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The Emergence of Epenthesis: An Incremental Model of Grammar Change

Rebecca L. Morley

The Ohio State University
Department of Linguistics
200 Oxley Hall
1712 Neil Ave.
Columbus, OH 43210

Abstract

Intervocalic consonant epenthesis is used as a case study for investigating grammar change. An emergentist framework is adopted, whereby a simple learning mechanism transforms a phonetically-based sound change into a synchronic phonological process. A two-part model of such 'grammaticalizing' change is developed, along with a formal analysis of the necessary model properties. This work demonstrates that perception-based consonant loss could, in principle, lead to synchronic epenthesis. However, the larger number of historic conditions required for its emergence are predicted to make it less likely than other outcomes such as deletion or suppletion (unpredictable alternation). An important corollary of the latter result is that theoretically dispreferred grammars do not necessarily have to be explicitly marked or removed from the learning space. Input to the hypothetical learner is automatically filtered by 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 mechanisms other than Universal Grammar are sufficient to produce the observed epenthesis typology without over-generating. Furthermore, it is argued that the research methodology is a promising one in general for explaining the universal tendencies of human languages.

Keywords
consonant epenthesis; evolutionary phonology; linguistic universals; phonologization

1 Introduction

The question addressed in this paper is how a process of consonant epenthesis can arise in a language which originally lacks epenthesis. Through careful exploration of the properties of a hypothetical learner, of that learner's input data, and of the proper phonological analysis of the resulting alternations, this work establishes a number of basic conditions, or axioms. Thus, from a hypothesized initial and final state, are deduced the logically necessary lexical and linguistic properties that will connect the two. The impetus for this approach derives in part from the desideratum of accounting for a broad range of possible synchronic grammars. The typology from which the general model and axioms are developed is one amassed by the author that exhibits variation both in the regularity of epenthesis and in the realization of the epenthetic segment or segments. It is found that the necessary synchronic alternations for morphologically conditioned epenthesis of a certain type will only be present if the following hold:

- Diachronic consonant deletion must occur both in consonant clusters and word-finally
- But only a subset of all consonant types can undergo deletion.
- Both consonant-initial and vowel-initial suffixes must be present before such deletion occurs

Synchronic epenthesis will result given these and other necessary historic conditions. Failure to meet one or more of those conditions, on the other hand, will result in different outcomes, such as deletion, or suppletion (unpredictable alternations). Comparison of their distinct historic trajectories allows predictions regarding the relative likelihood of any one outcome. Although no actual probabilities will be computed in this paper, qualitative differences between different outcomes will be discussed, with the goal being to elaborate these over time as more work is done in this domain.

Particular attention will be paid to default epenthesis, a basic operation in most generative phonological theory. In default epenthesis a consonant not present in the input, or underlying form, is inserted between two vowels. Such an insertion is typically taken as a language specific repair of sub-optimal syllable structure (e.g. Prince and Smolensky 1993/2004). Additionally, the identity of this consonant is fixed within a particular language. Default epenthesis of /t/ is illustrated in (1) with a partial verbal paradigm from the Arawakan language Axininca Campa (Spring, 1980; Payne, 1981; McCarthy and Prince, 1994).

(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'

It will be claimed that the emergence of default epenthesis requires the following additional conditions to those above:

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

Although the likelihood of such conditions being met is not known, the greater number of conditions that are required for this, as opposed to other possible outcomes, is a prediction about the relative rarity of default epenthesis (supported by the typological sample).

The remainder of the paper is organized as follows. In the following section a model of the origins of consonant epenthesis will be laid out. This model will place epenthesis within a larger framework that includes other possible outcomes, such as consonant or vowel deletion, vowel coalescence, suppletion, and contextually conditioned epenthesis. In Section 3 the typology of epenthesis patterns used to motivate the model will be discussed. In Section 4 the axioms given above will be derived from certain basic assumptions about learning and sound change. Finally, in Section 5, the results will be summarized, and current and future directions for research will be discussed.

2 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). 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. A misanalysis, or misperception, on the part of the listener can account for segments of the first type, where phonetic or acoustic traces produced by a speaker are interpreted as phonemic by the listener, e.g., /bantu + an/→[bantuwan] > /bantu + wan/(see Ohala, 1981; 1990; 1993). Segments that can fall into this category are /ʔ/, more underspecified in terms of both perceptual and articulatory features than any other stop, the glides: /j/,/w/,/ʋ/, and 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. For these reasons we will term this type of epenthesis Minimal Segment epenthesis.

Non-Minimal segments in epenthetic contexts, 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 an 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. Minimal segments are directly epenthetic; the listener re-analysis involves the addition of a segment to the speaker's original underlying form. Non-Minimal segments are indirectly epenthetic; for the trajectory described in this paper the listener re-analysis involves the removal of a segment from the speaker's original underlying form (which rule is later inverted). Non-Minimal segments are not minimal in epenthesis contexts, but they should be minimal in deletion contexts. Listeners are more likely to fail to recover segments that have fewer cues, shorter duration, and less complex articulations.

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 and Hall, 2001; Blevins, 2008). Dowe and Pulleyblank (2004) propose a harmony-as-faithfulness account of synchronic epenthesis, whereby more salient segments should fail both to delete and to insert. However, a purely general synchronic framework of this sort does not differentiate between segments with different diachronic origins, and thus does not capture the basic distinction between epenthesis types defined in this paper. Although the same underlying forces will apply in all cases (perceptibility/recoverability), the predicted segment will vary by historic context. The difference in markedness (or salience) between a coronal and a labial segment (or a velar segment) has been a large focus of work on epenthetic consonants. This difference, however, is only relevant to Non-Minimal epenthesis, and may not actually turn out to have much impact on synchronic systems (see Morley, under review). In contrast, the difference between glides and non-glides in inter-vocalic context in the present model represents a categorical difference in salience that will significantly shape synchronic grammars.

The implications for a theory of emergent phonological patterns will be fully explored in what follows. Let us begin with the Minimal type of epenthesis, and situate that synchronic outcome among a set of possible grammars that could result from diachronic changes to historic vowel-vowel sequences.

2a Minimal epenthesis

The typology of attested synchronic alternations arising from vowel hiatus across a morphological boundary is taken from Casali (1997) and shown in Table 1. Casali's original table used Axininca Campa as the example of segment epenthesis. Since our model treats Axininca Campa as a case of Non-Minimal epenthesis, the description of that language will be deferred to the following section. It will be replaced in Table 1 by Turkish, which epenthesizes a Minimal Segment: /j/. Malay is also added to Table 1 to represent the full set of possible outcomes. Malay is described as an example of Minimal segment epenthesis conditioned by vowel quality. This distinction will become important in a moment.

Though these are synchronic patterns, this paper will be more interested in their possible origins due to historic and cognitive forces. The apparent universal dispreference for onsetless syllables may emerge 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). Differing features of those adjacent segments, and different amounts of overlap will lead to different perceptual effects. For the purposes of our model, Table 1 provides a description of a set of possible phonological end states. By assumption, phonetically motivated sound changes acting on vowel-vowel sequences will result in one of this set of grammars over time.

****Table 1 approx here*****

As the direct counterpart to Table 1, Figure 1 gives hypothesized diachronic trajectories for each of the synchronic alternations. Each line describes a unique historic path arising from a different timing relationship between articulatory 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. This general ordering relationship can be synchronically realized as merger of segments or features (as in Anufo or Ngiti), reduction in duration (resulting in a glide percept) (as in Igede), or complete loss of one or the other vowel (as in Emai) (cf. Zsiga, 1993; 1997; Gafos, 1996; Russell, 2008). A relative ordering of adjacent articulatory gestures that avoids overlap will preserve the two distinct vowel identities; this may only be achievable by the insertion of a syllable boundary, the phonetic reflexes of which may share perceptual characteristics with the glottal stop. We will assume this is the case for Modern Greek (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 (as in Malay) (Browman and Goldstein, 1990; Gick, 2003).

****Fig 1 approx here*****

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).
The distinction between representations involving overlapping rectangles and representations involving circles stands for the distinction between phonetic realizations and underlying phonological forms. The starting state for all synchronic grammars is a historic underlying /v+v/ sequence, either in the creation of a compound word, a phrase, or a morphologically complex form. The productions of these sequences involve some degree of gestural overlap, also part of the grammar of the speaker. The listener/learner exposed to these surface forms may recover the speaker's underlying forms. In this case, no change in the grammar occurs. In the case, however, where the listener mistakenly interprets the surface forms as the intended forms, his or her underlying forms will differ from the original speaker's (see, e.g., McMahon et al., 1994). By definition, at this stage 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 Phonologization (Yu, to appear)) but well outside the scope of the current paper. Here the mechanism will simply be stipulated as a necessary element of the model.

Fig. 1 also illustrates a proposed distinction between epenthesis languages at different points along the horizontal axis. I define Type I languages as those (like Malay) that exhibit context-dependence, and Type II languages (like Turkish) as those that exhibit context-free epenthesis patterns, or default epenthesis. Type II patterns can only arise through a process of generalization over Type I patterns. This is a testable prediction of the theory. The incremental learning model requires the learner to accumulate a sufficient amount of evidence before generalization can occur. Whether or not the process of phonologization is conceptualized as instantaneous or gradual, the claim is that such a stage is necessary, but not sufficient, to produce synchronic Type II epenthesis. Thus, 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).

As illustrated in Table 1, and described by Onn (1976), epenthesis in Malay involves either /w/, /j/, or /ʔ/ depending on context (after /u/, /i/, and /a/, respectively). Onn hypothesizes that the phonetic instantiation of /ʔ/ in Malay possesses pharyngeal characteristics, thus sharing place with the back vowel /ɑ/ (e.g., Tamil as analyzed by Lombardi (2002)). Context-dependent minimal epenthesis patterns can also involve /ʔ/ surfacing between identical vowels, as in Karo Batok (Woollams 1996). Under the articulatory model depicted in Fig. 1 this outcome could be the result of avoiding vowel merger. When the vowels are identical the usual degree of gestural overlap may result in a surface form that is perceptually indistinguishable from an underlyingly long vowel. By spacing the vowel gestures farther apart in time this outcome could be avoided, but the percept of a /ʔ/ may result instead (as proposed above for syllable boundaries in languages like Greek).

By hypothesis, the Turkish pattern originated as a phonetically conditioned process of multiple-segment epenthesis. Thus, the model predicts an early stage for Turkish analogous to the Malay or Karo Batok pattern. Also predicted is a possible future state for Malay, analogous to the Turkish, where the set {w, j, ʔ} has been reduced over time to a single segment. This is not a necessary progression, but merely a possible one, given the right circumstances. Later sections of this paper will be concerned with establishing exactly what those circumstances are. The working hypothesis is that a non-uniform frequency distribution over allomorphs and a large number of such allomorphs can induce generalization in learners (see Section 4d).

2b Non-Minimal epenthesis

Non-Minimal 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[1]. 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, Macchi, and Streeter, 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 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 (2) for a set of hypothetical stems and prefixes, where ↵ represents the reanalysis stage where the prefix-final segment comes to be considered epenthetic by the listener/learner.

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

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

This is the general scenario that will be assumed and elaborated throughout the rest of the paper. One 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 distribution of epenthesizing languages. 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 proposed epenthesis patterns is characterizable by a 2 x 2 matrix of possibilities: Non-Minimal or Minimal on one dimension; Type I or Type II along the orthogonal dimension. See Table 2. 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 Minimal epenthesis patterns, the sound change is directly tied to epenthesis. For Non-Minimal patterns, the final-deletion sound change is what must be phonologized. This is assumed as a pre-condition for the Non-Minimal pattern and is not investigated here.

****Table 2 approx here***

3 Typology

The model as developed so far is motivated in large part by a sample of epenthesis patterns that are taken as representative of the typology. In Morley (under review), a set of 56 candidate patterns were collected. Each pattern had been analyzed by at least one source as epenthesis. However, because of lack of consensus over the proper analysis of a

[1] 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.

number of the language patterns, Morley provides a reanalysis of the source data. These sources were typically general grammars, sometimes grammars of the phonology specifically, and occasionally only word list or dictionaries. Only where it was judged that sufficient evidence of the right type existed were candidate patterns deemed epenthesis. The major conclusions of that reanalysis are the following: default epenthesis patterns (Type II) are rare; of the small set of such languages no robust preference for, e.g., coronal over velar place of articulation can be inferred (see, e.g., Kean 1975; Paradis and Prunet 1991; de Lacy 2006); epenthesis of homorganic glides (Type I Minimal Segment), on the other hand, occurs relatively frequently. In general, epenthesis is highly restricted to individual morphological paradigms, and sometimes, to individual lexical items. These conclusions are reached via the development of a quantitative method for diagnosing epenthesis. That diagnostic requires that all the conditions in (3) be met.

(3)
(a) Alternation evidence exists
(b) Epenthesis does not act to reduce the well-formedness of syllables
(c) At least a minimum number of morphemes must participate
(d) No more than a maximum number of exceptions can exist

For (3a) to be met the morphemes associated with epenthesis must surface in certain contexts without the epenthetic segment. Tubatulabal meets this criterion. In (4) the genitive morpheme in Tubatulabal is shown suffixed to a vowel-final stem, with an accompanying [ʔ] (4a), and to a consonant-final stem – no [ʔ] (4b) (vowel harmony applies in (4a) but is irrelevant to the argument here).

(4) Tubatulabal (Voegelin, 1935)

a	*/kʊmuː+in/→*	*[kʊmu-ʔʊn]* father-P.GEN ‘of his own father’
b	*/pʊnihw+in/→*	*[pʊnih-win]* skunk-P.GEN “of his own skunk”

Maori fails criterion (3a) for the simple reason that it lacks consonant final stems (Hale, 1973). Additionally, the passive form varies by stem. By hypothesis, the analysis must either involve deletion of underlying stem-final consonants (5a), or suppletion: allomorphs indexed by stem (5b)[2].

(5) Maori (Hale, 1973)

a	*/awhit/→*	*[awhi]* embrace ‘to embrace’
	/awhit+ia/→	*[awhit-ia]* embrace-PASS “to be embraced”
b	*/awhi/→*	*[awhi]*

[2] But see de Lacy (2003) for an alternative analysis.

	embrace
	'to embrace'
/awhi + tia/→	*[awhi-tia]*
	embrace-PASS
	"to be embraced"

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 nouns of a particular class. 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 (6). In (6a), the 2nd person prefix exhibits what might be considered the expected reflex of epenthesis. However, in (6b) the accompanying deletion of the unstressed vowel has rendered the application of /t/ epenthesis opaque. In the resulting form, rather than the CV.CV.CV: structure that would have resulted without deletion, the CV of the original syllable surfaces as CCV. This is a less preferred syllable type typologically and according to markedness scales (see Prince and Smolensky, 1993/2004). Thus the pattern in Odawa Ojibwa fails criterion (3b).

(6) Odawa Ojibwa (Piggot, 1980)

a	*/ki + akatʃi/→*	*[kit-akatʃ]*
		2SG-be.shy
		'you are shy'
b	*/ni + iʃa:/→*	*[nt-iʃa:]*
		1SG-go
		'I go'

For the same reason, patterns involving syllable-final (coda) epenthesis are excluded from the typology. They may prove to have a similar diachronic source, but they cannot have the same synchronic analysis (improvement of syllable structure). Korean, for example, exhibits inter-consonantal epenthesis of nasals and obstruents in different contexts (Kim-Renaud 1974; Lee 1998). Amharic is analyzed by Broselow (1994) as inserting /t/ to satisfy templatic morphology; as a result, /t/ surfaces word-finally or as the second member of a two-consonant sequence.

Finally, the observed epenthesis pattern is required to be productive. This is to ensure that there is a synchronic grammar that is responsible for the surface forms – that they are not merely a lexicalized residue of historic change. It is not possible to be entirely confident that a pattern is synchronically active without independent evidence, usually experimental. We can, however, try to avoid the most ambiguous cases. The criterion that a certain minimum number of morphemes participate is based on the productivity condition. This is also why evidence is restricted to morphological environments, as these are the most likely to involve on-line processing.

A significant proportion of the minimal-segment languages in the sample are described as also epenthesizing word-initially[3]. Tamil, Wolof, Dutch, and Southeastern

[3] It is interesting that no non-minimal segments are found to epenthesize word-initially. This suggests that generalization of such a pattern may be blocked from this environment, and bears further investigation as the model of this paper is developed.

Armenian show a context-dependent pattern with a front/back, or high/low/back pattern. Hausa, Ilokano, Larike, Misantla Totonac, Nancowry, Selayarese, and Nootka require a glottal segment to precede vowel-initial words (see Morley, under review). It is hard to know, however, whether this process is synchronic, or if historically vowel-initial words now contain initial consonants underlyingly. These patterns, therefore, are not included in the final typology. They may, however, be explainable by the same mechanisms that we use to predict inter-vocalic epenthesis. In utterance context such words are spoken adjacent to other words with which they overlap to a certain degree. A vowel-initial word in contact with a vowel-final word introduces the same v+v environment that initiates the model of Fig. 1.

The final set of patterns that meet all criteria for Type II epenthesis are given in Table 3. Type I Minimal Segment epenthesis patterns are collected in Table 4. Although Maori and Odawa Ojibwa fail the diagnostics for epenthesis they represent patterns that *could*, according to the model introduced above, transform into Type II epenthesis over time. They fall into the Type I Non-Minimal Segment category. This type of pattern will be discussed further in Section 4d, with additional examples taken from the typological sample.

Table 3 approx here **

****Table 4 approx here*******

This collection of languages represents the typology of epenthesis that the diachronic model of this paper will be accountable for. The reanalysis in Morley (under review) did not find enough evidence for Type II epenthesis in more than 10 of the 56 patterns, despite the fact that each pattern had previously been identified as epenthetic. Similarly, the observed distribution did not provide statistical evidence for patterning by place of articulation, despite claims from markedness that coronal segments should be preferred as default segments. The data sample as a whole suggests a spectrum of “epenthesis-like” behavior. What the diachronic account offers is the potential to predict language patterns at all points along the spectrum, and to specify the necessary conditions for patterns of one type to transform to patterns of a different type 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. In what follows, the model introduced in Section 2 will be elaborated by the discovery of a set of necessary conditions. These are the conditions which will enable a generic learner to select Type II epenthesis in preference to any other possible analysis. In fact, many of those conditions are foreshadowed in the diagnostic criteria of (3). As the general principles of phonological analysis act to differentiate between competing analyses of the same set of data, this similarity should not be surprising.

4 Non-Minimal trajectories

The remainder of this paper is focused on Non-Minimal epenthesis: synchronic alternations that derive, by hypothesis, from historic segment loss. Although some basic pre-conditions have been established at this point, this is only the barest beginning of a model of grammar change. In the first place, it turns out that there are a multitude of hidden assumptions folded into (2) and its interpretation. Furthermore, elaborating the generalization mechanism of the incremental learning model of Fig. 1 will necessitate invoking a hypothetical language learner (who may or may not behave like a theoretical linguist). The input that learner receives will, in turn, need to be specified enough to determine the outcome of learning.

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 results regarding the outcomes of sound change. In the first instance, we must be careful to include a representative set of competing analyses. That is, we must ask whether we have failed to consider any grammars that might be better descriptions of the given data. In the second instance, we must model a sufficiently complex lexicon. That is, we must take care not to over-simplify the data to the extent that we are no longer modeling the problem of interest. These are pitfalls inherent to modeling work of any kind, but they may be more, or less, difficult to avoid, depending on the phenomenon being modeled. For the work in this paper, it will turn out that the critical discoveries will derive largely from a more comprehensive treatment of the model data.

4a Necessary & sufficient conditions I: sound change

Consider again the toy example in (2). It implies a number of conditions on sound change and re-analysis that are worth stating explicitly.

(7) Under deletion in consonant clusters C_1 deletes (alternatively, the prefix-final consonant deletes)
(8) Both consonant-initial and vowel-initial stems are present at time t_i (before deletion)
(9) At time t_j (after deletion), the underlying representation of the prefix is vowel-final, and the underlying representation of the stem is vowel-initial
(10) All prefixes end in the same consonant at time t_i (or generalization is required)

Assumption (7) is necessary to produce the alternation in (2); if C_2 deletes instead there will be no allomorphy with this prefix. Assumption (8) is also required to get the critical analysis started in the first place. With only one type of stem there will be no alternation, and therefore no phonological rule. Under traditional rule-based analysis[4], the decision about underlying forms, particularly the underlying form of the prefix, will have critical repercussions for the choice of rules (Assumption 9). Assumption (10) is required to avoid a deletion or suppletion analysis. Imagine that the language exemplified in (2) 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 designated Type II epenthesis.

Now consider the mirror-image scenario in which suffixation, rather than prefixation, is the locus of deletion: (11). It can immediately be seen that some of the

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

assumptions above lead to different conclusions. Namely, there is no alternation involving the suffix morpheme under deletion of C_1, and therefore no reason for the data to be re-analyzed as epenthesis.

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

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

An alternative trajectory which could lead to synchronic epenthesis (11′) would involve modifying condition 7 in the following way.

(7′) Under deletion in consonant clusters C_2 deletes (alternatively, the suffix-initial consonant deletes)

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

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

Which consonant deletes historically clearly has implications for our model of synchronic epenthesis (Assumption 7/7′). 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[5]. 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) finding 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. At this point in the analysis this observation appears to require that most cases of attested epenthesis occur at prefix+stem, rather than stem+suffix boundaries. The opposite distribution in the typology of Section 3 will force us to consider alternate diachronic trajectories in order to revise this prediction.

4b Necessary & sufficient conditions II: paradigms

Some version of Assumptions 7-10 is necessary for epenthesis to be a candidate analysis. However, surface forms which are consistent with an epenthesis analysis may be consistent with other analyses as well. Independent evidence is needed to establish which grammar is represented in the actual mind of the speaker. The guiding assumption of this paper is that grammar change comes about through two transformational processes; sounds, and the words in which they appear, change over time through misperception and misarticulation; and the alternations, or rules, in which those words participate change

[5] This is formulated as a highly ranked constraint on maintaining faithful mappings between related surface forms: O-O FAITH.

through a re-analysis on the part of the listeners/speakers. This second stage is a type of learning, although this paper will remain agnostic about whether that learning occurs inter- or intra- generationally. What this work seeks to establish are the logically necessary conditions that would allow a generic language learner to converge on an epenthesis hypothesis in preference to all other competitor hypotheses. In tandem, we ask how those necessary conditions could arise within a set of words that have attained their current surface forms through historical segment loss. That is, we will try to establish a scenario under which rule inversion could occur. In part, this enterprise will involve constraining the scope of the problem with facts that are known about morphological acquisition and sound change. Where those facts are not known, a working hypothesis of at least intuitive plausibility will be adopted. These stand-in hypotheses can be replaced at a future date. It will always be true in work of this nature that the axioms we discover are conditional; that is, they *must* be true, but only *given* the assumptions upon which they are based.

There is, in fact, an immediate gap in our knowledge. Condition (9) requires that listeners select underlying forms of a particular type. Therefore our model must establish the prior conditions that would lead to just such a selection. However, there is no universally established standard within phonology for determining underlying structure from a set of surface forms. Similarly, many aspects of morphological learning are not well established. In order to proceed we will adopt the following working hypotheses.

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

Kenstowicz and Kisseberth (1979) have shown that it is not possible in every instance for an underlying form to be chosen from among the surface members of a paradigm. However, for the paradigms considered here, such a choice will be possible; additionally, this simplification allows us to rule out certain analyses. In particular, assumptions (12) and (13) disallow underlying representations with material that never surfaces. Assumption (14) provides a way to deal with cases in which the data are completely ambiguous, and prune the number of paths we need to keep track of in our analyses (and thus, the length of this paper). This set of working hypotheses establishes a basic framework for the induction of grammatical alternations. We can now proceed to bootstrap the next set of conditions necessary for synchronic epenthesis to arise.

The next stage of modeling involves simulating morphological paradigms made up of different word types – essentially expanding the toy example in (11′). We will then apply our current induction hypotheses, making successive alterations either to the word types, or the properties of the learner, in order to produce the desired outcome. The set of morphemes in (15) was determined, through trial and error, to be sufficient to both produce and illustrate the necessary alternations.

(15)

Stem Type	Stem	Suffix	Suffix Type
Coronal-final	/pamit/	∅	Null
Vowel-final	/oru/	-/nu/	Consonant-initial
Non-coronal-final	/fisem/	-/o/	Vowel-initial

For reasons of space, only suffixation will be considered (due to the fact that the best examples of Non-minimal epenthesis patterns in Table 3 involve suffixation). We will also take only two dimensions of variation, with two points on each dimension (*consonant lost* × *number of deletion contexts*). Tables 5 and 6 together demonstrate the full combination of these dimensions in 4 scenarios. Either C_1 or C_2 deletes; and the sound change involves deletion only in CC clusters, or in both CC clusters and word-finally[6]. 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 considering exclusively up until now). Scenarios I and III specify a hypothetical sound change in which deletion applies in both contexts.

For each scenario, the three hypothetical stems and three hypothetical affixes are given. Prior to any sound changes these forms have the surface realizations given in (15). The 'Data' in Tables 5 and 6 represent the spoken forms to which the listener has access subsequent to the hypothesized sound changes. The 'Analysis' represents the underlying forms that this listener will posit, according to the assumptions in (12)-(14).

****Table 5 approx here****

Table 6 approx here*

Beginning with Scenarios II and IV, Assumptions (12) and (13) lead the learner to posit an underlying final consonant for the stems /pamit/ and /fisem/. These are the default, uninflected forms. In Scenario II, this directly entails a synchronic deletion analysis; stem-final consonants delete when adjacent to a suffix-initial consonant. For Scenario IV an epenthesis analysis of /n/ intervocalically is possible ([orunu]), but deletion is the outcome by Assumption (14). Deletion is also consistent with the lack of epenthesis in the [oruo] form. This is demonstrated in the right-most panels of Tables 5 and 6.

Scenarios I and III include deletion in word-final contexts. This single alteration changes the learner analysis. This follows directly from Assumption (12) which precludes consonant-final underlying forms (/pami/, /fise/). Thus the deletion analysis is ruled out. Instead, a number of unpredictably conditioned allomorphs surface; this outcome is characterized as synchronic 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). However, 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.

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

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

(16) 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; 2002; Pierrehumbert, 2000 for word-specific changes). Furthermore, non-uniformity has the desired effect of leaving a residue of consonant-final stems. Table 7 illustrates 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 13), 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 the final set of conditions that will allow Type II epenthesis to be realized.

Table 7 approx here*

4c Necessary & sufficient conditions III: generalization

Table 7 provides, for the first time, scenarios that could lead directly to a default epenthesis pattern of the kind found in Axininca Campa (see (1)). This would require the partially conditioned allomorphy to become completely conditioned by stem-final segment type (vowel/consonant). In Scenario I′ it can be seen that 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:

(17) Regularization over all allomorphs that occur after vowel-final stems (reduction to –CVX)

(18) *Failure* to generalize to consonant-final stems (retaining the –VX allomorph)

(19) Regularization across all affixes, such that all affixes choose the same C in -CVX/-VX alternations

The necessity of these additional conditions can be seen once we scale up our simulated three stem/two affix paradigm. Each of (17)-(19) is taken individually and applied to Scenario I′. See Table 8, with four new historically vowel-final stems (/oru/, /pefi/, /me/, /gada/, /umu/), and four new historically coronal-final stems (/kifun/, /egan/, /femot/, /nagit/). Condition (17) requires that the second column of Table 8a reduce to the third column. If all final coronals deleted historically, then multiple coronal segments may appear with the /o/ suffix; here /n/ and /t/. These must be reduced to a single segment. All historically vowel-final stems must adopt this ending as well, such that all *synchronically* vowel-final stems surface as stem+[to] in their inflected forms. Condition (18), on the other hand, halts the generalization process short of converting stems like /fisem/, so that [fisemo] does not become [fisemto].

Condition (19) extends the process such that additional affixes participate. To our original vowel-initial suffix -/o/, add the set -/ina/,-/ub/,-/efe/,-/aro/. Table 8b illustrates the additional regularization that would be required for the same epenthetic segment to be realized in all contexts. Taken together, these three conditions act to produce a set of alternations that can be described as /t/ surfacing exactly when a sequence of adjacent vowels would otherwise result. This is functionally equivalent to a process of /t/ epenthesis.

Table 8a,b approx here *****

The generalization conditions (17)-(19) are conditions on the Generalization mechanism of Fig. 1. They are hypothesized to be identical for both Minimal and Non-Minimal epenthesis, and act to transform Type I to Type II systems. This is illustrated by Fig. 2, an expansion of the right side of Fig. 1. Type I Minimal segment epenthesis is defined as context-dependent, or assimilative. Type I Non-Minimal segment epenthesis may be a clear case of synchronic deletion, or it may be ambiguous. These patterns may be characterizable as prosodically conditioned allomorphy, alternations involving 'latent' segments, or morphologically restricted epenthesis (Zoll, 1998; Paster, 2006; Lombardi, 2002). Of the two routes in Fig. 2, Scenario III′ is less likely than Scenario I′. The gray dotted border represents the typologically dispreferred nature of C_2 deletion. In both Scenarios 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).

Fig 2 approx here*

4d Generalization conditions

In this section we briefly explore factors that could lead to satisfaction of the generalization conditions in (17)-(19). In the first place, we examine the details of a small set of natural languages that have been categorized as Type I epenthesis (see Morley, under review). From these examples we then speculate about the historic origins of such systems, and the ways in which they might change in the future. The necessary work to more fully characterize the generalization process of Figs. 1 and 2 is described via a set of ongoing experiments in which carefully constructed morphological paradigms are taught to adult listeners.

Tsishaath Nootka is one of the sample languages that fails the criteria for Type II epenthesis. Stonham (1999) writes that /ʔ/ is epenthesized in certain circumstances, but 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 + u:p + 'atɬ + 'itʃas/→	*[t'i-ʔu:p'-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'u: + aʃt + i:ɬ + 'atɬ/→	*[tɬ'u:-kʷaʃt-i:ɬ-ʔatɬ]* dry-dried-do-NOW 'they dried it now'

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

c	*/ʔaqi + i:ɬ + ħak/→*	*[ʔaqi-tʃi:ɬ-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 fact that /q/ and /ʃ/ epenthesis apply after both vowels and nasals, but before consonants, suggests that these patterns are the residue of loss of the middle consonant of a three consonant sequence. By hypothesis, this consonant deleted in poorly cued environments (after non-sonorants), but was spared otherwise. In fact, it seems as if Nootka might be better described as exhibiting synchronic deletion rather than epenthesis. Stonham does actually offer a rule of /q/ deletion across morpheme boundaries as an alternative, but seems to disprefer it. In any case, such an alternation carries the potential for re-analysis as epenthesis. However, generalization of the /q/ or /ʃ/ patterns such that Type II epenthesis could be inferred would necessitate re-analysis of the suffix as vowel-initial, either by supplying an imagined vowel, or by dropping the initial /ħ/. Since this portion of the suffix does not alter, there does not seem to be sufficient motivation for such a re-analysis.

The /k/ epenthesis facts, on the other hand, may be more susceptible to re-analysis. The fact that this epenthesis occurs post-vocalically in all instances argues against an origin in the loss of suffix material; even if the suffix began with a complex cluster, both consonants would be cued by vowel transitions. However, stem-final segment loss – but only before certain suffixes – could produce the observed pattern.

Assuming that not all synchronically /u/-final stems were diachronically /uk/-final stems a certain amount of generalization must already have occurred. The final necessary stages would require a leveling of the historic difference in deletion contexts such that the /k/ was now deleted from all pre-consonantal contexts. Additionally, the process would need to spread to vowel-initial suffixes that do not currently trigger /k/ epenthesis. At this stage /k/ epenthesis would still only apply /u/-final stems. The fact that /ʔ/ epenthesis holds more generally, independent of vowel identity, could be a bar to further generalization. Conversely, however, /ʔ/ epenthesis may fail to level a sufficiently robust sub-pattern of /k/ epenthesis.

Kodava exhibits a similar system of local predictability. 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 */oodi+ija/→* *[oodi-ja]*
read-2SG.PST
'you read'

/j/ and /v/ epenthesis may have a natural origin, but, by hypothesis, /k/ epenthesis emerged through a more indirect route. /k/ epenthesis occurs after /n/-final stems as well as vowel-final ones. This suggests that /k/ was originally part of a suffix morpheme that deleted in post-consonantal environments, except after nasals: C_2 rather than C_1 loss. What makes a synchronic epenthesis analysis potentially preferable to an analysis of synchronic deletion is the fact that all /a/-initial suffixes, of which there are at least 5, exhibit the same pattern. Either all suffixes were historically /k/-initial, or generalization has occurred based on the shared /a/ vowel.

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). From a system in which the intervocalic segment probably varied by suffix morpheme, generalization to default /k/ is hypothesized to have occurred. This pattern would have to have been robust to avoid leveling by competing generalizations involving glide epenthesis. These competitors, however, are hypothesized to limit further generalization of the /k/-epenthesis contexts.

Both Nootka and Kodava seem to consist of a split pattern of Minimal and Non-Minimal epenthesis. Since they fail to employ a single default epenthetic segment they are characterized as Type I patterns. It has been argued, however, that a certain amount of generalization was necessary to bring about the current alternations in each language. Through examination of the surface forms of both languages, an attempt was made to reconstruct the forms over which generalization would have needed to apply (or to fail to apply). Generalization as defined here refers to replacing a set of historic morphological variants with a single form. A tendency to generalize is a desirable property from the perspective of inducing a Type II epenthesis system. However, from an accuracy perspective it is an undesirable property for a learner. The more a learner generalizes, the less detail they retain, the less true they are to what they have heard.

Although most language learning experiments 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. Many artificial grammar 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 and Thiessen, 2003). On the other hand, it is not possible for learners to process and encode statistics at an arbitrary level of precision, over all possible structures, learning all possible correlations. There is experimental evidence that not all discoverable lexical patterns are productively used by speakers (see Zimmer, 1969; Becker et al. 2011), and typological evidence that not all phonetic precursors have an equal likelihood of being phonologized (Moreton 2008). For structures that are learnable, however, there may be certain factors that lead to less, or more, detailed learning. Learners seem to preserve the relative frequencies of variants in the input (frequency matching) under a wide range of conditions (see Estes, 1972 and references therein). As Hudson Cam and Newport (2005) suggest, however, a highly non-uniform training distribution might be the key to inducing generalization of the most frequent variant (frequency boosting).

Some studies indicate that infants and young children may generalize more readily than adult learners (Singleton, 1989; Newport, 1990; Senghas and 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. 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 alternations involving twenty surface variations of a particular suffix occurring with different base words, with none of them 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, boosting from roughly 21% to 100%.

A breakdown in frequency matching might also be induced by interference from words or paradigms that are similar in ways that are not typically considered to be grammatically relevant. It is well known that similarities of various kinds play 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 associations could blur certain boundaries, allowing alternations to spread. 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 reverse 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)).

Under the hypothesis that the amount of boosting is a function of the relative frequency of the variant, an initial boost will lead to more boosting over time, all else being equal. Generalization, however, may be blocked in certain domains. This was suggested above for the case of Kodava, where the natural process of homorganic glide insertion fails to occur when the suffix morpheme begins with /a/. Conversely, /k/ epenthesis could be said to be blocked from spreading to other contexts in which homorganic glides are predictably epenthesized.

These hypotheses are currently under investigation in experimental work directly linked to the model of this paper. All experiments involve training adult participants on small paradigms of made-up words designed to emulate various stages of the proposed diachronic trajectory from non-epenthesis to epenthesis. Participants do not receive explicit training on an epenthesis pattern; rather they are exposed to word-picture pairs that occur in singular-plural sets. For example, a picture of an apple appears on the computer screen, accompanied by the word [ratu] played over the headphones. Immediately following, a picture of two apples appears, accompanied by the spoken plural form: [ratuwək]. Once training has concluded participants are asked to provide the spoken plural form for novel singular words. See Fig. 3.

Fig. 3 approx here *

The effect of non-uniform distributions of multiple allomorphs has been preliminarily tested within this paradigm (Morley, 2011). Participants were trained on three allomorphs of the plural suffix that were partially predictable, but occurred in unequal numbers. For stems ending in front vowels, 2/3 took the plural suffix -/wək/; and 1/3, the suffix -/ək/. For stems ending in back vowels, 2/3 took the suffix -/ək/; and

1/3, the suffix -/jək/. Additionally, back-vowel final stems occurred twice as frequently as front-vowel final stems. Over all, the suffix -/ək/ was 2.5 times as likely as either of the suffixes -/jək/ or -/wək/. Participant response more or less preserved this distribution for test items that were novel consonant-final stems: darum → darumwək 14%; darumjək 15%; darumək 63% (with the remainder accounted for by "other" responses: errors, ambiguous sounds, or segments unrelated to training).

This same global rate (5:2) was observed for novel front-vowel final stems. However, only one third of front-vowel final stems during training took the -/ək/ allomorph. Thus the results indicate that this allomorph has been boosted to more than twice the expected rate in this context. The local predictability of vowel type is absorbed into the context-free statistics. This is in contrast to conditions in which the allomorphy was completely predictable, and the distribution similarly asymmetric. Under those conditions participant responses matched the local distribution much more closely. The hypothesis is that the fact that allomorphs were only partially predictable by vowel class encouraged learners to over-ride local distributional statistics.

These results provide part of the answer to the question of when learners will regularize input, and are similar to results obtained in work on other phonological domains. Goldrick (2004) trained participants on word-position restricted segment distributions. In one condition /f/ occurred only in onset position, while /v/ occurred equally often in onset and coda. He found that learners merged the distributions of /f/ and /v/ such that both segments were treated as having a 75% probability of occurring in onset position, and a 25% probability of occurring in coda position.

Kapatsinski (2010) taught participants a morphological alternation that mimicked the variable velar palatalization rules in Russian. While stem-final velars palatalized exceptionlessly before the morpheme -/i/, -/i/ also affixed to non-velar final stems. The alternative –/a/ morpheme, on the other hand, never affixed to velar-final stems. He found that in the case where the –/a/ morpheme occurred with 75% of the non-velar final stems, rates of velar palatalization before -/i/ were high. But when the –/i/ morpheme was the one that occurred with 75% of non-velar final stems the rate of velar palatalization was significantly reduced. The sub-pattern of velar palatalization was subject to generalization from non-velars based on the fact that they shared the property of belonging to the class of –/i/ suffixing stems.

Following up on these results, the next set of proposed experiments continues to identify the factors that allow generalization versus those that forbid it. In terms of consonant epenthesis, the vowel-consonant boundary may be more robust than that between vowels of different types (such as front and back). The prediction is that morphemes will not cross this boundary, even if doing so would simplify the paradigm as a whole. An experiment is currently being run with a training distribution that is consistent with an epenthesis alternation. There are two contrasting conditions, predictable:{ratu-jək skibe-wək darum-ək}; and an unpredictable and non-uniform distribution of allomorphs for vowel-final stems, coupled with a consistent vowel-initial allomorph for consonant-final stems: {ratu-tək skibe-kək fi-tʃək vu-pək darum-ək}. An additional condition has been designed with a grammar that is meant to simulate a coexisting Minimal and Non-Minimal pattern of epenthesis, similar to the alternations in Kodava and Nootka. There, the training pattern involves the front glide allomorph occurring after front vowel stems (Minimal), but the Non-Minimal segment [t] occurring after back vowel stems (consonant-final stems are held out): {ratu-tək skibe-jək}. Once the entire set of conditions has been run and analyzed we will be able to more explicitly elaborate the circumstances sufficient to meet conditions (17)-(19).

4e Summary & discussion

This section has presented some 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: Non-Minimal Type II Epenthesis (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 historical 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 itself 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-final and vowel-final 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 (or is otherwise incomplete)

The next step is specifying any unstated properties upon which the above conditions are dependent. Those in (24b) require certain learning outcomes, and certain unknown learning inputs. Section 4d speculated on a number of factors that might enable the axioms in (24b) to hold, and thus allow for the emergence of epenthesis under specific historical circumstances. A set of experiments to test these proposed factors, both completed and in progress, was described. 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. 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.

5 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-assessing the facts, and re-formulating the appropriate representations 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 synchronic grammar: the Axininca-Campa-like epenthesis pattern (see (1)). This outcome was first situated within a larger model capable of producing a range of other epenthesis patterns, as well as deletion, coalescence, and gliding. This allowed a set of synchronic phonological patterns to be linked to a common diachronic source within a single articulatory/perceptual framework. 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 covers considerable ground: following a grammatical pattern from inception to generalization.

The methodology developed in this paper is a sort of rational simulation analysis, systematically discovering the relevant properties of a representative morphological paradigm. This is a set of surface forms, and inferred underlying forms, that mirror the operation of epenthesis. The necessary conditions were found to apply to 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 be present before the sound change occurred (both vowel-final stems and consonant-final), and the distribution of 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 would change is the estimate of the likelihood for any particular synchronic outcome.

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. However, 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 underlying phonetic source. The observation that there is a relationship between coarticulatory variation and sound change is not a new one. 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 same time, these conditions establish which initial states will not lead to the desired final state. Without the right kind of asymmetric distribution of allomorphs, generalization will not occur; without the right set of pre-change forms, sound change will not produce the right kind of asymmetric distribution. These sequential requirements act as filters on synchronic outcomes, and thus provide a source of explanation for the observed typological distribution (e.g., rare Type II systems). It has been claimed that substantive innate constraints are required to explain language universals (Kiparsky, 2004; 2006; de Lacy, 2006; Kingston and de Lacy, 2006). The work in this paper 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.

Additionally, the emergentist approach affords the ability to predict languages that do not conform to posited phonological universals. For example, a proposed implicational hierarchy over place of articulation predicts that velar epenthesis should never arise when less marked segments, such as coronal ones, are available (Prince and Smolensky, 1993/2004; de Lacy, 2006). The reanalyzed typology, however, provides evidence for two velar epenthesis languages, and the model provides a mechanism for them to arise, in exactly the same way as the coronal epenthesis languages. Due to the small set of patterns that was ultimately identified as default epenthesis it was not possible to argue for a bias towards one segment type over another in this environment. However, a bias towards coronal epenthesis would potentially be observable over a larger sample. The model, in fact, suggests a mechanism for such a preference to emerge: higher rates of deletion of coronal segments. This effect could in turn be based in the particular articulatory features of coronal segments (see Jun, 2004).

Rather than incontrovertible absolutes, Universals as characterized by typologists are, in fact, typically couched as tendencies (e.g., Greenberg, 1966; Maddieson, 1984). It is probably more accurate to characterize human languages as demonstrating strong tendencies, or substantive biases (Wilson, 2006). These biases can reside in the learning mechanism (analytic bias), the articulatory and perceptual systems (channel bias), or both (Moreton, 2008). This paper has effectively identified an additional type of channel bias, what could be termed an environmental bottleneck; this results from the interaction between the structure and distribution of the lexical items, and the paradigmatic structure of the language undergoing change. The full set of results of this paper stand, additionally, as a test of the research methodology. I believe 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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Table 1: Typology of Vowel Hiatus Repairs. Adapted from Casali (1997) (with additions).

Type of Repair	Example Alternations		Language
Coalescence	*/fa+i/ → [.fɛɛ.]*	"take it"	Anufo
	take-3SG		
Diphthong Creation	*/izo#ɔkʊ/→[i.zo͡ɔ.kʊ]*	"reed sugarcane"	Ngiti
	reed sugarcane		
Glide Formation	*/gu#ɔba/→[.gwɔ.ba.]*	"weave a mat"	Igede
	weave mat		
Vowel Deletion	*/ɔli#ebe/→[ɔ.le.be]*	"the book"	Emai
	the book		
Syllable Boundary	*/oloena#erxome/→[o.lo.e.na.er.xo.me]*	"I continually come"	Modern Greek
	continually I.come		
Epenthesis (Minimal Seg)	*/ankara+ E/→[ankaraja]*	'to Ankara'	Turkish
	Ankara-DAT		
Conditioned Epenthesis (Minimal Segs)	*/məŋ+gula+i/→[məŋgulaʔi]*	'cause to sweeten'	Malay
	ACT-sweeten-CAUS		
	/bantu+an/→[bantuwan]	'aid, relief'	
	aid-NOM		
	/udʒi+an/→[udʒijan]	'test'	
	test-NOM		

Table 2: Epenthesis taxonomy with examples of each class

	TYPE I	TYPE II
MINIMAL	*Malay*	*Turkish*
NON-MINIMAL	*Odawa Ojibwa*	*Axininca Campa*

Table 3: Type II Epenthesis

Non-Minimal Segments		Minimal Segments	
Seg.	Language	Seg.	Language
t	Cree	ʔ	Selayarese
t	A. Campa	ʔ	Tubatulabal
k	Waropen	ʔ	Misantla Totonac
g	Buryat	j	Turkish
n	Dutch	j	Berber

Table 4: Type I Minimal Segment Epenthesis

Seg.	Language	Seg.	Language
j,w,ʔ	Malay	w,j	Manipuri
j,w,ʔ	Wolof	w,j	Argobba
j,w,ʔ	Guinaang	w,j	Alywarra
j,w,ʔ	Karo Batak	v,j	Kodava
j,w,ʔ	Hausa	ʋ,j	Malayalam
w,j	Balangao	j,ʔ	Ilokano
w,j	Dakota	w,j,h	Cairene Arabic
w,j	Ao	ʋ,j	Dutch

Table 5: C_1 historic loss under suffixation
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		

Table 6: C_2 historic loss under suffixation
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		

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		

Table 8a: Generalization across hypothetical stems – reduction in suffix allomorphy

	After Re-Analysis	After Generalization
Historically Vowel-final	/oru/ + /o/→[oruo]	[oruto]
	/pefi/ + /o/→[pefio]	[pefito]
	/me/ + /o/→[meo]	[meto]
	/gada/ + /o/→[gadao]	[gadato]
	/umu/ + /o/→[umuo]	[umuto]
Historically Coronal-Final	/pami/ + /to/→[pamito]	[pamito]
	/kifu/ + /no/→[kifuno]	[kifuto]
	/ega/ + /no/→[egano]	[egato]
	/femo/ + /to/→[femoto]	[femoto]
	/nagi/ + /to/→[nagito]	[nagito]

Table 8b: Generalization across hypothetical suffix morphemes – reduction in stem allomorphy

	After Re-Analysis	After Generalization
Historically Vowel-final	/oru/ + /o/→[oruo]	[oruto]
	/oru/ + /ina/→[oruina]	[orutina]
	/oru/ + /ub/→[oruub]	[orutub]
	/oru/ + /efe/→[oruefe]	[orutefe]
	/oru/ + /aro/→[oruaro]	[orutaro]

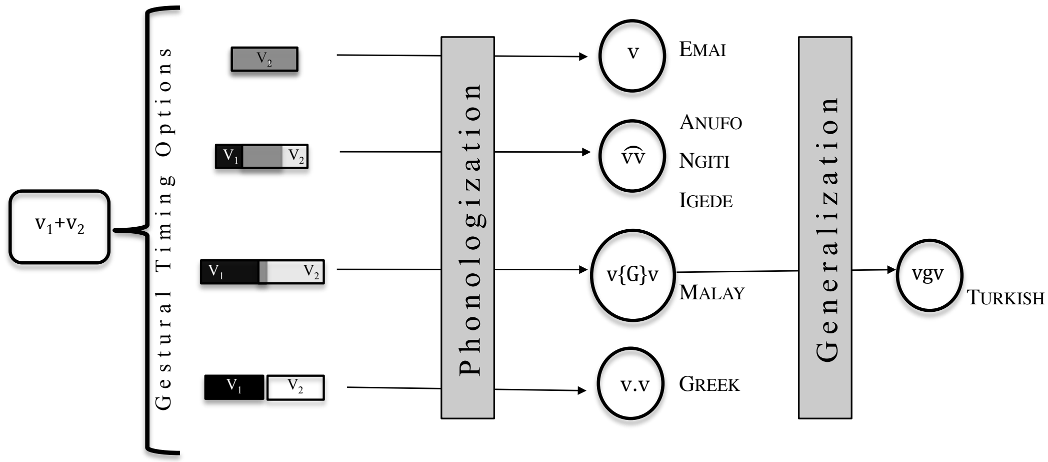


Figure 1

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

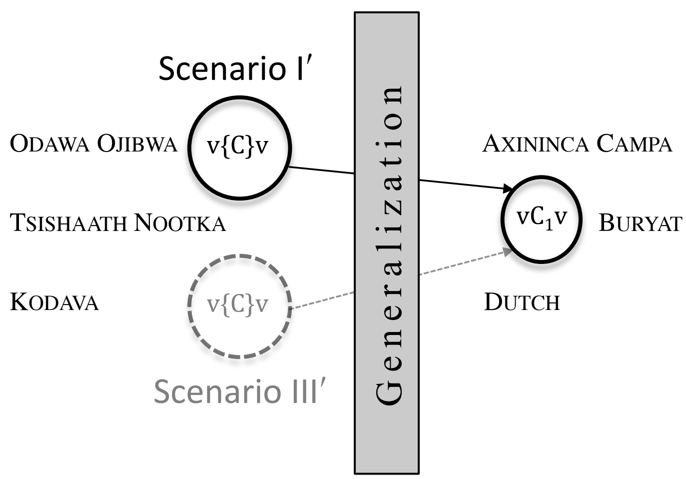


Figure 2

Routes to Non-Minimal Segment Epenthesis: generalization from Scenario I′ or Scenario III′. Dotted gray borders indicate lower likelihood of Scenario III′ route (C_2 deletion).

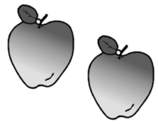
Training		Test	
[ratu]	[ratuwək]	[darum]	???
			

Figure 3
Schematic of training and test conditions for generalization experiments.