The Emergence of Epenthesis:
An Incremental Model of Grammar Change

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Abstract

Consonant epenthesis is used as a case study for investigating grammar change over time. An emergentist account is adopted, whereby a substantively naïve learner transforms a phonetically-based sound change into a synchronic phonological rule or constraint. A two-part model of such 'grammaticalizing' change is developed, along with a formal analysis of the necessary model properties. This work demonstrates that epenthesis is a possible emergent system, but that other outcomes (i.e. deletion, suppletion) are more likely. An important corollary of the latter result is that unrestricted learners can produce restricted typologies. This is a consequence of restricted input: asymmetries in the way sound changes occur, the way sounds are organized in words, and the way words are organized in paradigms. The conclusion is that the research methodology developed here is capable of determining possible origins for the universal tendencies of human languages, and that mechanisms other than Universal Grammar are sufficient to produce the observed epenthesis typology.

Keywords
Consonant epenthesis; Evolutionary Phonology; Linguistic universals; Phonologization; Optimality Theory

1 Introduction

Consider the data in (1), illustrating a partial verbal paradigm from the Arawakan language Axininca Campa (Payne, 1981).

(1) Axininca Campa (Payne, 1981)

/in + koma + ako/→	*[iŋ-koma-tako]* 3SG-paddle-DAT 's/he paddles for'
/in + koma + aa/→	*[iŋ-koma-taa]* 3SG-paddle-REP 's/he paddles again'
/koma + aants^{h}i/→	*[koma-taants^{h}i]* paddle-INF 'to paddle'

This pattern is widely analyzed as epenthesis of /t/ across a morphological boundary that brings two vowels into contact (Spring, 1980; Payne, 1981; McCarthy & Prince, 1994). Within the terms of standard Optimality Theory (OT) epenthesis occurs because – among other things – the universal constraint ONSET is highly ranked in the Axininca Campa phonological grammar; syllables are required to have onsets. /t/ epenthesis in particular occurs because /t/ is the least marked – most preferred – segment. This markedness constraint is typically taken not only to be universal, but inviolable as well; that is, no individual language may re-order the relevant constraints such that some other segment (e.g., /k/) is the epenthetic default (Prince & Smolensky, 1993/2004).

OT delineates one possible explanation for the pattern in (1): substantive restrictions on the learner's hypothesis space. The strong version of this position is that learners are endowed with a set of universal constraints and learning consists only and entirely of induction of the relevant constraint ranking. A direct corollary of this position is that though languages may change over time, even drastically, they can only change along certain restricted dimensions: from OT-expressible grammars to OT-expressible grammars. An alternative account is that such apparently universal constraints are emergent from a less restricted learner, over a naturally more restricted set of inputs. That is, the class of learnable grammars is much larger, but the ways in which sounds and words change conspire to block certain grammars from being learned. This hypothesis is tested with a formal model of inductive learning over the products of simulated historical sound changes.

One important feature that an emergentist approach offers is the ability to predict languages that *do not* conform to known phonological universals. In fact, 'Universals' as characterized by typologists have almost always been couched as tendencies rather than absolutes (e.g., Greenberg, 1966; Maddiesen, 1984). It is probably more accurate to characterize human languages as demonstrating strong tendencies, or "substantive biases" (Wilson, 2006). These biases might reside in the learning mechanism ("analytic" bias), the articulatory and perceptual systems ("channel" bias), or both (Moreton, 2008). The strong emergentist position places the bias entirely in the channel (see Blevins, 2004; Ohala, 1981, and more).

While the generativist account described above is known in certain cases to fail by being too restrictive (e.g., for the phoneme inventory of Hawaiian), emergentism often stops at predicting occurrence, without offering an account of occurrence probability. The ideal theory would be one that were able to predict grammars A, B, and C as possible, at the same time explaining why A is significantly more likely than B, and C is vanishingly rare. This work is a first attempt at estimating such relative probabilities by following an emergentist account along the entire route from diachronic source to synchronic grammar.

The question is how an epenthesis grammar can arise from a language which originally lacks epenthesis. Through careful exploration of the properties of the learner, of that learner's input data, and of the proper phonological analysis of the resulting grammar, this work establishes a number of basic conditions, or axioms[1], for the emergence of an Axininca Campa-like pattern. The general conclusion is that the mechanisms of language processing alone – within the limits of our current knowledge – are sufficient to capture the typology of consonant epenthesis – as far as it is known.

2 "True Epenthesis"

Epenthesis is typically taken within generative linguistic theory as a language-specific solution to satisfy a general dispreference for syllables without onsets. In Optimality Theoretic terms, the constraint that requires syllable onsets – ONSET – is highly ranked. Crucially, it is ranked above a constraint that mandates against inserting material into the surface form that has no counterpart in the input: DEP. What also must outrank DEP are additional constraints, such as MAX, which act to prevent other possible "repairs", such as deletion (Prince and Smolensky, 1993/2004). An illustrative alternation of the assumed input and output forms is given in (2), where the epenthetic segment is the glottal stop which appears only in the surface form of (2a).

(2) Tubatulabal (Voegelin, 1935)

a *\/kʊmuː+in/→* *[kʊmu-ʔʊn]*
father-GEN
'of his/her own father'

b *\/pʊnihw+in/→* *[pʊnihw-in]*
skunk-GEN
'of his own skunk'

There is not, however, universal agreement about how to diagnose epenthesis patterns, or whether a given pattern ought to be characterized as epenthesis, or as something else entirely. This is certainly true for cases where the data are not completely consistent or the pattern is obscured by other phonetic and phonological processes. However, there is also an inherent ambiguity to the analysis of epenthesis with respect to the alternative of deletion. To make this clear, consider an analysis in which the underlying forms for the surface forms in (2) are instead chosen as in (3). Rather than epenthesis in the environment between two vowels, what now obtains is glottal stop deletion in a post-consonantal environment.

[1] This term, along with the related 'axiomatics', is due to Paul Smolensky.

(3) Tubatulabal (Voegelin, 1935)

a	*/kʊmuː + ʔin/→*	*[kʊmu-ʔʊn]* father-GEN 'of his/her own father'
b	*/pʊnihw + ʔin/→*	*[pʊnihw-in]* skunk-GEN 'of his own skunk'

Morley (under review) devotes considerable space to a discussion of this analytic problem. The framework of that paper, and the typology that results from a particular family of diagnostics will be assumed throughout. Most relevant for present purposes will be the assumption that there is a set of minimally necessary epenthesis-consistent evidence that the learner must be exposed to. Among that set is the type of alternation data shown in (2) and (3) in which the affix of interest surfaces in both a vowel-adjacent and consonant-adjacent environment. Later sections will discuss further conditions for differentiating between deletion and epenthesis.

3 Typology

The data in the following tables are taken from Morley (submitted), and represent the set of language patterns that, from a sample of 56 candidates, can, by moderately restrictive criteria, be analyzed as epenthesis. These criteria include the alternation condition previously described, as well as quantitative thresholds for demonstrating widespread applicability. The patterns are divided into two tables for reasons that will be elaborated through the following sections of the paper. For now, Table 1 is taken to represent systems of what will be defined as "Minimal" segment epenthesis (as in, 'minimal' departure from the input). These segments are glides, the glottal stop, and occasionally fricatives. Table 2 contains all other segments.

It should be noted that the number of patterns in Table 2 is small – relative to the number of such proposed systems that were investigated in the sample: 5/20 (see Morley submitted). Minimal segment epenthesis patterns occur more frequently. Furthermore, among Non-Minimal systems, dorsal segments (k, g), occur roughly as frequently as coronal segments (t, n), contra certain theories of place of articulation markedness (e.g., Kean, 1975; Paradis & Prunet, 1991; Prince & Smolensky, 1993/2004; de Lacy, 2006). There may be an over-all preference for j, ʔ, or both. However, the size of the sample is too small to draw any robust statistical conclusions.

Table 1: "Minimal" Segment Epenthesis Patterns

	Seg.	Language	Phonological Domain	Source(s)
1	j,w,ʔ	Malay	Suffixation	Onn (1976)
2	j,w,ʔ	Wolof	Suffixation	Ka (1994)
3	j,w,ʔ	Guinaang	Suffixation	Gieser (1969)
4	j,w,ʔ	Karo Batak	V+V†	Woollams (1996)
5	j,w,ʔ	Hausa	Certain suffixes	Jagger (2001)
6	w,j	Balangao	V+V	Shetler (1976)
7	w,j	Dakota	V+V	Shaw (1980)
8	w,j	Ao	V+V⁜	Gowda (1975)
9	w,j	Manipuri	V+V	Bhat & Ningomba (1997)
10	w,j	Argobba	Suffixation⁜	Leslau (1997)
11	w,j	Alywarra	word boundaries†	Yallop (1977)
12	v,j	Kodava	Suffixation	Ebert (1996)
13	ʋ,j	Malayalam	Suffixation	Asher & Kumari (1997)
14	j,ʔ	Ilokano	Prefixes	Hayes & Abadi (1989)
15	w,j,h	Cairene Arabic	Heterogeneous collection of templates and suffixes	Watson (2002)
16	ʋ,j	Dutch	Host+Clitic	Booij (1995)
17	ʔ	Selayarese	V+V;V=V	Mithun (1986)
18	ʔ	Tubatulabal	V+V	Voegelin (1935)
19	ʔ	Misantla Totonac	V+V	Mackay (1994, 1999)
20	j	Turkish	Suffixation	Underhill (1976)
21	j	Berber	Suffixation	Guerssel (1986) Hdouch (2008) Jilali (1976)

Table 2: Non-Minimal Segment Epenthesis

	Seg.	Language	Phonological Domain	Source(s)
22	t	Cree	personal possessive prefixes	Wolfart (1973)
23	n	Dutch	ə-final host+clitic†	Booij (1995)
24	k	Waropen	verbal person prefixes	Anceaux (1961) Held (1942)
25	g	Buryat	verbal suffixes on long-vowel final stems	Poppe (1960)
26	t	A. Campa	Verbal Suffixes	Payne (1981)

This collection of languages represents the typology of epenthesis that the diachronic model of this paper will be accountable for. The low verification rate implies that "default" epenthesis (epenthesis that is robustly distinguishable from other processes, like deletion), is a rare synchronic pattern. The distribution of the non-minimal segment systems will be taken provisionally as evidence that all segments are possible in epenthetic position, with no preference for any particular place of articulation.

† Optional in all environments.
⁜ Not completely predictable by vowel.

Finally consider one more type of pattern, a pattern that fails to meet all criteria for inclusion in Table 2, but which, nevertheless, exhibits certain properties associated with epenthesis. Piggot (1980) describes a process of /t/ epenthesis in Odawa Ojibwa which occurs at the juncture between the vowel-final personal prefixes and vowel-initial non-dependent nouns. In turns out that this process is also accompanied by deletion of unstressed vowels. The actual surface forms that result from the interaction of these proposed rules are given in (4). In (4a), the 2nd person prefix exhibits what might be considered the expected reflex of epenthesis. However, in (4b) the accompanying vowel deletion has rendered the application of /t/ epenthesis opaque. And in (4c) and (4d) deletion occurs because the context for epenthesis is not present (the noun in (4c) belongs to the "dependent" class; the prefix in (4d) does not belong to the personal prefix class).

(4) Odawa Ojibwa (Piggot, 1980)

a *\/ki + akatʃi/→* *[kit-akatʃ]*
2SG-be.shy
'you are shy'

b *\/ni+iʃaː/→* *[nt-iʃaː]*
1SG-go
'I go'

c *\/ni+oːss/→* *[n-oːss]*
1SG-father
'my father'

d *\/kiː+pi+iʃaː+w/→* *[kiː-p-iʃaː]*
PST-forward-come-3SG
's/he came hither'

The data sample as a whole suggests a continuum of "epenthesis-like" behavior of which only a very small subset of patterns are properly characterized as instances of grammatical (that is, synchronic) epenthesis. What the diachronic account offers is the potential to specify the necessary conditions for that small set to arise (or not arise) over time. To be clear, the diachronic analysis is not intended to replace the synchronic analysis, but to augment it. In the process, the burden of explanation will be re-parceled out between the processes of perception, learning, and online grammatical computation.

4 The origins of epenthesis

This section will begin development of a model based on the principles of Evolutionary Phonology, following closely general proposals by Blevins (2004; 2008). Originally, some kind of misanalysis on the part of the listener/learner is assumed, a misanalysis which arises from properties of the articulatory and perceptual systems (Ohala, 1981; 1990; 1993). From this perspective segments can be divided into two types: those that are plausible as "accidental" (also called emergent, or excrescent) in the flanking context of two vowels, and those that are not. /ʔ/, for example, is more underspecified in terms of both perceptual and articulatory features than any other stop. Then there are the glides: /j/,/w/,/ʋ/, and in some cases glide-like fricatives: /h/,/v/,/ɣ/. From a perceptual and articulatory perspective these segments are minimally disruptive of the transition from one vowel to the next, and often share a place of articulation with the leading vowel. It has, in fact been noted that epenthetic material tends to represent a phonetically minimal deviation from the faithful output (Steriade, 2001), and that the same consonants that epenthesize also tend to delete (Vaux & Hall, 2001; Blevins, 2008), hence, "Minimal Segments".

Non-Minimal Segments, on the other hand, cannot arise in this way by hypothesis. A listener, for example will never hear /waa/ as [wata], nor will a speaker ever produce [wata] for the underlying /waa/, even under conditions of hyper-articulation. This split parallels the difference between what Blevins (2008) calls 'Natural' patterns, involving epenthesis of an intervocalic glide (or a laryngeal gesture (h,ʔ) at a prosodic boundary), and 'Unnatural' patterns. The latter involve multiple changes: either subsequent strengthening of the intervocalic glide, or reanalysis of previous consonantal loss (interpretation of a pattern of consonant deletion as consonant insertion in the complementary environments). Minimal Segment epenthesis and Non-Minimal Segment epenthesis are therefore hypothesized to possess distinct diachronic origins. The implications for a theory of emergent phonological patterns will be fully explored in what follows. To begin, let us task the model with accounting for both types of epenthesis system, as well as the outcomes of vowel-vowel production that do not result in epenthesis.

4a Vowel hiatus typology

The typology of attested alternations arising from vowel hiatus across morphological boundary is taken from Casali (1997) and shown in Table 3. As can be seen, a large number of language-specific solutions (or repairs) are possible in an apparent attempt to avoid onsetless syllables. Instead of surface hiatus, one or the other of the vowels may be deleted (as in Emai), the vowels may coalesce and merge their features (as in Anufo), or a new consonantal segment may be introduced between the vowels (as in Axininca Campa). Casali's analysis (and standard Optimality Theory) collapse all cases of epenthesis, regardless of segment. In fact, the constraints responsible for triggering epenthesis are generally separate from the constraints that are taken to determine the epenthetic segment. In light of the previous discussion, however, I will add two more types to Casali's table. Turkish is analogous to Axininca Campa, except that the epenthetic segment (/j/) happens to be a member of the Minimal class. Malay is also a Minimal segment epenthesis language, but allows multiple epenthetic segments, conditioned by vowel quality. This distinction will become important in a moment. Finally, the 'non-repair' solution predicted by full rerankability of OT constraints is represented by the Greek pattern.

Table 3: Typology of Vowel Hiatus Repairs. Adapted from Casali (1997) (with additions).

Type of Repair	Example Alternations		Language
Coalescence	/fa+i/ → [.fɛɛ.] take-3SG	"take it"	Anufo
Diphthong Creation	/izo#ɔkʊ/→[i.zo͡ɔ.kʊ] reed sugarcane	"reed sugarcane"	Ngiti
Glide Formation	/gu#ɔba/→[.gwɔ.ba.] weave mat	"weave a mat"	Igede
Vowel Deletion	/ɔli#ebe/→[ɔ.le.be] the book	"the book"	Emai
Syllable Boundary	/oloena#erxome/→[o.lo.e.na.er.xo.me] continually I.come	"I continually come"	Modern Greek
Epenthesis	/no+n+pisi+i/→[.nom.pi.si.ti] 1SG-FUT-sweep-FUT	"I will sweep"	Axininca Campa
Epenthesis (Minimal Seg)	/ankara+ E/→[ankaraja] Ankara-DAT	'to Ankara'	Turkish
Conditioned Epenthesis	/məŋ+gula+i/→[məŋgulaʔi] ACT-sweeten-CAUS	'cause to sweeten'	Malay
	/bantu+an/→[bantuwan] aid-NOM	'aid, relief'	
	/udʒi+an/→[udʒijan] test-NOM	'test'	

4b "Natural" epenthesis

Casali frames his typology in terms of phonological constraints within synchronic grammars, but this paper will be more interested in the possible origins of those patterns due to historic and cognitive forces. The apparent universal dispreference for onsetless syllables is potentially an emergent phenomenon from processes that erode features of one or both of two immediately adjacent vowels. As is well known, naturally produced speech involves ordering the articulatory gestures for adjacent segments such that they overlap in time (e.g., Browman and Goldstein, 1986; Byrd and Saltzman, 1998; Zsiga, 2000). Depending on the features of those adjacent segments, this will lead to different perceptual effects. Figure 1 gives hypothesized trajectories for Natural Epenthesis systems arising in this way. Each line describes a unique historic path arising from a different timing relationship between articulatory gestures.

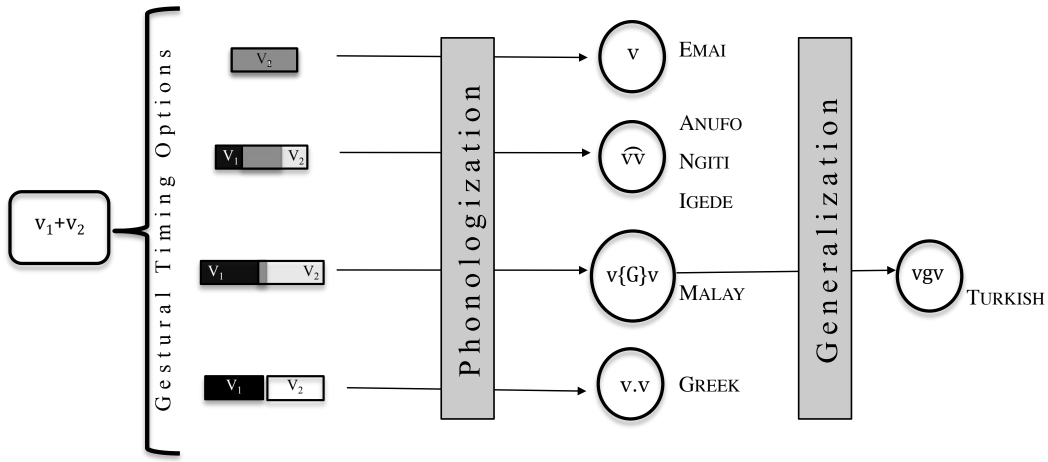

Figure 1
An incremental learning model of the emergence of different grammars as 'repairs' of vowel hiatus (v+v). Each circle represents a possible language. v/v͡v deletion/coalescence. v.v: syllable boundary. v{G}v: variable phonological epenthesis. vgv: default phonological epenthesis. The overlapping rectangles represent different timing options for the adjacent sets of vowel gestures.

Since adjacent vowels involve the use of the same set of articulators in different configurations, anticipation of the second vowel strongly influences the production of the first vowel (e.g., Ohman, 1966; Recasens, 1984; 1989). As a result, features of the first vowel may become perceptually masked, or merged with those of the following vowel. These possibilities are illustrated in the top two timing options of Fig. 1 with various phonological outcomes: coalescence of features, merger of segments, reduction in duration (resulting in a glide percept), or complete loss of one or the other vowel (cf. Zsiga, 1993; 1997; Gafos, 1996; Russell, 2008). If, on the other hand, the speaker makes an adjustment in their productions such that both vowels can be robustly recovered from the speech signal, this might result in the percept of a syllable boundary[2], and/or a glottal stop (lowest timing option). The final possibility is characterized as something in between the other three in terms of inter-gestural timing. At some point in the articulation of the first vowel the articulators begin moving to the target location for the production of the second vowel. This transition is smooth, and long enough to produce the acoustic trace of a phone between the two vowels – an "intrusive" glide (Browman & Goldstein, 1990; Gick, 2003).

At this point in the model, the speaker's representation consists of the vowel targets, and the timing relations between the gestures necessary to produce each target. All productions are continuous language-specific instantiations of underlying /v+v/, and any surface deviations from [vv] are unintended consequences of the production of that sequence. The timing options in Fig. 1 are attributed to the general competition between signal compression and signal recovery, or ease of articulation and ease of perception (e.g., Hunnicutt, 1985; Cutler, 1987; 1995; Lindblom, 1996; Kirchner, 1998).

A change in the synchronic grammar requires a further step: that the gestural coordination relations become reinterpreted as the goals, rather the consequences, of production. This, in turn, induces a change in the underlying representations (see, e.g., McMahon et al., 1994). By definition, the phonetic pattern has become phonologized (Hyman, 1976). How exactly this comes about is a current topic of increasing study (see, for example, the forthcoming volume *Origins of Sound Change: Approaches to*

[2] While phonologically, the surface forms are faithful to the input, and the syllables lack onsets, I hypothesize that some type of articulatory change is necessary to achieve this result. That is, to prevent the eventual loss of featural cues due to natural overlap, I posit that some effort, in the form of the re-timing of articulatory gestures, must be expended (see Fig. 1). This is purely speculative on my part, and not due to Casali (1997).

Phonologization), but well outside the scope of the current paper. Here the mechanism will simply be stipulated as a necessary element of the model.

Figure 1 represents the possible progression of Blevins' 'Natural' type of epenthesis, and implies a second distinction between epenthesis languages at different points along the horizontal axis. Type I patterns will be defined as those (like Malay, Balangao, etc. in Table 1) that exhibit context-dependence, and Type II languages (like Turkish, Buryat, etc. in Table 2, and the bottom section of Table 1) as those that exhibit default epenthesis patterns. Type I have not been generalized to the maximum possible degree whereas, by definition, Type II patterns have.

Incrementality within this model refers to the fact that default epenthesis languages involving Minimal Segments (such as Turkish) arise only through at least two intermediary stages: re-analysis of gradient information as categorical ('Phonologization'), and abstraction over a class of segments and words ('Generalization'). Consider the data on Malay (last row of Table 3), where Onn (1976) reports that epenthesis involves either /w/, /j/, or /ʔ/ depending on context (after /u/, /i/, and /a/, respectively[3]), with the output demonstrating minimal relative deviation from the adjacent vocalic features.

By hypothesis, the Turkish pattern originated in the same way, as a phonetically conditioned process of multiple-segment epenthesis. Similarly, for Malay, the set {w, j, ʔ} has the potential to be reduced over time to a single segment, that is, to pass through the generalization stage. This is not a necessary progression, but merely a possible one, given the right circumstances. Whatever else those circumstances might entail, the current hypothesis is that a non-uniform frequency distribution and high variability are possible contributing factors (see Section 5 for discussion). Imagine that a large enough majority of lexical items exhibit the /j/ pattern of epenthesis, that is, more stems end in /i/ than other vowels. This is the kind of situation that could eventually lead to a language of the Turkish type (/j/ in all vowel hiatus contexts, regardless of vowel quality). This mechanism, of course, like the mechanism of phonologization, will bear much further investigation (see Morley (in prep) for experimental work in this domain).

4c "Unnatural" epenthesis

Unnatural epenthesis patterns are hypothesized to originate from a segment already fully present in the speech signal (Blevins, 2008). An independent sound change of some kind acts on this segment, and the surface alternations that result are reinterpreted by the listener/learner as the result of a synchronic rule. Blevins provides the example of consonant weakening and eventual deletion intervocalically[4]. The scenario we will consider here, tailored as it is to concatenative morphology, will be somewhat different, although reasoning proceeds along the same lines.

Following vowels typically provide robust environments for the detection of preceding consonants. Following consonants, however, are apt to mask the transitional cues that signal the place of the preceding consonant and weaken the percept of that consonant in general (Fujimura, 1976; Repp, 1977; Hura et al., 1992). This type of masking can lead to loss of certain features, such as nasality, voicing or place. In the extreme, the entire consonant may fail to be recovered by the listener. A diachronic

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[3] In the cases where glottal stop is part of a 'minimal' epenthesis pattern it is interpreted as sharing (pharyngeal) place with the back vowel /a/ (e.g., Tamil as analyzed by Lombardi (2002)).

[4] Lavoie (2001) actually reports only 13 cases of deletion out of 92 examples of lenition; voiced velar fricatives, glides, and /h/ are predominantly deleted in her sample, with one instance of /t/ deletion.

change of this kind can result in a synchronic pattern in which, for example, a consonant-final prefix surfaces sometimes without its final consonant. Re-analysis of this pattern (or 'rule inversion', see Vennemann, 1972) is possible because deletion contexts mirror epenthesis contexts.

An example of the relevant type of deletion pattern is given in (5) for a set of hypothetical stems and prefixes, where ↵ represents the reanalysis stage where the underlined segment comes to be considered epenthetic by the listener/learner.

(5) /kit/ + /pamit/ → [kitpamit] > [kipamit] ↵ /ki/ + /pamit/

/kit/ + /oru/ → [kitoru] > [kitoru] ↵ /ki/+t+/oru/

A corollary of the re-analysis proposal is that any consonantal segment of the proto-language's inventory that surfaces in morpheme-final position is a possible epenthetic consonant in the modern language. This includes both Minimal as well as Non-Minimal segments. Additionally, if certain types of segments are universally more likely to delete in CC environments than others (see Jun, 2004), then such a bias is expected to be reflected in the epenthesis distribution. Finally, segments which occur more often in a given language are more likely, by chance, to participate in morphological re-analysis, and to participate more often.

The full taxonomy of epenthesis patterns is characterizable by a 2 x 2 matrix of possibilities: Unnatural or Natural on one dimension; Type I or Type II along the orthogonal dimension. See Table 4. The process of Generalization applies equally to all Type II systems. Similarly, the process of Phonologization must occur for all natural sound changes, that is, all internal sound changes. For Natural epenthesis patterns, the sound change is directly tied to epenthesis. For Unnatural patterns, the final deletion sound change is what must be phonologized. This is assumed as a pre-condition for the Unnatural pattern and is not investigated here.

Table 4: Epenthesis taxonomy with examples of each class

	TYPE I	TYPE II
NATURAL	*Malay*	*Turkish*
UNNATURAL	*Odawa Ojibwa*	*Axininca Campa*

The remainder of this paper is focused on the Unnatural epenthesis types. Although some very basic pre-conditions have been established at this point, this represents only the very beginning of a model of grammar change. It will turn out that there are a multitude of hidden assumptions folded into (5) and its interpretation. Furthermore, elaborating the Generalization mechanism of the incremental learning model of Fig. 1 will necessitate invoking a plausible language learner (who may or may not behave like a theoretical linguist), and giving very careful consideration to the input that learner receives. That input will need to be specified by characterizing the exact form of the posited deletion sound changes, and the exact nature of the morphemes that undergo those changes.

5 "Unnatural" trajectories

Here, and in the following sections, the guiding research methodology is simply to be very literal about the use of distributional evidence for phonological analysis. It will turn out that this alone will lead to some non-obvious conclusions about the necessary conditions for the emergence of 'Unnatural' epenthesis systems. Failure to consider a sufficient number of hypothetical lexemes, segments, or inflections can lead to premature exclusion of possible learner analyses, and thus, premature conclusions about the predictions of a given theory. Later, it will be argued that this research program has broad promise for investigating the historic sources of synchronic patterns of all kinds.

5a Necessary & sufficient conditions I: sound change

Consider again the toy example in (5). It implies a number of conditions on sound change and re-analysis that are worth stating explicitly.

(6) Under deletion in consonant clusters C_1 deletes (alternately, the prefix-final consonant deletes)
(7) Both consonant-initial and vowel-initial stems are present at time t (before deletion)
(8) The learner picks the relevant prefix UR to be vowel-final, and the relevant stem UR to be vowel-initial
(9) All prefixes end in the same consonant; or other factors lead to generalization

Assumption (6) is necessary to produce the alternation in (5); if C_2 deletes instead, there will be no allomorphy with this prefix. Assumption (7) is also required to get the critical analysis started in the first place. With only one type of stem there will be no evidence to the learner of an alternation, and therefore no phonological rule. Under traditional rule-based analysis, the decision about underlying forms (Assumption 8) will have critical repercussions for the choice of rules[5], in particular, the underlying form the learner picks for the prefix. Assumption (9) allows for an epenthesis analysis, rather than a deletion one. Imagine that the language exemplified in (5) contains the following additional prefixes {/an/-, /mis/-, /ok/-}. Deletion, followed by rule inversion, will lead to epenthesis of /t/,/n/,/s/, and /k/ – predictable only by morpheme. One of these will have to become the default segment for this pattern to be considered true epenthesis (i.e., Type II epenthesis).

Now consider the mirror-image scenario in which suffixation, rather than prefixation, is the locus of deletion: (10). It can immediately be seen that some of the assumptions above lead to different conclusions. Namely, there is no alternation involving the suffix morpheme under deletion, and therefore no reason for the learner to re-analyze the data as epenthesis.

(10) /pamit/+/nu/ → [pamitnu] > [paminu] ↵ /pami/ + /nu/

/oru/ + /nu/ → [orunu] > [orunu] ↵ /oru/ + /nu/

An alternative trajectory which could lead to synchronic epenthesis (10′) would involve modifying condition 6 in the following way.

(6′) Under deletion in consonant clusters C_2 deletes (alternately, the suffix-initial consonant deletes)

(10′) /pamit/+/nu/ → [pamitnu] > [pamitu] ↵ /pamit/ + /u/

/oru/ + /nu/ → [orunu] > [orunu] ↵ /oru/ + n +/u/

[5] This stage of analysis is still necessary under an OT account that does away with underlying representations in the SPE sense (Chomsky & Halle 1968). This is because a learner must still learn the words of their language, and must determine the ranking of constraints based on how they assess faithfulness violations to hypothetical morphemes.

Which consonant deletes historically clearly has implications for our model of synchronic epenthesis (Assumption 6/6′). Wilson (2000) marshals typological and experimental evidence in support of the conclusion that where deletion occurs to reduce CC clusters, it is the first of these consonants that is most likely to delete. The experimental evidence has been referenced above. The typological evidence includes cases of C_1 deletion in the following languages: Diola-Fogny, Basque, Capanahua, Attic Greek, W. Greenlandic, Wintu, Appalai, Carib, Choctaw, Chumash, Kamaiura, Tamil, Urubu-Kaapor, Spanish, Erromangan, Icelandic, Kobuk Inupiaq, Tangale, Tunica, and Yawelmani Yokuts. Wilson does report at least one instance of C_2 deletion in Turkish which he analyzes as arising because of the necessity for paradigm uniformity (highly ranked O-O Faith). A similar asymmetry is found for place assimilation with an overwhelming bias towards regressive assimilation (Webb, 1982; Jun, 1995).

This conclusion is potentially complicated by Casali's (1997) findings that determining deletion in VV sequences involves such considerations as the length of the affix, whether the segment is morpheme-final or morpheme-initial, and whether the morpheme belongs to the class of lexical or functional words. However, for the moment, let us simplify to the statement that C_1 deletion is much more likely, although C_2 deletion is possible. This observation will affect the likelihood assigned to each possible diachronic route considered below.

5b Necessary & sufficient conditions II: paradigms

Some version of Assumptions 6-9 is necessary for an epenthesis analysis to be possible. Remaining mostly agnostic about whether learners actually converge on an analysis that involves explicit epenthesis, we will go on to specify additional minimally necessary conditions for them to do so. In tandem, we will ask how those necessary conditions could arise within a set of words that have attained their current surface forms through a process of deletion. That is, we will try to establish a plausible scenario for rule inversion to come about.

Previous sections described the hypothesized role of the speaker and listener in phonetic, and later, phonological language change. This section describes the role of the learner in inducing structure from collections of utterances or words. Subsequently, a more explicit characterization of the learner's role in regularizing such structure will be made – filling in parts of the Generalization mechanism represented in Fig. 1.

There is, in fact, no universally established standard within phonology for extrapolating underlying structure from a set of surface forms (for a number of sequentially discarded proposals see Kenstowicz & Kisseberth, 1979: ch.6). Similarly, many aspects of morphological learning are not well established. In order to proceed, a number of hypotheses must be made. The following will be added to the working assumptions of this paper.

(11) Learners pick underlying forms that are isomorphic with the default member of the paradigm
(12) The default member of the paradigm is the 'uninflected' member[6]
(13) Ties are always decided in favor of a deletion analysis

Assumptions (11) and (12) rule out underlying representations with material that never surfaces, and, in fact, abstract underlying representations altogether, and are certainly not uncontroversial claims within linguistic theory. They are useful for the moment in providing unique solutions to analytic problems, and are sufficient for the

[6] Or perhaps the most frequent (cf. Albright 2002)

relatively transparent paradigms considered in this paper. Assumption (13) allows us to deal with cases in which the data is completely ambiguous, and prune the number of paths we need to keep track of in our analyses (and thus, the length of this paper). As usual, other assumptions might be made, and justified – as these are, partially – by cognitive considerations.

The above assumptions will now be applied to a set of simulated linguistic forms, chosen as representative of the relevant morpheme types. For reasons of space, only suffixation will be considered (due to the fact that the best examples of Unnatural Epenthesis patterns in Table 2 involve suffixation). Let us also take only two dimensions of variation, with two points on each dimension (*deleting consonant* × *number of deletion contexts*). There are other possibilities of course, but these were selected with an eye towards plausibility, and as an illustration of a methodology for formulating the interaction between diachrony and synchrony.

Tables 5 and 6 should be read in the following way. The “Scenario” describes the hypothesized sound change in each case. There are two possible values for each dimension: whether C_1 or C_2 deletes; and whether the sound change involves deletion only in CC clusters, or in both CC clusters and word-finally[7]. Scenarios I and II (Table 5) both involve deletion of C_1 in two-consonant clusters. Scenarios III and IV (Table 6) involve deletion of C_2. Scenarios II and IV specify a hypothetical sound change in which only consonants in clusters undergo deletion (the case we have been exploring exclusively up until now). Scenarios I and III specify a hypothetical sound change in which deletion applies in both contexts.

For each scenario, four hypothetical stems, and two hypothetical affixes are given. Prior to any sound changes these forms have the following surface realizations: [pamit] (coronal-consonant final), [oru] (vowel-final), and [fisem] (non-coronal-consonant final); the affixes appear invariably as [nu] and [o]. The ‘Data’ in Tables 5 and 6 represent the spoken forms to which the listener has access subsequent to the hypothesized sound changes. Each lexeme occurs in an uninflected form, as well as with each of the two suffixes. The ‘Analysis’ represents the underlying forms that this listener will posit, according to the assumptions in (11)-(13).

Table 5: C_1 historic loss under a suffixation paradigm.
Original hypothetical morphemes: /pamit/, /oru/, /fisem/, -/nu/, -/o/

	Scenario I: $C_1 + C_2 > C_2$; $C\# > \#$			Scenario II: $C_1 + C_2 > C_2$		
Data	[pami]	[paminu]	[pamito]	[pamit]	[paminu]	[pamito]
	[oru]	[orunu]	[oruo]	[oru]	[orunu]	[oruo]
	[fise]	[fisenu]	[fisemo]	[fisem]	[fisenu]	[fisemo]
Analysis	/pami/	/pami/+/nu/	/pami/ +/to/	/pamit/	/pamit/+/nu/	/pamit/ +/o/
	/oru/	/oru/+/nu/	/oru/+/o/	/oru/	/oru/+/nu/	/oru/+/o/
	/fise/	/fise/+/nu/	/fise/+/mo/	/fisem/	/fisem/+/nu/	/fisem/+/o/
	UNCONDITIONED ALLOMORPHY			**DELETION**		

[7] In terms of the perception account elaborated in previous sections for the case of CC environments, C# environments are treated as CPause sequences which are similarly inferior to CV in providing transitional cues to the features of C_1.

Table 6: C_2 historic loss under a suffixation paradigm.
Original hypothetical morphemes: /pamit/, /oru/, /fisem/, -/nu/, -/o/

	Scenario III: $C_1 + C_2 > C_1$; $C\# > \#$			Scenario IV: $C_1 + C_2 > C_1$		
Data	[pami]	[pamitu]	[pamito]	[pamit]	[pamitu]	[pamito]
	[oru]	[orunu]	[oruo]	[oru]	[orunu]	[oruo]
	[fise]	[fisemu]	[fisemo]	[fisem]	[fisemu]	[fisemo]
Analysis	/pami/	/pami/+/tu/	/pami/+ /to/	/pamit/	/pamit/+/nu/	/pamit/ +/o/
	/oru/	/oru/+/nu/	/oru/+/o/	/oru/	/oru/+/nu/	/oru/+/o/
	/fise/	/fise/+/mu/	/fise/+/mo/	/fisem/	/fisem/+/nu/	/fisem/+/o/
	UNCONDITIONED ALLOMORPHY			**DELETION**		

Beginning with Scenarios II and IV, Assumptions (11) and (12) lead the learner to posit an underlying final consonant for the stems /pamit/ and /fisem/. In Scenario II, this directly entails a deletion analysis under suffixation of the consonant-initial suffix. For Scenario IV an epenthesis analysis is possible, but deletion is the outcome by Assumption (13). This is demonstrated in the right-most panels of Tables 5 and 6.

Scenarios I and III include the word-final environment in the contexts of deletion. This single alteration changes the learner analysis. This follows from Assumption (11) which precludes consonant-final underlying forms (/pami/, /fise/), and thus rules out the deletion analysis. Instead, a number of unpredictably conditioned allomorphs surface; this outcome is characterized as suppletion. In Scenario I the allomorphy involves only the second suffix, (surfacing as -o,-to, and -mo). In Scenario III, both suffixes exhibit variation (-kit,-tit,-mit). Neither of these scenarios supports an eventual epenthesis analysis. This is because, by the very sound change that created the allomorphy, all evidence of final consonants is eradicated. An alternation between one suffix that occurs with vowel-final stems, and another that occurs with consonant-final stems is impossible for the simple reason that there are no more consonant-final stems, either in surface or underlying forms. Recall that the alternation evidence was the very first condition proposed for an epenthesis analysis.

Now, consider a re-formulation of the scenarios of sound change: only certain consonants, or certain natural classes of consonants are deleted.

(14) Diachronic consonant loss targets certain segments preferentially

This non-uniformity is a plausible diachronic model (see Winitz et al., 1971; Ohala, 1990; Steriade, 1995; Kang, 1999; Jun, 2004; etc. for featural, segmental asymmetries; and Phillips, 1984; Bybee, 2001; 2003; Pierrehumbert, 2001 for word-specific changes), and it has the desired effect of leaving a residue of consonant-final stems. Table 7 shows the outcome when only the coronals (/t/ and /n/) are deleted. Since this reformulation doesn't change the analysis under Scenarios II or IV in any useful way (due to Assumption 12), they are dropped from further consideration. Crucially, rather than completely unconditioned allomorphy (i.e., suppletion) as in Scenarios I and III, Scenarios I′ and III′ lead to partially prosodically conditioned allomorphy. As we will see shortly, this outcome, the direct result of non-uniform sound change, provides the necessary pre-conditions for a possible epenthetic re-analysis to take place. The following section describes what further conditions must obtain for that outcome.

Table 7: Non-Uniform sound change: only coronal consonants lost
Original hypothetical morphemes: /pamit/, /oru/, /fisem/, -/nu/, -/o/

a. C_1 loss

Scenario I′: $C^c_1 + C_2 > C_2$; $C^c\# > \#$			
Data	[pami]	[paminu]	[pamito]
	[oru]	[orunu]	[oruo]
	[fisem]	[fisemnu]	[fisemo]
Analysis	/pami/	/pami/+/nu/	/pami/ +/to/
	/oru/	/oru/+/nu/	/oru/+/o/
	/fisem/	/fisem/+/nu/	/fisem/+/o/
	PARTIALLY CONDITIONED ALLOMORPHY		

b. C_2 loss

Scenario III′: $C_1 + C^c_2 > C_1$; $C^c\# > \#$			
Data	[pami]	[pamitu]	[pamito]
	[oru]	[orunu]	[oruo]
	[fisem]	[fisemu]	[fisemo]
Analysis	/pami/	/pami/+/tu/	/pami/+ /to/
	/oru/	/oru/+/nu/	/oru/+/o/
	/fisem/	/fisem/+/u/	/fisem/+/o/
	PARTIALLY CONDITIONED ALLOMORPHY		

5c Necessary & sufficient conditions III: generalization

The synchronic systems hypothesized to result in Table 7 provide, for the first time, sufficient conditions to carry the analysis forward. To meet the epenthesis alternation criterion the partially conditioned allomorphy must become completely conditioned by stem-final segment type (vowel/consonant). In Scenario I′ what should be the post-consonantal allomorph of the second suffix, -/o/, also occurs after some vowel-final stems (namely, the ones that were historically vowel-final). The same is true in Scenario III′. The first suffix, on the other hand, is correctly conditioned, but takes multiple forms (-/tu/,-/nu/). Therefore, the following generalization conditions must be met:

(15) Regularization over all allomorphs that occur after vowel-final stems (reduction to –C…)

(16) *Failure* to generalize to consonant-final stems, such that the single vowel-initial allomorph is retained.

(17) Regularization across all affixes, such that all affixes choose the same -C…/-V… alternation

Once full generalization has occurred, the requirements exemplified by the languages in Table 2 are met (see Morley submitted). To facilitate comparison with the discussion of 'Natural' languages in previous sections, this information can be visualized in the form of Fig. 2. The generalization mechanism is hypothesized to be the same in both the 'Natural' and 'Unnatural' cases. In both Scenario I′ and Scenario III′ it is C_1 that can be expected to become the default epenthetic segment. This is because even though C_2 deletes in III′ under affixation, C_1 deletes word-finally (see Assumption 12).

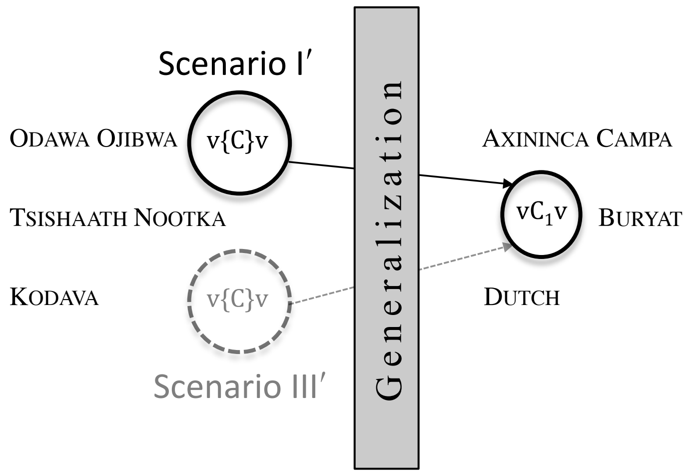

Figure 2
Routes to Unnatural Epenthesis: generalization from Scenario I′ or Scenario III′. Dotted gray borders indicate lower likelihood of Scenario III′ route (C_2 deletion).

Type II systems are ones that have reached the last stage of generalization (the far right of Fig. 2). Type I systems are those that are on the left of that dividing line in Fig. 2. Type I systems may be clear cases of synchronic deletion, or they may be ambiguous. They may be characterizable as prosodically conditioned allomorphy, or 'latent' segments, or morphologically restricted epenthesis (Zoll, 1998; Paster, 2006; Lombardi, 2002). Of the two routes, Scenario III′ is (much) less likely than Scenario I′. This is indicated by the gray dotted border in Fig. 2, representing the typologically dispreferred nature of C_2 deletion.

For both scenarios the full generalization outcome for the second suffix is realized in the paradigm of alternations in (18); Scenario III′ also generalizes the first suffix as in (19). The particular segment that ends up as the epenthetic default will depend on other factors to be discussed below.

(18) /pami/+/o/ →[pamito]
/oru/+/o/ →[oruto]
/fisem/+/o/→[fisemo]

(19) /pami/+/u/ →[pamitu]
/oru/+/u/ →[orutu]
/fisem/+/u/→[fisemu]

5d Generalization conditions

Odawa Ojibwa was described in (4) as an 'intermediate', or Type I system. Another example, similar, but with its own particulars, is Tsishaath Nootka, where epenthesis of /ʔ/ occurs in certain circumstances. Stonham (1999) writes that the "exact mechanism for determining [application]… remains unclear." He gives the examples in (20a), but notes that across other morphological junctures coalescence or deletion occurs instead.

(20) Tsishaath Nootka (Stonham, 1999)

a *｜qiː + iː + ʔaːɬa/→* *[qiː-ʔiː-ʔaːɬa]*
long.time-go-always
'it always took a long time to go'

/t'i + uːp + 'atɬ + 'itʃas/→ *[t'i-ʔuːp'-atɬ'-itʃas]*
sing-MOM.CAUS-NOW-3SG.QUOT
'they sang'

Stonham goes on to say that "for many suffixes, when they are attached to a base ending in /u/…/k/ will be epenthesized." This occurs even when the suffix is consonant-initial, resulting in a consonant cluster. See (20b).

b */ts'u + sats/→* *[ts'u-ksats]*
wash-vessel
'wash tub'

/tɬ'uː + aʃt + iːɬ + 'atɬ/→ *[tɬ'uː-kʷaʃt-iːɬ-ʔatɬ]*
dry-dried-do-NOW
'they dried it now'

If the base ends in /i/ or /a/, on the other hand, /tʃ/ (or /ts/) appears between the base and suffix: (20c).

c */ʔaqi + iːɬ + ħak/→* *[ʔaqi-tʃiːɬ-ħak]*
what-make-2SG.Q
'what are you making?'

Finally, bases ending in sonorants are reported to insert /ʃ/ before /t/-initial suffixes, and to insert /q/ before (some) /ħ/-initial suffixes.

This rather idiosyncratic collection of processes and segments may be somewhat unified by describing them as the residue of non-uniform deletion. The final segment of the stem has been lost in certain contexts. Sometimes that final segment was /ʃ/, sometimes /k/, and other times, /q/. The fact that /k/ 'epenthesis' occurs both before consonants as well as vowels argues that prosodic generalization has not occurred. Instead, it is possible, as Stonham states, that native speakers of Tsishaath Nootka have adopted a different generalization, for example, that stems ending in /u/ trigger /k/ epenthesis, regardless of the nature of the suffix. Another possibility is that speakers have simply memorized a finite set of otherwise unpredictable alternations (see Hale, 1973).

In Kodava a certain amount of generalization appears to have occurred, but is potentially prevented from spreading (that is, blocking evolution into a Type II system) by the fact that the system as it stands is highly predictable and robustly learnable. Ebert (1996) describes four outcomes for vowel hiatus across morpheme boundaries: /j/ epenthesis, /v/ epenthesis, /k/ epenthesis, and deletion/shortening. There are exceptions to these general patterns, but each has its well-defined domain: /j/ epenthesis after front vowels (21a); /v/ epenthesis after back vowels (21b); /k/ epenthesis before /a/ (21c); and deletion when the two vowels are identical (21d).

(21) Kodava (Ebert, 1996)

a	*/elli + uu/→*	*[elli-juu]* where-even 'anywhere'
b	*/boɳɖu + aa/→*	*[boɳɖu-vaa]* necessary-Q 'is it necessary?'
c	*/kuɖi + a/→*	*[kuɖi-ka]* drink-HORT 'let's drink!'
d	*/ʌɭɯdi + ija/→*	*[ʌɭɯdi-ja]* write-2SG.PST 'you wrote'

/j/ and /v/ epenthesis may have a natural origin, but, by hypothesis, /k/ epenthesis emerged through a more indirect route, possibly deletion of the initial segment of a historic -/ka/ morpheme. If synchronic /k/ epenthesis occurs before all /a/-initial suffixes (and there are enough of these to argue against coincidence), then the ∅/k alternation must have generalized to include morphemes that historically began with different segments. By hypothesis, this generalization was limited by another process which already applied in predictable environments. /k/ epenthesis carved out what would have been part of the environment of glide epenthesis (/j/ in the example above). This might have led to unpredictable variation; instead, a sub-pattern involving final /a/ as part of the conditioning environment arose. This happenstance is posited to both allow for the alternation to remain stable, and to account for its narrow scope. As in Nootka, this epenthesis occurs even when the stem form ends in /n/.

For languages like Nootka and Kodava to become Type II systems the generalizations in (15-17) must occur. Again, we ask what lexical and paradigmatic factors might influence such an outcome. The provisional hypothesis adopted is that in cases where the amount of material becomes too large, or the conditioning environments too complicated to keep track of, generalization will result, transforming a language like Odawa Ojibwa into one like Axininca Campa, or a language like Tsishaath Nootka into one like Misantla Totonac.

As Hudson Cam & Newport (2005) suggest, a highly non-uniform distribution might be the key to inducing frequency boosting, as opposed to frequency matching (see Estes, 1972 and references therein). Although most experimental studies seek to show learner generalization as a proof of some aspect of linguistic competence, it is not clear that ready generalization (either across allomorphs, or to withheld segments which share a natural class) is necessarily an adaptive trait for language learning. Speakers must, and can, keep track of a large number of very specific and detailed information to be natively fluent. And many learning experiments on adult subjects have, in fact, shown that listeners are resistant to generalize in many circumstances, even ‘linguistically natural’ ones (e.g., Peperkamp, 2003; Peperkamp et al., 2003; Saffran & Thiessen, 2003).

Some studies indicate that infants and young children, on the other hand, may generalize more readily (Singleton, 1989; Newport, 1990; Senghas & Coppola, 2001). This may be due to a number of different factors; one suggestion being a limited capacity to encode and remember distinguishing linguistic contexts. Rather than a particular facility for language learning, it is a breakdown in the interconnected processes of perception, memory and learning that accounts for the difference between adult and child performance. Under this hypothesis, the same, or similar, behavior could be induced in adult learners by taxing the cognitive system in some way. An obvious way to do this is to construct a system with a high degree of variability, a low degree of predictability, and a large vocabulary size (cf. Wilson, 2003).

Imagine a system of morphological alternation involving twenty surface variations of a particular suffix occurring with different base words, none of which are predictable from phonological, syntactic, semantic or social factors. Under a uniform distribution of the allomorphs, the expectation might be that learners will continue to produce all twenty allomorphs, but will gradually lose the original contexts, such that free variation will result. Under a highly non-uniform distribution, one in which, say, one allomorph occurs five times as frequently as the others, this highly likely allomorph may come, over time, to dominate the distribution, ‘frequency boosting’ from roughly 21% to 100%.

A breakdown in cognitive processing may be similarly induced by competition from unrelated associations. It is well known that similarity plays a role in many aspects of speech processing, from slower reaction times to words that reside in dense neighborhoods of similar sounding words, to priming – lowered reaction times – for semantically related words presented in temporal proximity (e.g., Rosinski, 1977; Lupker, 1979; Dell, 1986; Newman et al., 1997; Vitevitch et al., 1999). Even under circumstances of regular memory load these factors may well play a role in generalization. Take a system with a high degree of homophony across affixes (e.g., Axininca Campa, with the following highly similar affixes (among others) {-/a/,-/aa/,-/ak/,-/ako/,-/aɰ/,-/aβ̞/, -/aβ̞/} Payne (1981)). A partially conditioned case of allomorphy that arises in a single paradigm (a la Scenarios I′ and III′) may be ‘incorrectly’ transferred to other paradigms, both morphologically and semantically unrelated, but phonologically similar. The reversed relationship may hold as well, where the semantic/morphological associations cause transfer of a phonological process from, say, one member of the class of personal prefixes, to all members of the class of personal prefixes (functionally equivalent to a paradigm uniformity pressure (e.g., Kenstowicz, 1997; Steriade, 2000)). Once a certain critical mass of ‘epenthetic’ morphemes have been reached, the likelihood of generalization may domino, spreading to more and more unrelated domains. However, as suggested above for the case of Kodava, this process may be blocked by pre-existing robustly predictable sub-paradigms.

5e Summary & discussion

This section has presented a number of hypotheses about how phonological and morphological learning might occur. These are collected and re-stated in (22).

(22)

- Learners pick underlying forms that are isomorphic with the default, 'uninflected', member of the paradigm
- Ties are always decided in favor of a deletion analysis

This paper has no strong commitment to these assumptions, and merely offers them as a foothold for the elaboration of a formal model. Similarly, a set of hypotheses about the nature of diachronic change were proposed, re-stated in (23). Although these were grounded in experimental and typological evidence, they may prove to be inaccurate or incomplete.

(23)

- Under deletion in consonant clusters C_1 deletes (overwhelmingly)
- Coronals are more likely to be lost historically under articulatory/perceptual masking

A set of conditions were then derived for the emergence of a specific kind of synchronic phonological pattern: "Unnatural" Default Epenthesis. Those conditions were neither arbitrary nor motivated on independent empirical or theoretical grounds. They followed directly from the assumptions in (22) and (23). Thus, *if* one accepts those hypotheses, it is argued that the additional conditions are *logically necessary* in order to arrive at the grammar of interest. The first of these conditions, or axioms, takes the form of necessary initial conditions. This is re-stated in (24a). Other axioms take the form of necessary properties of the learning mechanism, re-stated in (24b). Finally, necessary conditions on sound change are re-stated in (24c). The second of these appears above (in a more specific form) as an independently motivated hypothesis, but turns out to also be a required condition within the current model.

(24a)

- Both consonant-initial and vowel-initial stems are present before deletion occurs

(24b)

- Regularization occurs over all allomorphs of a given affix that are vowel adjacent
- Regularization occurs across all affixes that are vowel-adjacent
- Regularization *fails* to occur *across* prosodic (consonant/vowel) contexts

(24c)

- Both consonants in clusters and consonants word-finally are lost
- Diachronic deletion affects certain segments preferentially

The next step is specifying any unstated properties upon which the conditions are dependent. Those in (24b) require certain learning outcomes, and certain unknown learning inputs. Section 5e speculated on a number of factors that might enable the axioms in (24b) to hold, and thus allow for the emergence of epenthesis in specific historical circumstances. This incremental and explicit exploration of possible diachronic trajectories allows for the model so developed to make concrete predictions about the expected typology of epenthesis grammars. This follows by establishing an estimate for the likelihood of any type of synchronic grammar to act as a precursor system, and of the particular lexical and historic conditions that would be necessary for the shift to take place.

6 General discussion & conclusions

A number of the premises adopted in this work are based in large part on proposals within the Evolutionary Phonology program. This framework places the explanatory burden for synchronic patterns fully on the diachronic forces that give rise to them. At their extremes, both synchronic theory and diachronic theory lay claim to being autonomous. This paper instead takes the view that the study of one is critical to the study of the other. As such, one major goal was to link diachrony to synchrony in a way that would shed light on the phonological typology. The first steps in doing this involved re-formulating the appropriate representations and facts of the synchronic patterns. From the diachronic end, the project involved filling in many of the missing pieces of a plausible historic trajectory.

The focus in this paper has been on one particular type of outcome: the Axininca-Campa-like epenthesis pattern (see (1)). This type of grammar was first situated within a larger model that is capable of producing a range of other epenthesis patterns, as well as deletion, coalescence, and gliding. This framework allows all such synchronic phonological patterns to be linked to a proposed articulatory and perceptual source. The model is far from complete, but it represents at least two important achievements; it is a large step forward in terms of an explicit instantiation of the principles of Evolutionary Phonology, and it achieves significant depth: following a grammatical pattern from inception to generalization.

The methodology developed for this purpose is a sort of rational simulation analysis, systematically discovering the relevant properties of a representative morphological paradigm. These include the types of segments that would need to undergo deletion (a subset of consonants at the ends of words and in clusters), the types of words that would need to occur before sound change (both vowel-final stems and consonant-final), and the lexical types most likely to lead to generalization (low variability on word-final consonants, coupled with high homophony on suffixes). This work, however, is not, and never could be, exhaustive. For example, one proposal for a historic source of consonant epenthesis is glide epenthesis followed by hardening (Blevins, 2008). Potentially many other unexplored routes exist as well. These facts do not change the argument, or the methodology of this paper. What they do change is the estimate of the likelihood for any particular synchronic outcome.

Although it is clear in this work that the number of parameters is quite large, and the scope of a particular investigation must be strictly limited to avoid a proliferation of possible trajectories, the model, if constrained appropriately, can produce usable results. In the first place, this work establishes the possibility that a particular phonological pattern – epenthesis – can be derived from an ultimately phonetic source. The observation that there is a relationship between coarticulatory variation and sound change is an old one. And there is a large body of experimental work establishing articulatory and perceptual precursors for sound change and synchronic alternations (see, for example, Ohala, 1981; 1993; Kawasaki, 1986; Beddor, 2009). However, there are no accounts, to my knowledge, that have been corroborated by modeling work which extends along a complete diachronic trajectory.

Secondly, this work establishes parameters for predicting distinct outcomes: which Type I epenthesis systems are the most likely to lead to Type II epenthesis systems, which diachronic deletion scenarios are most likely to lead to such Type I systems. At the extreme, these are conditions for when such patterns *will not* arise. In particular, the requirements that consonant loss apply non-uniformly, and in both clusters and word finally, are fairly transparent from consideration of Tables 5-7. But prior to such an analysis are quite non-obvious. Bottlenecks such as this provide a source of explanation for the observed typological distribution. It has been claimed that substantive innate constraints are required to explain language universals (Kiparsky, 2004; 2006; de Lacy, 2006; Kingston & de Lacy, 2006). This work demonstrates that while such innate mechanisms may be sufficient, they cannot be considered necessary *a priori*, given the evidence for an alternative mechanism for restricting model outputs to just those preferred, or naturally occurring grammars.

Finally, this work generates a number of specific areas of research that will allow for elaboration and falsification. The collected typology indicates that Type II systems – fully generalized, default systems – are rare (Morley under review). There might be a number of reasons for this. First, it could be less likely for Natural systems to generalize. This is plausible since there is a predictable, phonetically conditioned pattern that listeners can potentially extract. Since Natural systems outnumber Unnatural ones in the sample, the lower rate of generalization in the former leads to over-all low rates of Type II patterns. Type II patterns may also be unlikely because generalization is not particularly likely in Unnatural systems either. This conclusion will depend in part on how common Unnatural Type I systems turn out to be (as they have considerable potential to be under-reported).

Furthermore, it might turn out, for example, to be relatively easy to regularize within a morphological paradigm, and to maintain a separation of prosodic categories, but much less likely for generalization to span morphological paradigms. And consider again the prosodic categories of consonant and vowel; these might be irrelevant under conditions of perfect learning, in which it is easy for the learner to memorize the arbitrary associations between affix and stem. But in a learning situation in which the number of variants is high and memorization is not reliable, a bias towards associating one type of allomorph with a vowel-final stem, and a different one with a consonant-final stem might emerge entirely as a product of the learner's pre-existing grammatical system – a 'substantive bias' (Wilson, 2006). These questions are all ones that can be addressed experimentally. As the direct counterpart to the theoretical work presented in this paper, artificial grammar learning experiments are currently underway to test the precise statistical, phonetic, and distributional parameters for learner generalization in precursor epenthesis systems (Morley *in prep*).

The work in this paper represents a good-faith effort to treat language as a complex cognitive system considered not just at a single moment in time, but at all moments in time. Attempting this type of large-scope research makes it very clear where mechanisms are missing in our theories, mechanisms that are critical to go from a gradient, phonetic domain, to a phonological one, from individual words and segments, to phonotactics, rules or constraints, from diachronic change to synchronic alternation. Properties of human languages as a class that *could be* emergent will be identifiable in this way. And what remains unexplained by this method will be classifiable as part of an additional "analytic" or "substantive" component of grammar. Based on the results of the present paper which stand, in part, as a type of existence proof of the research methodology, I conclude that this type of formal analysis approach is highly promising for producing explicit and rigorous tests of some of the most far-reaching claims of linguistic theory.

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