Gaps in factorial typology: The case of voicing in consonant clusters

Scott Myers

University of Texas at Austin

Mar. 2002

s.myers@mail.utexas.edu

Abstract

In many languages, a voiceless obstruent cannot occur after a nasal. In some languages such a sequence is avoided through voicing assimilation, but in others through deletion of the nasal or of the obstruent, or changing the nasal into an oral stop. This variety of responses can be expressed in OT through different constraint rankings. Other ways of avoiding such a sequence, such as epenthesis or metathesis, are not attested. These patterns correspond to rankings that are unattested.

It is shown that such gaps in factorial typology are pervasive, and cannot be addressed through ad hoc revisions of the constraints or representations. It is argued that the attested rankings correspond to patterns that arise through simple sound changes from phonetic patterns, while the unattested rankings cannot have such an origin. This approach suggests phonetics influences not only markedness in phonology, but also constraint ranking.

One of the attractive properties of Optimality Theory is that it provides a simple expression of the fact that the same configuration can be avoided in different ways and to different extents in different languages. The avoided configuration violates some markedness constraint(s), and each way of avoiding it violates some faithfulness constraint. Different rankings of these constraints yield different ways of avoiding the marked configuration, as well as the case in which the marked structure is allowed. These different results can be displayed in a **factorial typology**, in which each possible ranking of the relevant set of constraints is shown to be attested in some language.

This paper is concerned with the problem of gaps in factorial typologies. It is argued that while there is often more than one attested ways of avoiding a marked configuration, it is hardly ever the case that every way of avoiding the configuration is attested. Thus given a markedness constraint and the set of all conflicting faithfulness constraints, it is the norm for some of the possible rankings to be unattested.

It will be argued that there is no formal problem with the unattested rankings, but that the patterns they represent are unlikely to arise diachronically from phonetic patterns. The attested rankings, on the other hand, correspond to simple perceptually-based sound changes. Thus gaps in factorial typology do not constitute a problem for the formal theory of OT, but rather represent a manageable challenge for the theory of phonologization (Hyman 1976, Ohala 1993).

1. Examples of gaps

Pater (1999) provides a particularly clear demonstration of the usefulness of factorial typology in his discussion of the avoidance of the sequence of a nasal followed by a voiceless obstruent. Such a cluster is forbidden in a wide variety of languages. The most common way in which it is avoided is **voicing assimilation**, changing the voicing of the post-nasal obstruent to match that of the nasal. Pater notes, for example, that in the Puyo Pungo dialect of Quechua, an obstruent after a nasal in another morpheme must be voiced (Orr 1962). An obstruent that in other contexts is voiceless is realized as voiced when it occurs after a nasal, as in the genitive *–pa* ~ *-ba*:

(1) sinik-**p**a "porcupine's" kam-**b**a "yours" hatum-**b**a "the big one's"

A nasal followed by a voiceless obstruent can occur within a morpheme, however, as in *ʃiŋki* "soot". The same pattern holds in <u>Zoque</u> (Wonderly 1951: 120). In other languages, the restriction holds within morphemes as well as in derived forms: <u>Tarascan</u> (Friedrich 1975: 62), <u>Wembawemba</u> (Hercus 1986: 8), <u>Modern Greek</u> (Joseph and Philippaki-Warburton 1987: 230-231), <u>Arusa</u> (Levergood 1987: 12, <u>Japanese</u> (Itô. Mester and Padgett 1995: 575), <u>Kikuyu</u> (Clements 1985: 244), <u>Kimatuumbi</u> (Odden 1996: 91), <u>Mwera</u> (Harries 1950: 6-11), and <u>Yao</u> (stops only: Ngunga 2000: 60-61).

Such a pattern is easily expressed through constraint ranking. Pater (1999) posits the markedness constraint ***NC̥** in (2), which penalizes the avoided configuration. The faithfulness constraints in (3), based on those of McCarthy and Prince (1995), reflect different ways in which such a configuration could be avoided. The IDENT constraints are stated in terms of feature classes, following Padgett (1995).

(2) *NC̥: A nasal cannot be followed by a voiceless obstruent.

(3) (a) IDENT-LAR: If an output segment has an input correspondent, the two must agree in all laryngeal feature specifications (i.e. [voice], [spread glottis], [constricted glottis]).

(b) IDENT-NASAL: If an output segment has an input correspondent, the two must agree in [nasal].

(c) IDENT-MAJOR: If an output segment has an input correspondent, the two must agree in the major class features [consonantal] and [sonorant].

(d) MAX: Every segment in the input must have a correspondent in the output.

(e) DEP: Every segment in the output must have a correspondent in the input.

(f) LINEARITY: If a string of output segments have input correspondents, the two strings must correspond in all linear order relations among their members.

The ranking *NC̥, Faith (3b-f) >> IDENT-LAR forces the avoidance of NC̥ clusters through voicing assimilation, as illustrated in the following tableau:

(4)

/kam + pa/	*NC̥	MAX	IDENT-LAR
(a) kampa	*!		
(b) kapa		*!	
☞ (c) kamba			*

But assimilation is not the only way in which such clusters are avoided. Pater (1999) points out that in some languages a sequence of a nasal followed by a voiceless obstruent is eliminated by deletion rather than assimilation. A sequence of a nasal followed by a voiceless obstruent is eliminated by deletion of the nasal in Venda (Ziervogel, Wentzel, and Makuya 1972: 25), Yaka Kongo (van der Eynde 1968), and Swahili (Ashton 1947: 3, 83) . In Venda, for example, the noun class 9 marker is a nasal which is realized before a voiced obstruent, as in (5a,b), but not before a voiceless one, as in (5c).

(5) (a) n-guvho "blanket (Class 9)"

(b) n-dou "elephant (Class 9)"

(c) kholomo "fowl (Class 9)" (*n-kholomo)

In other languages, such sequences are eliminated by deletion of the voiceless obstruent: Oshikwanyama (Steinbergs 1985), Kihehe (Odden and Odden 1985: 498), Madurese (Stevens 1968: 83), Chamorro (Topping 1969), Bahasa Indonesian (Lapoliwa 1981: 106- 108), and Yao (fricatives only: Ngunga 2000: 60-61). In Madurese, for example, the nasal final prefix /paŋ-/ induces the deletion of following voiceless stem-initial consonants.

(6) (a) paŋ-arap “hope”

(b) pam-uti “bleach” (/-puti/)

(c) paɲ-ukur “razor” (/cukur/)

Whether it is the nasal or the voiceless obstruent that is deleted, the faithfulness constraint MAX is violated. MAX must be dominated by *NC̥ and by the other faithfulness constraints in (3).[1]

Yet another way in which languages get rid of sequences of a nasal followed by a voiceless obstruent is by replacing the nasal with an oral counterpart. In Mandar, for example, a nasal before a voiceless obstruent is replaced by its voiceless oral stop counterpart, e.g. /N + t/ → [tt] (Pater 1999: 320). The same process occurs in Kaingang (Henry 1948: 195-196) and optionally in Toba Batak (Hayes 1986: 480). In Mandar, the result is a voiceless stop geminate, while in Kaingang and Toba Batak the underlying nasal retains its place of articulation (e.g. / m + t/ → [pt]). The nasal in these cases is turned into an oral obstruent, violating IDENT-NAS (3b). This constraint must therefore be dominated by *NC̥ and by the other faithfulness constraints in (3).

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[1] Pater proposes that nasal substitution as in Madurese is actually a case of fusion rather than deletion, so that the winning mapping is $/N_1 + p_2/ \rightarrow [m_{1,2}]$. This is certainly a plausible alternative to deletion, but he also suggests that the loss of the nasal in cases like Venda is a true case of deletion. This is rather arbitrary, since fusion could just as well lead to the apparent deletion of the nasal, as in the mapping $/N_1 + p_2/ \rightarrow [p_{1,2}]$.

Finally, there are of course many languages in which a nasal can be followed by a voiceless obstruent. In English, for example, there are such words as *blanket* with the sequence [ŋk], *lamp* with [mp], *chance* with [ns], and *lymph* with [mf]. This state of affairs can be expressed through ranking of all the faithfulness constraints in (3) above *NC̥.

However, there are some ways of avoiding such clusters that are easy to express through ranking of the constraints in (2) – (3), but which are not attested. Pater (1999: 319) points out that there never seems to be epenthesis to break up such clusters, so that / m + p/ is mapped to something like [məp], but / m + b/ remains unmodified. Yet it is simple to express such a pattern. Epenthesis violates DEP, so epenthesis will be the favored response to nasal + voiceless obstruent clusters if DEP is dominated by *NC̥ and the other faithfulness constraints in (3). This ranking is illustrated in (7).

(7)

/m + p/	*NC̥	IDENT-LAR	IDENT-NAS	MAX	DEP
(a) mp	*!				
(b) mb		*!			
(c) pp			*!		
(d) p				*!	
(e)☞ məp					*

This is a gap in the factorial typology of these constraints. The distributional pattern corresponding to this ranking is not attested.

Another unattested way of avoiding a sequence of a nasal followed by a voiceless obstruent is through **metathesis**. The constraint *NC̥ penalizes a sequence of a nasal followed by a voiceless obstruent, but not a sequence of a voiceless obstruent followed by a nasal. A mapping such as /m + p/ → [pm] would eliminate the markedness violation, at the cost of a violation of the faithfulness constraint that opposes metathesis, LINEARITY (3f). This mapping will be chosen as the preferred one if LINEARITY is ranked below *NC̥ and the other faithfulness constraints in (3).

There also is no case in which a sequence of a nasal followed by a voiceless obstruent is resolved by **lenition**, changing the obstruent to a sonorant. If /m +p/ were mapped to [mʍ], the output would not violate *NC̥, since that doesn't apply to nasal-sonorant sequences. Such a mapping would violate IDENT-MAJOR, so it would be the preferred mapping if IDENT-MAJOR was dominated by *NC̥ and the other faithfulness constraints in (3).

If we assume every ranking of the constraints should correspond to a possible language, these gaps must be worrisome. It could be that some of these cases will turn up as we include more languages into our sample, but the longer they stay unattested, the less these gaps seem like accidents of the sample.

Such gaps in factorial typologies are pervasive. It is generally not the case that every way in which a marked structure could be avoided is attested. Indeed, it is generally the case that the unattested rankings outnumber the attested ones.

Consider, for example, another pattern involving voicing in consonant clusters. It is quite common for languages to have a restriction on clusters of obstruents such that they must agree in voicing, as in <u>Dutch</u> (Booij 1995: 58-64), <u>Slovak</u> (Rubach 1993: 280-284), <u>Polish</u> (Rubach 1984: 206), <u>Russian</u> (Halle 1959), <u>Latin</u> (Niedermann 1910: 67-68), <u>Modern Irish</u> (Ó Siadhail 1989: 89-90), <u>Sanskrit</u> (Whitney 1891: 55), and <u>Sudanese Arabic</u> (Abu-Mansour 1996: 208). In all these cases, a sequence of obstruents disagreeing in voicing is avoided through the assimilation of one obstruent to the other in voice (in most cases, the first obstruent changes to agree with the following obstruent).

Lombardi (1999: 272) examined these cases, and posited the following markedness constraint to express the avoided configuration:

(8) AGREE: Obstruent clusters should agree in voicing.

If IDENT-LAR is dominated by AGREE as well as every other faithfulness constraint that conflicts with AGREE, the result will be the well-attested pattern of obstruent voicing assimilation.

But there are other equally simple ways available to avoid a sequence of obstruents disagreeing in voicing. A vowel could be inserted between them (/t + b/ → [təb]), violating DEP. One of the obstruents could be deleted (/t + b/ → [b]), violating MAX. One of the obstruents could be changed into a sonorant (/t + b/ → [tw]), violating IDENT-MAJOR. Each pattern is readily expressible through a ranking of AGREE and the other faithfulness constraints over the faithfulness constraint that is violated. Yet none of these patterns are attested.

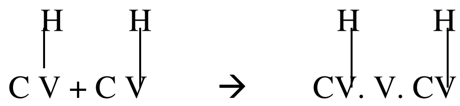
Nor is this under-representation of rankings limited to voicing in consonant clusters. In tone, for example, one avoided configuration is a sequence of identical tones on adjacent tone-bearing units. Such a configuration violates a tonal instance of the Obligatory Contour Principle (Leben 1978, McCarthy 1986, Myers 1997a):

(10) OCP-T: Adjacent identical tones are prohibited.

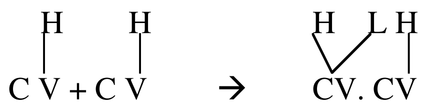
Myers (1997a) shows that such configurations are avoided in different ways in different Bantu languages. In <u>Shona</u>, if the first of two like tones is associated with more than one tone-bearing unit, it is retracted away from the second, and otherwise the second of the like tones is deleted. In <u>Rimi</u>, the first of two like tones is deleted. In <u>Chichewa</u>, the second of two like tones is retracted rightward away from the first.

But other plausible means of eliminating the OCP violation are unattested. There is no case in which a sequence of like tones is broken up by the insertion of a vowel or a tone to render them nonadjacent.

(11) (a) Unattested epenthesis driven by OCP-T



(b) Unattested tone insertion driven by OCP-T



Both vowel insertion and tone insertion occur, but neither is used to remove violations of OCP - T.

The pervasiveness of the gaps in factorial typologies has not been readily apparent just because most factorial typologies presented in OT work involve a severely limited set of "relevant" constraints. It is only when we consider all the faithfulness constraints and all the ways that a representation could be changed to avoid a markedness violations that it becomes clear that gaps are in fact the norm.

Because they are so pervasive, it seems unlikely that any tinkering with the constraints or the representations will suffice to fill them all. Lombardi (1995). for example, argues that the lack of deletion or epenthesis to eliminate laryngeally mixed obstruent clusters can be addressed by assuming a privative representation of voicing, and a faithfulness constraint for feature change that is also violated by insertion or deletion. The result of these proposals is that insertion or deletion could never be preferred to voicing assimilation to satisfy a constraint on voicing like AGREE. Unfortunately, the proposal would have the same result in the case of nasal-obstruent clusters, where deletion is in fact attested. Moreover, the proposal does not address other ways in which laryngeally mixed obstruent clusters could be avoided, such as turning one of the obstruents into a sonorant. An approach to unattested rankings must be as general as the phenomenon itself.

2. Some possible approaches to the problem

2.1. Fixed rankings

One way to limit the possible rankings is to introduce universally fixed rankings. Prince and Smolensky (1993), for example, use universally fixed rankings of markedness constraints to capture hierarchies of markedness such as the preference for more sonorous segments as syllable peaks.

In the case of the *NC̥ rankings, one could state that the faithfulness constraints that can be dominated in these cases are universally dominated by those that are never crucially dominated by *NC̥. This would yield the following fixed ranking: DEP, LINEARITY, IDENT-MAJOR >> IDENT-LAR, MAX, IDENT-NAS. This fixed ranking would remove the possibility of the unattested rankings above, since they would all involve a reversal of one of these fixed rankings.

One problem with this approach is that it is inherently *ad hoc*. There is no reason that the fixed ranking is this way rather than the opposite. It is thus quite different from the hierarchies of constraints that Prince and Smolensky (1993), where the ranking of markedness constraints corresponded to a substantive hierarchy of perceptual salience.

Moreover, the fixed ranking fails to capture the fact that the dispreferred ways of avoiding a sequence of a nasal followed by a voiceless obstruent are dispreferred only with respect to that particular marked structure. Deletion is preferred to epenthesis as a way of avoiding violations of *NC̥, but it is certainly not the case that deletion is always preferred to epenthesis. Epenthesis is often favored over deletion as a way of eliminating unsyllabifiable clusters (Prince and Smolensky 1993). Violations of CODA-COND, for example, banning heterorganic clusters (Prince and Smolensky 1993), are avoided by insertion of an epenthetic vowel in Ponapean (Itô 1989), but by consonant deletion in Diola Fogny (Sapir 1965, Itô 1986).

Such variation would be difficult to express if faithfulness constraints were to locked into a universal fixed ranking.

Pater (1999) suggests in passing that the absence of epenthesis to eliminate the sequence of a nasal followed by a voiceless obstruent could be expressed by a universal fixed ranking of DEP over *Nc̥. But such an approach, as Pater points out himself, provides no answer to the question of what distinguishes the faithfulness constraints that universally dominate this markedness constraint from the others that don't. It doesn't explain what distinguishes the rankings that are avoided from the ones that are attested.

2.2. Targeted constraints

Wilson (2001) addresses certain gaps in factorial typology by positing a class of constraints called **targeted constraints**. A targeted constraint not only specifies a marked structure that is avoided, but also expresses a preference for how that structure is avoided. Wilson notes, for example, that when a consonant cluster is simplified, it is generally the first consonant that is deleted rather than the second. To account for this, he posits a constraint, NOWEAKCONS, which states that any candidate that has a marked cluster is less harmonic than a cluster that is identical except that the first consonant is deleted. Since there is no corresponding targeted constraint favoring deletion of the second consonant, no ranking will select that consonant for deletion.

It would be straightforward to extend constraints of this sort to account for the fact that the only attested way of eliminating laryngeally mixed obstruent clusters is through assimilation. The relevant constraint would say that any candidate that has a laryngeally mixed obstruent cluster is less harmonic than a candidate that is identical except in voicing of the first member of the cluster. The absence of deletion, epenthesis and lenition as ways of avoiding such clusters would then be due to the absence of corresponding target constraints favoring those processes.

However, this approach would not work well in the cases in which there is more than one attested way for avoiding the same configuration, as in the case of a nasal followed by a voiceless obstruent. One could posit different targeted constraints for the different ways of avoiding this configuration, but then one would lose the essential insight of Prince and Smolensky (1993) that the avoided configuration is the same in all these cases.[2]

2.3. Phonologization

In this paper I will defend the view that gaps in factorial typologies do not in fact present a real problem for the theory of constraints and ranking. The unattested rankings are formally irreproachable.

They are unattested, it will be argued, because the patterns they represent are unlikely to arise diachronically through natural sound changes on the basis of phonetic patterns. Phonologization is the process of phonetic patterns being reanalyzed over time as phonological patterns. The basic idea is that the inherent limitations on phonologization are the means by which phonetic facts shape phonology.

According to this view, the set of all possible rankings defines not the set of human languages, but rather a set of formally possible human languages. The attested rankings represent a small subset of this formal universe – the subset that is consistent with how phonological patterns emerge.

The idea that limits on sound change shape synchronic sound patterns is of course not new. It was the consensus view of historical linguists in the 19th and early 20th century, such as Paul (1960). It has been reasserted in various forms in recent work by Ohala (1993), Hale and

[2] The same objection applies to the P-map approach to asymmetries in assimilation proposed in Steriade (2001). It also has the property that it zeroes in on one way of avoiding a marked structure, and so has difficulty with cross-linguistic variation in the ways a given structure is avoided.

Reiss (1999), Blevins and Garrett (1998), and Blevins (1999). The contribution of the present work is to show how the limits on sound change shape patterns of voicing in consonant clusters, and to explore the implications of these patterns for an optimality-theoretic approach to phonology.

3. The phonetics of voicing in consonant clusters

To see how phonetic patterns of voicing in clusters can shape phonological patterns, we must first consider what those phonetic patterns are. In particular, we must ask how the realization of a voicing specification is affected by juxtaposition with a consonant with the opposite voicing specification.

The effect of one consonant on the voicing of a neighboring consonant is due to **laryngeal coarticulation** - the overlap of the laryngeal gesture for one segment with the gestures for another segment. Munhall and Löfqvist (1992) used transillumination to track glottal width during the [s] and the [t] of the phrase *kiss Ted*, produced at various rates, and with stress either on the first word or on the second. They found that at slower rates two distinct glottal opening gestures could be seen, while at faster rates the two gestures overlapped to produce one extended gesture.

When the two consonants in a cluster disagree in voicing, overlapping of laryngeal gestures means an overlap of a glottal abduction for a voiceless consonant with a glottal adduction for a voiced consonant. The result is a “blended” (Browman and Goldstein 1990) or “undershot” (Lindblom 1963) compromise between the two. Thus we expect that voiced consonants will be less voiced next to a voiceless consonant than elsewhere, and that a voiceless consonant will be more voiced next to a voiced consonant than elsewhere.

Westbury (1979) found some assimilatory effects in “mixed” voiceless-voiced and voiced-voiceless stop clusters. For example, 4% of all voiceless-voiced clusters showed voicing throughout the cluster (p. 41). Docherty (1992: 165) likewise found that voiced obstruents have less voicing during the oral occlusion if they occur next to a voiceless consonant than if they occur intervocalically.

Hayes and Stivers (1996) compared voicing in nasal + voiceless stop clusters in English to that in [ɹ] + voiceless stop. They found that significantly more of the stop closure was voiced in the former condition than in the latter.

In order to further clarify these effects, an experiment was designed to test whether there are significant effects on the acoustic cues of one consonant based on the laryngeal class of its neighbor. In particular, the clusters investigated were those that are of importance in the phonology of voicing: obstruent clusters, and clusters including a nasal and an obstruent.

3.1. Methods

Four adult native speakers of American English participated in the study: two males and two females. None of the four speakers had a pronounced regional accent.

The materials consisted of 50 sentences of the form "It's W who wants to X Y Z", where W is a name, X, Y, and Z are a verb, noun and adverb, respectively. Subjects were instructed to emphasize the capitalized name after "it's", and to pronounce the rest of the sentence as if it were backgrounded, old information. Examples are given in (12).

(12) (a) It's SYLVIA who wants to woo Curt now.

(b) It's FREDERICK who wants to hug Sam now.

(c) It's GLORIA who wants to phone Cal now.

The cluster to be analyzed was the one formed by the juxtaposition of the verb and the following noun. The verbs were monosyllables ending in a vowel (e.g. *know* or *woo*), a voiced velar stop (e.g. *hug* or *rig*), a voiceless velar stop (e.g. *kick* or *like*), or an alveolar nasal (e.g. *phone* or *clean*). The nouns were monosyllabic names beginning with a voiceless velar stop (e.g. *Cal* or *Kate*), a voiced velar stop (e.g. *Gail* or *Gus*), a voiceless alveolar fricative (e.g. *Sam* or *Sue*), a voiced alveolar fricative (e.g. *Zack* or *Zoe*), or a nasal (e.g. *Ned* or *Nate*). The resulting clusters thus include voiced and voiceless velar stops in the following contexts:

(13) (a) intervocalically
(b) before a voiced fricative
(c) before a voiceless fricative
(d) before an alveolar nasal
(e) after an alveolar nasal

These segments were chosen for ease of segmentation.

The sentences were printed out in large print in random order, with three repetitions of each sentence. Subjects read the sentences, separated by pauses, in a sound-treated room, and their utterances were recorded with a DAT tape recorder. Each subject read through the list three times, producing a total of 150 utterances per speaker, including 15 for each combination of voicing type and environment. Thus with four speakers, a total of 600 utterances were recorded.

The recordings were redigitized into sound files on a Macintosh computer, using the Macquirer acoustic analysis package produced by SciCon R & D. Two displays were generated for each sentence: a wide-band spectrogram, and an expanded waveform in which the shape of individual pulses were clearly discernable.

The measure of voicing was the percentage of the stop closure that displayed periodic pulsing (Percent voicing). This was chosen as a measure, rather than some other cue, because it is a direct acoustic reflex of vocal fold vibration, and can be measured in preconsonantal context as well as in prevocalic position. It has been shown that the amount of voicing during occlusion is higher in voiced obstruents than in voiceless ones (Lisker, Abramson, Cooper, and Schvey 1969), and that it is a significant perceptual cue for identifying voiced and voiceless sounds (Parker, Diehl and Kluender 1986, Lisker 1986).

The closure duration and the duration of voicing during closure were measured in the expanded waveform, with each measurement point checked against the spectrogram. The criteria for determining the boundaries of the closure and of the voicing were the standard ones defined in Peterson and Lehiste (1960), Westbury (1979), and Docherty (1992).

3.2. Results: Nasal contexts

The widespread avoidance of voiceless obstruents after nasals suggests that voicing contrasts in postnasal obstruents might be obscured by coarticulatory effects from the preceding nasal. To test this, instances of voiced and voiceless stops after a nasal were compared to instances after a vowel. The following segment was a vowel in all cases. Pooling data across speakers, a total of 359 tokens were included in the comparison.

A boxplot graph of the voicing percentage in each condition is given in Fig. 1, and the corresponding means are given in Table 1.

Figure 1: Voicing percentage by voicing category and nasal context

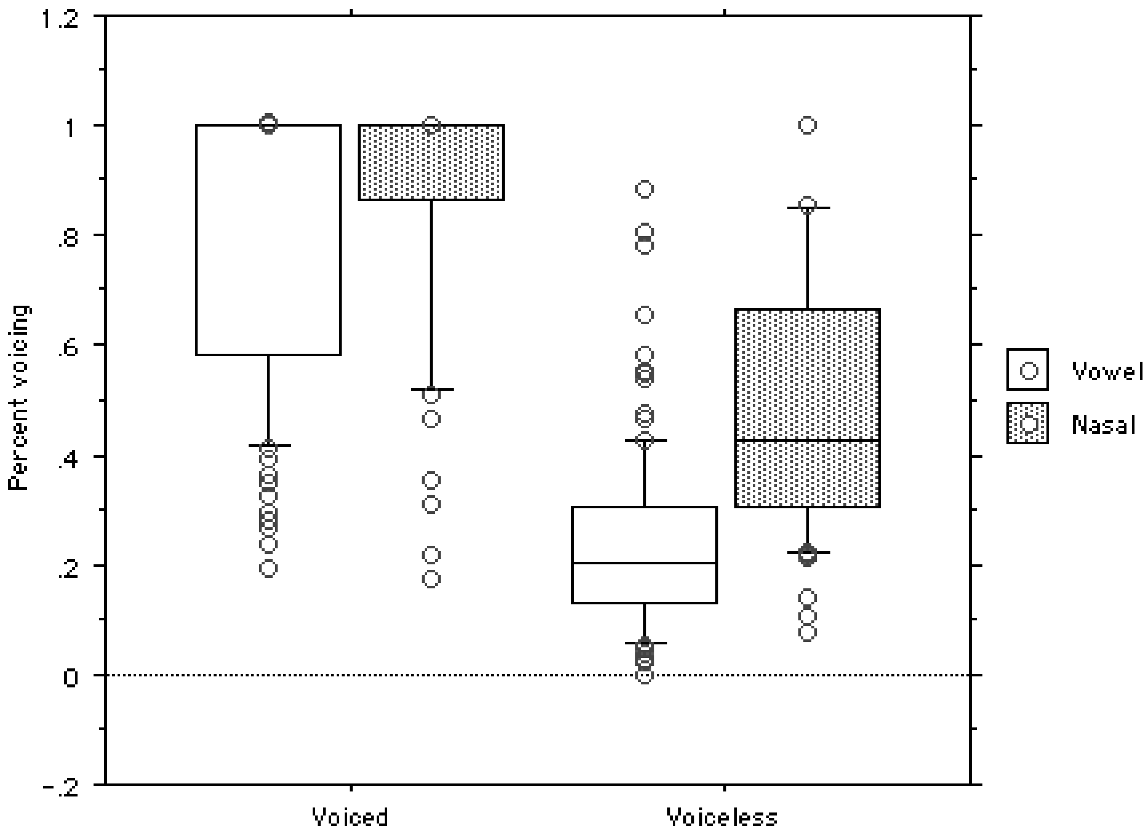


Table 1: Mean voicing percentage in nasal and oral contexts

	After a vowel	After a nasal
Voiced	.81	.88
Voiceless	.17	.24

It can be seen that the percent voicing is considerably higher in voiced stops than in voiceless ones, confirming that percent voicing is a useful cue distinguishing the two categories. But the percent voicing is markedly higher after a nasal than after a vowel, especially for voiceless stops.

An ANOVA analysis was performed in which voicing percentage was the dependent variable, and the independent variables were the voicing category of the stop (voiced or voiceless), and the preceding segment (vowel or nasal). The results are given in Table 2.

Table 2: ANOVA analysis of voicing percentage in nasal contexts

Factor	d.f.	F	p
Voicing category	1, 355	386.7	<.0001
Context	1, 355	41.2	<.0001
Interaction	1, 355	14.3	.0002

The main effect of voicing category and context are highly significant. The interaction between the two factors is also significant, due to the fact that context affected the voiceless stops more than the voiced ones. Voiced stops have a very high voicing percentage in postvocalic position, so there are limits as to how much more voiced they can get.

It can be concluded that perseverative coarticulation from the nasal onto the following stop has the result of making the stop more voiced in that context than after a vowel.[3] This is consistent with the finding of Hayes and Stivers (1996) that voiceless stops had more voicing after a nasal than after a liquid. This suggests that the postnasal context is one where it is more difficult than elsewhere to distinguish voiced from voiceless stops, and where listeners are more likely to mistake a voiceless for a voiced stop. English allows voiceless stops after nasals, but they are less voiceless in this context than elsewhere.

3.3. Results: Obstruent clusters

Obstruent clusters in which the members disagree in voicing are avoided in the world's languages. Such laryngeally mixed obstruent clusters are however allowed in English (*afghan*, *abstract*). The second comparison of the experiment was intended to determine whether the percent voicing of the first member of such a cluster is affected by the voicing of the second

[3] It was also found in further analysis that there was no significant difference in voicing between postvocalic stops before a vowel and such stops before a nasal.

member. Voiced and voiceless stops were compared in three contexts: before a voiced obstruent (a fricative), before a voiceless obstruent (a fricative), and before a sonorant (a vowel or nasal). In all cases, the preceding segment was a vowel. Pooling across speakers, a total of 438 tokens were included in this comparison.

A boxplot of the voicing percentage in the different conditions is given in Fig. 2, and the corresponding means and standard deviations in Table 3.

Fig. 2: Voicing percentage by voicing category and obstruent context

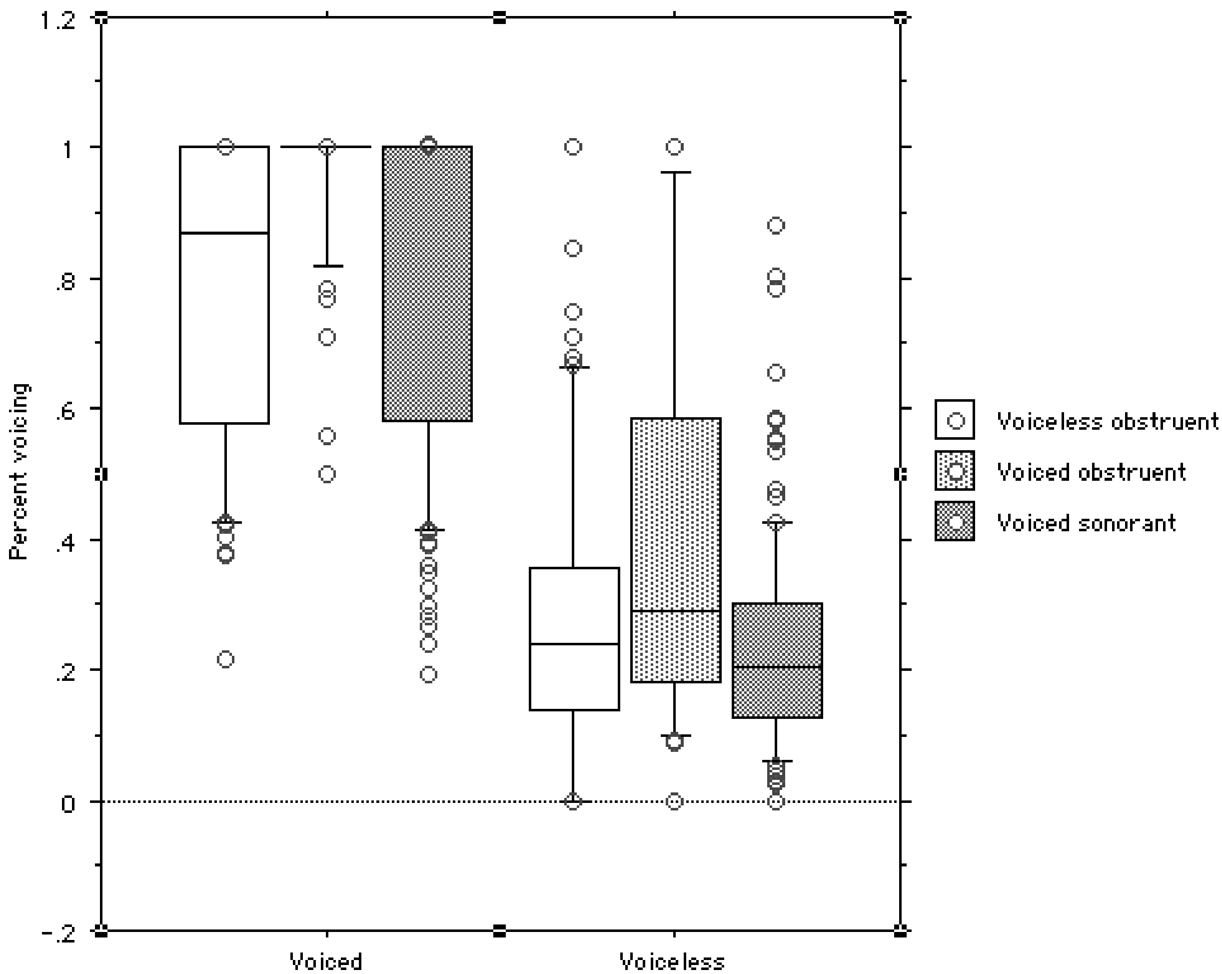


Table 3: Mean voicing percentage by voicing category and obstruent context

	Before a vowel	Before a voiced obstruent	Before a voiceless obstruent
Voiced	.81	.96	.80
Voiceless	.24	.39	.29

As in the first comparison, the voicing percentage is high for voiced stops and low for voiceless ones. But the voicing percentage for both categories is markedly higher before a voiced obstruent than in the other two contexts.

An ANOVA analysis was performed with voicing percentage as the dependent variable, and with the independent variables of voicing category (voiced or voiceless) and following context (vowel, voiced obstruent, voiceless obstruent). The results are given in Table 4.

Table 4: ANOVA analysis of voicing percentage by following context

Factor	d.f.	F	p
Voicing category	1, 472	707.5	<.0001
Following context	2, 472	20.4	<.0001
Interaction	2, 472	0.9	.42

The significant main effect for voicing category indicates that voiced stops had significantly more voicing than voiceless ones. But the effect of context is also significant, and planned post-hoc analysis with Fisher's PLSD indicates that voicing is significantly greater before a voiced obstruent than in the other two contexts. There was no significant difference between the context before a vowel and that before a voiceless obstruent, and no significant interaction.

Thus while laryngeally mixed obstruent clusters occur in English, the first member of such a cluster is affected by the voicing of the second member. A phonemically voiceless stop has a significantly higher percent voicing when it occurs before a voiced obstruent than elsewhere. This suggests that this is a context where it is somewhat more difficult than elsewhere to distinguish a voiceless stop from a voiced one, and a context where we might expect one voicing category to be mistaken for the other.

4. Patterns of phonologization

Marked phonological structures are those that tend to be misheard as something else (Steriade 1995, Hume and Johnson 2001a). A sound change occurs when learners generalize such a perceptual error, replacing the previous speaker's intended structure with another, more consistent with what they perceive (Ohala 1981,1993). An important limit on sound change is that it must be driven by misidentifications that are common enough to motivate a generalization. Thus sound changes generally involve the replacement of one structure with something that is perceptually similar. In this section, it is argued that this limit adequately distinguishes the attested ways of avoiding laryngeally mixed clusters from the unattested ones.

4.1. Assimilation

We have seen that the acoustic distinction between voiced and voiceless stops is diminished in two laryngeally mixed consonant clusters: a sequence of a nasal followed by an obstruent, and a sequence of two obstruents. Such contextual weakening of the cues that distinguish two categories can lead to confusion on the part of the listener, and particular on the part of the language learner, as to which category is intended in this context. If enough learners mistake one category for another in this context, this will lead to a sound change in which the original partially devoiced or partially voiced stop is reinterpreted by the learner as a categorically voiced or voiceless stop, respectively.

This is **hypocorrection** in the sense of Ohala (1993). The language learner mistakenly hears a voiced stop where the speaker is producing a coarticulated voiceless stop. The learner has therefore failed in this case to apply the general perceptual compensation for coarticulatory effects. If this happens enough, the learner concludes that only voiced stops occur after a nasal or that the obstruent before another obstruent always matches it in voicing. The language learner then has a categorical pattern of voicing assimilation where the previous speakers had just laryngeal coarticulation effects. The coarticulation effects have been phonologized.

The resulting sound change not only eliminates mixed clusters, but it also specifies how such clusters are to be replaced. The learner has mistaken the laryngeal category of the stop, so that is what changes in the resulting phonological pattern. The learner isn't looking for ways to avoid laryngeally mixed clusters, but rather simply fails to realize that there are such clusters. The choice of assimilation as a way of avoiding laryngeally mixed clusters is a side effect of how such clusters are misheard.

4.2. Deletion/ Denasalization

It is natural for coarticulation to get phonologized as assimilation, since coarticulation always does lead to some portion of one segment getting more similar to a neighboring segment. But work such as Ohala (1981, 1983, 1993) and Browman and Goldstein (1990) has shown that coarticulation can have acoustic effects that can lead to non-assimilatory perceptual errors on the part of the listener.

Browman and Goldstein (1990) have shown how coarticulation can lead to apparent deletion of a segment. In the phrase *perfect memory*, the medial [ktm] is often rendered in such a way that the velar closure of the [k] covers the initial transition into the [t], and the following bliabial [m] closure covers the transition out of the [t]. The result is that the alveolar closure of the [t] has no audible effect: [pɹ̥fi**km**ɛmɹi]. Browman and Goldstein refer to this effect as "gestural hiding".[4]

In this light, let us now consider the sequence of a nasal followed by a voiceless obstruent. In English, such a sequence is produced with full voicing of the nasal and indeed with the voicing of the nasal enduring into the following obstruent. But in other languages, the voicelessness of the obstruent in such a sequence is anticipated on the nasal. Huffmann and Hinnebusch (1998), for example, show that such a sequence in Pokomo is produced with variable voicing of the nasal ranging from fully voiced to fully voiceless. Nasals in this context are transcribed as voiceless by Viljoen and Amakali (1978) for Ndonga, and Kimenyi (1979) for Kinyarwanda.

Devoicing of a nasal obscures the formants that identify it is a nasal. A voiceless nasal is very quiet. There is no voice source, and the open nasal passage is too broad to generate any noisy air turbulence except at very great rates of airflow. If the acoustic environment is not perfect, this faint stretch of breathiness can easily be mistaken for silence (as anyone can attest who has tried to teach the sound to a phonetics class in a large room).

For listeners who fail to hear the voiceless nasal in this position, one interpretation could be that the nasal has been deleted, and these listeners could adjust their phonological system to yield a pattern of deletion of a nasal before a voiceless sound, as in Venda in (2). Alternatively, if listeners hear only silence before a voiceless stop, they could easily interpret the silence as being the first part of a closure for a stop cluster. This could yield a voiceless oral stop in this position, and the pattern of denasalization of a nasal before a voiceless obstruent, as in Mandar, Kaingang, and Toba Batak.

A perceptually weak voiceless nasal could also emerge in a sequence of a nasal followed by a voiceless stop if the velic lowering gesture of the nasal endures into the following voiceless

[4] Another instance of gestural hiding is the schwa deletion evident in the pronunciation [mɛmɹi] as opposed to [mɛməɹi] (Browman and Goldstein 1990: 369).

stop, yielding a period of voiceless nasal airflow. Listeners in this case could once more fail to hear the quiet nasal, and deduce that the expected voiceless stop was deleted. This could lead to the pattern of deletion of a voiceless obstruent after a nasal, as in Madurese.

Thus coarticulatory devoicing of a nasal can lead to a nonassimilatory phonological pattern of deletion or denasalization in nasal-obstruent clusters. This is because a nasal that is devoiced through laryngeal coarticulation can be mistaken for something that isn't a nasal at all.

But consider, on the other hand, the effects of coarticulation within an obstruent cluster. Devoicing of an obstruent under the influence of a voiceless obstruent will just yield a voiceless obstruent, which is not going to be more likely to be missed perceptually in this context than in any other one. In such a cluster, there is no degree of overlap between the laryngeal gestures that will lead to one of the obstruents becoming inaudible. Sufficient overlap of the oral gestures could lead to gestural hiding, but such an effect would not be any greater in the case of a laryngeally mixed obstruent cluster than in a homogenous one.

The phonetic effects of coarticulation are thus different in a nasal-obstruent cluster than in an obstruent cluster, because a devoiced nasal can be misheard as nothing, while a devoiced obstruent is no more likely to be so misheard than a phonemically voiceless obstruent. Thus deletion of one of the two consonants is a natural sound change in nasal-obstruent clusters, but not in obstruent-obstruent ones.

This phonetic asymmetry between coarticulatory effects in the two kinds of clusters accounts for the difference between them in phonological behavior. Deletion of an obstruent in a laryngeally mixed obstruent cluster would be a simple way to eliminate violations of the markedness constraint AGREE. There is a straightforward ranking of well-motivated constraints that would yield such a pattern. But phonological patterns originally arise in languages through phonologization, and there is no simple path that would lead from a phonetic pattern in obstruent clusters to such a deletion pattern. There is no laryngeal coarticulation effect in such clusters that could lead to a perceived deletion just in the case of laryngeally mixed obstruent clusters.

4.3. Epenthesis

Gestural overlap can also lead to the perceived insertion of segments (Ohala 1983, Browman and Goldstein 1990). Where a nasal precedes a fricative in English, as in *prince*, there must be a transition from a configuration with an oral closure and open velum to a configuration with oral constriction and a closed velum. If the movement from oral closure to oral constriction is perfectly synchronized with the movement from open velum to closed velum, then the result will be a nasal stop followed by an oral fricative: [pɹɪns]. But most speakers of English close the velum in such a sequence before they release the oral closure. This leads to an intervening period in which there is oral closure combined with a velic closure, i.e. an oral stop. This is the intrusive oral stop in pronunciations such as [pɹɪn^{t}s] (Fourakis and Port 1986, Warner and Weber 2001). Such an intrusive stop can be reinterpreted as obligatory, as in Zulu, where nasal + fricative sequences are prohibited and are systematically replaced by nasal + affricate (Doke 1926).

Another way an epenthesis pattern can emerge is through reinterpretation of a consonant release as a vowel. Especially with a voiced stop, the release of closure and return to a more open vocal tract can result in a vowel-like periodic wave with prominent spectral peaks. This can be seen in spectrograms of English in hypercareful pronunciations of a word with a final voiced stop, such as *bag*. Such releases are often transcribed, when they are transcribed, with a schwa-like vowel, sometimes superscripted to indicate their short duration, as in Dell and Elmedlaoui's (1985) narrow transcriptions of Indlawn Tashliyt Berber. Dell and Elmedlaoui treat them as being phonologically irrelevant transitions, while Guerssel (1977) treat corresponding vowels in another dialect of Berber as being full schwa vowels. Whether this difference represents a real difference between the dialects due to sound change, or it is a difference in interpretation between trained linguists, we can assume that children learning the language could find this a subtle distinction. If listeners hear these transitions as vowels, they can interpret the pattern as one of phonological epenthesis of a vowel.

Now consider a sequence of a nasal followed by a voiceless obstruent. If the voiceless obstruent is a fricative, such a sequence can be the site of an intrusive stop. But the resulting sequence then is still a sequence of a nasal followed by a voiceless obstruent (an affricate). If, on the other hand, the nasal was systematically released before the onset of the obstruent, this could yield a transition that could be interpreted as a vowel, but this wouldn't depend on the voicing of the following obstruent. There are thus no phonetic variants of these clusters which have a period that could be mistaken for a vowel just in the case that the nasal is followed by a voiceless obstruent. The same reasoning holds as well of the obstruent-obstruent clusters.

Epenthesis would be a simple way to eliminate laryngeally mixed clusters, and it is a frequent means of eliminating other sorts of marked clusters (e.g. heterorganic ones). There is a straightforward ranking of well-motivated constraints that would lead to epenthesis in just this case. But there is no phonetic pattern that could be interpreted in this way. There is thus no natural sound change that could lead to the emergence of such a phonological pattern.

4.5. Phonologization: Metathesis

Blevins and Garrett (1998) show how coarticulatory effects can lead to metathesis. When the cue for a consonant is sufficiently extended, such as the glottalization of segments before a glottal stop, it can lead to confusion as to where that consonant is located in the string. Thus when glottal stop follows a vowel, the glottalization can extend to the beginning of the preceding vowel. Listeners can then get confused as to whether the vowel precedes the glottal stop, or vice versa, leading to metathetic sound changes such as Vʔ > ʔV.

But things are different in the case of a sequence of a nasal followed by a voiceless obstruent. The cues for obstruent voicing constriction are not as extended as those for glottalization, and those for obstruency (low amplitude and noise) are quite local. We have seen that in some cases the voicelessness of the obstruent can extend leftward all the way to the beginning of the preceding nasal, but this could not lead to confusion as to the linear order of the nasal and the obstruent, since the obstruency cues would remain in place after the nasal. There are no phonetic variants in which the obstruent cues occur early in the nasal, so there can be no basis for an interpretation of nasal + obstruent as obstruent + nasal.

Metathesis is a reasonable way of avoiding violations of *NÇ̥, and it can be expressed through ranking of that markedness constraint over LINEARITY. But there is no phonetic pattern arising out of laryngeal coarticulation that could be reinterpreted in those terms. Thus this formally plausible pattern is unlikely to arise through phonologization.

4.6. Lenition

Another unattested way of eliminating mixed clusters is to get rid of an obstruent in the sequence by changing it to a sonorant, e.g. / m + p/ → [mʍ], or /t + b/ → [tw]. Such a change would eliminate the markedness violation, since both *NÇ̥ and AGREE require the presence of an obstruent. This pattern can be straightforwardly expressed by ranking these markedness constraints and all other faithfulness constraints above IDENT-MAJOR, which opposes changes in major class features such as [sonorant].

Changes from a sonorant to an obstruent are well attested in lenition contexts such as between two vowels (Hock 1991:83, Harris 1990). This can arise from undershoot: in passing from an open vocal tract to a closed one and back to an open one, it can be the case that the closing movement is incomplete when the return to an open configuration begins. Undershoot of the constriction of an obstruent leads to a more open articulation, which can be interpreted by listeners as a sonorant.

But in the sequences we are dealing with, nasal-obstruent and obstruent-obstruent, there is no such open articulation to trigger such an effect. One or the other member of the sequence might be subject to undershoot, but this would be independent of whether the cluster is mixed in voicing. There is therefore no phonetic pattern that could serve as the source for a phonological pattern of sonorization to eliminate laryngeally mixed clusters.

5. Conclusions and implications

I have argued that gaps in factorial typology are pervasive and natural. There can be more than one way of avoiding a marked structure, but we never find attested every conceivable way of avoiding that structure.

This is not, however, a problem for Optimality Theory, since the attested cases can be distinguished from the unattested patterns in terms of how they could arise diachronically. The attested cases are ones that arise out of a perceptual reinterpretation of a phonetic pattern, while the unattested cases are ones that do not correspond to a natural phonologization of a phonetic pattern. Such unattested rankings are not anomalous as rankings, but they just cannot arise in any simple way through natural sound changes. If they arise at all, they must arise through a more improbable chain of diachronic changes (Hyman 2001).

Because there is an explanation for such gaps, we don't have to add machinery to our model of phonology in order to eliminate them. No amount of fiddling with the representations and constraints will close the gaps we have seen in the typology of voicing patterns. The proposed analysis of patterns of voicing in clusters thus just incorporates the markedness constraints proposed and motivated by Pater (1999) and Lombardi (1999), and the faithfulness constraints proposed by McCarthy and Prince (1995). It has been argued that the gaps in the factorial typology of these constraints cannot and should not be addressed by revision of these constraints or one's assumptions about the representation of voicing.

Factorial typologies are essential tools in motivating proposed constraints. The case for a proposed constraint is strengthened when we can show that it does work in a variety of different rankings. However, if some rankings involving that constraint are unattested, that doesn't necessarily weaken the case for the constraint, since such gaps are natural and expected. Such cases just raise the question of why the pattern represented by that unattested ranking should be an unlikely one to arise historically.

The factorial typology of all constraints, according to this view, does not, by itself, define the set of human phonologies, but rather defines a set of formally expressible phonological systems. The subset of systems that we're actually likely to find in the world are selected by the blind but phonetically–biased process of sound change. The mini-sound-changes in which a listener mishears a sound with weak cues provide the basis not only for the configurations that are avoided in phonology, but also for the ways they are avoided. The avoided (marked) structures are those that are likely to be mistaken for something else. The ways in which such a structure is avoided is determined by what its realizations can be mistaken for.

Another implication of these proposals concerns phonetic grounding of phonology. It has been presupposed here, as in such work as Archangeli and Pulleyblank (1994), Steriade (1995), Hayes (1996), Myers (1997b) and Hume (2001), that phonetic patterns have a decisive role in constraining the range of phonological patterns. But it has been shown that the influence of phonetics on phonology cannot be expressed just by insisting that constraints be phonetically grounded, as those works suggest. We have seen that the **ranking** of constraints is also constrained by phonetic patterns of perceptual confusion.

Moreover, if the limits on the diachronic process of phonologization limit the most likely phonological patterns to ones that are phonetically natural, it is unclear why this constraining force should be recapitulated in the formal machinery of constraints and rankings. The constraints can be seen as modelling pure patterns of distribution, and the fact that those patterns tend to mimic phonetic ones can be attributed to their diachronic origin through phonologization (Hale and Reiss 1999).

The same sort of logic applies to extreme rankings with impractical results. One ranking has all the markedness constraints dominating at least one faithfulness constraint. This ranking yields just one unmarked form, with maximally unmarked segments in a maximally unmarked syllable arrangement, e.g. [ta]. No language is like this, but we don't necessarily have to alter the set of constraints to make this case inexpressible. A language with just one expression has obvious practical liabilities as a means of communication, so if we allow it as a formal possibility, we can be confident that such a system is unlikely to emerge as a real language.

The most common phonological patterns are phonetically natural, but of course phonetically unnatural patterns also occur. Hyman (2001) presents some clear cases of patterns that work entirely counter to the constraint *Nç̥. In Tswana, for example, a nasal followed by a voiced obstruent is changed into a nasal followed by a *voiceless obstruent* (e.g. / N + b/ → [mp]), exactly the opposite from what we would expect from *Nç̥. Hyman also shows how such a pattern can emerge from a chain of independent sound changes, each of which individually is phonetically reasonable. The model of human languages needs to be flexible enough to recognize the possibility of such a system, and as Hyman points out, the rarity of such cases results from the fact that they can only result from particular sequences of sound changes. The common, phonetically natural patterns are those that can arise from one natural, phonetically-based sound change. The more eccentric patterns are less common because they require specific conjunctions of independent sound changes.

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