Abstract

This paper presents an OT analysis of stop epenthesis, which as well as reflecting the basic pattern of stop insertion can also model the available quantitative data on variability of stop epenthesis and the phonetic difference between epenthetic and underlying stops. However, accounting for these factors requires the introduction of two very powerful mechanisms within OT, absolute ranking with noise added to rankings at evaluation time (Boersma 1998), and allowing the phonetic realization access to the underlying representation. Such a powerful theory may not be desirable, but this need for very powerful mechanisms to model quantitative data is probably not restricted to OT. Using this example, this article examines the relationship between phonetics and phonology in OT.

1. Introduction

Stop epenthesis is an alternation that lies at the interface of phonetics and phonology: there are reasons to consider it a phonological alternation, part of the grammar, but it is clearly articulatorily motivated and closely related to language-specific phonetics. It is also a highly variable alternation, even within speakers, and there is evidence that epenthetic stops are not phonetically equivalent to underlying stops. Furthermore, considerable quantitative data on production of epenthetic stops is available in the past literature. This paper provides an optimality-theoretic (OT) analysis of stop epenthesis that is consistent with the available quantitative data. This leads to investigation of the mechanisms necessary for OT to account for variable, articulatorily based alternations and furthers inquiry into the relationship between phonetics and phonology in OT.
1.1. Stop epenthesis

In many languages, an epenthetic stop can occur within nasal–fricative clusters or heterorganic nasal–stop clusters. Some examples in English, (1a), and Dutch, (1b), appear below (Wetzels 1985; Fourakis and Port 1986; Ohala 1995; Warner and Weber 2001).

(1) a. [dɛmt] ~ [dɛmpt] ‘dreamt’
    [timstɛ] ~ [timpstɛ] ‘teamster’
    [pɛms] ~ [pɛnts] ‘prince’

b. [hɛmt] ~ [hɛmpt] ‘shirt’
    [lɑŋs] ~ [lɑŋks] ‘along’
    [hɑŋt] ~ [hɑŋkt] ‘hangs’

Such epenthesis is often highly variable, even within a single speaker’s productions. In some cases, reanalysis leads to a historical change, as in the development of Modern English empty from Old English emtige (Ohala 1995), but often, there is synchronic variation without such reanalysis, (1). This article is concerned with how such synchronic epenthesis can be modeled in OT.

There are several other environments in which epenthetic stops occur, such as between a nasal and a following liquid (e.g. English thimble from older thumle). Much discussion has centered around the relationship between nasal–liquid and nasal–obstruent epenthesis. Ohala (1995, 1997) relates both types to stop epenthesis in the cluster /ls/, as in else [ɛlts] ~ [ɛls], as well as to epenthesis of a [p] in the cluster /mn/. All of these types involve overlap of adjacent gestures. Lombardi (1998a) discusses an unrelated type, in which a stop is epenthesized between vowels to provide a syllable onset. This article will address only epenthesis in nasal–obstruent clusters, since this type of epenthesis is cross-linguistically common and more quantitative data is available for it than for the other types.

The production of epenthetic stops in a nasal–obstruent environment is clearly based in articulation: during a nasal, the velum is lowered, and there is a complete closure somewhere in the oral cavity. The velum must be closed for the following obstruent. If the velum closes before the oral closure for the nasal is released, that release will produce a stop at the place of articulation of the nasal. Some researchers have proposed different scenarios (Ali et al. 1979), but all accounts involve mistiming of the changes in place, voicing, and velic closure.
1.2. Phonological analyses of stop epenthesis

Despite this articulatory origin, stop epenthesis has often been treated as a phonological phenomenon, in part because epenthesis is language-specific. Fourakis and Port (1986) found that American English speakers epenthesize in 100% of tokens of words ending in /ns/, but South African English speakers never epenthesize in the same environment. Whether to epenthesize, how often, and in which environments, is part of the language-specific knowledge a speaker must have. Furthermore, epenthetic stops can provide the environment for other phonological patterns. Wetzels (1985) points out that, in derivational terms, stop epenthesis feeds the glottalization of coda voiceless stops, although this may apply in British RP but not in American English (Gussenhoven and Jacobs 1998: 131–132). Thus, if one produces a glottalized [t] in prints or cents, one is likely to also produce one in prince or sense, at least in British English.

Researchers have analyzed epenthesis in various derivational theories. Anderson (1976) suggests that epenthetic stops involve the following obstruent’s values of the features [sonorant], [nasal], and [voice] spreading partially into the time domain of the preceding nasal. This timing adjustment, rather than inserting an additional segment, “create[s] a time period of the utterance which belongs partly to one segment, partly to another” (Anderson 1976: 339). Wetzels (1985) proposes an autosegmental version of this approach, in which the [−nasal] and [−voice] feature values of the obstruent spread onto the preceding nasal, creating a contour segment much like a prenasalized stop (i.e. a cluster /ms/ with an epenthetic stop is equivalent to [mps]). Piggott and Singh (1985) analyze consonant epenthesis solely through syllabification rules and view epenthesis as a repair of ill-formed syllable structures. The crucial innovation in their analysis is a rule that moves a sonorant from the coda to the nucleus of a syllable, leaving an empty slot in the coda, which is eventually filled by the epenthetic stop.

Fourakis and Port (1986), in addition to showing that epenthesis is language-specific, also find that epenthetic stops are not phonetically equivalent to underlying voiceless stops: in pairs such as dense (with epenthetic [t]) vs. dents, the [t] is significantly longer and the nasal significantly shorter if the [t] is underlying. Fourakis and Port argue that epenthesis therefore cannot involve the phonological insertion of a stop (a point Anderson [1976] also made, although without quantitative evidence). They suggest a new type of phonological rule to represent such processes that affect timing without affecting the segmental string: phase rules. They propose that these phase rules are language-specific and take
a phonological representation as their input, with gestural timing or gestures as their output. They point out that such rules would be very similar to temporal phonetic-implementation rules in generative phonology.

Clements (1987), in a feature geometry analysis, proposes an oral-cavity node that dominates place features and the feature [continuant], but no other features. He suggests that stop epenthesis involves spreading the oral-cavity node from the nasal to the following obstruent, making the obstruent into a contour segment (which allows for the phonetic differences between epenthetic and underlying stops). This proposal differs from Wetzels’s (1985) in that it spreads features from the nasal onto the obstruent rather than the reverse, thus the contour segment in the /ms/ would be [p全媒体] rather than [mp]. Clements argues that epenthesis must be a phonological rule and cannot be simply a matter of phonetic differences in timing because it feeds coda glottalization, as discussed above. He points out that if epenthesis involved only phonetic-implementation rules, it could not introduce the featural structure necessary to trigger the glottalization rule.

Thus, most previous analyses of epenthesis have treated it as a phonological process of some sort. However, with the introduction of optimality theory, the relationship between phonology and phonetics in linguistic theory has changed. Furthermore, past analyses of stop epenthesis cannot be maintained in OT, for reasons discussed below. The main questions to be addressed in this article are how to model stop epenthesis in OT, and whether an alternation such as stop epenthesis should be modeled in OT, that is, what the phonological status of stop epenthesis is. In the remainder of this paper, I will first present an analysis of a simplified version of stop epenthesis in OT (section 2), without incorporating variability or the phonetic difference. Then I will discuss the implications of introducing variability into the analysis (section 3), and how to model the phonetic difference between epenthetic and underlying stops (section 4). Finally, I will discuss implications for the relationship between phonetics and phonology in the grammar (section 5). The analysis will focus on epenthesis as it appears in Dutch, but it largely holds for at least American and British RP English as well.

2. OT analysis of a simplified stop-epenthesis pattern

Several constraints are necessary in order for the phonology to produce epenthetic stops, in a simplified situation in which epenthetic stops are always produced where the environment for them occurs, and the epenthetic stop is equivalent to an underlying stop. (That is, as a beginning
point, the analysis will reflect a hypothetical system in which both /ns/ and /ŋt/ clusters, for example, are always produced as [nts, ŋkt], and the epenthetic [t, k] are phonetically identical to the [t, k] produced in underlying /nts, ŋkt/ clusters.) There are two possible approaches to this problem, differing in whether the constraints refer to phonetic motivation and in how similar they are to the usual OT analysis of vowel epenthesis.

2.1. *Stop epenthesis as equivalent to vowel epenthesis*

Epenthesis of the sort motivated by syllable structure, such as epenthesis of a vowel to break up a consonant cluster, is generally analyzed in OT as interaction between a markedness constraint against some syllable structure, the constraint DEP, which disfavors epenthesis, and general segmental-markedness constraints (McCarthy and Prince 1995). The highly ranked syllable-structure markedness constraint makes the underlying string of segments impossible, leading to violation of lower-ranked DEP. The general markedness constraints choose the least marked segment as the best one to appear epenthetically.

Stop epenthesis is not motivated by syllable-structure constraints: it results in syllables with more coda consonants than the underlying form has, and it can occur regardless of whether the nasal–obstrictuent cluster is within one syllable or spans a syllable boundary (as in *teamster* in [1a], and cf. Figure 1 below). However, it can be analyzed similarly to syllable-structure-motivated epenthesis, using markedness constraints against the clusters in which epenthesis occurs ([2]–[3]) instead of constraints on syllable structure. These constraints cause violation of DEP, and low-ranked general markedness constraints, (4), select a stop as the segment to epenthese. The constraints against the relevant clusters involve local conjunction (Smolensky 1995; Alderete 1997), such that the conjoined constraints are only violated if both of their component constraints are violated within the consonant cluster.

(2) [*NC & AGR(pl)]
   *NC*: no nasal–voiceless obstruent clusters (Pater 1996)
   AGREE(place): adjacent consonants must have identical values for all place features (abbreviated AGR(pl).) (Lombardi 1998b)
(3) [*NC & *FRIC]*
   *NC*
   *FRICATIVE*: do not have fricatives.
(4) *VOWEL*: do not have vowels.
   *SONORANT*: do not have sonorants.
   *STOP[=vc]*: do not have voiceless stops.
The conjoined constraint in (2) is violated only by heterorganic nasal–voiceless obstruent clusters. The conjoined constraint in (3) is violated by any nasal–voiceless fricative cluster, regardless of place. These separate constraints are necessary because epenthesis occurs in homorganic as well as heterorganic nasal–fricative clusters, but only in heterorganic nasal–s-top clusters.

The constraints in (4), and similar ones for other segment types, are ranked rather low and so are active only in determining which segment appears epenthetically. The constraints in (2)–(4), along with DEP, MAX, and a faithfulness constraint for place IDENT(Pl), interact to produce output forms with epenthesis in the relevant clusters, (5). For convenience of representation in the tableau, all of the markedness constraints against particular classes of segments except *STOP[−vc] are listed as one constraint *SEGMENT.

(5) /zwem-t/ [zwempt] ‘swims’

<table>
<thead>
<tr>
<th>/zwem-t/</th>
<th>[*NC &amp; AGR_(pl)]</th>
<th>IDENT_(pl)</th>
<th>MAX</th>
<th>DEP</th>
<th>*SEGMENT</th>
<th>*STOP[−vc]</th>
</tr>
</thead>
<tbody>
<tr>
<td>a. zwemt</td>
<td>★</td>
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<tr>
<td>b. zwemt</td>
<td>★</td>
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<tr>
<td>c. zwemt</td>
<td>★</td>
<td>★</td>
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<td>d. zwemt</td>
<td>★</td>
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<td></td>
<td>★</td>
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<tr>
<td>e. zwemt</td>
<td>★</td>
<td>★</td>
<td></td>
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<td>★</td>
<td>★</td>
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<tr>
<td>f. zwemt</td>
<td>★</td>
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<td>★</td>
<td>★</td>
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<tr>
<td>g. zwemt</td>
<td>★</td>
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<td>★</td>
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</tbody>
</table>

An output identical to the input (candidate a) is ruled out by the high-ranking conjoined constraint. This violation cannot be solved by place assimilation (candidate b) because of the constraint on identity of place. Deleting either the nasal or the obstruent (c) would violate MAX. Candidates d, e, f all satisfy the conjoined constraint but violate DEP by epenthesizing some segment. Since a voiceless stop is what is epenthesized, the general markedness constraint against voiceless stops must be ranked lower than the constraints against other types of segment. Candidate g demonstrates that the conjoined constraint will choose the correct voiceless stop as the epenthetic segment. Since the optimal form involves epenthesis rather than place assimilation, deletion, or maintaining the marked cluster, DEP must be ranked lower than [*NC & AGR(pl)],
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IDENT(pl), or MAX. This and the ranking of *STOP[−vc] below the markedness constraints against other segment types are the only crucial constraint rankings in the analysis.

For a form with an underlying nasal–voiceless fricative cluster, such as /wëns/ ‘wish’, the conjoined constraint [*NC & *FRIC] is the one that is violated by the maximally faithful form [wëns]. Otherwise, the analysis parallels the one in (5). In this analysis, homorganic nasal–voiceless stop clusters such as /nt/ in /wnt-t/ ‘wnts’ do not result in epenthesis because the form maximally faithful to the underlying form does not violate the conjoined constraint. Although such clusters do violate *NC they do not violate AGREE(place).

This analysis does not require that stop epenthesis be considered as different from vowel epenthesis in any way. This has one apparent problem, however: Dutch also has vowel epenthesis, (6).

(6) /mëlk/ [mëlk ~ mëlök] ‘milk’
/film/ [film ~ film] ‘film’
/wërk/ [wërk ~ wërk] ‘work’

This type of epenthesis occurs in clusters of a liquid followed by a [−coronal] consonant. Clearly, different markedness constraints (not discussed here) are involved in the occurrence of schwa epenthesis. The conflict with the analysis presented above is in the choice of epenthetic segment. If *STOP[−vc] must be ranked lower than markedness constraints against other segment types in order for an /mt/ cluster to gain an epenthetic stop rather than an epenthetic vowel, then why is it a schwa that is epenthesized in the forms in (6)? There may be no reason, aside from stop epenthesis, to think that voiceless stops are the least marked segments of the language. Furthermore, analyzing vowel and stop epenthesis using the same mechanism disguises the fact that stop epenthesis has a clear articulatory origin in overlap of gestures, while schwa epenthesis does not. Epenthetic stops also share features with the surrounding segments, while epenthetic vowels often do not. Thus, it is perhaps not markedness constraints at all that determine the epenthetic segment in stop epenthesis.

2.2. An analysis using constraints on articulations

Stop epenthesis occurs in both heterorganic and homorganic nasal–fricative clusters but only in heterorganic nasal–stop clusters. Articulatorily, this is because an epenthetic stop is created if the velum closes before the oral closure for the nasal has been released. In both parental articulations.
heterorganic nasal–stop clusters, the oral closure for the nasal must be released in order to make the postnasal obstruent. However, in a homorganic nasal–stop cluster, the oral closure for the nasal is not released during the nasal — there is a single release for the NC cluster, and it is the release of the stop.

Thus, a constraint against having a release associated with a nasal, as in (7), could be involved in stop epenthesis. Since the oral closure made during a nasal must be released eventually (at least for speech to continue without massive faithfulness violations), this constraint, when unviolated, has the effect of requiring a nasal to be followed by a homorganic stop. A homorganic nasal–stop cluster such as /mp/ does not violate this constraint, because the nasal has no release independent of the release of the following stop. Since place is very difficult to perceive during a nasal (Ohala 1975), and the burst of a following stop provides stronger place cues, this constraint is phonetically motivated.

(7) *NASALRELEASE: Do not release the oral closure of a nasal consonant (abbreviated *NASREL).

Nasals occur freely before vowels in Dutch, so this constraint is clearly violable. However, a conjoined constraint [*NÇ & *NASREL] would be violated only if the nasal’s oral closure were released during the nasal and there were a following voiceless obstruent. Using this constraint, it is possible for the choice of epenthetic segment to fall not to general markedness constraints that choose the least marked segment of the language, but to the ranking of the separate constraints *NASREL and *NÇ, (8).

(8) /zwem-t/ [zwempt] ‘swims’

<table>
<thead>
<tr>
<th>/zwem-t/</th>
<th>[*NÇ &amp; *NASREL]</th>
<th>IDENT(pl)</th>
<th>MAX</th>
<th>DEP</th>
<th>*NASREL</th>
<th>*NÇ</th>
</tr>
</thead>
<tbody>
<tr>
<td>a. zwemt</td>
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<td>b. zwemt</td>
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<td>c. zwet</td>
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<td>e. zwemat</td>
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<td>f. zwemft</td>
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<td>g. zwemkt</td>
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</table>
This analysis differs from the one above primarily in the mechanism that determines the identity of the epenthetic segment. Here, any epenthetic consonant other than a stop homorganic to the nasal will violate the high-ranking conjoined constraint. An epenthetic vowel fails because the separate constraint *NASREL is ranked higher than the separate constraint *NC. In order for nasals to be able to precede vowels without epenthesis occurring, DEP must be ranked higher than *NASREL, as shown in (9). The constraint ranking shares with the analysis in (5) the ranking of DEP below the conjoined constraint, IDENT(pl), and MAX. Otherwise, the constraints are not crucially ranked.

(9) /bìnən/ [bɪnən] ‘inside’

<table>
<thead>
<tr>
<th>/bìnən/</th>
<th>*[NC &amp; *NASREL]</th>
<th>IDENT(pl)</th>
<th>MAX</th>
<th>DEP</th>
<th>*NASREL</th>
<th>*NC</th>
</tr>
</thead>
<tbody>
<tr>
<td>a. ɛ:].bìnən</td>
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<td>b. bintən</td>
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</table>

This analysis presents no conflict with Dutch vowel epenthesis, because *NC and *NASREL do not affect the liquid–consonant clusters in which vowel epenthesis occurs. Vowel epenthesis depends on the usual interaction of syllable structure constraints, DEP, and general markedness constraints, with the least marked segment epenthesized. Stop epenthesis as analyzed here, however, depends on a constraint barring independent releases for nasals. This analysis also has the advantage over the one in (5) that a single conjoined constraint, *[NC & *NASREL], is sufficient to cause epenthesis in both nasal–stop and nasal–fricative clusters, despite the difference regarding homorganicity. I will adopt this as the basic analysis of stop epenthesis in the following discussion.

2.3. Factorial typology

The constraint ranking above, which leads to epenthesis, holds in Dutch and in American and British English (aside from the issue of variability, discussed below). However, if the conjoined constraint forbidding the relevant clusters were ranked below IDENT(pl), DEP, and MAX, the underlying form would surface without epenthesis. This is the case in South African English, in which Fourakis and Port (1986) find no stop epenthesis. If IDENT(pl) were ranked lower than the conjoined constraint, MAX and DEP, this would result in assimilation in heterorganic NC clusters. This is the case in Japanese. Whether a homorganic nasal–
fricative cluster such as /ns/ in such a language would surface with epenthesis or with the cluster intact would depend on the relative rankings of the conjoined constraint, MAX and DEP.

Finally if MAX were ranked lower than the conjoined constraint, IDENT(pl), and DEP, this would result in deletion of either the nasal or the obstruent in all nasal–fricative or heterorganic nasal–stop clusters. Homorganic nasal–stop clusters would be possible, however. I am not aware of any language with this pattern. Steriade (2001) shows that this type of gap in the factorial typology occurs in a broad range of phonological alternations, and she relates such gaps to perceptibility differences among candidates. Thus, the lack of languages with low-ranked MAX leading to deletion in these clusters is not a problem specific to this analysis.

2.4. Articulatory ease versus perceptibility

Much recent literature in optimality theory suggests that phonology consists of a balance between the speaker’s desire to minimize articulatory effort and the need to be understood (Flemming 1995; Silverman 1996; Kirchner 1997; Flemming i.p., among others). Reduction of articulatory effort is usually considered to include such phenomena as deletion of segments, weakening (reduction of constriction), assimilation that reduces articulatory movement between adjacent segments, or making fewer contrasts along a particular acoustic dimension in a language. The need to be perceived, on the other hand, can be manifested as a tendency to keep surface forms faithful to their underlying forms, to use segments that have acoustically salient qualities, to reach the targets of gestures, or to make sufficient contrasts along a particular dimension in a language.

At first glance, the cross-linguistic data on stop epenthesis seem to be an excellent case of this. If epenthesis is attributed to the speaker failing to coordinate the timing of velic closure and oral release correctly, producing epenthesis might involve less articulatory effort than avoiding it. In order to not epenthesize, the relative timing of two gestures must be coordinated correctly, while a considerable range of “sloppy” gestural timing would lead to epenthesis. Thus, it might seem that American and British English and Dutch have an ease of articulation constraint (i.e. “LAZY” [Kirchner 1997]) ranked higher than a faithfulness constraint. South African English, on the other hand, would have a highly ranked faithfulness constraint, which would have the effect of requiring correct relative timing of the velic and oral gestures. This would be motivated
by a need to keep the surface form similar to the underlying form in order to be perceptible.

However, there are several reasons not to accept this as the basis of an analysis of stop epenthesis. First, there is some evidence that epenthetic stops may actually be a target in speech production rather than simply the result of insufficient control over timing. Fourakis and Port (1986) find that American English speakers produce epenthetic [t] in 100% of tokens with the cluster /ns/, and Warner and Weber (2001) find the same for Dutch speakers for /ns/ within a syllable (see Figure 1 below). (Blankenship [1992] finds much lower rates of epenthesis in /ns/ for American English, but her study is of connected speech and includes /ns/ clusters across word boundaries and with stress after as well as before the cluster, unlike Fourakis and Port’s study.) If epenthesis were produced because these languages place a low priority on accurate timing, one would expect that the velar closure and oral release would sometimes coincide (preventing epenthesis) simply by chance, particularly in careful speech, or that velar closure would sometimes occur after the oral release instead of before it. A distribution in which the mistiming is always in the same direction is an unlikely result of ease of articulation. Thus, epenthesis in /ns/ in American or British English or Dutch occurs not because the phonology allows speakers to be sloppy, but because part of speakers’ language-specific knowledge is that there should be epenthesis in that environment.

Furthermore, stop epenthesis may not provide a good example of a phenomenon that makes articulation easier at the expense of perceptibility. Since place cues during nasals are weak (Ohala 1975), the addition of a homorganic burst may make the place of the nasal more perceptible, particularly in the nasal–heterorganic stop clusters, where the following stop cannot provide much information about the place of the nasal. In sum, epenthesis may neither contribute to ease of articulation nor decrease perceptibility and thus does not stem from the interaction of these factors.

3. Modeling variability: how often is epenthesis produced?

Stop epenthesis is highly variable. Even in languages that show epenthesis in 100% of tokens in some environments, such as American English and Dutch for tautosyllabic /ns/, other environments show considerable variability. All studies that report experimental data on production of epenthetic stops find variability in at least some environments (Barnitz 1974; Ali et al. 1979; Fourakis and Port 1986; Blankenship 1992; Warner and
Ali et al. (1979), for example, report silent gaps indicative of epenthesis in approximately 60% of English tokens with /ns, nʃ, ms, mʃ/ clusters. Figure 1 shows data, partially from Warner and Weber (2001), on production of epenthetic stops in codas and across syllable boundaries in Dutch. This data represents 10–14 nonword items in each condition, produced by two speakers, with two productions from one speaker. See Warner and Weber [2001] for details of methods.) In this study, epenthesis occurred in approximately 60% of /mt/ clusters that cross syllable boundaries and approximately two-thirds of coda /mt, mk/ clusters, with somewhat higher rates still below 100% in /nk, nʃ/ clusters (regardless of syllable structure). This is largely the result of variation within each speaker, not just variation across speakers.

3.1. Approaches to variability in OT: nonranking vs. absolute ranking

Several researchers suggest that variability results from constraints being crucially unranked relative to each other, that is, from the order of constraints in the grammar being only partially fixed (Anttila 1997; Nagy and Reynolds 1997; Anttila and Cho 1998). If two constraints are crucially unranked, it is presumed that in a given production, the actual ranking of these constraints relative to each other is determined randomly. In half of a speaker’s productions, one of these constraints will predominate, and in the other half, the other constraint will predominate. Thus, if candidate A violates one of these constraints, and candidate B the other, and the candidates do not differ in violations of other constraints of the language, then a speaker will produce candidate A half the time and candidate B half the time. If three constraints are crucially unranked relative to each other, and a candidate violates just one of those (while some other candidate violates the other two unranked constraints), it will be the optimal candidate in two-thirds of productions, namely whenever the constraint it violates does not predominate over the other two.

Anttila and Cho (Anttila 1997; Anttila and Cho 1998) analyze corpora of written Finnish for occurrences of the genitive plural morpheme, which is variable for certain classes of nouns. They provide an OT analysis of the phonological factors involved and calculate the percentage of tokens in the corpora that show each variant for each environment. They find that the percentage of occurrence of each variant in the corpus is closely related to the number of constraints that variant violates, and that an analysis using crucially unranked constraints can predict the results. Nagy and Reynolds (1997) reach similar conclusions for the variable phenomenon of final deletion in Faetar.
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Key:
- ■ Speaker 1a
- □ Speaker 1b
- □ Speaker 2
- ■ two productions by the same speaker

A: word-final clusters (e.g. /zymk/)
B: cluster crosses a syllable boundary (e.g. /zymkæn/)

Figure 1. Proportion of items in which speakers produced an epenthetic stop, by speaker and cluster
In contrast to this approach, Boersma (1998) proposes that all constraints are ranked, but ranking is absolute rather than relative. Thus, the grammar includes knowledge about how much higher one constraint is ranked than another, unlike standard OT. Furthermore, Boersma suggests that noise is added to the ranking values at evaluation time. This means that if two constraints are ranked close to each other, the lower-ranked one may sometimes become more highly ranked than the higher-ranked one for the purposes of a particular production. This way of handling variation is more powerful than crucial nonranking. Since constraints may be ranked any distance from each other, a particular constraint can be predicted to dominate another constraint in any proportion of productions. In a crucial nonranking analysis, however, if only two constraints are involved, the only possible variable outcome is 50% production of each candidate, and if three constraints are involved, a candidate can only appear in one-sixth, one-third, half, or two-thirds of productions. Finer predictions require larger numbers of crucially unranked constraints, with a particular pattern of violations.

3.2. A nonranking analysis of epenthesis

The crucial nonranking approach (Anttila 1997; Nagy and Reynolds 1997; Anttila and Cho 1998) cannot model the facts of stop epenthesis successfully. In heterorganic nasal–voiceless stop clusters in Dutch or American English, one finds epenthesis, maintenance of the marked cluster, or perhaps place assimilation, especially in fast speech (Ali et al. 1979; Warner and Weber 2001). In the analysis exemplified in (8) above for the word /zwêmt/ ‘swims’, the candidate with epenthesis ([zwêmpt]) violates the constraint DEP, the candidate with no change to the cluster ([zwêmt]) violates the conjoined constraint [*NC & *NASREL], and the candidate with place assimilation the constraint IDENT(pl). None of these candidates violates more than one of these constraints. If all three of these constraints are crucially unranked relative to each other, these three candidates would each appear in one-third of productions, as shown in (10).

(10) Possible outcome rankings of crucially unranked constraints

<table>
<thead>
<tr>
<th>Ranking</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>[*NC &amp; *NASREL] &gt; IDENT &gt; DEP</td>
<td>epenthesis</td>
</tr>
<tr>
<td>[*NC &amp; *NASREL] &gt; DEP &gt; IDENT</td>
<td>assimilation</td>
</tr>
<tr>
<td>IDENT &gt; [*NC &amp; *NASREL] &gt; DEP</td>
<td>epenthesis</td>
</tr>
<tr>
<td>IDENT &gt; DEP &gt; [*NC &amp; *NASREL]</td>
<td>cluster maintained</td>
</tr>
<tr>
<td>DEP &gt; [*NC &amp; *NASREL] &gt; IDENT</td>
<td>assimilation</td>
</tr>
<tr>
<td>DEP &gt; IDENT &gt; [*NC &amp; *NASREL]</td>
<td>cluster maintained</td>
</tr>
</tbody>
</table>
If assimilation never occurs in clusters in the relevant environment, with all productions showing either epenthesis or no change to the cluster, one could conclude that IDENT(pl) is crucially ranked above the other two constraints, with those two crucially unranked relative to each other. This would produce 50% tokens with epenthesis and 50% with the cluster intact.

Neither of these situations is what we find in stop epenthesis. Although data on the frequency of place assimilation versus epenthesis versus maintenance of heterorganic clusters may not be available, none of the experimental studies on epenthesis report widespread place assimilation. In the /nf/ test words Ali et al. (1979) used, such as infant and gunfire, place assimilation is probably dependent on speaking rate. In the /ms/ words, such as Tecumseh, hamstring, and room service, place assimilation is unlikely at any speech rate. Warner and Weber (2001) report a very low rate of ambiguous or assimilated nasals, but since their speakers were instructed not to assimilate nasal place, this is not conclusive.

If there is little or no assimilation in such clusters in careful speech, then crucially unranked constraints would predict 50% occurrence of epenthesis. However, as discussed above, in clusters that have epenthesis frequently but less often than 100%, rates of epenthesis range from approximately 60% to 95% depending on the cluster (Ali et al. 1979; Warner and Weber 2001). Other clusters have rates of epenthesis less than 50%, but few of the clusters are near 50% (only /mk/ crossing a syllable boundary in the data in Figure 1). In order for a nonranking analysis to produce, for example, 60% epenthesis and 40% maintenance of the cluster (the overall average for clusters crossing a syllable boundary in Figure 1), there would have to be five crucially unranked constraints involved, with one candidate violating two constraints and the other violating the other three constraints. However, only two constraints ([*NC˚ & *NASREL] and DEP) are involved in the choice between epenthesis and maintenance of the cluster. Even if other constraints, not actively involved in epenthesis, were included in the group of crucially unranked constraints, as shown in (11), the proportion of productions with epenthesis would remain at half.

(11) Random ranking of three constraints:
C3 is a constraint that is not violated by the form either with or without epenthesis

<table>
<thead>
<tr>
<th>Ranking</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>[*NC˚ &amp; *NASREL] &gt; DEP &gt; C3</td>
<td>epenthesis</td>
</tr>
<tr>
<td>[*NC˚ &amp; *NASREL] &gt; C3 &gt; DEP</td>
<td>epenthesis</td>
</tr>
<tr>
<td>C3 &gt; [*NC˚ &amp; *NASREL] &gt; DEP</td>
<td>epenthesis</td>
</tr>
</tbody>
</table>
C3 > DEP > [*NC & *NASREL] cluster maintained
DEP > [*NC & *NASREL] > C3 cluster maintained
DEP > C3 > [*NC & *NASREL] cluster maintained

The same holds true if the additional constraint C3 is violated by both surfacing candidates. Thus, in order to generate approximately 40% maintenance of the cluster and 60% epenthesis, one would have to include three more constraints with a particular pattern of violations in the crucially nonranked group with the conjoined constraint and DEP. To generate most other proportions (e.g. 70% epenthesis), even more additional constraints would be necessary. The separate constraints *NASALRELEASE and *NC cannot be crucially nonranked along with the conjoined constraint and DEP, because they must be ranked below DEP (as argued above). Presumably, including any other constraints unrelated to epenthesis that happen to have the necessary pattern of violations in the group of unranked constraints would have undesired side-effects on the grammar. Anttila (1997) suggests that when observed percentages of variants produced do not closely match percentages predicted by a nonranking analysis, a more careful grammar with more constraints in the nonranked group might solve the problem. However, finding appropriate additional constraints to add to the nonranked group is not a trivial matter.

Variability across consonant clusters presents an additional problem. All of the previous studies that report quantitative data on epenthetic-stop production find that epenthesis is more frequent in some clusters than others, and most find this even if clusters with 100% or 0% epenthesis are excluded. The constraint [*NC & *NASALRELEASE] should perhaps be split into several more specific constraints, each applying to particular environments, such as nasal–fricative clusters vs. nasal–stop clusters. However, a given form without epenthesis would violate only one of these subconstraints, so no crucial nonranking analysis could produce more epenthesis in nasal–fricative than nasal–stop clusters. Fifty percent epenthesis would still be predicted for both environments.

3.3. An absolute ranking analysis of epenthesis

Using Boersma’s (1998) approach to variability, the data on epenthesis are more tractable. The pattern found for many clusters in American English and Dutch is that place assimilation in the relevant clusters is rare or nonexistent, and the clusters are produced more often with epenthesis than without it. This indicates that IDENT(pl) and MAX are
ranked considerably higher than the conjoined constraint [\textasteriskcentered NC \& *NASALRELEASE], which is ranked only slightly higher than DEP, which is ranked considerably higher than the separate constraints *NASALRELEASE and *NC. Adding noise to the constraint rankings will sometimes give DEP a higher outcome ranking than the conjoined constraint, leading to preservation of the marked cluster rather than epenthesis.

In Boersma’s (1998) theory, constraints have an initial ranking on an absolute but arbitrary scale (perhaps from 1 to 100). A parameter “ranking spreading” determines the amount of noise added to the rankings. Using initial rankings of 52 for the conjoined constraint and 50 for DEP, and a ranking spreading value of 2 (as Boersma uses), DEP will have an outcome ranking higher than the conjoined constraint in 24% of productions. (See Boersma [1998] for how this is calculated.) For an environment in which epenthesis occurs in 76% of productions, this would be the appropriate outcome. Initial rankings of 51 and 50 would give epenthesis in 64% of tokens. Unlike in the nonranking approaches (Anttila 1997; Nagy and Reynolds 1997; Anttila and Cho 1998), if finer discrimination is necessary to provide a match with observed frequencies, only the precision of the scale for absolute ranks, or the value of ranking spreading, need be altered. For example, initial rankings of 50.717 for the conjoined constraint and 50 for DEP would produce 60.006% epenthesis and 39.994% maintenance of the cluster.

In a language with occasional place assimilation as well as frequent epenthesis and less frequent maintenance of the cluster, the IDENT(pl) constraint, the conjoined constraint, and DEP would all have initial rankings not far from each other on the absolute scale. In order for assimilation to be the least common outcome, IDENT(pl) must be ranked the highest of the three constraints and must be further separated from the conjoined constraint and DEP than those two are from each other. Initial rankings of 53 for IDENT(pl), 50 for the conjoined constraint, and 49 for DEP (still with a value of 2 for ranking spreading) produce 61.8% tokens with epenthesis, 34.7% tokens with maintenance of the cluster, and 3.5% assimilation.9 Other constraints (MAX, *NASALRELEASE, *NC) must be ranked far enough above or below these three constraints for ranking reversals to be extremely rare. (Boersma [1998] points out that a separation of 8 between two constraints’ initial rankings will result in a reversal in only 0.2% of productions, and that variants produced this rarely can be considered speech errors.)

The differences in frequency of epenthesis by environment can be analyzed in this system as well, by splitting the conjoined constraint into
subconstraints, as discussed above. For example, Warner and Weber (2001) find that epenthesis occurs very often in nasal–fricative coda clusters, but only in a majority of tokens with most nasal–stop coda clusters, as shown in Figure 1 above. This indicates that the constraint [*NC_{fric} & *NASALRELEASE] (ruling out a nasal being released before a voiceless fricative) is ranked somewhat higher than the constraint [*NC_{stop} & *NASALRELEASE] (ruling out a nasal being released before a voiceless stop). The latter is itself ranked only slightly higher than DEP. Thus, DEP often obtains an outcome ranking higher than [*NC_{stop} & *NASALRELEASE], leading to maintenance of the nasal–stop cluster, but rarely obtains an outcome ranking higher than [*NC_{fric} & *NASALRELEASE].

Warner and Weber (2001) find that epenthesis is more likely if the nasal–obstruent cluster is within a syllable than if it spans a syllable boundary (average of 69% epenthesis in codas and 60% across syllable boundaries, Figure 1). Splitting the conjoined constraint into a higher-ranked version that targets only marked clusters within the syllable and a general version that prohibits the marked cluster anywhere, with DEP ranked in between the two, would give this result. In most cases, the general conjoined constraint would have an outcome ranking lower than DEP, but the syllable-specific version would have an outcome higher than DEP, so epenthesis would occur only for tautosyllabic clusters. However, when the general conjoined constraint gained an outcome ranking higher than DEP, epenthesis would occur regardless of syllable structure, and when DEP gained an outcome ranking higher than both versions of the conjoined constraint, epenthesis would occur in neither environment. Differences in the frequency with which epenthesis occurs in particular clusters could be modeled in a similar way. This would involve multiplying the number of versions of the conjoined constraint but would not introduce any new mechanisms to the theory.

This analysis demonstrates that constraints may be crucially ranked relative to each other in this type of analysis of variability, even though the same constraints would not be crucially ranked if variability were not accounted for. For example, if epenthesis occurs in 100% of tokens with the relevant environment, it is impossible to determine the relative ranking of IDENT(pl), MAX, and [*NC & *NASALRELEASE], since the low ranking of DEP determines the outcome. However, if epenthesis occurs in a majority of tokens, the marked cluster is maintained in some tokens, and place assimilation occurs occasionally, the ranking of all three constraints relative to each other, as well as relative to DEP, is crucial. Thus, the additional information about frequency of outcomes requires more specification in the grammar. The nonranking approaches
4. Phonetic difference between epenthetic and underlying stops

As discussed in section 1.2 above, Fourakis and Port (1986) show that durations of segments in words such as dense [dents] with epenthesis are not the same as in dents [dents] with underlying /t/. A simple generative-phonological approach to stop epenthesis would involve inserting the appropriate stop into nasal–obstruent clusters, obliterating the phonetic difference between epenthetic and underlying stops. One issue in earlier phonological literature on epenthesis is how to represent the insertion of something that sounds much like a stop but is not phonetically equal to the normal stops of the language.

4.1. Contour-segment approaches

The most common solution to this problem in the literature is to represent epenthesis as changing either the nasal or the following obstruent into a contour segment, rather than inserting an additional segment, as discussed in section 1.2 above. These analyses, however, cannot be maintained in OT. Introducing a contour segment (either [m_p] or [p_s] for epenthesis in an /ms/ cluster) would involve ranking constraints against such segments (i.e. *PRENASALIZED STOP for [m_p]) relatively low. In languages such as English and Dutch that do not have such segments aside from epenthesis, these constraints would normally be ranked very high, preventing such segments from ever surfacing in the language. However, if these constraints were ranked lower in the grammar, such segments might then appear in the language in other environments, aside from epenthesis, as well. Under the principle of richness of the base, such segments could be in the underlying representation and would then surface if these constraints were not ranked very high. This was not a problem in the derivational contour-segment accounts, since deriving a new type of segment in a derivational analysis does not imply that underlying forms could contain that segment.

There are two other reasons to reject the contour-segment account, neither specific to OT. First, while prenasalized stops are a known segment type in the world’s languages, heterorganic affricate-like contour segments, such as the [p_s] of Clements’s (1987) account, are not widely
known as a type of single segment. Furthermore, when listeners reanalyze epenthetic stops, leading to historical change, they always reanalyze them as stops, not as contour segments (Ohala 1995, 1997). Stop epenthesis in a nasal–obstruent environment does not seem to lead historically to the introduction of prenasalized stops or other contour segments, although it is in general possible for perceptually motivated historical change to introduce new segments to a language (Ohala i.p.).

4.2. A correspondence solution

The contour-segment approach solves the problem of phonetic difference between epenthetic and underlying stops by introducing a different type of segment to the language, so that epenthetic stops are not actually the same segment as underlying stops. This avoids direct reference to the underlying representation in determining the phonetic realization of a stop. In OT, the introduction of new segment types may be undesirable, but reference to the underlying representation is less difficult, since OT is nonderivational. One way to maintain the phonetic difference in OT would be to allow the phonetic-realization component of the language access to information about the underlying representation. One aspect of knowledge in the phonetic realization component, which might be language-specific, would be a stipulation that stops with a correspondent in the input are longer and have louder bursts than stops without an input correspondent. Nasals before stops with an input correspondent are shorter than nasals before stops without an input correspondent.

This method extends the usual mechanisms of correspondence theory (input–output correspondence, output–output correspondence, etc.), allowing the input–output correspondence mapping to influence the phonetic interpretation of the output. This proposal would expand the power of the theory, perhaps undesirably much. However, it makes use of facts about standard OT theory, namely the preservation of input information at all levels of phonology.

This addition removes the last obstacle to modeling the data on epenthetic stops in OT. The basic pattern, variability in production, and the phonetic difference between epenthetic and underlying stops can all be handled in an OT analysis. Most past phonological work on stop epenthesis has treated the phenomenon as part of the phonology of a language, usually involving contour segments. The OT analysis given here treats stop epenthesis as purely phonological (although phonetically motivated through the *NASALRELEASE constraint), without the use
of contour segments. In the next section, I will discuss the relationship of epenthesis to phonetics, and whether such an analysis is ideal.

5. Epenthesis and the phonetics–phonology interface

In classic generative phonology and modified versions of it, there is a phonological component of the grammar, and possibly a language-specific phonetic component of the grammar, followed by phonetic implementation rules (Pierrehumbert 1994). Within optimality theory, there have been several approaches to the relationship between phonetic and phonological aspects of language production. The approach most similar to the generative phonological model would involve a phonological component, modeled in OT, and a phonetic component, including some language-specific knowledge, which could be modeled through rewrite rules (Pierrehumbert 1994), or through some type of “windows” within which realizations fall (Cohn 1998). Some recent work in OT includes all variation in sounds in a single component, obliterating the distinction between phonology and phonetics (Flemming 1995; Kirchner 1997; Flemming i.p.). For example, Flemming (i.p.) proposes that similar phonetic and phonological processes, such as coarticulation and assimilation, can be modeled in the same grammar, both using constraints that are evaluated quantitatively. The major difference between this proposal and more usual OT phonology is that violations of all constraints are weighted and summed to give a total cost for a given surface form, rather than higher-ranking constraints having complete precedence over lower-ranking ones.

Gussenhoven (1998) explores such a merger of phonetics and phonology for intonation but rejects it. He shows that certain tonal and intonational phenomena can be analyzed through a combination of phonological constraints (e.g. constraints requiring a tone to be associated with the stressed syllable) and phonetic constraints (specifying in milliseconds how long it takes for pitch to rise, for example). Violations of the latter constraints are measured in milliseconds, not number of violations. Both phonetic and phonological constraints are included in the same grammar and are ranked relative to each other. As for epenthesis, if one adopts this style of OT, the question becomes whether stop epenthesis occurs because of a markedness constraint such as [\(\ast \text{NC} \& \ast \text{NASALRELEASE}\)] or because of a constraint requiring a certain relative timing of velic closure and oral release in milliseconds. Gussenhoven concludes, however, that this mixture of phonetic and phonological constraints in the same component of the grammar is not a legitimate
approach to the relationship of phonetics and phonology. Rather, he proposes separate phonological and phonetic components of the grammar, and that the phonetic component may involve “tolerance windows” instead of constraint violation (similar to Cohn’s [1998] suggestion).

If a division into phonological and phonetic components is accepted, the literature offers several criteria for determining whether a particular phenomenon is phonological or phonetic. However, many of these criteria, such as language specificity, have been rejected. (Many authors [e.g. Kingston and Diehl 1994] have shown that some clearly phonetic aspects of the speech signal are language-specific.) Some authors suggest that only phonetic processes are variable (Myers 1995), but the data on variability in Finnish morphophonology (Anttila 1997; Anttila and Cho 1998) clearly contradict this. Many authors claim that phonology is categorical while phonetics is gradient. However, many phenomena are unclear in this regard: the alternation between dark and light /l/ in English would seem to be categorical and phonological, but Sproat and Fujimura (1993) show that it is gradient, and conditioned by strength of prosodic boundary as well as syllable position. Myers (1995: 129) suggests that “a phonological pattern is a pattern in the distribution of phonetic targets in a language, while a phonetic pattern is a pattern in the ranges of realizations associated with a target.” In practice, though, it is often unclear whether variation in articulations constitutes separate “targets” or not.

Perhaps the best criterion is that phonological phenomena manipulate symbols, while phonetic phenomena manipulate articulations or acoustic targets. Cohn (1998) refers to this criterion and mentions the “vocabulary” phonological versus phonetic alternations use. There are certainly phenomena in speech that manipulate only symbols, such as most morphophonological patterns. There are also aspects of speech that manipulate only articulations or acoustic targets — how long the VOT for a particular aspirated stop in a particular language should be, or how long a transition between segments should take, for example.

However, relatively few phenomena can be definitively classified as one or the other of these types. Phenomena that, in the terms of lexical phonology, are structure-preserving clearly manipulate only symbols. (Flemming [i.p.] also mentions this criterion.) If a sound P₁ is replaced with another, P₂, which also exists in underlying representations in the language, and the resulting sound P₂ behaves in all ways like instances of P₁ that are present in the underlying representation, then this phonological alternation must manipulate the symbols P₁ and P₂ rather than their articulations. Otherwise, there would be no reason for the P₂ that arises through this alternation and the P₂ that is underlingly present to be
identical. If this condition is not met, though, it is difficult to say whether an alternation involves symbols or articulations. Flapping in English could be described as the categorical substitution of the symbol “flap” for the symbol “alveolar stop.” However, it could also be described as a reduction in duration of oral closure (and failure to cease voicing because of the briefness of the closure), leading to the characteristic flap articulation. Since “postlexical” phonological processes are included in the phonological component in OT, the problem of what is “postlexical” but phonological and what is phonetic remains.

Stop epenthesis is one of the phenomena that could be described in either symbolic or articulatory/acoustic terms. One of the major reasons in the literature for considering epenthesis to be part of the phonology of a language has been glottalization of epenthetic stops (Clements 1987). Although there is no experimental evidence, it is claimed that speakers who glottalize in words like prints also glottalize in words like prince (at least in British RP, but perhaps not in American English [Gussenhoven and Jacobs 1998]). If stop epenthesis manipulates only articulations and not symbols, then the environment for glottalization, at least in British RP, would have to refer to articulations. One might state that glottalization occurs during a vowel or sonorant before a period of velic closure that temporally coincides with an oral closure and a lack of voicing. This would include both underlying and epenthetic stops. However, this simultaneous velic and oral closure must also be in the coda of a syllable. Although many types of phonetic variation are conditioned by syllable structure, if the epenthetic stop does not exist as a symbolic unit, it is difficult to see how it can be in a coda or not.

Thus, the interaction with glottalization provides at least one reason why stop epenthesis should be considered phonological, at least in some dialects of English. Another reason is theory-internal: since some work in OT does not distinguish between phonetic and phonological patterns and uses the same mechanisms to model all variation in sounds, it is useful to determine whether it is even possible to model stop epenthesis within the OT phonology. Here, I have shown that this is indeed possible. Representing a simplified version of epenthesis, in which epenthesis occurs wherever its environment is present, and epenthetic stops are identical to underlying stops (section 2.2), requires no mechanisms beyond the usual in OT. However, when the available quantitative data on production of epenthesis are taken into account, one must introduce two rather powerful mechanisms into OT in order to model the data accurately. The variability in production of epenthesis, since it tends to involve proportions other than 50% epenthesis and critically uses only two constraints in the choice between variants that do surface, requires the use of Boersma’s (1998)
powerful absolute-ranking method. Furthermore, since OT cannot allow a contour-segment analysis of epenthetic stops, modeling the durational differences between epenthetic and underlying stops requires the introduction of a very powerful mechanism, namely allowing the phonetic realization direct access to information about the underlying form. If these additions make OT into an excessively powerful theory, then perhaps stop epenthesis should be relegated to a separate phonetic component of the grammar after all. Since stop epenthesis clearly originates in overlap of articulatory gestures, this would not be a surprising move. Although this would involve a departure from the previous literature modeling epenthesis as phonological, the only major problem to solve would be the interaction of epenthesis and glottalization in British RP.

However, the problem may be more general: if more quantitative data on variability, gradience, and phonetic differences among sounds are taken into consideration in phonological analyses, the problems encountered in accurately representing stop epenthesis within the phonology are likely to appear in other phonological alternations as well. Recent research has shown that variability and gradience, both in phonetic realizations of variants and in the percentage of productions of categorically different variants, are far more widespread than traditional phonology has acknowledged (Sproat and Fujimura 1993; Pierrehumbert 1994; Guy 1997). If quantitative data on phonological or phonetic alternations is to be accurately modeled by OT, such powerful mechanisms as those discussed here will also be necessary for many cases other than stop epenthesis. That is, modeling quantitative data will make OT into an excessively powerful theory. Although this could be viewed as a shortcoming of the theory, it is likely that the same problem would apply to other formal theories of phonology as well.

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Notes

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The phonology of epenthetic stops

University of Arizona, P.O. Box 210028, Tucson, AZ 95721-0028, USA: E-mail: nwarner@email.arizona.edu.

1. This article is concerned only with the synchronic variety of epenthetic stops, (1), which have not been reanalyzed as part of the underlying representation, as the originally epenthetic /p/ in “empty” has. Discussion in the paper of whether epenthetic stops are phonological or not refers to whether they are inserted by the phonology, rather than the phonetics, of the language, not to whether they have been reanalyzed as in “empty.”

2. The picture regarding nasal place assimilation versus epenthesis in Dutch is actually more complicated. Within a syllable, heterorganic consonant clusters are impossible, but coronals may appear in a syllable appendix (i.e. /hem/ ‘shirt’ but */hemk/). Within a morpheme, heterorganic clusters except those ending in coronals are quite rare, even across a syllable boundary (Booij 1995). A few do exist, as in /imker/ ‘beekeeper’. To account for the fact that heterorganic clusters not ending in a coronal and not crossing a morpheme boundary are likely to show assimilation rather than epenthes, it may be necessary to split the IDENT(pl) constraint into two subconstraints, a higher-ranked one applying at morpheme boundaries and a lower-ranked general one. However, the interaction of these constraints with the syllable-structure constraints necessary to allow heterorganic clusters only if they end in coronals is beyond the scope of this paper.

3. And also /rn/.

4. Although Carlos Gussenhoven reports a case in which it appeared to be inviolable in child speech (personal communication).

5. Fourakis and Port (1986) investigate a limited range of nasal–obstruent epenthesis environments, but one can assume that a language with no epenthesis in /ns/ clusters, which they did test, is unlikely to have epenthesis in other environments, since epenthes is more common in /ns/ than in most other clusters in languages that do have epenthesis.

6. However, since epenthetic-stop bursts are often rather weak (Ali et al. 1979; Fourakis and Port 1986; Warner and Weber 2001), it may be that they do not contribute much place information. The relative contributions of the nasal and the epenthetic burst to place perception have not been tested.

7. Only the data on word-final clusters (that in Figure 1a) appears in Warner and Weber (2001), but the methodology described there also applies to the medial clusters (Figure 1b), which data was collected in an extension of that study.

8. With three unranked constraints, there are six possible rankings. A given candidate can win in 0, 1, 2, 3, 4, or 6 of these rankings, thus in 1/6, 2/6, 3/6, or 4/6 of productions (as well as the nonvariable patterns of all or no productions). No combination of violations leads to a single candidate winning in exactly 5 of the 6 rankings. It is also possible for constraint A to be invariably ranked above B, while the relationship of C to both A and B is variable. However, this does not lead to any additional possible outcomes.

9. These percentages were determined from the outcomes of 1,000,000 random trials, using the “Praat” software program. The actual probability of one constraint having the lowest outcome ranking of three, given particular original rankings, is not currently known (Boersma, personal communication). However, 1,000,000 trials should be sufficient to provide an accurate estimate.

10. Pierrehumbert (1994) shows that instrumentally detectable glottalization (of underlying, not epenthetic stops), at least in the absence of a falling intonation contour, is not as widespread as it is generally thought to be. Thus, an instrumental study of glottalization might fail to support the contention that epenthetic stops cause it.
However, since no experimental evidence is available, I will assume that previous auditory observations of glottalization before epenthetic stops are correct.

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The phonology of epenthetic stops


