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

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Abstract

This paper addresses two linked phenomena of longstanding interest: the existence of child-specific phonological patterns which are not attested in adult language, and the puzzling developmental trajectory of these patterns. While some child-specific phonological patterns wane gradually as the child matures, others follow a U-shaped curve, and still others persist unchanged for an extended period before being abruptly eliminated. We propose a single new theoretical approach, termed the A-Map model, to account for the origin and time course of child-specific phonological patterns. The A-map model marries exemplar-based memory with a constraint-based grammar. 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 then influenced by the distributional properties of motor-acoustic traces of previous productions, stored in the eponymous A(rticularatory)-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.

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

1. Introduction

We propose a new theoretical approach to two linked phenomena of longstanding interest to linguists and acquisitionists: the existence of child-specific phonological patterns which are not attested in adult language, and the puzzling developmental trajectory of these patterns. 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 (see, e.g., Bernhardt & Stemberger 1998), but others are idiosyncratic and specific to certain individuals, especially in the earliest period of word productions (see, e.g., Ferguson & Farwell 1975; Macken 1979; Vihman & Croft 2007). One might expect child-specific patterns to arise out of some initial misconstrual by the child of the ambient data, and to diminish gradually over time as the child is exposed to an increasing amount of evidence. However, actual trajectories of child-specific patterns can differ from this developmental path in several key ways, which have attracted attention in the literature. We focus in this paper on U-shaped curves in phonological development (e.g., Bowerman 1982; Becker & Tessier 2011) and on the common but curious trajectory in which a pattern that a child would seem to have outgrown is prolonged, then abruptly eliminated.

We propose a single model to account for the origin and time course of child-specific phonological patterns. Our approach is grounded in exemplar theories of memory and in the much-discussed overlap between phonetics and phonology. Due to motor immaturity, children experience performance limitations that cause their outputs to differ from adult target forms in both systematic and sporadic ways. Children's future productions are then influenced by the motor-acoustic traces left by their past productions. We propose that children's phonology is shaped by a conflict between two essential tensions: 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). We term our account the A-MAP MODEL.

We begin with a discussion of child-specific phonological patterns (section 2) and of models that have been proposed to capture them (section 3). In section 4, we explore the role of performance limitations in children's trajectories of speech development, with a focus on the

conflicting functional pressures of accuracy (matching the adult target) and precision (maintaining a stable output across multiple realizations of a given target). We introduce the A-Map model in section 5, followed by an illustrative case study in section 6. In section 7, we focus on the A-map's capacity to capture the elimination of child-specific phonological patterns, and in section 8 we highlight the model's ability to account for various dimensions of variation within and across children's phonological development. We conclude in section 9 with a brief discussion of the implications of the A-map model for adult phonological systems.

2. Child-specific speech patterns

2.1. 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. 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-medial 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 are attested marginally or not at all, whereas velar fronting is a commonly observed process in children aged three and younger. 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 well-attested child pattern of positional velar fronting shows precisely the opposite bias, neutralizing lingual place contrasts in strong position only:

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

a. Fronting of velars in prosodically strong positions

cup	[^h tʰʌp]	1;09.23
again	[ə'dɪn]	1;10.25
hexagon	[^h hɛksə,dɔn]	2;02.22
conductor	[tʌn'dʌktə]	2;01.21

b. Absence of velar fronting in prosodically weak positions

monkey	[^h mʌŋki]	1;08.10
bagel	[^h bejgu]	1;09.23
octopus	[^h ʌktəpʊs]	2;04.09
back	[^h bæk]	1;10.02

Another example of a child-specific pattern is major place assimilation of consonants to vowels. Bates, Watson & Scobbie (2002) cite Fudge's (1969) example of an English-learning child aged 1;4 whose realization of alveolar, labial, and velar obstruent place was contingent on the place of the following vowel; data are given in (2). (See also Fikkert & Levelt 2008 on a similar phenomenon in Dutch.) Target labial and velar stops took on alveolar place before a front vowel, while target alveolars were 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 (data from Bates, Watson & Scobbie 2002, citing Fudge 1969)

a. Alveolar place before a front vowel

drink	[ti]
again	[den]

b. Labial place before a back rounded vowel

ball	[bo]
book	[bo]
dog	[bobo]

c. Velar place before a back unrounded vowel

truck	[kʌk]
garden	[gʌŋ]
doggie	[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 third, often-cited example of child-specific phonology is child consonant harmony (e.g., Smith 1973; Stoel-Gammon & Stemberger 1994; Goad 1997; Pater 1997, 2002; Pater & Werle 2001, 2003; Becker & Tessier 2011). 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 & Werle 2001, citing Compton & Streeter 1977)

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

dog	[gɔg]	1;5.14
bug	[gʌg]	1;5.18

b. Regressive assimilation: Labial trigger, coronal undergoer

top	[pʌp]	1;5
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c. Progressive assimilation: Velar trigger, coronal or labial undergoer

coat	[kok]	1;5.18
cup	[kʌk]	1;5.13

Consonant harmony is related to the class of speech patterns sometimes termed “whole word processes,” since the interaction of noncontiguous consonants cannot be characterized in terms of simple segment-level substitutions (Macken 1979; Vihman & Croft 2007). Children are known to exhibit processes, potentially quite idiosyncratic, affecting part or all of the structure of

a word. In some cases, a few favored phonological shapes recur across the lexicon, with varying degrees of similarity to the actual adult targets they represent. When a particular shape, or template, becomes established in a child's speech, the child may preferentially acquire other lexical items that match the template, while less similar words may be adapted to fit the template (Vihman & Velleman 2000; Vihman & Croft 2007).¹ Priestly's (1977) classic examples of template effects in the output of an English-acquiring boy aged 1;10-2;2 are repeated in (4):

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

basket	[bajak]
blanket	[bajak]
tiger	[tajak]
turkey	[tajak]
fountain	[fajan]
flannel	[fajan]

3. Approaches to child-specific phonology

The existence of child-specific phonological patterns is problematic for 'continuity' models which assume that child and adult grammars draw from the same grammatical space (e.g., Macnamara 1982; Pinker 1984). 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 (1998, 2008) 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 inebriated speech of the captain of the Exxon Valdez (Johnson, Pisoni & Bernacki 1990), which featured "misarticulation of /r/ and /l/, deaffrication, final devoicing" (Hale & Reiss 1998: 669). The pure performance

¹ Although we will argue that the model proposed below can account for template effects, we do not adopt the extreme position whereby "the basic phonological unit is a word template" (Vihman & Croft 2007: 684).

approach makes it possible to maintain a strong version of the continuity hypothesis: children are posited to have adult grammars, with any 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 (see, 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 are more often conditioned by discrete units. In our previous example (1), the pattern of positional velar fronting exhibited by Inkelas & Rose's (2007) case study subject E 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 (see, 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, to appear; 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, 1947; MacWhinney 1978; Bowerman 1982; Fikkert 1994; Freitas 1997; Bernhardt & Stemberger 1998; Inkelas & Rose 2003, 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 a systematic pattern of incorrect production, 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 which 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 is driven by a constraint *#k (“No word-initial dorsals”), while Dinnsen et al. (2011) posit a constraint AGREE that requires all consonants in a word to share the same major place of articulation. 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. As soon as constraints such as these are introduced into a universal constraint inventory, of course, it must be explained why their effects are not attested in adult language. Adoption of a nativist approach to child patterns thus weakens the capacity of the theory to generate a restrictive model of adult typology.

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 positing that children may also infer their own unique constraints from perceptual, articulatory or distributional properties of the input. For example, in their discussion of child-specific consonant harmony as exemplified in (3), Becker & Tessier posit that the child “was driven by concerns of some articulatory nature to induce the constraint AGREE(KVT),” which enforces the observed pattern of lingual harmony. The idea of transient constraints takes on

particular significance in connection with the child-specific phonological illustrated in (4), which would be difficult to frame in terms of a universal constraint inventory.

In principle, the transient phonology approach offers increased flexibility to model child-specific phonological patterns without predicting their attestation in adult typology. In practice, to our knowledge, no model has explicitly proposed an update mechanism to explain how child-specific constraints can be eliminated over the course of maturation. Thus, the transient phonology approach still shares with nativist theories the daunting challenge of explaining why the constraints responsible for child-specific phonology disappear so completely 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 link between these patterns and child-specific functional pressures on production and/or perception. This linkage permits the A-map model to offer a natural account of the origin and the cessation of child-specific patterns. As the functional pressures on production and perception are resolved with the maturation of the child, the associated phonological patterns also naturally wane. The A-map model rests on the key assumption, familiar from exemplar theories of memory, that past productions are stored and made available to the grammar. We propose that child-specific patterns can arise as a phonologized reflex of previous error patterns, but unlike the transient phonology approach, we do not posit child-specific constraints like AGREE(KVT). Instead, the A-map model holds that child-specific phonological patterns arise through the influence of a universal constraint favoring 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.

In referencing stored traces of past errors, our 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. In directly referencing speech-motor pressures within a grammatical account, the A-map model stakes out new conceptual territory that occupies a middle ground between pure performance and nativist/transient phonology approaches.

In section 4, we identify several key performance limitations that can give rise to child-specific phonological patterns. Section 5 then introduces the A-Map model, which folds these performance pressures into the child's grammar so as to yield patterns that are systematic and categorical but also intrinsically transient.

4. Performance limitations shaping child speech patterns

The performance limitations that shape children's speech patterns can be divided into three categories: anatomical differences, restrictions on motor planning, and predisposition toward random breakdowns in motor encoding and execution. Under the influence of these limitations, children exhibit frequent performance errors which often are qualitatively different from those made by adults. We contend that the systemization of these errors gives children's phonological grammars their unique quality.

Anatomical differences: The first performance limitation arises from significant differences between the young child's articulatory anatomy and that of the adult. An often-noted difference between young children and adults is the size and placement of the tongue. 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). This has a demonstrable effect on articulation, most notably as discussed in the context of positional velar fronting by Inkelas & Rose (2003, 2007). However, it is important to note that positional velar fronting cannot be characterized as a necessary consequence of the dimensions of the immature vocal tract, since not all children exhibit this process. Other forces, physical and grammatical, must be understood to play a role in the systematization of velar fronting.

Motor planning differences: The second limitation lies in the immature motor planning system, which may lead the child to replace complex speech targets with gesturally simpler alternatives (e.g., Kent & Miolo 1995). 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 from the active jaw articulator (e.g., MacNeilage & Davis 1990a,b; Green, Moore & Reilly 2002).

The difficulty that young children have in planning discrete articulatory gestures can be understood to motivate certain child speech patterns, including the consonant-vowel interactions seen in (2). 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. This accounts for very young children’s tendency to produce babbling sequences which combine front vowels with coronal consonants or back vowels with velar consonants. Even in older children who can produce some jaw-independent tongue movements, there is a persisting bias favoring speech sounds that can be realized with ballistic gestures in which the tongue and jaw function as a single unit (e.g., Edwards et al. 1999). Stop consonants can be produced with ballistic gestures, whereas fricatives and liquids require more refined movements in which the tongue must be shaped independently of the jaw. Children’s tendency to produce ballistic gestures can be understood to underlie common speech sound substitutions such as stopping of fricatives, which is especially likely to apply in prosodically strong positions (e.g., Marshall & Chiat 2003; Rose to appear). Finally, even if a child can produce jaw-independent lingual gestures in simple contexts such as CV syllables, he/she may have difficulty combining multiple discrete gestures into a complex sequence. This can yield sequencing or assimilatory errors, including consonant harmony.

Speech errors. The third limitation reflects the relative instability of speech-motor encoding and execution in child speech production. While even skilled adult speakers produce speech errors, it is known that 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. These factors play a key role in the present analysis, as we assert that the child's grammar can sometimes circumvent unstable speech-motor encodings by giving preference to a form that is less than fully faithful but can be realized reliably. We explore the role of speech errors in greater depth in the exposition of our model in the following section.

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

Putting together the existence of child-specific phonological patterns, their evident connections to performance pressures, and the U-shaped development that some patterns exhibit, we propose a new model of phonological learning in which children's phonology is shaped by a conflict between two essential tensions. The first pressure is the child's desire to match adult productions of a given word, even if performance limitations are likely to cause the child to fall short of the intended target. The opposing pressure is a preference to avoid performance failure, i.e. to select a production target that can be attained consistently, even if it is not a perfect phonetic match for the adult input. In the proposed model, formulated within the Harmonic Grammar framework (Legendre, Miyata & Smolensky 1990; Smolensky & Legendre 2006; Pater 2009), these two pressures are expressed by grammatical constraints, ACCURATE and PRECISE. ACCURATE favors a candidate whose expected acoustic output is a close match for the adult acoustic target, while PRECISE favors any candidate whose associated motor plan maps reliably to a narrowly defined acoustic goal region. Both constraints are informed by the A-map, an interface between exemplar memory and the grammar which distills motor-acoustic traces from the child's previous productions into a vector of information about the mapping from a given motor plan to acoustic space (e.g., Stevens 1989; Lin & Mielke 2008).

In short, the A-Map model marries exemplar-based memory with a constraint-based grammar, treating production as an ongoing, grammatically governed competition between the pressures of motor plan reliability and acoustic accuracy. Our approach is intended as an enrichment, rather than a replacement, of constraint-based approaches to phonology and phonological development. The constraints we propose co-exist with the conventional faithfulness and markedness constraints of Optimality Theory (Prince & Smolensky 1993/2004)

and Harmonic Grammar (Legendre, Miyata & Smolensky 1990), but these play a limited role in the present paper due to our lack of focus on phonological alternations.

5.1. Representing speech experience in exemplar memory

In keeping with an episodic or exemplar-based model of phonology (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. Virtually every word token that a child has heard or produced will leave a memory trace. For very young children, exemplar memory is primarily organized at this 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; Curtin, Byers-Heinlein & Werker 2011). For the purposes of the present paper, we will confine ourselves to modeling word-sized representations.

It is difficult to graphically depict the episodic traces of entire words, although they can be conceptualized as dynamic trajectories through multiple dimensions of acoustic space. Figure 1 is a common type of depiction of the episodic traces of phones, whose pattern of clustering reveals multiple distinct phoneme categories. In exemplar theory, categories are 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 (Maye, Werker & Gerken 2002; Pierrehumbert 2003; Munson, Edwards & Beckman 2005). Figure 1 shows two clear categories emerging from the distribution of the individual traces, as well as a more ambiguous cluster that may represent a third category. Because new traces are constantly being formed and old traces decay over time, probability distributions are constantly evolving; this dynamic quality will play a crucial role in our account of differences between child and adult speech patterns.

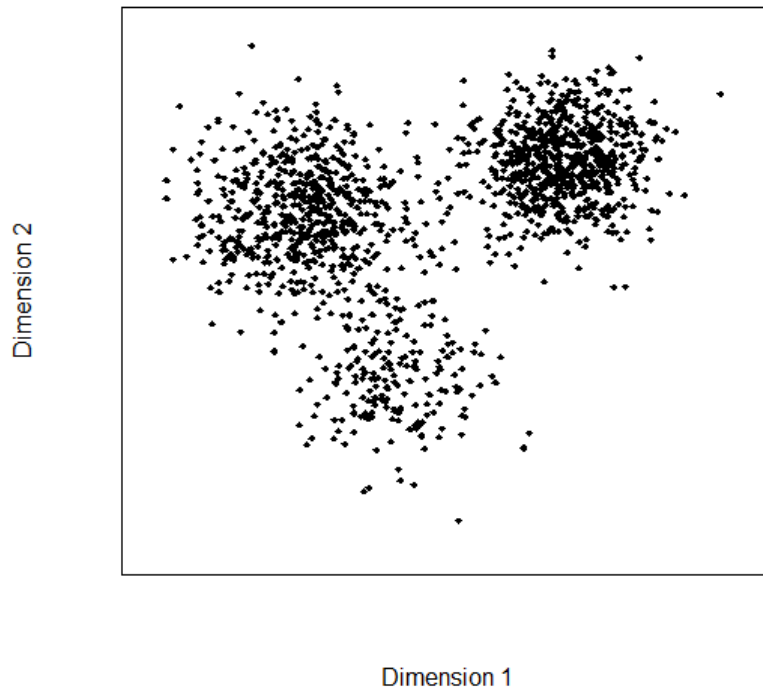


Figure 1: Episodic traces in two arbitrary dimensions of phonetic space. [Based on figures from Scobbie (2007), Pierrehumbert & Gross (2003)]

While the focus in most exemplar models is on acoustic phonetic traces, it is sometimes argued that these are accompanied by articulatory traces, at least for those exemplars that represent the speaker's own productions (Johnson 1997; Schweitzer 2010). We conceptualize these traces in the framework of an INTERNAL MODEL (e.g., Wolpert & Kawato 1998; Wolpert, Ghahramani & Flanagan 2001; Shiller, Rvachew & Brosseau-Lapr e 2010; Tian & Poeppel 2010; Hickok 2012; Scott 2012). In an internal forward model, an EFFERENCE COPY of a planned motor action is sent to perceptual centers of the brain, generating an estimation of the sensory consequences of the motor plan. In the case of speech, these predictions include auditory as well as somatosensory correlates of a motor plan. The sensory-motor associations that make up the internal model are learned implicitly through the individual's experience of producing and perceiving speech. The internal model is thus a dynamic entity, and if the sensory consequences predicted for a motor plan do not match the actual sensory outcome (as in the case of a motor execution error), the model can be updated accordingly. To implement the internal model in an exemplar-based grammar, we assume that the speaker stores not only acoustic traces of tokens heard and produced, but also traces of the efference copies generated during motor planning,

with links between them. We use the term MOTOR-ACOUSTIC TRACES to refer to these linked clouds of efference copies and associated acoustic outputs in exemplar space.²

5.2. Accuracy and precision in speech production

The A-map model of child speech is built around the potentially competing factors of ACCURACY and PRECISION. Both are calculated over the motor-acoustic traces in exemplar space described above. The parameters of accuracy and precision are schematized in Figure 2, which compares three hypothetical motor plans. Each of the numbers on the dartboards represents the acoustic trace of one of the child’s past productions of one of the three motor plans. The dartboards themselves symbolize the child’s encoding of an adult acoustic target, with the bull’s-eye representing the center of the acoustic distribution of adult tokens of the intended speech string.³

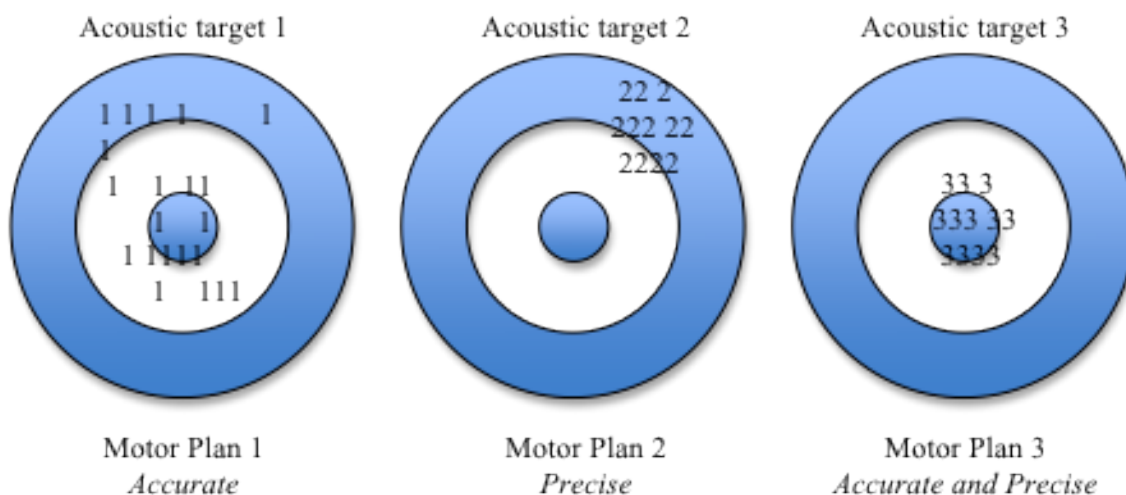


Figure 2: Accuracy and precision are distinct and potentially competing pressures in speech-motor learning

² 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 traces are known to be important for acquiring and producing speech (Guenther, Ghosh & Tourville 2006; Gick & Derrick 2009, Ghosh et al. 2010).

³ Throughout the paper, we will use “adult target” as shorthand for a rather complex range of inputs that combine to form the acoustic model that the child aims to reproduce. In most cases, multiple speakers contribute to the cloud of traces making up the adult target, and some of these speakers may be older children or esteemed peers rather than adults. We assume that different sub-regions of the cloud can take on greater or lesser weights in different sociolinguistic circumstances, potentially accounting for phenomena such as phonetic accommodation to an interlocutor.

Accuracy refers to the acoustic similarity between the child's production and the center of the adult output for the same speech target. In line with other models of child phonology, we assume that the child learner is motivated to produce an output that is acoustically similar to his/her perceptual encoding of previous productions of the same target by adults in the environment. In Figure 2, Motor Plans 1 and 3 are accurate, in the sense that the center of the child's distribution of acoustic outputs is close to that of the adult 'target'.

A more novel aspect of our model is the role attributed to the parameter of precision. If a given motor plan can be realized identically across multiple repetitions, the resulting cloud in acoustic space will have a small diameter and minimal scatter; this is an example of a precise motor-acoustic mapping. In Figure 2, Motor Plans 2 and 3 are more precise than Motor Plan 1. Even in skilled adults, there will always be some random noise creating token-to-token variability in the execution of a motor plan. Variability may be greater in the context of a speech target with more complex motor characteristics, such as /l/, which consists of two sustained gestures that require precise relative timing. Studies of motor learning report that individuals show a reliable preference for movement trajectories that are associated with lower variability in task-relevant dimensions (Wolpert, Ghahramani & Flanagan 2001; Todorov & Jordan 2002).

An important factor influencing the relative precision of different speech targets is the existence of interference among similar motor plans, or what we term *MOTOR PLAN REFERRAL*. This describes a situation in which a speaker selects a specific motor plan for execution, but an unintended motor plan is executed instead of the target plan. Our notion of motor plan referral is related to accounts of adult 'slips of the tongue' in interactive models of speech production (e.g., Dell 1986). In Dell's model, multiple phoneme targets receive varying degrees of activation from a lexical target, and the phoneme that is most strongly activated will be produced. Because we are dealing with children, whose representations contain less segmental and featural detail and whose motor limitations are greater, we focus on errors that arise at the level of motor planning rather than phonological encoding.⁴ Like phonological encoding, motor planning is a competitive process in which multiple plans receive some degree of activation, and the most strongly activated plan is executed (e.g., Klaes et al. 2012).

Motor plan referral is depicted, extending the dartboard metaphor somewhat imperfectly, in Figure 3. The speaker selects Acoustic Target 1 and activates the corresponding Motor Plan 1.

⁴ See Hickok (2012) for a proposal that unifies linguistic and motoric levels of encoding.

In this hypothetical example, however, Motor Plan 2 has a higher degree of activation (perhaps due to recent or frequent execution), and it is this motor plan that is executed instead of the target. We assume that the speaker's motor-acoustic exemplar space is updated in two ways in this situation. First, a new motor-acoustic trace representing the mapping from Motor Plan 2 to Acoustic Target 2 is laid down. Second, because the speaker intended to execute Motor Plan 1, the speaker's internal model is updated with a link from this *intended* motor plan to the *actual* acoustic outcome. This mistaken mapping results in an increase in the diameter and diffuseness of the cloud of acoustic outputs associated with Motor Plan 1.

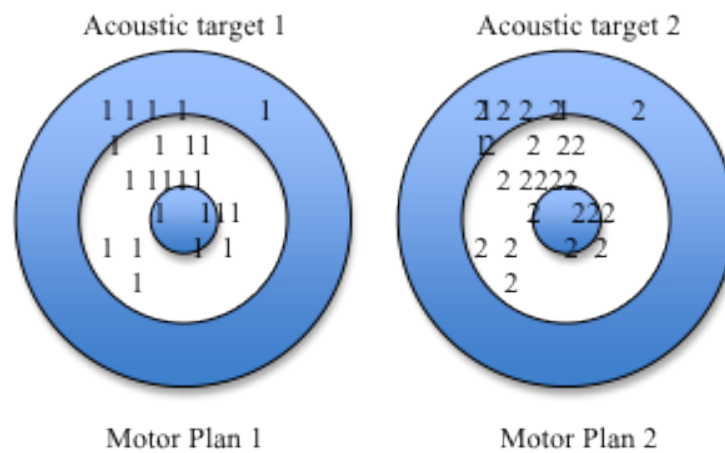


Figure 3: Accidental referral from Motor Plan 1 to Motor Plan 2 reduces the precision of Motor Plan 1

If errors of motor plan referral were uncommon and random, the noise they introduce to the space of motor-acoustic mappings would be disregarded. However, like adult slips of the tongue, these errors are subject to biases. We assume that a cloud of stored efference copies has a baseline level of activation that determines how readily the motor routine in question will be executed. The likelihood of referral is thus dictated by the level of activation of the target cluster relative to surrounding clouds that represent competing motor plans. A cloud's baseline activation level is influenced by frequency, with densely populated clouds having a higher level of activation than sparse clouds (Pierrehumbert 2002). In addition, the recency of last activation will affect the level of activation of a particular cloud. Similarity also plays a role, with a greater likelihood of interference between targets with similar articulatory properties (Garrett & Johnson

2011). If the target motor plan is weakly activated (because it has been executed only a small number of times, or has not been attempted recently), or if similar motor plans in the immediate neighborhood are highly activated, referral to a non-target motor plan is likely to occur.

These factors contribute to systematic regularities in errors of motor plan referral, where some targets are particularly vulnerable to error, while others act as attractors for errors of referral from other targets. These asymmetries in motor plan referral can create and reinforce differences in the precision of motor-acoustic mappings associated with different targets. As we argue below, these differences in precision can then be grammatically expressed in systematic patterns of substitution.

5.3. Between exemplar space and constraint-based grammar: the A-map

Rather than assuming that the grammar operates directly over the raw contents of motor-acoustic exemplar space, we propose that there is an interface between these episodic traces and the formal computations of the phonology. This interface, which we refer to as the A(rticulatory)-map, is a distillation of information about motor plans, acoustic outcomes, and the links between them.⁵ For each phonological candidate form c (which might be a word or a smaller-sized chunk of speech), there is a corresponding entry in the A-map, represented as a vector with three components:

- 5) A-map vector for candidate c : $\langle MP_{mean}, A_{mean}, A_{SD} \rangle$

MP_{mean} represents a stored motor plan for a given speech target. More precisely, it is the center of a cloud of efference copies representing previous executions of closely related motor plans. For simplicity, we will sometimes treat MP_{mean} as MP , a single motor plan that idealizes the properties of the cloud. We will further simplify by representing MP with IPA phones rather than gestural scores or other representations of articulatory detail. A_{mean} represents the location in multidimensional acoustic space of the cloud of outcomes associated with executions of motor plan MP . The value of A_{mean} is an average across the locations of all points linked to motor plan MP , weighted by the strength of activation of component traces. Because we also use IPA

⁵ We do not take a committed view on the cognitive status of the A-map; it may have a physical analogue in the brain, or it may turn out to be a convenient shorthand that allows us to manage the complexity of exemplar dynamics in the context of a formal phonological model.

phones to represent A_{mean} , the first two entries in most $\langle MP_{mean}, A_{mean}, A_{SD} \rangle$ vectors are notated similarly. To keep them visually distinct, we surround MP_{mean} with slashes and A_{mean} with square brackets. Finally, A_{SD} represents the standard deviation of the entire distribution of acoustic outcomes associated with MP . A_{SD} concisely encodes information about the reliability or precision of the mapping from motor plan to acoustic output.

Our choice of terminology for the A-Map evokes Steriade's (2001, 2008) P-Map hypothesis, in which the computations of the grammar are influenced by a tacit body of knowledge about differences in perceptual salience across various contrasts and contexts. While both the A-Map and the P-Map highlight the interaction between phonetic knowledge and the phonological grammar, the two models differ in important ways. First, Steriade's P-map was originally conceptualized as a static body of knowledge about the degree of perceptual similarity between pairs of speech sounds in a range of prosodic and phonetic contexts. By contrast, the A-map is a dynamic entity: both the child's predicted acoustic output and his/her encoding of the adult target category are continuously updated over the course of linguistic experience. Second, Steriade proposed that the information contained in the P-map is expressed through correspondence constraints of the form 'underlying X must not surface as Y.' Constraints that militate against correspondence between an input and a highly dissimilar output are ranked higher than constraints governing the correspondence between perceptually more similar forms. In our model, the same effect of favoring perceptually minimal changes is accomplished using different-sized violations of a single weighted constraint, described below.

5.4. Constraints: PRECISE and ACCURATE

The competing forces of precision and accuracy are formally implemented in the A-Map model by two constraints: PRECISE and ACCURATE.⁶ PRECISE, a markedness constraint, is formally defined in (6).

6) PRECISE:

For a candidate $c_{[i]}$ with A-map vector $\langle MP_{mean [i]}, A_{mean[i]}, A_{SD[i]} \rangle$, assign a penalty in proportion to the magnitude of $A_{SD[i]}$.

⁶ Earlier versions of this research used different names for these constraints. ACCURATE was called PMATCH, while PRECISE was called RECYCLE.

In a grammatical comparison of candidates, PRECISE will assign a greater penalty to a candidate whose motor plan MP is associated with a broad, diffuse cloud of acoustic outcomes (high A_{SD}). A candidate whose motor plan is associated with a compact cloud of acoustic outcomes (low A_{SD}) will violate PRECISE minimally.

By contrast, ACCURATE favors a candidate whose predicted acoustic consequence is a close match for the adult acoustic target. ACCURATE makes reference to a point T (*Target*), which represents the center of the acoustic cloud of adult productions of the target word or speech chunk, as encoded by the child.⁷ For a candidate $c_{[ij]}$, ACCURATE compares T to $A_{mean[i]}$, as in (7).

7) ACCURATE:

For a candidate $c_{[ij]}$ with A-map vector $\langle MP_{mean[i]}, A_{mean[i]}, A_{SD[ij]} \rangle$, assign a penalty in proportion to the distance in acoustic space between $A_{mean[i]}$ and the target T .

Like other high-level constraints (e.g., MAX, IDENT; Prince & Smolensky 1993/2004), PRECISE and ACCURATE should technically be regarded as umbrella constraints that encompass a family of sub-constraints. PRECISE could be defined at any of several levels of granularity (e.g., word, syllable, phoneme), and we assume that in reality it applies at multiple levels in an overlapping fashion. In a similar way, we envision a class of ACCURATE subconstraints, 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 will 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). 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 the word.

⁷ For present purposes, we 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).

5.5. Relation to conventional constraints

PRECISE is intended to obviate the markedness constraints that have been introduced in the literature solely to account for child-specific phonology and are not motivated in adult phonological systems. An example is the constraint *#k (Morrisette, Dinnsen & Gierut 2003; Dinnsen 2008). This constraint can be used to model the child-specific pattern of velar fronting, but it conflicts with models of positional markedness effects in adult phonology, which have proposed that markedness constraints against subsegmental features in prominent positions cannot exist (Smith 2000; de Lacy 2001).

However, we assume that PRECISE and ACCURATE do coexist with the conventional markedness and faithfulness constraints that are posited to account for adult patterns in Optimality Theory and related models. The literature is divided over the provenance of such constraints. Classical, or what we earlier termed ‘nativist’, versions of Optimality Theory (e.g., Tesar & Smolensky 2000; Boersma & Hayes 2001) assume that constraints are universal and innate. An alternative position (e.g., Levelt & van Oostendorp 2007; Hayes & Wilson 2008) holds that conventional constraints emerge as generalizations over the featural and/or distributional properties of the ambient language that serves as the input to the child’s learning process. The Gradual Learning Algorithm (Boersma 1997) and the Gradual Learning Algorithm for Harmonic Grammar (HG-GLA; Boersma & Pater 2007) are examples of mechanisms that allow the child to arrive at an appropriate weighting for these constraints.

For very young children, whose phonological representations may still be coarse-grained and who experience substantial differences in the reliability of motor plans across targets, ACCURATE and PRECISE play the dominant role in the selection of candidate outputs. This is the phase of phonological learning that constitutes the focus of the present paper. For adults, whose representations are finer-grained, phonological computations are dominated by conventional constraints referring to segmental units and their positions within syllables, feet, etc. The influence of PRECISE is attenuated because adults’ greatly refined motor control means that candidates no longer differ meaningfully in their projected precision (see section 7). Similarly, ACCURATE becomes more of a fine-tuning mechanism, potentially responsible for such effects as sociolinguistic variation and accommodation to interlocutor in different conversational settings.

5.6. Evaluation of candidates

In (8)-(9), we give a toy example to illustrate the interaction of ACCURATE and PRECISE in modeling a child speaker's choice of the optimal motor-acoustic mapping for a given adult target. Recall that for an adult acoustic target centered in acoustic space at T , the grammar evaluates a set of candidates, 1 to n , each associated with a vector of the type in (5): $\langle MP_{mean}, A_{mean}, A_{SD} \rangle$. In example (7), two candidates are considered for the adult target [si]. For one candidate, the associated motor plan MP represents a close approximation of the motor plan adults use to produce [si]. In this example, the child has executed this motor plan successfully in the past, and the center of the distribution of acoustic outputs, A_{mean} , falls in the vicinity of adult [si]. However, the child has demonstrated low reliability in hitting this acoustic target, with outputs reflecting frequent fricative errors ranging from [θi] to [ti] to [fi]. The candidate is thus associated with a high A_{SD} . The other candidate is linked to a motor plan featuring a simple alveolar stop, with the corresponding cloud of acoustic outputs centered around [ti]. Because the child can execute this simpler motor routine with a high degree of reliability, it has a low A_{SD} . Candidate (8a) is evaluated more favorably by ACCURATE, because the center of its projected acoustic cloud is a better match for the adult acoustic target T . Candidate (8b) fares better with the constraint PRECISE, since it is more reliably executed, despite being less accurate.

- 8) Toy example in which ACCURATE is weighted more strongly than PRECISE; the winner (a) has a diffuse cloud whose center is closer to the adult target.

	Adult target: [si]	ACCURATE	PRECISE	H
		$w = 2$	$w = 1$	
☞ a.	$\langle /si/, [si], 2 \rangle$	0	-2	-2
b.	$\langle /ti/, [ti], 1 \rangle$	-1	-1	-3

The tableau in (8) follows the conventions of Harmonic Grammar (HG), which relies on weighting, as opposed to ranking, of constraints to select the optimal output from a set of possible candidates (Legendre, Miyata & Smolensky 1990; Smolensky & Legendre 2006; Pater 2009).⁸ Constraint violations are represented with negative numbers indicating the magnitude of

⁸ Weighting provides a level of analytical flexibility that is not readily achieved through ranking, which is why we choose HG over classical Optimality Theory. The idea of combining exemplar-based representations into HG also

the associated penalty. The $H(\text{armony})$ 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 lowest H score is selected for production. In tableau (8), the constraint ACCURATE is arbitrarily given a weight of 2, while PRECISE is given a weight of 1, indicating that this grammar places more emphasis on accuracy than precision. The magnitudes of constraint violations are schematic, selected for ease of exposition. We represent [ti] as one unit away from [si] in acoustic space, and we indicate that the diameter of the cloud of acoustic outcomes associated with /si/ is twice the size of that associated with /ti/.⁹ In this tableau, the more accurate candidate (8a) has the least negative H score and wins out over the more precise candidate (8b).

In tableau (9), the relative weights of PRECISE and ACCURATE have been reversed. The winner in this case is candidate (9b), whose associated cloud of acoustic outcomes is precise and compact, though not a perfect match for the adult acoustic target.

- 9) Toy example in which PRECISE is weighted more strongly than ACCURATE; the winner (b) has a compact cloud whose center is farther from the adult target.

	Adult target: [si]	PRECISE	ACCURATE	H
		$w = 2$	$w = 1$	
a.	$\langle /si/, [si], 2 \rangle$	-2	0	-4
☞ b.	$\langle /ti/, [ti], 1 \rangle$	-1	-1	-3

Note that in these HG tableaux, the A_{SD} value appears twice for each candidate: once in the candidate vector itself, and once (negatively valued) in the PRECISE column; the violation of PRECISE, by definition, is equal to $-A_{SD}$. In the interest of notational economy, we will omit A_{SD} from candidate vectors in subsequent tableaux. For the same reason, we will also omit the second element of the vector, A_{mean} , from most tableaux. This is because the idealized motor plan MP and the center of the associated acoustic distribution A_{mean} are represented by identical IPA phones in a preponderance of cases. It is possible for the two to differ, though, in which case the full vector notation is available for use. (See section 6.1 for some discussion of a relevant situation.)

connects with other proposals in the literature that relate formal phonology to connectionist models of neural activity in speech processing (e.g., Smolensky & Legendre 2006; Goldrick & Daland 2009).

⁹ Ideally, the magnitude of an ACCURATE violation would be calculated from confusion matrices derived from the individual whose behavior is being modeled. Because we are modeling *types* of possible behavior, rather than the behavior of specific individuals, we do not attempt this kind of quantitative detail.

6. Case study: positional velar fronting in the A-map model

In this section we apply the A-Map model to an actual example of a substitution pattern, that of fronting of word-initial velar plosives. This child-specific speech pattern was discussed in section 2, as well as in Inkelas & Rose (2003, 2007) and McAllister Byun (2012).

6.1. The A-map for lingual plosives

Behind the scenes of any A-map analysis is the A-map itself; thus, we begin this example with a review of the motor control factors that affect children's performance during attempts to realize initial velar stops. While we limit ourselves to the consideration of extragrammatical factors in this section, below we will see how these phonetic biases form the basis for a grammatical pattern of velar fronting mediated by the constraints ACCURATE and PRECISE.

Children with a pattern of positional velar fronting clearly have access to candidate motor plans that can map with reasonable accuracy to the acoustics of [k].¹⁰ From the standpoint of accuracy, a child aiming to match adult initial [k] should always choose the motor plan for a discrete gesture in which the tongue dorsum contacts the velum, here represented as /#k/. As discussed above, though, controlling the tongue is a challenging task for the developing motor system. The motor plan for a discrete lingual gesture is in competition with related motor plans such as the plan for a ballistic tongue-jaw gesture. Because the ballistic gesture is easy to execute and frequently used by most child speakers, it has a high baseline level of activation. A young child who attempts MP /#k/ is likely to experience at least occasional referral to the ballistic motor plan. However, ballistic tongue-jaw gestures tend to produce undifferentiated linguo-palatal contact that extends across alveolar, palatal, and velar regions (Gibbon 1999). We will use conjoined place of articulation, e.g., /tk/, to represent a ballistic gesture that results in undifferentiated lingual contact. Perceptually, children's undifferentiated gestures can be classified as velar, alveolar, or something in between (Gibbon, Hardcastle & Dent 1995; Gibbon 1999; Munson et al. 2010; Munson, Johnson & Edwards 2012). However, Gibbon & Wood (2002) report that while the perceptual consequences of undifferentiated gestures vary across children, they tend to be stable within a given child. If a child exhibits undifferentiated gestures

¹⁰ If the pattern of fronting is positional, the child produces correct [k] in final and usually some medial contexts. Moreover, we note that few child speech patterns apply in 100% of cases, and even children who demonstrate robust application of a phonological substitution were typically observed to produce the target sound in babbling or earlier stages of meaningful speech (i.e., U-shaped development; see references cited in Section 3.1).

and is perceived to exhibit the process of velar fronting, we can infer that this child habitually releases undifferentiated closure in the coronal region, yielding a [t]-like percept. Because selection of the motor plan for a discrete velar gesture is associated with frequent referral to an undifferentiated gesture ($/\#tk/$) that is perceived as [t], the child's internal model will encode a high level of variability in the acoustic outcomes associated with the selected $MP / \#k/$. This variability is reflected in the A-map as a large A_{SD} . Figure 4 illustrates the acoustic scatter that arises when the immature speaker attempts to produce the motorically challenging target $/\#k/$:

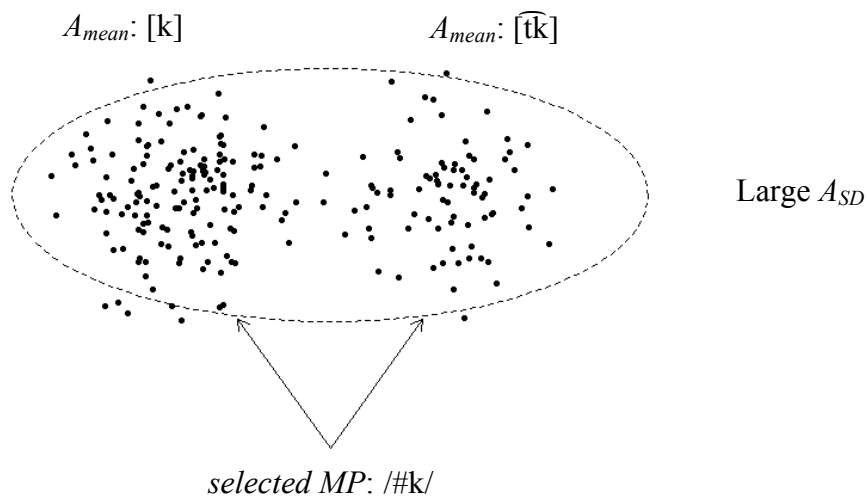


Figure 4: When motorically challenging $MP / \#k/$ is selected, there is frequent motor referral to related $MP / \#tk/$. The mapping from $MP / \#k/$ to acoustic space is broad and unstable (large A_{SD}).

Although Figure 4 depicts only the target motor plan ($MP / \#k/$), the child's implicit learning processes also keep track of the motor-acoustic mapping for the undifferentiated motor plan $/tk/$ and other non-target motor plans. Due to its motorically simple nature, $MP / \#tk/$ maps with a high degree of reliability onto a narrow region of acoustic space, as shown in Figure 5. We represent the acoustic outcome as $[tk]$. As discussed above, this output would typically be perceived and transcribed as [t], but we preserve the conjoined-place notation to indicate that there are presumed to be small (covert) acoustic differences between an undifferentiated gesture perceived as coronal and a true coronal stop produced with discrete linguo-palatal contact. Crucially, we assume that if ballistic gestures make up their own mode in motor-acoustic exemplar space, there is an associated candidate with the A-map vector $\langle / \#tk/, [tk], A_{SD} \rangle$. Due to the reliable nature of the motor-acoustic mapping, this candidate has a smaller A_{SD} than $MP / \#k/$.

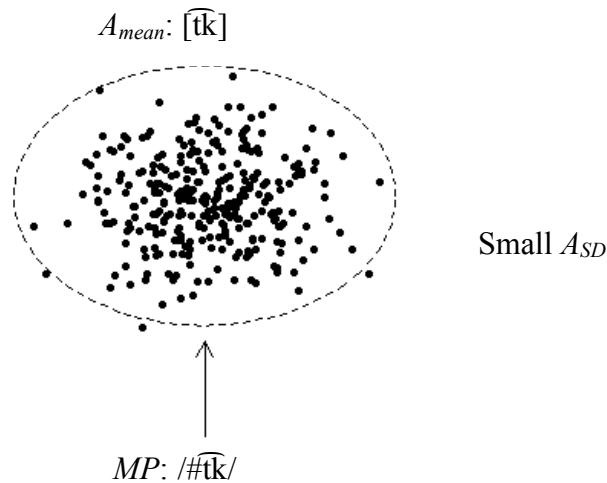


Figure 5. When simpler $MP / \widehat{\#tk} /$ is targeted directly, there is a low likelihood of motor plan referral. The mapping from motor plan to acoustic space is narrow and compact (small A_{SD}).

Previous work (Inkelas & Rose 2003, 2007; McAllister Byun 2012) has argued that the motor control task of producing a discrete lingual gesture is more challenging in an initial or prosodically strong context than in a final or prosodically weak context. This difference has been attributed to the larger magnitude of gestural excursions in prosodically strong contexts. Basic research from the motor learning literature has reported that the amount of random error noise in the execution of a motor plan is proportional to the magnitude of the movement (Schmidt et al. 1979; Wolpert, Ghahramani & Flanagan 2001). Thus, the allophone in a prosodically weak context will have a more compact cloud of acoustic outcomes and a correspondingly lower value of A_{SD} .

6.2. Positional velar fronting: constraint interaction

In this section, we demonstrate how PRECISE and ACCURATE apply to the case of velar fronting, for which we sketched a fragment of the A-map in the previous section. Example (10) depicts the grammar of a child for whom positional velar fronting is in full force. This example crucially assumes a higher weight for the markedness constraint PRECISE than for the faithfulness constraint ACCURATE; this resonates with the standard assumption that markedness outranks or outweighs faithfulness in the earliest stages of grammatical development (Gnanadesikan 1995;

Jesney & Tessier 2011). The precise numerical values of the weights assigned to ACCURATE and PRECISE, as well as the violation magnitudes listed for each candidate, are arbitrary; only the relative magnitudes are of importance.

In (10), candidates compete in the production of *key*, a target word with an initial velar. We include only a subset of candidates that realize the vowel in identical, faithful fashion, and we accordingly omit any violations associated with the vowel from the tableaux that follow. As discussed above, candidates are represented only by *MP*, an idealization of the first component of the A-map vector; A_{mean} is omitted because its representation would be identical to that of *MP*, and A_{SD} appears as the magnitude of each candidate's PRECISE violation. In (10), candidate (a) features faithful velar place, candidate (b) features an undifferentiated gesture perceived as coronal, and candidate (c) features fronting to true coronal place. The relative magnitude of the PRECISE violations incurred by candidates (a) and (b) follows from the A-map sketch offered above. In candidate (a), the discrete lingual gesture required to produce differentiated dorsal contact (*MP* /k/) incurs a relatively large A_{SD} , here represented with magnitude 2. In candidate (b), the significantly smaller A_{SD} associated with the motorically simple undifferentiated gesture / \widehat{t} k/ is represented with value .5. The only remaining question is the status of candidate (c), which features fronting to true coronal place. We assume that production of a discrete lingual gesture is just as difficult, and referral of the unstable motor plan to an undifferentiated gesture just as likely, for a coronal target as for a velar target. However, in this case there is general convergence between the acoustic consequences of the undifferentiated gesture and the discrete lingual gesture. We assume that alternation between true coronal [ti] and undifferentiated [\widehat{t} ki] yields a somewhat more variable acoustic signal than consistent targeting of an undifferentiated gesture, but the PRECISE violation should still be considerably smaller in this case than for velar candidate (a). We adopt 1 as an intermediate value.

10) Comparison of candidates for target *key* (evaluation of onset/strong position)

	Adult target: [ki]	PRECISE	ACCURATE	<i>H</i>
		$w = 3$	$w = 2$	
a.	< /ki/>	-2		-6
☞ b.	< / \widehat{t} ki/>	-.5	-1.75	-5
c.	< /ti/>	-1	-2	-7

We now turn to the evaluation of faithfulness constraint ACCURATE for the candidates in (10). The least precise candidate, (a), incurs no violation of ACCURATE; its projected acoustic outcome [ki] converges with the child’s encoding of the adult target. Fronted candidate (c) incurs the greatest violation of ACCURATE, represented with magnitude 2. Because an undifferentiated gesture released in the coronal region is typically perceived as coronal, we assign a similar ACCURATE violation to candidate (b). The violation magnitude in this case is very slightly lower because children’s fronted /k/ sounds are judged to be slightly but significantly more /k/-like than true (underlying) /t/ when fine-grained perceptual measures are used (Munson et al. 2010). However, the difference in the magnitude of the ACCURATE violations associated with candidates (b) and (c) is not crucial to our account. Due to the high weight of PRECISE assumed for this stage of development, the most harmonic candidate is the form that incurs the lowest PRECISE violation—in this case, undifferentiated candidate (b).

This grammar predicts a different result when the target velar is in weak position. In the preceding section, it was argued that the motor difficulty of executing a discrete lingual gesture is lower, and A_{SD} correspondingly smaller, in a prosodically weak context. This difference is represented in (11) by decreasing all PRECISE violations by half. The magnitudes of ACCURATE violations are also reduced by .5 to reflect the lower salience of perceptual contrasts in final position. Under these circumstances, it is faithful candidate (11a) that emerges as most harmonic:

11) Comparison of candidates for target *peek* (evaluation of coda/weak position)

	Adult target: [pik]	PRECISE	ACCURATE	<i>H</i>
		$w = 3$	$w = 2$	
a.	< /pik/ >	-1		-3
b.	< /pit̪k/ >	-.25	-1.25	-3.25
c.	< /pit/ >	-.5	-1.5	-4.5

A period of systematic substitution like that illustrated in (10)-(11) is often preceded by a period of relatively greater accuracy, forming the well-known U-shaped trajectory to which we alluded in the introduction and section 3.1. In the present model, the U-shaped trajectory is a natural consequence of changes in the A-map in very early learning stages. Above it was shown that the value of A_{SD} is sensitive to the articulatory complexity of a target sound or sound

sequence. However, the standard deviation of a distribution is also sensitive to the number of observations, with a small sample size yielding a high standard deviation. In the earliest stages of development, when targets are represented by only a small number of traces, values of A_{SD} will be high across the board. With PRECISE thus failing to differentiate among candidates, the determination will fall to ACCURATE, and the faithful candidate will be selected for production. However, this does not mean that the candidate will be realized accurately in 100% of cases; there is a high likelihood of a performance error, such as referral to a more stable undifferentiated gesture. The tableau in (12) represents the developmentally very early time point where sufficient observations have not been collected for a well-specified A-map.

12) Comparison of candidates for target *key* before differences in precision have solidified

	Adult target: [ki]	PRECISE	ACCURATE	<i>H</i>
		$w = 3$	$w = 2$	
☞ a.	< /ki/ >	-3		-9
b.	< /tki/ >	-3	-2	-13
c.	< /ti/ >	-3	-2	-13

A related line of reasoning holds promise to explain the puzzling phenomenon of systematic segment preferences or template effects in very early stages of speech development (e.g., Vihman & Velleman 2000; Vihman & Croft 2007). If a particular motor plan becomes stable at a time when most motor routines are unreliable and thus associated with very high A_{SD} values, the grammatical influence of PRECISE could drive the child to use the stable motor plan for a range of different targets.

6.3 Interim summary

In the preceding sections, we argued that the A-map model allows us to capture the systematic phonological conditioning observed in a pattern such as positional velar fronting, without losing sight of the fundamental phonetic underpinnings of this process. Changes in the A-map over time also make it possible to capture the U-shaped trajectory that is often reported in developmental phonological processes. As we will see in the following section, further changes in the A-map can additionally explain the maturational elimination of processes such as positional velar

fronting and their corresponding absence from adult typology. A flowchart summarizing the A-map model is provided in Figure 6:

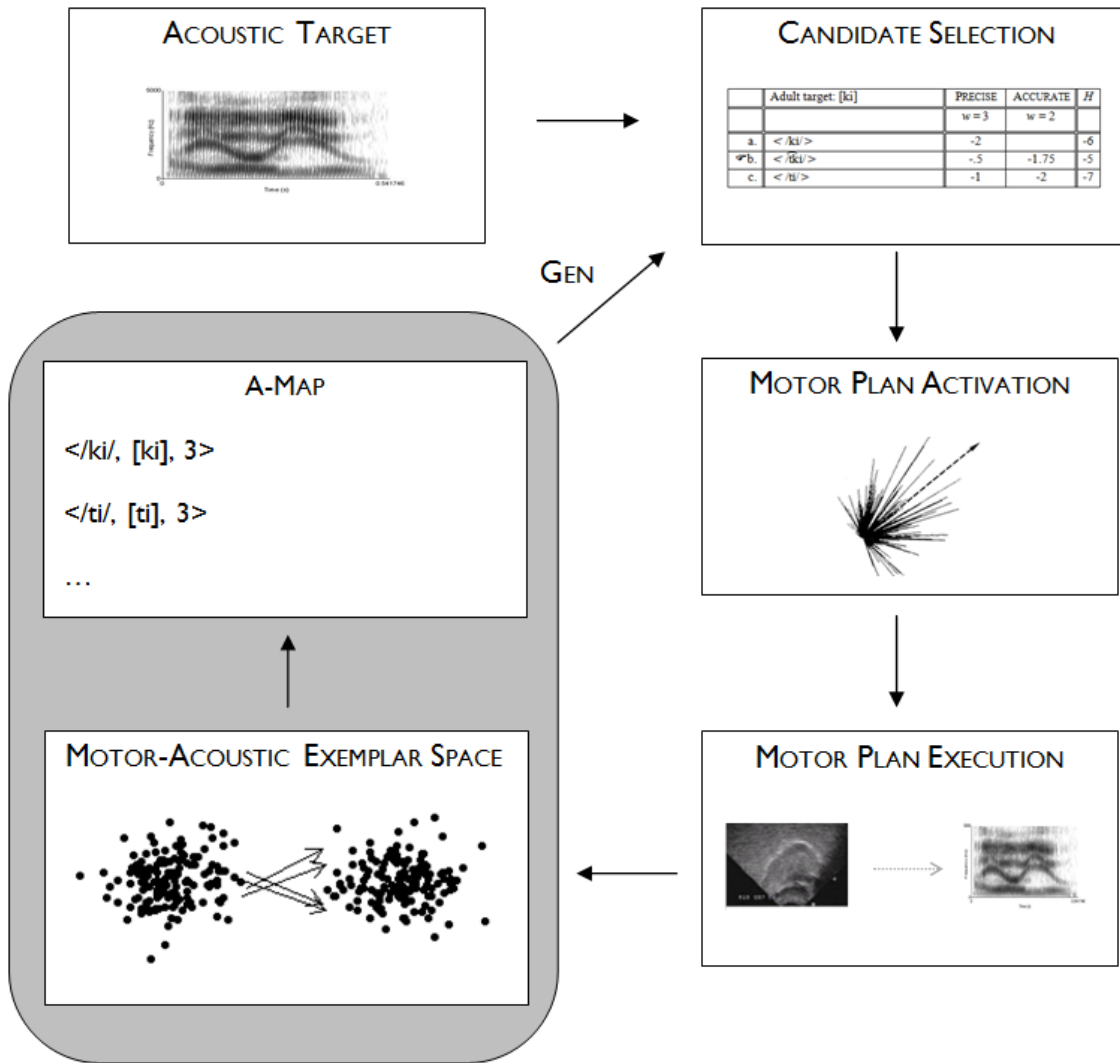


Figure 6. Flowchart situating the A-map within the phonological grammar

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

Recall that one of our core goals in proposing a new model of child 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, it is necessary to assume that they 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, and the A-map is updated to reflect these changes, child-specific patterns driven by PRECISE will be eliminated entirely.

It is important to note that PRECISE itself is not a child-specific constraint; it remains present in the adult grammar, although its influence is greatly attenuated. We also note that we are not proposing to do away with 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 are 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 reduces the magnitude of the PRECISE violation incurred by a given target. (It is important to keep in mind that the A-map determines the magnitude of PRECISE violations, 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 (such as /#tk̃/) map more reliably to acoustic space than discrete lingual gestures (such as /#k/). Targets like /#k/ and /#tk̃/, which previously had very different values of A_{SD} (high for the discrete lingual gesture, low for the undifferentiated gesture), will now converge on similar values. This “flattening” of the A-map is a crucial component in the elimination of patterns such as velar fronting.

But in order for the A-map to flatten, the child must first have opportunities to observe that a previously error-prone target can now be executed with increased reliability. Under the influence of PRECISE, the child's grammar may uniformly select a simplified, highly reliable candidate instead of a more accurate match for the adult target. In such a case, the properties of the mapping in motor-acoustic exemplar space will not change, and the A-map for that target will not reflect any maturational changes that increase the child's likelihood of successfully executing a more difficult plan. The A-Map model thus predicts that a stable pattern of error can persist until some outside impetus causes the child to attempt the more difficult motor plan. We review one such case in the following section.

8. Case study: Abrupt elimination of a phonological pattern in the A-map model

We illustrate the elimination of a phonological pattern due to changes in the A-map with the case of an English-learning female code-named C, originally discussed in Bedore, Leonard & Gandour (1994). This child displayed a rather unusual pattern of consonant substitutions, producing a dental click [ɽ] for the target coronal sibilants /s, z, ʃ, ʒ, ʒ, ʒ, dʒ/. C was characterized as a child with phonological delay/disorder, although her medical history was unremarkable and developmental milestones were attained on schedule. C was reported to have produced clicks from the start of her meaningful speech production at approximately one year of age. Examples of C's click substitutions are provided in (13). The substitution was uniformly present in both spontaneous speech and in productions elicited in a naming task. However, Bedore et al. report that C was stimulable for sibilant fricatives, meaning that she could produce an acceptable imitation of an adult model. (It is unknown whether this imitation occurred in isolation or in a syllable or word context.)

13) C's click substitutions (data from Bedore, Leonard & Gandour 1994)

- | | |
|------------------|-----------|
| a. Target /s, z/ | |
| saw | [ɽ] |
| this | [ðɽ] |
| preschool | [pwiɽ] |
| sometimes | [əmtaimɽ] |
| b. Target /ʃ, ʒ/ | |
| shark | [ark] |
| shoe | [u] |
| treasure | [tweɽ] |
| fish | [fiɽ] |

c. Target /tʃ, dʒ/	
chair	[ɛr]
match	[mæ]
jelly	[ɛwi]
orange	[owən]

In contrast to these substitutions, fricative manner was generally preserved in C's realization of the non-sibilant targets /f, v, θ, ð/, as illustrated in (14).

14) C's target-like productions of non-sibilant fricatives

a. Target /θ, ð/	
teeth	[tiθ]
that	[ðæt]
thing	[θɪŋ]
b. Target /f, v/	
feet	[fit]
before	[bəfou]
have	[hæv]
even	[ivən]

The case of C is noteworthy for several reasons. First, it provides a clear demonstration of the need for a perceptually-oriented faithfulness constraint like *Accurate*. As Bedore et al. point out, the dental click is neither featurally nor articulatorily a good match for sibilant targets, but the high-frequency spectral energy that defines the class of sibilants is similar to the noise produced at the release of [t]. This acoustic/perceptual similarity offers the best explanation for C's pattern of substituting clicks for sibilants. Crucially, the high-frequency spectral energy of sibilants also sets them apart from non-sibilant fricatives, which patterned differently in C's output.

A grammar with both *PRECISE* and *ACCURATE* constraints offers a straightforward account of how a perceptually similar but featurally divergent target could become established in the phonology of a child like C. We assume that at an early point in her development, C tried to produce sibilant fricatives and found that her attempts routinely led to performance errors. It is unlikely that the dental click was a recurring performance error for a sibilant target; more common errors that bear a closer articulatory resemblance to the target, such as stopping, probably predominated. However, it appears that C recognized that a stop does not constitute a particularly good perceptual match for a sibilant target, and she was therefore driven to

experiment with different variants that might differentiate her [t] for /s/ from her [t] for /t/.¹¹ All of this experimentation would mean that there was not a single, stable mapping from /s/ to [t], with the result that [t] would not be highly favored by PRECISE. We assume that C happened to produce a dental click in the course of this exploration, which allowed her to observe that [ɰ] offers a perceptual match for the high-frequency spectral energy of /s/, but with a lesser degree of articulatory complexity. (Although clicks are cross-linguistically rare, they are described as relatively early-emerging sounds in languages whose inventories include them; e.g., Mowrer & Burger 1991). With ACCURATE favoring [ɰ] and PRECISE neutral between [t] and [ɰ], the result is a systematic pattern of click substitution. This outcome is depicted in the tableau in (15). (As in previous tableaux, we abstract away from any violations involving the vowel.)

15) Comparison of candidates for target *see*

	Adult target: [si]	PRECISE	ACCURATE	H
		$w = 2$	$w = 1$	
a.	</si/>	-1		-2
b.	</ti/>	-.5	-1	-2
☞ c.		-.5	-.5	-1.5

The second interesting aspect of the case of C is the extremely rapid elimination of her pattern of click substitution, also documented in Bedore et al. (1994). After her initial evaluation, C was enrolled in intervention intended to encourage more accurate production of sibilant targets. However, she attended only four sessions spanning two weeks before being discharged with fully correct production of all sibilants—an unusually short duration of treatment. The first treatment session targeted initial /s/ in monosyllabic words with various vowels. C was reported to imitate this target without error during intervention activities, but with only a single exception, she continued to substitute clicks for sibilants in her spontaneous speech. The second session targeted /s/ in final position of monosyllabic words with various vowels. Again, C produced all targets correctly within the treatment session, but carryover to spontaneous speech remained limited. However, an abrupt change occurred between this session and the start of the next

¹¹ See Ferguson & Farwell (1975) for previous documentation of this type of exploration in child speech development.

treatment session, when C presented with correct production of all sibilant targets in spontaneous speech.

The rapid change undergone by C provides us with a few key data points. First, she must have perceived sibilants correctly and formed roughly appropriate categories for different sibilants, including voiced and voiceless fricatives and affricates. Otherwise, it would not have been possible for her to produce a full range of sibilants following treatment that targeted only a single phoneme, /s/. It is also clear that C was motorically capable of producing sibilants, since she was able to imitate them even before the start of her treatment sessions.¹² Moreover, C was an older child; years of input from adults in her environment had surely provided abundant evidence for the demotion of a constraint such as *SIBILANT. From the standpoint of a conventional model of phonological learning, the persistence of C's substitution seems mysterious, but a simple explanation is available in the A-map framework. The click substitution was established early on, when C was motorically incapable of producing sibilants. Over time, speech-motor maturation occurred, but C continued to produce a stored, stable form—the click substitution—due to the grammatical influence of PRECISE. What changed, then, during C's three treatment sessions? In the therapy context, heightened attention to the adult target may give a temporary boost to the weight of faithfulness constraints (McAllister Byun 2012). With enhanced ACCURATE outweighing the influence of PRECISE, C was enabled to utilize the motor plan for a sibilant—which she had already mastered in her vocal play—in the context of meaningful speech. This created an opportunity for C's A-map to be updated to reflect her recently acquired ability to map reliably from a sibilant motor plan to the appropriate acoustic target. Crucially, due to the grammatical influence of PRECISE, C had not attempted to produce a sibilant in the context of meaningful speech for some time, meaning that the points in exemplar space representing her early errors would have decayed to a considerable extent. These old traces would be readily overwritten by C's new, successful attempts, with the consequence that a small number of successful productions could yield a substantial change in the A_{SD} for sibilant targets. Expressed in the grammar through PRECISE, this change to the A-map can account for the abrupt increase in C's accurate productions across all sibilant targets.

¹² It is possible that she had been producing sibilants in nonspeech contexts (e.g., [s] for a snake's hiss, [ʃ] for *shush*) prior to treatment.

9. The A-map and idiosyncrasy in child phonology

Modern phonological frameworks have no trouble accounting for variability in the output of a speaker's grammar across utterances. Solutions to the problem of variability include partially ordered constraints (Kiparsky 1993; Anttila 1997) and noise in the evaluation of constraint rankings or weights, as in stochastic OT (Boersma & Hayes 2001) or noisy Harmonic Grammar (Boersma & Pater 2007). However, variability in child grammar is qualitatively distinct from that found in adult speech. Children differ widely in what phonological processes apply or what structures are favored, and in when and how rapidly a process is eliminated from the grammar. Children even differ in the extent of variability in their speech—some children seem to favor a limited number of outputs that can be realized reliably, while others attempt a wider range of targets, with less consistent results (e.g., Vihman & Greenlee 1987). In light of these facts, previous accounts of child phonology have argued that an extragrammatical explanation for variability in child speech is theoretically desirable (Hale & Reiss 2008; Becker & Tessier 2011). In the A-map model, however, the full range of child phonological variation can be captured within the grammar; it is a natural consequence of the fact that grammatical operations are computed with reference to a multidimensional exemplar space that keeps track of all of the inputs perceived and outputs produced by a speaker. Below we explain how three major types of variability in child speech are captured by the A-map model.

9.1. Variability as to which patterns apply

In the A-map model, the phonological structures that a child favors will be influenced by the child's experience of the stability with which different motor plans can be executed. Children differ with respect to which motor plans represent the most stable attractors. This is because the mapping from motor plans to acoustic space is influenced by a multitude of factors, including the specific properties of the child's articulatory anatomy, the salience with which a given target has appeared in the child's input, and most importantly, the child's own history of previous production attempts. Since no two children are exactly the same with regard to these factors, it goes without saying that the phonological patterns produced by PRECISE and the A-map will differ from child to child. However, all children operate under grossly the same motoric constraints, which Green et al. (2000) describe as “biases in the developmental course of

oromotor control” (p. 239). The A-map model predicts that phonological patterns that coincide with these motor biases (as well as universal perceptual pressures) will recur across many children, while leaving room for individual exceptions. This pattern of broad tendencies with individual variability is precisely what we see in actual data from children acquiring phonology.

9.2. Trajectories for the elimination of phonological patterns

If the elimination of phonological patterns were governed exclusively by a mechanism of incremental constraint demotion such as the HG-GLA, we would expect to observe gradual, across-the-board improvements affecting all aspects of a child’s production. In actuality, the obsolescence of child-specific speech patterns does not tend to follow this developmental path. Some patterns diminish incrementally, while others persist in stable form for a lengthy period before disappearing abruptly. Such differences exist even within the grammar of an individual child. Because the A-map model includes two distinct mechanisms that contribute to the elimination of child-specific patterns, it can accommodate a range of maturational trajectories, both within and across speakers. This capacity to capture the elimination of different patterns on different time courses constitutes an important argument in favor of the A-Map model.

An example of abrupt, categorical elimination of a phonological process was provided in the above case study of C’s click substitutions. The argument, in brief, was that C underwent motor maturation that made her capable of producing sibilants, but she did not attempt these targets in meaningful speech due to the ongoing grammatical influence of PRECISE. However, in a structured setting that drew C’s attention to the acoustic properties of sibilant targets and presumably increased the weight of ACCURATE relative to PRECISE, C was able to eliminate her click substitution in an extremely short period of time. In this example, it was critical that C went for a long time without attempting to produce sibilant targets, with the consequence that the highly decayed traces of her off-target productions could be quickly overwritten by a small number of correct productions.

Under different circumstances, the elimination of PRECISE effects can occur in a more gradual fashion. An example comes from case study subject “Ben,” a four-year-old English-speaking boy diagnosed with phonological disorder who also exhibited hallmarks of a deficit in speech-motor planning (McAllister Byun 2012). Ben’s velar fronting was sensitive to prosodic context, similar to the conditioning described for case study subject E (Inkelas & Rose 2003,

2007). But while E's velar fronting was eliminated in an abrupt, categorical fashion, Ben's application of fronting decreased incrementally over the six months in which he was observed (ages 3;10 to 4;4). The A-map framework enables us to capture the contrast between Ben's gradual suppression of velar fronting and the abrupt elimination exhibited by children like E and C. As a child receiving intervention for speech sound disorder, Ben was constantly encouraged to increase the phonetic accuracy of his attempts at velar targets. In the therapy setting, which may temporarily boost the weight of ACCURATE relative to PRECISE, it can be presumed that Ben's grammar sometimes did select a fully faithful form as the target for production. In contrast with the above-described case of C, however, it appears that the motor constraints that initially gave rise to Ben's pattern of velar fronting remained in effect, and he continued to produce motor implementation errors such as referral to an undifferentiated gesture. Thus, instead of diminishing, the A-map penalty for velar targets was reinforced with new evidence of the unstable nature of the motor-acoustic mapping. But like any motor skill, Ben's production of discrete lingual gestures tended to become more reliable over the course of repeated practice, and the cloud representing his outputs shifted over time to form a more compact distribution in acoustic space. Such a shift can only unfold gradually, since it depends on the decay of traces representing past motor implementation errors.

In summary, 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 lifted before high-weighted ACCURATE drives the child to attempt faithful production, the elimination 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.

9.3. Differences in the extent of variability across children

A phenomenon that has received relatively little attention in formal phonology is the existence of across-speaker differences in the extent of variability in the output of the grammar. Such inter-

speaker differences may be minor among adult speakers, but they are highly pronounced in child speech (Ferguson 1979). In their longitudinal study of 10 typically developing children at one and three years of age, Vihman & Greenlee (1987) reported that children differed widely in the level of variability in their output at age one, ranging from 0-89% inconsistent use of phonological processes. They also found that the extent of variability in a child's speech at age one was strongly predictive of variability at age three. Vihman & Greenlee thus proposed that children acquiring phonology can be classified according to two learning styles: children in the "systematic/stable" category make extensive use of a small but reliable repertoire of speech units, while "exploratory/variable" children attempt a wider range of targets, with inconsistent results.

In the A-map model, the "systematic-stable" versus "exploratory-variable" distinction can be captured on the assumption that children can differ in the initial weights assigned to *PRECISE* and *ACCURATE*, or in a plasticity factor that affects the rate at which these constraints are promoted or demoted over cycles of learning (Jesney & Tessier 2011). Children with a high initial weight and/or low plasticity of *PRECISE* would fall on the systematic-stable end of the continuum, attempting primarily those forms that are within their capacity for consistent production. Children who start with a low weight of *PRECISE*, and/or a high plasticity that permits rapid changes in that weight, might fall under the exploratory/variable heading: they tend to attempt more complex forms, yielding a mix of correct and incorrect outputs. Our suggestion that a difference typically attributed to temperament may in fact have a grammatical component can be compared to recent work reporting that personality traits correlate with such low-level phonetic properties as the degree of compensation for coarticulation in perception (Yu 2010).

10. Discussion

Our original goal in developing a new model of the acquisition of phonology was to capture several intersecting phenomena that are often overlooked by, or are difficult to capture within, most existing models of acquisition. These include (a) the inextricable nature of phonetic performance limitations and phonological patterns in child speech; (b) the existence of child phonological patterns that lack any counterpart in adult typology; and (c) the highly variable, individualized nature of output forms and learning trajectories across children.

The concept of the A-map evolved out of our efforts to acknowledge the importance of performance factors arising from children's immature motor abilities without denying the fundamentally grammatical nature of many child patterns. In the adult phonological literature, motorically based speech errors are generally not perceived to fall within the space of grammatical phenomena.¹³ This is a safe assumption because in normal adult speakers, motorically based errors have a low rate of occurrence and a near-random distribution, yielding few meaningful differences in the propensity for error across targets. The case of child speakers is different, since children are attempting to replicate adult acoustic targets using speech structures and motor control skills that may deviate significantly from the adult norm. These differences cause children's outputs to diverge from the adult acoustic target in partially predictable ways. As we saw above, despite identifiable roots in performance limitations, children's errors often have a categorical, systematic quality that is inconsistent with the character of true performance breakdowns. The A-map model captures this overlap between motor difficulty and phonological pressures by enhancing the grammar with information about the child's previous experience of motor plan reliability, expressed through the A-map and PRECISE constraints.

Although the output patterns produced by the A-map and PRECISE are particular to child speakers, the PRECISE constraints themselves are not child-specific. Once anatomical and motor maturation have run their full course, values of A_{SD} will be similar across 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.

Because PRECISE constraints remain latent in the adult grammar, our model also makes the interesting prediction that child-like phonological patterns might reemerge in adult speakers who experience a loss of motor control function. 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 constraints could then drive systematic phonological repairs of the problematic sequences. This model is

¹³ However, Goldrick & Daland (2009) have argued that adult speech errors can be understood as the product of stochastic disruptions to the computations of a Harmonic Grammar.

consistent with evidence indicating that error patterns produced by adults with acquired speech deficits rarely have the random character of pure performance errors, but rather show regularities that can be captured through the formalism of constraint-based grammars (e.g., Buchwald 2009).

The A-map model is also able to account for several previously unexplained aspects of variability in child speech. While adult production is variable, children's production is much more so. Differences between child speakers are particularly pronounced, and previous models have not been able to explain satisfactorily why children differ so widely with respect to which processes they apply, as well as when and how rapidly they eliminate them. The exemplar component of our model keeps track of a child's individual history of production and perception of different targets, and the A-map and PRECISE provide a mechanism by which these episodic traces can shape the computations of the grammar. The A-map model can thus 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; Gahl, Yao & Keith 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 account for these phenomena. More broadly, the A-map model can be regarded as an additional step toward the overarching goal of a multidimensional, interactive model that situates phonological acquisition in the larger context of the child's cognitive, motor, and perceptual development.

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