variability in early attempts to produce a new speech target, followed by reduced variability once the child transitions to a stable error pattern, then another increase in variability before the child converges on stable correct production.

While the question framed above has not been investigated directly, existing research from Goffman and colleagues suggests that this is a promising direction. In general, the literature using kinematic tracking to document speech-motor development has found that articulator trajectories are more variable in child speakers than adults, and in children with impaired language development than typical children (e.g. Goffman & Smith 1999; Goffman 2004). Such findings are compatible with a model where child speech errors are conceptualized as the product of limitations on speech-motor performance. However, a pure performance model would also predict that articulator trajectories produced in connection with speech errors should be more variable than trajectories produced in connection with accurate outputs. Contrary to this expectation, Goffman, Gerken & Lucchesi (2007) found little evidence of correlation between segmental measures of accuracy and kinematic measures of stability, either in typically developing children or children with language impairment. This same finding makes sense from the point of view of the A-map model: some child speech errors are random performance

breakdowns and should thus show high motor variability, but other errors systematically substitute a form associated with a stable motor plan and thus should show particularly low variability. If a longitudinal study were to show that variability in the motor-acoustic mapping is not reduced when a child makes a transition into a segmentally consistent error pattern, this could be considered evidence against our model in its present shape.

## 2. *Multiple trajectories for the elimination of phonological patterns*

By invoking both A-map ‘flattening’ and a gradual, learning-based demotion of PRECISE, our model predicts a range of trajectories for the elimination of phonological patterns. This can be contrasted with the more limited predictions of a model in which child-specific pattern elimination is governed exclusively by a mechanism of incremental constraint demotion such as the HG-GLA. The latter type of model predicts gradual, across-the board improvements affecting all aspects of a child’s production. In actuality, the obsolescence of child-specific speech patterns is not confined to this one path. Some patterns diminish incrementally, while others persist in stable form for a lengthy period before disappearing abruptly. An example of the former type can be seen in McAllister Byun’s (2012) study of velar fronting, where gradual increases in the case study subject’s production of faithful velars were observed continuously between ages 3;10 and 4;4. A contrasting example of abrupt, categorical elimination of a phonological process is provided in Bedore, Leonard & Gandour’s (1994) case study of an English-acquiring child who produced a dental click [t̪] for all target coronal sibilants. The authors initiated intervention to encourage more accurate production of sibilant targets, but within a week of enrollment, the child presented with correct production of all sibilant targets in spontaneous speech.

In the A-map framework, the difference between abrupt/categorical and gradual trajectories of suppression of phonological patterns can be explained in terms of a difference in the relative timing of motor maturation and the reweighting of ACCURATE relative to PRECISE. If the motor limitations that initially drove the error are eliminated before high-weighted ACCURATE drives the child to attempt faithful production, the cessation of PRECISE effects will be rapid and appear categorical. By contrast, if the child continues to attempt the adult target while motor constraints remain in force, elimination of the error is predicted to have a more gradual and incremental character. Note that this mechanism can account for differences within as well as across children, since different motor skills (such as achieving jaw-independent control of the tongue or forming a midline lingual groove) will be mastered at different points in

a given child's development. Future work will aim to highlight the contrast between the A-map and competing models in their ability to capture the elimination of different patterns on different time courses.

### 3. *Effects of PRECISE that span multiple patterns*

A third aspect of the A-map model that is amenable to empirical testing is the prediction that the relative weighting of PRECISE and ACCURATE within a child's phonology should show relatively stable effects across multiple phonological patterns. That is, a child with high-weighted PRECISE should show a general preference to replace articulatorily challenging targets with motorically stable substitutions, while a child with high-weighted ACCURATE might continue to attempt to produce his/her closest approximation of all adult targets, even at the expense of motor reliability. This prediction is supported by an existing literature documenting differences in the extent of speech variability across child speakers. Vihman & Greenlee (1987) proposed that children can be classified according to broad two learning styles: *systematic and stable*, or *exploratory and variable*. They found that these differences in "tolerance for variability" constituted a stable within-child parameter: variability in a child's speech at one year old was highly predictive of variability at age three. The predictions of the A-map model could be tested in a kinematic study of children classified as systematic/stable or exploratory/variable: children in the latter group should show a higher level of variability not only in how their outputs are transcribed, but also in basic measures of stability in articulatory trajectories across repeated utterances. Again, we have yet to investigate this question directly, but recent work by Vick and colleagues points in a promising direction. Vick et al. (2012) collected numerous measures of segmental and acoustic accuracy and acoustic and articulatory stability from 63 typically developing speakers. A subgroup discovery algorithm revealed three clusters within this sample of speakers. Two groups showed comparable levels of segmental accuracy but differed in that one group was characterized by "high stability" and one by "high variability" in both acoustic and articulatory measures. The third group was distinguished by low segmental accuracy in the absence of elevated articulatory variability. Vick et al. posited that this group could reflect "a state in which the child generates relatively stable speech productions at the expense of a limited phonemic repertoire" (Vick et al. 2012:2897).

## 10. Conclusion

The preceding decade of phonological research has seen a surge of interest in areas of intersection between traditional phonological generalizations and usage-based and psycholinguistic phenomena. Our work sits squarely at this nexus. The A-map model can be seen as the most recent addition to a body of work investigating how properties of personal experience can influence phonological and phonetic behavior. This list includes such well known entries as frequency of exposure to lexical items (e.g. Hooper 1976; Jurafsky et al. 2001; Gahl 2008); neighborhood density of the individual's lexicon (e.g. Dell & Gordon 2003; Zamuner 2009; Gahl, Yao & Johnson 2012); and exposure to multiple dialects, languages, or even voices (e.g. contributions to Johnson & Mullennix 1997; see also Werker & Curtin 2005; Curtin, Byers-Heinlein & Werker 2011). However, these properties deriving from the input to child speakers do not tell the complete story of phonological development. As we saw above, the properties of the input do not readily account for template effects (e.g. Vihman & Velleman 2000), nor for cases of children with phonological delay/disorder whose phonological patterns may not be eliminated despite extended exposure to highly focused input (e.g. McAllister Byun 2012). By incorporating the A-map, which keeps track of the child's individual history of the relative ease or difficulty of producing a particular target, we can better account for these phenomena. More broadly, the A-map model can be regarded as an additional step toward the overarching goal of a multidimensional model situating phonological acquisition in the larger context of the child's cognitive, motor, and perceptual development.

## References

- Ahn, Sang-Cheol. 1998. *An Introduction to Korean Phonology*. Seoul, Korea: Hansin Munhwasa.
- Alderete, John, Jill Beckman, Laura Benua, Amalia Gnanadesikan, John McCarthy & Suzanne Urbanczyk. 1999. Reduplication with Fixed Segmentism. *Linguistic Inquiry* 30(3). 327–364.
- Babel, Molly. 2011. Imitation in Speech. *Acoustics Today* 7(4). 16–23.
- Babel, Molly. 2012. Evidence for Phonetic and Social Selectivity in Spontaneous Phonetic Imitation. *Journal of Phonetics* 40(1). 177–189.
- Barlow, Jessica A. 1997. A Constraint-Based Account of Syllable Onsets: Evidence from Developing Systems. Indiana University Ph.D. Dissertation.
- Barnes, Jonathan. 2006. *Strength and Weakness at the Interface: Positional Neutralization in Phonetics and Phonology*. Walter de Gruyter.
- Bates, Sally, Jocelyne M.M. Watson & James M. Scobbie. 2002. Context-conditioned Error Patterns in Disordered Systems. In Martin J. Ball & Fiona E. Gibbon (eds.), *Vowel disorders*, 146–185. Woburn, MA: Butterworth-Heinemann.
- Becker, Michael & Anne-Michelle Tessier. 2011. Trajectories of Faithfulness in Child-Specific Phonology. *Phonology* 28(2). 163–196.
- Bedore, Lisa M., Laurence B. Leonard & Jack Gandour. 1994. The Substitution of a Click for Sibilants: A Case Study. *Clinical Linguistics & Phonetics* 8(4). 283–293.
- Bernhardt, Barbara H. & Joseph P. Stemberger. 1998. *Handbook of Phonological Development from the Perspective of Constraint-Based Nonlinear Phonology*. San Diego: Academic Press.
- Bernhardt, Barbara & Carol Stoel-Gammon. 1994. Nonlinear Phonology: Introduction and Clinical Application. *Journal of Speech and Hearing Research* 37(1). 123–143.
- Bills, Shannon & Chris Golston. 2002. Prosodic and Linear Licensing in English Acquisition. In Lesley Carmichael, Chia-Hui Huang & Vida Samiian (eds.), *Proceedings of the Western Conference on Linguistics (2001)*, 13–26. Fresno: California State University.
- Boersma, Paul. 2011. A Programme for Bidirectional Phonology and Phonetics and Their Acquisition and Evolution. In Anton Benz & Jason Mattausch (eds.), *Bidirectional Optimality Theory*. Amsterdam: John Benjamins.
- Boersma, Paul & Joe Pater. 2007. Constructing Constraints from Language Data: The Case of Canadian English Diphthongs. Paper presented at the 38th Conference of the North East Linguistic Society, Ottawa.
- Bosma, James F. 1985. Postnatal Ontogeny of Performances of the Pharynx, Larynx, and Mouth. *The American Review of Respiratory Disease* 131(5). S10–15.
- Bowerman, Melissa. 1982. Starting to Talk Worse: Clues to Language Acquisition from Children's Late Speech Errors. In Sidney Strauss (ed.), *U-shaped Behavioral Growth*. New York: Academic Press.
- Buchwald, Adam. 2009. Minimizing and Optimizing Structure in Phonology: Evidence from Aphasia. *Lingua* 119(10). 1380–1395.
- Buchwald, Adam & Michele Miozzo. 2011. Finding Levels of Abstraction in Speech Production: Evidence from Sound-Production Impairment. *Psychological Science* 22(9). 1113–1119.
- Buckley, Eugene. 2003. Children's Unnatural Phonology. In Pawel Nowak & Corey Yoquelet (eds.), *Proceedings of the 29th Annual Meeting of the Berkeley Linguistics Society*, 523–534. Berkeley: Berkeley Linguistics Society.

- Burkinshaw, Kelly. 2014. Segmental and Prosodic Development: A Corpus-based, Cross-linguistic Investigation. Memorial University of Newfoundland M.A. Thesis.
- Chiat, Shula. 1983. Why Mikey's Right and My Key's Wrong: The Significance of Stress and Word Boundaries in a Child's Output System. *Cognition* 14. 275–300.
- Chiat, Shula. 1989. The Relation between Prosodic Structure, Syllabification and Segmental Realization: Evidence from a Child with Fricative Stopping. *Clinical Linguistics and Phonetics* 3(3). 223–242.
- Cohn, Abigail C. 1990. Phonetic and Phonological Rules of Nasalization. Los Angeles, CA: University of California at Los Angeles Ph.D. Dissertation.
- Compton, Arthur J. & Mary Streeter. 1977. Child Phonology: Data Collection and Preliminary Analyses. *Papers and Reports on Child Language Development* 13. 99–109.
- Correia, Susana. 2009. The Acquisition of Primary Word Stress in European Portuguese. Lisbon: Lisbon University Ph.D. Dissertation.
- Correia, Susana, Teresa da Costa & Maria João Freitas. 2010. *Corpus of European Portuguese Phonological Development*. Lisbon: Lisbon University/CLUL.
- Costa, Teresa da. 2010. The Acquisition of the Consonantal System in European Portuguese: Focus on Place and Manner Features. University of Lisbon Ph.D. Dissertation.
- Crelin, Edmund S. 1987. *The Human Vocal Tract: Anatomy, Function, Development, and Evolution*. New York: Vantage Press.
- Curtin, Suzanne, Krista Byers-Heinlein & Janet F. Werker. 2011. Bilingual Beginnings as a Lens for Theory Development: PRIMIR in Focus. *Journal of Phonetics* 39(4). 492–504.
- Davis, Stuart. 2010. Distributional Evidence for the Foot from the L1 Acquisition of American English. *Phonological Studies* 13. 39–50.
- Dell, Gary S., Lisa K. Burger & William R. Svec. 1997. Language Production and Serial Order: A Functional Analysis and a Model. *Psychological Review* 104(1). 123–147.
- Dell, Gary S. & Jean K. Gordon. 2003. Neighbors in the Lexicon: Friends or Foes. In Niels O. Schiller & Antje S. Meyer (eds.), *Phonetics and Phonology in Language Comprehension and Production: Differences and Similarities*. New York: Mouton de Gruyter.
- Dinnsen, Daniel A. 2008. A Typology of Opacity Effects in Acquisition. In Daniel A. Dinnsen & Judith A. Gierut (eds.), *Optimality Theory, Phonological Acquisition and Disorders*, 121–176. London: Equinox.
- Dinnsen, Daniel A., Christopher R. Green, Michele L. Morrisette & Judith A. Gierut. 2011. On the Interaction of Velar Fronting and Labial Harmony. *Clinical Linguistics & Phonetics* 25(3). 231–251.
- Edwards, Mary Louise. 1996. Word Position and the Production of Fricatives. In Barbara H. Bernhardt, John Gilbert & David Ingram (eds.), *Proceedings of the UBC International Conference on Phonological Acquisition*, 149–158. Somerville, MA: Cascadilla Press.
- Ferguson, Charles A. & Carol B. Farwell. 1975. Words and Sounds in Early Language Acquisition. *Language* 51. 419–439.
- Fikkert, Paula. 1994. *On the Acquisition of Prosodic Structure*. (HIL Dissertations in Linguistics 6). The Hague: Holland Academic Graphics.
- Fikkert, Paula & Clara Levelt. 2008. How does Place Fall into Place? The Lexicon and Emergent Constraints in Children's Developing Grammars. In Peter Avery, B. Elan Dresher & Keren Rice (eds.), *Contrast in Phonology: Theory, Perception, Acquisition*, 231–268. Berlin: Mouton de Gruyter.
- Flemming, Edward S. 2002. *Auditory Representations in Phonology*. New York: Routledge.

- Fletcher, Paul. 1992. Language Development from Two to Three. *Clinical Linguistics & Phonetics* 6(4). 329–330.
- Fletcher, Samuel G. 1973. Maturation of the Speech Mechanism. *Folia Phoniatrica* 25. 161–172.
- Fletcher, Samuel G. 1989. Palatometric Specification of Stop, Affricate, and Sibilant Sounds. *Journal of Speech and Hearing Research* 32. 736–748.
- Fowler, Carol A. & Michael T. Turvey. 1980. Immediate Compensation in Bite-Block Speech. *Phonetica* 37(5-6). 306–326.
- Freitas, Maria João. 1997. Aquisição da Estrutura Silábica do Português Europeu. University of Lisbon Ph.D. Dissertation.
- Fudge, Eric C. 1969. Syllables. *Journal of Linguistics* 5. 253–286.
- Gahl, Susanne. 2008. “Time” and “Thyme” Are Not Homophones: The Effect of Lemma Frequency on Word Durations in Spontaneous Speech. *Language* 84(3). 474–496.
- Gahl, Susanne, Yao Yao & Keith Johnson. 2012. Why Reduce? Phonological Neighborhood Density and Phonetic Reduction in Spontaneous Speech. *Journal of Memory and Language* 66(4). 789–806.
- Ghosh, Satrajit S., Sita Kakunoori, Jean Augustinack, Alfonso Nieto-Castañón, Ioulia Kovelman, Nadine Gaab, Joanna A. Christodoulou, Christina Triantafyllou, John D.E. Gabrieli & Bruce Fischl. 2010. Evaluating the Validity of Volume-based and Surface-based Brain Image Registration for Developmental Cognitive Neuroscience Studies in Children 4 to 11 Years of Age. *NeuroImage* 53(1). 85–93.
- Gibbon, Fiona E. 1999. Undifferentiated Lingual Gestures and their Implications for Speech Disorders in Children. *Proceedings of the XIVth International Congress of Phonetic Sciences* 3. 1913–1916.
- Gick, Bryan, Peter Anderson, Hui Chen, Chenhao Chiu, Ho Beom Kwon, Ian Stavness, Ling Tsou & Sidney Fels. 2014. Speech Function of the Oropharyngeal Isthmus: A Modelling Study. *Computer Methods in Biomechanics and Biomedical Engineering: Imaging & Visualization*. 1–6.
- Gick, Bryan W., Penelope Bacsfalvi, Barbara May Bernhardt, Sunyoung Oh, Slade Stolar & Ian Wilson. 2008. A Motor Differentiation Model for Liquid Substitutions in Children’s Speech. *Proceedings of Meetings on Acoustics, Vol. 1*. 1–9.
- Giulivi, Sara, D. H. Whalen, Louis M. Goldstein, Hosung Nam & Andrea G. Levitt. 2011. An Articulatory Phonology Account of Preferred Consonant-Vowel Combinations. *Language Learning and Development* 7(3). 202–225.
- Goad, Heather. 1997. Consonant Harmony in Child Language: An Optimality-theoretic Account. In S. J. Hannahs & Martha Young-Sholten (eds.), *Focus on Phonological Acquisition*, 113–142. Amsterdam: John Benjamins.
- Goad, Heather & Yvan Rose. 2003. *Segmental-prosodic Interaction in Phonological Development: A Comparative Investigation*. Special Issue, *The Canadian Journal of Linguistics / La revue canadienne de linguistique* 48(3/4): 139-452.
- Goad, Heather & Yvan Rose. 2004. Input Elaboration, Head Faithfulness and Evidence for Representation in the Acquisition of Left-edge Clusters in West Germanic. In René Kager, Joe Pater & Wim Zonneveld (eds.), *Constraints in Phonological Acquisition*, 109–157. Cambridge: Cambridge University Press.
- Goffman, Lisa. 2004. Kinematic Differentiation of Prosodic Categories in Normal and Disordered Language Development. *Journal of Speech, Language, and Hearing Research* 47(5). 1088–1102.



- Goffman, Lisa, LouAnn Gerken & Julie Lucchesi. 2007. Relations between Segmental and Motor Variability in Prosodically Complex Nonword Sequences. *Journal of Speech, Language, and Hearing Research* 50(2). 444–458.
- Goffman, Lisa & Anne Smith. 1999. Development and Phonetic Differentiation of Speech Movement Patterns. *Journal of Experimental Psychology: Human Perception and Performance* 25(3). 649–660.
- Goldrick, Matthew & Robert Daland. 2009. Linking Speech Errors and Phonological Grammars: Insights from Harmonic Grammar Networks. *Phonology* 26(01). 147–185.
- Green, Jordan R., Christopher A. Moore, Masahiko Higashikawa & Roger W. Steeve. 2000. The Physiologic Development of Speech Motor Control: Lip and Jaw Coordination. *Journal of Speech, Language, and Hearing Research* 43. 239–255.
- Green, Jordan R., Christopher A. Moore & Kevin J. Reilly. 2002. The Sequential Development of Jaw and Lip Control for Speech. *Journal of Speech, Language, and Hearing Research* 45(1). 66–79.
- Grunwell, Pamela. 1981. *The Nature of Phonological Disability in Children*. London: Academic Press.
- Guenther, Frank H. 1994. A Neural Network Model Of Speech Acquisition And Motor Equivalent Speech Production. *Biological Cybernetics* 72. 43–53.
- Guenther, Frank H., Satrajit S. Ghosh & Jason A. Tourville. 2006. Neural Modeling and Imaging of the Cortical Interactions Underlying Syllable Production. *Brain and Language* 96(3). 280–301.
- Hale, Mark & Charles Reiss. 1998. Formal and Empirical Arguments Concerning Phonological Acquisition. *Linguistic Inquiry* 29(4). 656–683.
- Hale, Mark & Charles Reiss. 2008. *The Phonological Enterprise*. Oxford: Oxford University Press.
- Halle, Morris & Kenneth N. Stevens. 1959. Analysis by Synthesis. In W. Wathen-Dunn & L.E. Woods (eds.), *Proceedings of the Seminar on Speech Compression and Processing*, D7. USAF Cambridge Resource Center.
- Halle, Morris & Kenneth N. Stevens. 1962. Speech Recognition: A Model and a Program for Research. *IRA Transactions of the PGIT, IT-8*. 155–159.
- Halle, Morris & Kenneth N. Stevens. 1979. Some Reflexions on the Theoretical Bases of Phonetics. In Björn Lindblom, Sven E. G. Öhman & Gunnar Fant (eds.), *Frontiers of Speech Communication Research*, 335–349. New York: Academic Press.
- Hansson, Gunnar. 2001. Theoretical and Typological Issues in Consonant Harmony. University of California at Berkeley Ph.D. Dissertation.
- Hayes, Bruce. 1999. Phonetically Driven Phonology: The Role of Optimality Theory and Inductive Grounding. In Michael Darnell, Edith Moravcsik, Frederick J. Newmeyer, Michael Noonan & Kathleen Wheatley (eds.), *Functionalism and Formalism in Linguistics, Vol. 1: General Papers*, 243–285. Amsterdam and Philadelphia: Benjamins.
- Hayes, Bruce & Colin Wilson. 2008. A Maximum Entropy Model of Phonotactics and Phonotactic Learning. *Linguistic Inquiry* 39(3). 379–440.
- Hazan, Valerie & Sarah Barrett. 2000. The Development of Phonemic Categorization in Children Aged 6–12. *Journal of Phonetics* 28(4). 377–396.
- Hickok, Gregory. 2012. Computational Neuroanatomy of Speech Production. *Nature Reviews Neuroscience* 13(2). 135–145.

- Hickok, Gregory & David Poeppel. 2007. The Cortical Organization of Speech Processing. *Nature Reviews Neuroscience* 8(5). 393–402.
- Hooper, Joan Bybee. 1976. Word Frequency in Lexical Diffusion and the Source of Morpho-phonological Change. In William Christie (ed.), *Current Progress in Historical Linguistics*, 96–105. Amsterdam: North Holland.
- Hume, Elizabeth. 1996. Coronal Consonant, Front Vowel Parallels in Maltese. *Natural Language & Linguistic Theory* 14(1). 163–203.
- Ingram, David. 1974. Phonological Rules in Young Children. *Journal of Child Language* 1. 49–64.
- Inkelas, Sharon & Yvan Rose. 2003. Velar Fronting Revisited. In Barbara Beachley, Amanda Brown & Fran Conlin (eds.), *Proceedings of the 27th Annual Boston University Conference on Language Development*, 334–345. Somerville, MA: Cascadilla Press.
- Inkelas, Sharon & Yvan Rose. 2007. Positional Neutralization: A Case Study from Child Language. *Language* 83(4). 707–736.
- Johnson, Keith. 1997. Speech Perception without Speaker Normalization: An Exemplar Model. In Keith Johnson & John W. Mullennix (eds.), *Talker Variability in Speech Processing*, 145–165. San Diego, CA: Academic Press.
- Johnson, Keith. 2006. Resonance in an Exemplar-based Lexicon: The Emergence of Social Identity and Phonology. *Journal of Phonetics* 34. 485–499.
- Johnson, Keith & John W. Mullennix (eds.). 1997. *Talker Variability in Speech Processing*. San Diego, CA: Academic Press.
- Johnson, Keith, David Pisoni & Robert Bernacki. 1990. Do Voice Recordings Reveal whether a Person is Intoxicated? *Phonetica* 47. 215–237.
- Jurafsky, Daniel, Alan Bell, Michelle L. Gregory & William D. Raymond. 2001. Probabilistic Relations between Words: Evidence from Reduction in Lexical Production. *Frequency and the Emergence of Linguistic Structure*, 227–254. Amsterdam: John Benjamins.
- Kan, Pui Fong, Neeraja Sadagopan, Lauren Janich & Marixa Andrade. 2014. Effects of Speech Practice on Fast Mapping in Monolingual and Bilingual Speakers. *Journal of Speech, Language, and Hearing Research* 57(3). 929–941.
- Kao, Mimi H., Allison J. Doupe & Michael S. Brainard. 2005. Contributions of an Avian Basal Ganglia-forebrain Circuit to Real-time Modulation of Song. *Nature* 433(7026). 638–643.
- Keating, Patricia A. 1988. The Phonology-Phonetics Interface. In Frederick J. Newmeyer (ed.), *Linguistics: The Cambridge Survey, Volume 1: Grammatical Theory*. Cambridge: Cambridge University Press.
- Kent, Ray D. 1981. Articulatory-Acoustic Perspective on Speech Development. In Rachel E. Stark (ed.), *Language Behavior in Infancy and Early Childhood*, 105–126. New York: Elsevier.
- Kent, Ray D. 1992. The Biology of Phonological Development. In Charles A. Ferguson, Lise Menn & Carol Stoel-Gammon (eds.), *Phonological Development: Models, Research, Implications*, 65–90. Timonium, Maryland: York Press.
- Keyser, Samuel Jay & Kenneth Noble Stevens. 2006. Enhancement and Overlap in the Speech Chain. *Language* 82(1). 33–63.
- Krakow, Rena A. 1999. Physiological Organization of Syllables: A Review. *Journal of Phonetics* 27(1). 23–54.

- Kuhl, Patricia K., Rey R. Ramírez, Alexis Bosseler, Jo-Fu Lotus Lin & Toshiaki Imada. 2014. Infants' Brain Responses to Speech Suggest Analysis by Synthesis. *Proceedings of the National Academy of Sciences* 111(31). 11238–11245.
- Lacy, Paul de. 2002. The Formal Expression of Markedness. University of Massachusetts at Amherst Ph.D. Dissertation.
- Legendre, Géraldine, Yoshiro Miyata & Paul Smolensky. 1990. *Harmonic Grammar: A Formal Multi-level Connectionist Theory of Linguistic Well-formedness. Theoretical foundations*. Department of Computer Science: University of Colorado, Boulder.
- Leonard, Laurence B. & Karla K. McGregor. 1991. Unusual Phonological Patterns and their Underlying Representations: A Case Study. *Journal of Child Language* 18. 261–271.
- Leopold, Werner F. 1939. *Speech Development of a Bilingual Child: A Linguist's Record, Vol. 1: Vocabulary Growth in the First Two Years*. Evanston, IL: Northwestern University Press.
- Leopold, Werner F. 1947. *Speech Development of a Bilingual Child: A Linguist's Record, Vol. 2: Sound-learning in the First Two Years*. Evanston, IL: Northwest University Press.
- Levelt, Clara & Marc van Oostendorp. 2007. Feature Co-occurrence Constraints in L1 Acquisition. In Bettelou Los & Marjo van Koppen (eds.), *Linguistics in the Netherlands 2007*, 162–172. Amsterdam: John Benjamins.
- Lin, Susan & Katherine Demuth. 2015. Children's Acquisition of English Onset and Coda /l/: Articulatory Evidence. *Journal of Speech Language and Hearing Research* 58(1). 13.
- Locke, John L. 1983. *Phonological Acquisition and Change*. New York: Academic Press.
- Macken, Marlys A. 1979. Developmental Reorganization of Phonology: A Hierarchy of Basic Units of Acquisition. *Lingua* 49. 11–49.
- Macken, Marlys A. 1996. Phonological Acquisition. In John A. Goldsmith (ed.), *The Handbook of Phonological Theory*, 671–696. Cambridge, MA: Blackwell.
- Macnamara, John. 1982. *Names for Things: A Study of Child Language*. Cambridge, MA: Bradford Books / MIT Press.
- MacNeilage, Peter F. & Barbara L. Davis. 1990a. Acquisition of Speech Production: The Achievement of Segmental Independence. In William J. Hardcastle & Alain Marchal (eds.), *Speech Production and Modeling*, 55–68. Dordrecht: Kluwer Academic Publishers.
- MacNeilage, Peter F. & Barbara L. Davis. 1990b. Acquisition of Speech Production: Frames, then Content. In Marc Jeannerod (ed.), *Attention and Performance XIII: Motor Representation and Control*, 453–476. Hillsdale, NJ: Lawrence Erlbaum.
- MacWhinney, Brian. 1978. *The Acquisition of Morphophonology*. Chicago: University of Chicago Press.
- Marshall, Chloe & Shulamuth Chiat. 2003. A Foot Domain Account of Prosodically-conditioned Substitutions. *Clinical Linguistics and Phonetics* 17(8). 645–657.
- Maye, Jessica, Janet F. Werker & LouAnn Gerken. 2002. Infant Sensitivity to Distributional Information Can Affect Phonetic Discrimination. *Cognition* 82(3). B101–B111.
- Mayo, Catherine & Alice Turk. 2004. Adult–child Differences in Acoustic Cue Weighting are Influenced by Segmental Context: Children are not always Perceptually Biased toward Transitions. *The Journal of the Acoustical Society of America* 115(6). 3184–3194.
- McAllister Byun, Tara. 2011. A Gestural Account of a Child-specific Neutralization in Strong Position. *Phonology* 28(3). 371–412.

- McAllister Byun, Tara. 2012. Positional Velar Fronting: An Updated Articulatory Account. *Journal of Child Language* 39(5). 1043–1076.
- McAllister Byun, Tara & Sharon Inkelas. 2014. Child Consonant Harmony and Phonologization of Performance Errors. In Hsin-Lun Huang, Ethan Poole & Amanda Rysling (eds.), *NELS 43: Proceedings of the Forty-Third Annual Meeting of the North East Linguistic Society*, 291–302. Amherst, MA: GLSA.
- McCarthy, John J. & Alan S. Prince. 1994. The Emergence of the Unmarked: Optimality in Prosodic Morphology. In Mercè González (ed.), *Proceedings of the North Eastern Linguistic Society*, 333–379. University of Massachusetts Press.
- Menn, Lise. 1983. Development of Articulatory, Phonetic, and Phonological Capabilities. In Brian Butterworth (ed.), *Language Production*, vol. 2, 1–49. London: Academic Press.
- Menn, Lise, Ellen Schmidt & Brent Nicholas. 2009. Conspiracy and Sabotage in the Acquisition of Phonology: Dense Data Undermine Existing Theories, Provide Scaffolding for a New One. *Language Sciences* 31(2-3). (Data and Theory: Papers in Phonology in Celebration of Charles W. Kisseberth). 285–304.
- Menn, Lise, Ellen Schmidt & Brent Nicholas. 2013. Challenges to Theories, Charges to a Model: The Linked-Attractor Model of Phonological Development. In Marilyn M. Vihman & Tamar Keren-Portnoy (eds.), *The Emergence of Phonology: Whole-word Approaches and Cross-linguistic Evidence*, 460–502. Cambridge: Cambridge University Press.
- Mielke, Jeff. 2008. *The Emergence of Distinctive Features*. Oxford: Oxford University Press.
- Miozzo, Michele & Adam Buchwald. 2013. On the Nature of Sonority in Spoken Word Production: Evidence from Neuropsychology. *Cognition* 128. 287–301.
- Mooshammer, Christine, Philip Hoole & Anja Geumann. 2006. Interarticulator Cohesion within Coronal Consonant Production. *The Journal of the Acoustical Society of America* 120(2). 1028–1039.
- Morrisette, Michele L., Daniel A. Dinnsen & Judith A. Gierut. 2003. Markedness and Context Effects in the Acquisition of Place Features. *The Canadian Journal of Linguistics / La revue canadienne de linguistique* 48(3/4). 329–355.
- Munson, Benjamin, Jan Edwards & Mary E. Beckman. 2005. Relationships between Nonword Repetition Accuracy and other Measures of Linguistic Development in Children with Phonological Disorders. *Journal of Speech, Language, and Hearing Research* 48(1). 61–78.
- Munson, Benjamin, Beth A. Kurtz & Jennifer Windsor. 2005. The Influence of Vocabulary Size, Phonotactic Probability, and Wordlikeness on Nonword Repetitions of Children with and without Specific Language Impairment. *Journal of Speech, Language, and Hearing Research* 48(5). 1033–1047.
- Nam, Hosung, Louis Goldstein & Elliot Saltzman. 2009. Self-organization of Syllable Structure: A Coupled Oscillator Model. In François Pellegrino, Egidio Marsico, Ioana Chitoran & Christophe Coupé (eds.), *Approaches to Phonological Complexity*, 299–328. Berlin: Mouton.
- Ní Chiosáin, Máire & Jaye Padgett. 1993. *Inherent VPlace*. Linguistics Research Center: University of California, Santa Cruz.
- Nittrouer, Susan. 2002. Learning to Perceive Speech: How Fricative Perception Changes, and How It Stays the Same. *The Journal of the Acoustical Society of America* 112(2). 711–719.

- Pater, Joe. 1997. Minimal Violation and Phonological Development. *Language Acquisition* 6(3). 201–253.
- Pater, Joe. 2002. Form and Substance in Phonological Development. In Line Mikkelsen & Chris Potts (eds.), *Proceedings of the 21st West Coast Conference on Formal Linguistics*, 348–372. Somerville, MA: Cascadilla Press.
- Pater, Joe. 2004. Bridging the Gap between Receptive and Productive Development with Minimally Violable Constraints. In René Kager, Joe Pater & Wim Zonneveld (eds.), *Fixing Priorities: Constraints in Phonological Acquisition*, 219–244. Cambridge: Cambridge University Press.
- Pater, Joe. 2009. Weighted Constraints in Generative Linguistics. *Cognitive Science* 33. 1–37.
- Pater, Joe & Adam Werle. 2001. Typology and Variation in Child Consonant Harmony. In Caroline Féry, Antony Dubach Green & Ruben van de Vijver (eds.), *Proceedings of the Holland Institute of Linguistics — Phonology 5*, 119–139. Potsdam: University of Potsdam.
- Pater, Joe & Adam Werle. 2003. Direction of Assimilation in Child Consonant Harmony. *The Canadian Journal of Linguistics / La revue canadienne de linguistique* 48(3/4). 385–408.
- Phillips, Holly N., Nikhil A. Howai, Guy-Bart V. Stan & Aldo A. Faisal. 2011. The Implied Exploration-Exploitation Trade-off in Human Motor Learning. *BMC Neuroscience* 12(Suppl. 1). P98.
- Pierrehumbert, Janet B. 2001. Exemplar Dynamics: Word Frequency, Lenition and Contrast. In Joan L. Bybee & Paul Hoppe (eds.), *Frequency and Emergence in Grammar*, 137–157. Amsterdam: John Benjamins.
- Pierrehumbert, Janet B. 2002. Word-specific Phonetics. In Carlos Gussenhoven & Natasha Warner (eds.), *Laboratory Phonology VII*, 101–140. Berlin: Mouton de Gruyter.
- Pierrehumbert, Janet B. 2003. Phonetic Diversity, Statistical Learning, and Acquisition of Phonology. *Language and Speech* 46(2-3). 115–154.
- Pierrehumbert, Janet B. & Paul Gross. 2003. Community Phonology. University of Chicago.
- Pinker, Steven. 1984. *Language Learnability and Language Development*. Cambridge, MA: Harvard University Press.
- Pisoni, David B. 1997. Some Thoughts on “Normalization” in Speech Perception. In Keith Johnson & John W. Mullennix (eds.), *Talker Variability in Speech Processing*, 9–32. San Diego, CA: Academic Press.
- Poepfel, David, William J. Idsardi & Virginie van Wassenhove. 2008. Speech Perception at the Interface of Neurobiology and Linguistics: Prospects and Problems. *Philosophical Transactions of the Royal Society of London B: Biological Sciences* 363. 1071–1086.
- Poepfel, David & Philip J. Monahan. 2011. Feedforward and Feedback in Speech Perception: Revisiting Analysis by Synthesis. *Language and Cognitive Processes* 26(7). 935–951. (26 June, 2014).
- Priestly, Tom M.S. 1977. One Idiosyncratic Strategy in the Acquisition of Phonology. *Journal of Child Language* 4. 45–65.
- Prince, Alan S. & Paul Smolensky. 2004. *Optimality Theory: Constraint Interaction in Generative Grammar*. Cambridge, MA: Blackwell Publishing Ltd.
- Rose, Sharon & Rachel Walker. 2004. A Typology of Consonant Agreement as Correspondence. *Language* 80(3). 475–531.
- Rose, Yvan. 2000. Headedness and Prosodic Licensing in the L1 Acquisition of Phonology. McGill University Ph.D. Dissertation.

- Rose, Yvan. 2003. Place Specification and Segmental Distribution in the Acquisition of Word-final Consonant Syllabification. *The Canadian Journal of Linguistics / La revue canadienne de linguistique* 48(3/4). 409–435.
- Rose, Yvan. 2013. The Case for Features. Natural Classes and Phonological Development. Paper presented at the International Child Phonology Conference, Nijmegen, The Netherlands.
- Rose, Yvan. 2014. The Emergence of First Language Phonology: Perception, Articulation and Representation. In João Costa, Alexandra Fiéis, Maria João Freitas, Maria Lobo & Ana Lúcia Santos (eds.), *New Directions in the Acquisition of Romance Languages: Selected Proceedings of the Romance Turn V*, 35–61. Newcastle upon Tyne: Cambridge Scholars Publishing.
- Rose, Yvan & Julie Brittain. 2011. Grammar Matters: Evidence from Phonological and Morphological Development in Northern East Cree. In Mihaela Pirvulescu, María Cristina Cuervo, Ana T. Pérez-Leroux, Jeffrey Steele & Nelleke Strik (eds.), *Selected Proceedings of the 4th Conference on Generative Approaches to Language Acquisition North America (GALANA 2010)*, 193–208. Somerville, MA: Cascadilla Proceedings Project.
- Rose, Yvan & Sharon Inkelas. 2011. The Interpretation of Phonological Patterns in First Language Acquisition. In Colin J. Ewen, Elizabeth Hume, Marc van Oostendorp & Keren Rice (eds.), *The Blackwell Companion to Phonology*, 2414–2438. Malden, MA: Wiley-Blackwell.
- Rose, Yvan & Brian MacWhinney. 2014. The PhonBank Project: Data and Software-Assisted Methods for the Study of Phonology and Phonological Development. In Jacques Durand, Ulrike Gut & Gjert Kristoffersen (eds.), *The Oxford Handbook of Corpus Phonology*, 380–401. Oxford: Oxford University Press.
- Rvachew, Susan & Ellen Andrews. 2002. The Influence of Syllable Position in Children's Production of Consonants. *Clinical Linguistics and Phonetics* 16(3). 183–198.
- Schwartz, Richard G. & Larry B. Leonard. 1982. Do Children Pick and Choose? An Examination of Phonological Selection and Avoidance. *Journal of Child Language* 9. 319–336.
- Scobbie, James M. 2007. Interface and Overlap in Phonetics and Phonology. In Gillian Ramchand & Charles Reiss (eds.), *The Oxford Handbook of Linguistic Interfaces*, 17–52. Oxford: Oxford University Press.
- Scott, Mark. 2012. Speech Imagery as Corollary Discharge. Vancouver, BC: University of British Columbia Ph.D. Dissertation.
- Shaw, Patricia. 1991. Consonant Harmony Systems: The Special Status of Coronal Harmony. In Carole Paradis & Jean-François Prunet (eds.), *The Special Status of Coronals: Internal and External Evidence*, 125–157. (Phonetics and Phonology Series). San Diego: Academic Press.
- Shiller, Douglas M., Susan Rvachew & Françoise Brosseau-Lapré. 2010. Importance of the Auditory Perceptual Target to the Achievement of Speech Production Accuracy. *Canadian Journal of Speech-Language Pathology and Audiology* 34(3). 181–192.
- Smith, Anne & Lisa Goffman. 1998. Stability and Patterning of Speech Movement Sequences in Children and Adults. *Journal of Speech, Language, and Hearing Research* 41(1). 18–30.
- Smith, Jennifer L. 2002. Phonological Augmentation in Prominent Positions. University of Massachusetts, Amherst Ph.D. Dissertation.

- Smith, Neilson V. 1973. *The Acquisition of Phonology: A Case Study*. Cambridge: Cambridge University Press.
- Smolensky, Paul & Géraldine Legendre. 2006. *The Harmonic Mind : From Neural Computation to Optimality-Theoretic Grammar. Volume I: Cognitive Architecture; Volume II: Linguistic and Philosophical Implications*. The MIT Press.
- Spencer, Andrew. 1986. Towards a Theory of Phonological Development. *Lingua* 68. 3–38.
- Steriade, Donca. 1999. Phonetics in Phonology: The Case of Laryngeal Neutralization. *UCLA Working Papers in Linguistics* 3. 25–246.
- Steriade, Donca. 2001. Directional Asymmetries in Place Assimilation: A Perceptual Account. In Elizabeth Hume & Keith Johnson (eds.), *The Role of Speech Perception in Phonology*, 219–250. New York: Academic Press.
- Stevens, Kenneth N. 1972. The Quantal Nature of Speech: Evidence from Articulatory-acoustic Data. In Edward E. David & Peter B. Denes (eds.), *Human Communication: A Unified View*, 51–66. New York: McGraw-Hill.
- Stevens, Kenneth N. 1989. On the Quantal Nature of Speech. *Journal of Phonetics* 17(1-2). 3–45.
- Stevens, Kenneth N. & Samuel J. Keyser. 2010. Quantal Theory, Enhancement and Overlap. *Journal of Phonetics* 38(1). 10–19.
- Stoel-Gammon, Carol. 2011. Relationships between Lexical and Phonological Development in Young Children. *Journal of Child Language* 38(1). 1–34.
- Stoel-Gammon, Carol & Judith A. Cooper. 1984. Patterns of Early Lexical and Phonological Development. *Journal of Child Language* 11. 247–271.
- Stoel-Gammon, Carol & Joseph P. Stemberger. 1994. Consonant Harmony and Underspecification in Child Phonology. In Mehmet Yavas (ed.), *First and Second Language Phonology*, 63–80. San Diego: Singular Publishing Group, Inc.
- Storkel, Holly L., Junko Maekawa & Andrew J. Aschenbrenner. 2013. The Effect of Homonymy on Learning Correctly Articulated Versus Misarticulated Words. *Journal of Speech, Language, and Hearing Research* 56(2). 694–707.
- Sumner, Meghan & Arthur G. Samuel. 2009. The Effect of Experience on the Perception and Representation of Dialect Variants. *Journal of Memory and Language* 60(4). 487–501.
- Tessier, Anne-Michelle. 2008. *Biases and Stages in Phonological Acquisition: Learning an Optimality Theoretic Grammar Restrictively and Gradually, and the Theory of Error-Selective Learning*. Saarbrücken, Germany: VDM.
- Tessier, Anne-Michelle. 2013. Error-driven Learning in Harmonic Serialism. In Stefan Kleine & Shayne Sloggett (eds.), *Proceedings of the 42nd Meeting of the North East Linguistic Society*, 545–558. Amherst, MA: GLSA.
- Tian, Xing & David Poeppel. 2010. Mental Imagery of Speech and Movement Implicates the Dynamics of Internal Forward Models. *Frontiers in Psychology* 1. 1–23.
- Tuller, Betty & J. A. Scott Kelso. 1990. Phase Transitions in Speech Production and their Perceptual Consequences. In Marc Jeannerod (ed.), *Attention and Performance XIII: Motor Representation and Control*, 429–452. Hillsdale, NJ: Lawrence Erlbaum.
- Tuller, Betty & J. A. Scott Kelso. 1991. The Production and Perception of Syllable Structure. *Journal of Speech and Hearing Research* 34. 501–508.
- Veer, Burght Marius van 't. 2015. *Building a Phonological Inventory Feature Co-Occurrence Constraints in Acquisition*. Utrecht: LOT.

- Vick, Jennell C., Thomas F. Campbell, Lawrence D. Shriberg, Jordan R. Green, Hervé Abdi, Heather Leavy Rusiewicz, Lakshmi Venkatesh & Christopher A. Moore. 2012. Distinct Developmental Profiles in Typical Speech Acquisition. *Journal of Neurophysiology* 107(10). 2885–2900. doi:10.1152/jn.00337.2010.
- Vick, Jennell C., Thomas F. Campbell, Lawrence D. Shriberg, Jordan R. Green, Klaus Truemper, Heather Leavy Rusiewicz & Christopher A. Moore. 2014. Data-Driven Subclassification of Speech Sound Disorders in Preschool Children. *Journal of Speech, Language, and Hearing Research* 57(6). 2033–2050.
- Vihman, Marilyn M. 2014. *Phonological Development: The First Two Years*. Second Edition. Hoboken: Wiley-Blackwell.
- Vihman, Marilyn May, Marlys A. Macken, Ruth Miller, Hazel Simmons & Jim Miller. 1985. From Babbling to Speech: A Re-Assessment of the Continuity Issue. *Language* 61(2). 397–445.
- Vihman, Marilyn M. & William Croft. 2007. Phonological Development: Toward a “Radical” Templatic Phonology. *Linguistics* 45(4). 683–725.
- Vihman, Marilyn M. & Mel Greenlee. 1987. Individual Differences in Phonological Development: Ages One and Three Years. *Journal of Speech and Hearing Research* 30(4). 503–521.
- Vihman, Marilyn M. & Shelley L. Velleman. 2000. The Construction of a First Phonology. *Phonetica* 57(2-4). 255–266.
- Waterson, Natalie. 1971. Child Phonology: A Prosodic Review. *Journal of Linguistics* 7. 179–211.
- Werker, Janet F. & Suzanne Curtin. 2005. PRIMIR: A Developmental Framework of Infant Speech Processing. *Language Learning and Development* 1(2). 197–234.
- Whitehill, Tara L., Alexander L. Francis & Christine K. Y. Ching. 2003. Perception of Place of Articulation by Children with Cleft Palate and Posterior Placement. *Journal of Speech, Language, and Hearing Research* 46(2). 451–461.
- Wolpert, Daniel M., Zoubin Ghahramani & J. Randall Flanagan. 2001. Perspectives and Problems in Motor Learning. *Trends in Cognitive Science* 5(11). 487–494.
- Wolpert, Daniel M. & Mitsuo Kawato. 1998. Multiple Paired Forward and Inverse Models for Motor Control. *Neural Networks* 11. 1317–1329.
- Zamuner, Tania S. 2009. The Structure and Nature of Phonological Neighbourhoods in Children’s Early Lexicons. *Journal of Child Language* 36(1). 3–21.



---

<sup>1</sup> We gratefully acknowledge the following people for their useful questions and comments throughout the development of our model: Adam Albright, Michael Becker, Melinda Fricke, Bryan Gick, John Houde, Keith Johnson, Lise Menn, Jeff Mielke, Janet Pierrehumbert, David Poeppel, Donca Steriade, and Anne-Michelle Tessier. We also thank our two anonymous reviewers and the associate editor. In addition, this work has benefited from feedback from audiences at the *20<sup>th</sup> Manchester Phonology Meeting*, the *2012 International Child Phonology Conference*, the *2013 University of Chicago Workshop on Sound Change Actuation, Phonology 2013*, the *2013 Linguistic Institute Workshop on Variation in the Acquisition of Sound Systems, Phonology 2014*, and *North East Linguistic Society 45*. All errors are our own.

<sup>2</sup> Perceptual differences are also robustly documented, but for practical reasons, we restrict our scope of inquiry to the domain of production in the present paper.

<sup>3</sup> Following the notational conventions discussed in Rose & Inkelas (2011), we use || to denote ‘target’ phones (re: adult targets, see footnote 8), [] to represent actual phonetic forms, and // for abstract phonological representations.

<sup>4</sup> Here and elsewhere, child speakers’ ages are presented in the standard format of years;months.days.

<sup>5</sup> See also Fikkert & Levelt (2008) on a similar phenomenon in Dutch.

<sup>6</sup> Weighting provides a level of analytical flexibility that is not readily achieved through constraint ranking, which is why we choose HG over classical Optimality Theory. A maximum entropy model (e.g. Hayes & Wilson 2008), which converts harmony scores to probability distributions, would be an appropriate framework if we were modeling the frequency distributions of an individual’s variants; that is beyond the scope of this paper. Because our proposed model combines HG formalism with exemplar-based representations, it makes contact with other proposals in the literature that relate Harmonic Grammar to connectionist models of neural activity in speech processing (e.g. Smolensky & Legendre 2006; Goldrick & Daland 2009).

<sup>7</sup> For simplicity, we do not include the somatosensory dimension of the motor-sensory mapping in our model. However, a complete model would incorporate these considerations, since somatosensory targets are known to be important for acquiring and producing speech (Guenther,

---

Ghosh & Tourville 2006; Ghosh et al. 2010). See the Linked-Attractor model of Menn, Schmidt & Nicholas (2009, 2013) for discussion of the linkage between auditory/acoustic and oral-sensory exemplars.

<sup>8</sup> Throughout the paper, we will use ‘adult target’ as shorthand for a rather complex range of acoustic inputs that combine to form the acoustic model that the child aims to reproduce. In most cases, multiple speakers contribute to the target cloud, and some of these speakers may be older children or esteemed peers rather than adults. We also abstract away from any differences between the actual acoustic properties of the adult input and the child’s perceptual representation of those properties, although the literature shows that young children’s auditory-acoustic representations of speech targets are less refined than adults’ (Hazan & Barrett 2000; Shiller, Rvachew & Brosseau-Lapr e 2010) and may also differ in more substantial, qualitative ways (e.g. Nittrouer 2002; Mayo & Turk 2004).

<sup>9</sup> It is far from trivial to explain how the child learns to map from an adult input to his/her own closest approximation, since the child’s very different vocal tract puts him/her in a different region of acoustic space. However, this problem is not specific to our proposal but is shared by all models of speech acquisition. Accordingly, we will set this issue aside to focus on those properties that are distinctive to the current model.

<sup>10</sup> The term ‘A-map’ is inspired by Steriade’s (2001) P(erceptual)-map, which distills perceptual distinctiveness into a compact format that the grammar can index. The A-map and the P-map are of course different in numerous respects.

<sup>11</sup> In referencing stored traces of past errors, the A-map model makes conceptual connections with Tessier’s (2008, 2013) USELISTEDERROR model and Becker & Tessier’s (2011) notion that children might recycle previous forms as a way to streamline production processing, as well as to the proposal of Menn et al. (2009) that frequently repeated erroneous word productions can lead to the entrenchment of phonological templates. Our approach diverges from these both in the primary unit of analysis (words, versus segments in the A-map model) and, more importantly, in the explicit emphasis of the present model on the role of the stability of motor-acoustic mappings.

<sup>12</sup> The magnitudes of constraint violations are schematic, selected for ease of exposition. We ignore the rhyme, which remains constant across candidates, and evaluate ACCURATE and

---

PRECISE only relative to the onset fricative in each candidate. We represent [ˈda] as one unit away from [ˈʒa] in acoustic-perceptual space, and we represent  $Noise(MP_{/ʒa/})$ , the average distance between efference copies and actual acoustic-perceptual outcomes for /ʒa/, as double the size of the corresponding *Noise* value for the more stable target /da/.