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# *Phonetic Detail in Phonology: Evidence from assimilation and coarticulation*

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## 1. Assimilation and coarticulation

Assimilation and coarticulation both involve extending the duration of some property or feature. The similarities between these phenomena can be seen by comparing Basque vowel raising with vowel-to-vowel coarticulation in a language like English. In Basque the low vowel /a/ is raised to [e] following a high vowel. This gives rise to alternations in the form of the definite suffix, /-a/ (de Rijk 1970):

(1) sagar-a 'apple (def.)' mutil-e 'boy (def.)'

In an English sequence containing a low vowel preceded by a high vowel, like [-ilæ-] in 'relapse', the high vowel also conditions raising of the low vowel. But in spite of the parallels between these cases, standard analyses regard Basque vowel raising as phonological whereas the English vowel raising is regarded as non-phonological, being attributed to a phonetic process of coarticulation. In this paper, we will argue that this distinction is untenable. We will see that coarticulation can affect the distribution of contrasts, and therefore must be specified in the phonology. This opens up the possibility of giving a unified analysis of assimilation and coarticulation.

Analyzing coarticulation as phonological implies that phonological representations contain far more phonetic detail than is usually assumed to be the case. Vowel-to-vowel coarticulation involves fine degrees of partial assimilation in that vowels assimilate only partially in quality, and the effects may extend through only part of the duration of a segment (e.g. Öhman 1966). This conclusion thus flies in the face of the standard assumption that the richness of phonological representations should be severely restricted in order to avoid over-predicting the range of possible phonological contrasts. So before we turn to evidence that coarticulation is phonological, we will lay the groundwork by examining the arguments for limiting the detail in phonological representations and show that they are based on very questionable assumptions.

## 2. Phonetics and phonology

The issue of restrictions on detail in phonological representations has implications for the relationship between phonetics and phonology. Given the standard assumption that there is considerable phonetic detail which is excluded from phonological representations, this information must be supplied by the rules of a phonetic component of grammar. E.g. if contextual variation due to coarticulation is not represented in the phonology, it must be accounted for elsewhere. Furthermore, many of the phonetic rules entailed by this approach must be language-specific. This is certainly the case with respect to coarticulation (Magen 1984, Manuel and Krakow 1984, Manuel 1990, Keating and Cohn 1988, Whalen 1990). If, on the other hand, phonology does include these details, then the role of a phonetic component is potentially severely curtailed.

As noted above, the primary argument given for minimizing the detail in phonological representations is that this is necessary to avoid over-predicting the range of possible phonological contrasts. I.e. the range of attested linguistic contrasts is much smaller than the range of phonetic differences, and it is proposed that we should account for this observation by minimizing representational possibilities so it is only possible to represent attested contrasts in the phonology. This type of reasoning is stated clearly in the following comment on laryngeal features (Keating 1984:289):

> '...[Halle and Stevens] (and SPE) don't simply have the wrong features in these instances; they will ALWAYS have TOO MANY features because they want to describe exactly how individual sounds are articulated. While we want the phonological features to have some phonetic basis, we also want to distinguish possible contrasts from possible differences.'

The same idea is expressed in McCarthy's (1994) statement that 'An adequate theory of phonological distinctive features must...be able to describe all and only the distinctions made by the sound systems of any of the world's languages' (p.191).

The basis of this approach to the analysis of contrast is the assumption that any difference representable in lexical representations should in principle be a possible contrast, so to restrict possible contrasts, restrictions have to be imposed on possible representations. We will call this the representational theory of contrast. This assumption is far from necessary. The alternative pursued here is to suppose that well-formed contrasts are selected from a wide range of representational possibilities by constraints on contrasts. Restrictions on contrast are thus accounted for in terms of the theory of constraints rather than the theory of representations (see Kirchner, this volume, for a similar proposal).

Specifically, limitations on the range of possible contrasts can be accounted for in terms of constraints on the auditory distinctiveness of contrasts. We will propose that one of the fundamental requirements on contrasts is that they should be as distinctive as possible, so very fine distinctions will not generally be well-formed contrasts.

This approach offers a more satisfactory account of restrictions on attested contrasts than the representational theory. In the representational theory, restrictions on contrasts are accounted for primarily by limiting the feature set, as indicated by the quotes from Keating and McCarthy, above. Limiting the feature set does not account for restrictions on contrastive combinations of features. E.g. [nasal] can be contrastive, but it is never contrastive on pharyngeals, glottals or ejectives. There is an obvious explanation for this observation: Pharyngeals and glottals involve constrictions below the velic opening, so lowering the velum during such a constriction will result in little or no nasal airflow, and thus will not produce significant acoustic effects. So a difference in velic opening does not produce an adequate contrast in this environment. I.e. this restriction on contrast results from a constraint that contrasts satisfy a minimum distinctiveness requirement, not from the impossibility of representing such a contrast.

This mode of explanation can be generalized to account for more basic observations usually analyzed in terms of a limited feature set. For example, languages only contrast two degrees of nasalization; oral and nasal. In representational terms this observation is accounted for by positing a single binary feature nasal. The question remains as to why there is only one feature relating to nasality when, for example, the dimension of vowel height is usually represented by two features. A plausible answer to this question is that three degrees of nasalization could not be distinguished reliably because they would not be sufficiently perceptually distinct. Again, a constraint on the minimum distinctiveness that is adequate to support a contrast can account for the absence of this contrast, so there is no need to exclude finer degrees of nasalization from phonological representation.

The representational theory of contrast also leads to theory-internal conflicts. Feature theory does not only account for contrast, it must also allow us to formulate phonological rules or constraints. It is not clear that a single set of features can satisfy both requirements. It is clear that phonological statements can refer to universally non-contrastive properties such as syllabification, and we will see that it is also necessary to refer to segmental properties which are never contrastive. This conflict is given a simple resolution by abandoning the representational account of contrast.

A second argument for distinguishing phonetic and phonological representation is based on the existence of categorical phonological processes. For example, Basque vowel raising (1, above) is categorical in the sense that the result of raising /a/ to [e] is indistinguishable from underlying /e/, so raising effects a shift from one phonological category to another. The assimilation observed in vowel-to-vowel coarticulation is not categorical in this sense. The implicit claim is that categorical processes can only be accounted for in terms of representations that operate in terms of categories of the same kind. We will see that this is not the case. This pattern of categorical behaviour arises naturally from a constraint-based theory of contrast. To demonstrate this point, we must first outline a hypothesis concerning the specific constraints which contrasts are subject to. The account adopted here is dubbed the ‘Dispersion Theory’ after Lindblom’s (1986, 1990) ‘Theory of Adaptive Dispersion’, which it resembles in many respects. (A more detailed account is presented in Flemming 1995).

## 3. The Dispersion Theory of contrast

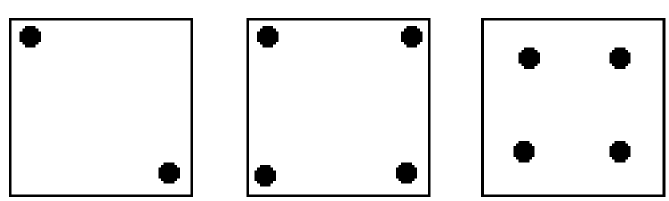
The core of dispersion theory is the claim that the selection of phonological contrasts is subject to three goals:

(2) i. Maximize the number of contrasts
ii. Maximize the distinctiveness of contrasts
iii. Minimize articulatory effort

These goals derive from the function of language as a means for the transmission of information. The number of phonological contrasts should be maximized in order to enable us to differentiate a substantial vocabulary of words. The auditory distinctiveness of the contrasts should be maximized so that the differences between words can be easily perceived by a listener. The third requirement, that effort should be minimized appears to be a general principle of human motor behaviour, and is not specific to language.

These ideas are far from new. They have antecedents in the work of Zipf (1949). They have been developed in most detail by Martinet (1952, 1955) and Lindblom (1986, 1990), who has developed quantitative models of contrast selection based on the principles of maximization of distinctiveness and minimization of effort.

An important property of these goals is that they conflict. This point can be illustrated by considering the selection of contrasting sounds from a schematic two dimensional auditory space, shown in figure 1. Figure 1a shows an inventory which includes only one contrast, but the contrast is maximally distinct, i.e. the two sounds are well separated in the auditory space. If we try to fit more sounds into the same auditory space, the sounds will necessarily be closer together, i.e. the contrasts will be less distinct (figure 1b). Thus the goals of maximizing the number of contrasts and maximizing the distinctiveness of contrasts inherently conflict. Minimization of effort also conflicts with maximizing distinctiveness. Assuming that not all sounds are equally easy to produce, attempting to minimize effort reduces the area of the auditory space available for selection of contrasts. For example, if we assume that sounds in the periphery of the space involve greater effort than those in the interior, then, to avoid effortful sounds it is necessary to restrict sounds to a reduced area of the space, thus the contrasts will be less distinct, as illustrated in fig 1c. Note that while minimization of effort and maximization of the number of contrasts both conflict with maximization of distinctiveness, they do not directly conflict with each other.



| (a) | (b) | (c) |
|---|---|---|
| Two segments | Four segments | Four segments |
| Most separation | Less separation | Least separation |
| More effort | More effort | Less effort |

Fig 1. Selection of contrasts from a schematic auditory space.

Given the conflict between the requirements imposed on contrasts, the selection of an inventory of contrasts involves achieving a balance between these requirements. A source of cross-linguistic variation is variation in the compromise that different languages adopt. Optimality Theory provides a suitable framework for formalizing this model since it analyzes the selection of contrasts as the problem of reaching an optimal compromise between conflicting requirements.

## 4. A formal model of dispersion

According to dispersion theory, determining an inventory of contrasts involves selecting sounds in accordance with the constraints on contrasts outlined above. To formalize this model, we need to provide auditory representations, and formulations of the constraints on contrast. We will regard sounds as located in a multi-dimensional auditory space with scalar dimensions. The distinctiveness of a contrast on a given dimension is the distance between the contrasting sounds. For example, the contrast [i-a] is more distinct on the dimension of first formant (F1) frequency than a contrast [i-e] or [e-a] (see Flemming 1995 for a feature-based representation of auditory distinctiveness).

i. *Maximize the number of contrasts*

We can implement the goal of maximizing the number of contrasts in terms of a ranked set of constraints, each requiring the maintenance of a particular number of contrasts (3). The fixed ranking ensures that failure to maintain *n* contrasts is penalized more severely than failure to maintain *n*+1 contrasts. I.e. the smaller the number of contrasts maintained, the greater the violation. This encodes the fact that the number of contrasts should be maximized.

(3) MAINTAIN 1 CONTRAST >> MAINTAIN 2 CONTRASTS >> ... >> MAINTAIN *n* CONTRASTS

ii. *Maximize the auditory distinctiveness of contrasts*

The requirement that the auditory distinctiveness of contrasts should be maximized can be decomposed into a ranked set of constraints requiring a given minimum auditory distance between contrasting forms (4). Minimum distance requirements are specified independently for each auditory dimension, thus the constraint 'MINDIST$_{F1}$ = i-a' states that sounds that contrast in F1 should differ by a distance equal in magnitude to the F1 difference between [i] and [a].

(4) MINDIST$_{F1}$ = i-e, e-a >> MINDIST$_{F1}$ = >>... >> MINDIST$_{F1}$ = i-a

To encode the fact that auditory distinctiveness should be maximized, smaller minimum distance requirements are ranked above larger ones, i.e. the less distinct the contrast, the greater the violation.

*Balancing the requirements on contrasts*

The language-specific balance between the constraints on contrasts is modelled by interleaving them. For simplicity we will consider contrasts on independent auditory dimensions separately. That is, in addition to specifying minimal distance requirements by dimension, we will adopt separate sets of MAINTAIN CONTRAST constraints for each dimension. This allows us to consider the contrasts on a given dimension more or less independently of contrasts on other dimensions.

The interleaving of constraints on F1 contrasts is illustrated in (5). The constraints are listed in a column, from highest to lowest-ranked.

(5) MAINTAIN 1 F1 CONTRAST >>
MINDIST$_{F1}$ = i-e, e-a >>
MAINTAIN 2 F1 CONTRASTS >>
MINDIST$_{F1}$ = i-a,
MAINTAIN 3 F1 CONTRASTS

This ranking yields two F1 contrasts (i.e. three distinct vowel heights), as shown in the tableau in (6). We are considering constraints on contrasts, so the candidates evaluated here are sets of contrasting forms rather than outputs for a given input.

The winning candidate, with three vowel heights, maintains two contrasts, but violates the minimum distance requirement that sounds contrasting in F1 should differ by a distance of the magnitude i-a. However if we attempt to satisfy this constraint, maximizing distinctiveness, as in the second candidate, we violate the higher-ranked requirement that we maintain two F1 contrasts. It is not possible to fit two contrasts of this magnitude on the F1 dimension. The winning candidate also violates MAINTAIN 3 F1 CONTRASTS. If we try to satisfy this constraint, maximizing the number of contrasts as in the third candidate, we violate the high-ranked constraint MINDIST$_{F1}$ = i-e, e-a since the contrasts i-ɪ and ɪ-e are less distinct than this minimum.

(6)

| | MAINTAIN 1 F1 CONTRAST | MINDIST$_{F1}$ = i-e, e-a | MAINTAIN 2 F1 CONTRASTS | MINDIST$_{F1}$ = i-a | MAINTAIN 3 F1 CONTRASTS |
|---|---|---|---|---|---|
| > i-e-a | | | | * * | * |
| i-a | | | * ! | | * |
| i-ɪ-e-a | | * ! * | | * * * | |

Thus the particular balance achieved here between maximizing the number of contrasts and maximizing the distinctiveness of the contrasts yields two contrasts. Altering the ranking results in a different balance. For example, if greater weight is given to maximizing distinctiveness, ranking MINDIST$_{F1}$ = i-a above MAINTAIN 2 F1 CONTRASTS, the winning candidate has just one maximally distinct F1 contrast (7).

(7)

| | MAINTAIN F1 CONTRAST | MINDIST$_{F1}$ = i-e, e-a | MINDIST$_{F1}$ = i-a | MAINTAIN 2 F1 CONTRASTS | MAINTAIN 3 F1 CONTRASTS |
|---|---|---|---|---|---|
| i-e-a | | | * ! * | | * |
| > i-a | | | | * | * |
| i-ɪ-e-a | | * ! * | * * * | | |

iii. *Minimization of effort*

Considerations of effort minimization do not play a central role in the examples below, so we will not discuss it further.

In the present context, the important feature of the dispersion model is that a small set of contrasts is selected from a large space of possibilities by the constraints on contrasts. Thus there is no need to limit representational possibilities in order to account for restrictions on contrasts. In the context of the dispersion theory we can see the burden in this regard lies with the substantive theory of minimum distance requirements: Possible contrasts will be restricted by the smallest differences that can provide the basis for an adequate contrast. I.e. the range of attested contrasts is much smaller than the range of phonetic differences because many are too small to support a contrast.

Having established that adding detail to phonological representations does not lead to any problems for the theory of contrast, we can now turn to evidence that we do in fact need much more detail than is usually included in phonological representations. We will argue that coarticulation effects, which are not usually represented phonologically, are in fact phonological and involve mechanisms that are also operative in assimilation. The argument proceeds from the assumption that any factor that affects the distribution of contrasts, such as neutralization processes, must be phonological. We will see that coarticulation affects the distribution of contrasts and therefore must be specified in the phonology.

## 5. Doubly-conditioned assimilation: Cantonese vowel fronting

We now turn to the first type of phenomenon demonstrating that coarticulation can condition the distribution of contrasts, namely doubly-conditioned assimilation as exemplified by Cantonese vowel fronting. This case also demonstrates how categorical assimilation can arise from partial assimilation, due to the need to maintain distinctiveness.

In Cantonese, vowels are fronted between coronals. The evidence is distributional: back vowels do not appear between coronals, only front vowels can appear in this position (Cheng 1989, Kao 1971). Thus the contrasts between front and back rounded vowels is neutralized. Examples are given in (9) and the vowel phonemes of Cantonese are shown in (8).

(8)

| | | |
|---|---|---|
| i | y | u |
| e | ø | ɔ |
| | a,aː | |

(9)

| | | | | |
|---|---|---|---|---|
| $t^{h}$yt | ‘to take off’ | *$t^{h}$ut | $t^{h}$uk | ‘bald head’ |
| $t^{h}$øn | ‘a shield’ | *$t^{h}$ɔn | $t^{h}$ɔk | ‘to carry (on shoulders)’ |
| $t^{h}$it | ‘iron’ | | | |

Fronting of vowels by coronals is well attested (Hume 1992). We will analyze this process in terms of the acoustic feature [+high F2]. Coronals have [+high F2] transitions, and front vowels are [+high F2], so fronting of a vowel can result from extending the [+high F2] transitions of the coronal into the vowel (Flemming 1995).

(10)

| | i | y | u | t(transitions) |
|---|---|---|---|---|
| high F2 | + | + | - | + |

The important point about the vowel fronting is that it is doubly-conditioned, a single coronal does not front an adjacent vowel (9). Doubly-conditioned assimilation processes are problematic for standard autosegmental approaches. Spreading a feature from two sources onto a target only achieves the same result as spreading the feature from one source (11), so the role of the second source is unexplained.

(11)

```
  x   x   x               x   x   x
  |       |               |       |
[+back][+back]          [+back][+back]
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A straightforward account of the double-conditioning in Cantonese vowel-fronting can be given if we allow for finer distinctions than are available in representations such as those in (11). In outline, a coronal has a coarticulatory fronting effect on an adjacent vowel. The fronting effect of a single coronal is partial, so a back vowel is still sufficiently distinct from a front vowel to maintain a contrast. The cumulative partial fronting produced by two coronals is great enough that a contrast cannot be maintained, and neutralization of the F2 contrast results. We will formalize this part of the analysis in terms of minimum distance constraints. I.e. cumulative partial fronting would result in a contrast which violates minimum distance constraints, so it is preferable to neutralize the contrast. Thus the categorical nature of the assimilation results from the need for contrasts to be between distinct categories.

The other component required for this analysis is a means of representing the kind of partial assimilation involved in consonant-vowel coarticulation. This is the issue addressed in the next section, then we will formulate the analysis of vowel fronting.

## 6. 'Maximize duration of [αF]'

Since we are concerned with consonant-vowel coarticulation, the situation we need to represent involves the transition between a consonant and a vowel. We will adopt a simple model according to which transitions can be of 'short' duration or 'long', and mono-moraic vowels are consequently of 'normal', 'short' or 'very short' duration, as illustrated schematically in (12). A transition feature can also be extended throughout the vowel, altering its basic quality[1].

(12)

| Release transitions | Vowel | Approach transitions |
|---|---|---|
| short | normal | short |
| long | short | short |
| long | v. short | long |

We can then posit constraints favouring the maximization of the duration of transition features. We hypothesize that maximization of feature duration is preferred since this distributes the cues to a contrast over a greater duration, and thus makes it more distinct (cf. Cole and Kisseberth 194, Kaun 1995). For example, nasalizing a vowel adjacent to a nasal consonant means that the nasalization contrast is marked on both the vowel and the consonant, instead of just on the consonant.

Constraints favouring the maximization of the duration of transition features can be decomposed into a fixed ranking of constraints requiring increasing duration of the features (13). We have called the constraint that requires extending a transition feature through the vowel MAX F TRANSITIONS.

(13) SHORT F TRANSITIONS >> LONG F TRANSITIONS >> MAX F TRANSITIONS

The distinctions made in this model can be exemplified from patterns of nasal coarticulation with adjacent vowels. For example, in English vowels are significantly, but not fully nasalized adjacent to nasals. This situation is specified by the schematic constraint ranking in (14). The top-ranked constraint requires long [nasal] transitions, where '[nasal]' denotes the auditory cues to vowel nasalization. This constraint is satisfied since it is ranked above *NASAL VOWEL, a constraint against nasalizing vowels (The proper basis of this constraint is probably maximization of the distinctiveness of vowel quality since nasalization renders vowel quality less distinct (Wright

[1]These possibilities could be represented by specifying timing slots for release, vowel and approach. Normal transition features are associated to release or approach only (i), whereas long transitions are associated to the vowel slot also (ii, iii). However, a full analysis of transitions will probably require finer distinctions to be made.

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(i)   x x x      (ii)   x x x      (iii)   x x x
      | | |             | | |              | | |
      R V A             R V A              R V A
```

1980)). The vowel is not fully nasalized because MAX [NASAL] TRANSITIONS is ranked below this constraint.

(14) LONG [NASAL] TRANSITIONS >> *NASAL VOWEL >> MAX [NASAL] TRANSITIONS

Agwagwune differs from English in that nasal coarticulation is minimized because nasality is contrastive on vowels (Huffman 1988). The ranking for this situation is given in (15). Maintaining the vowel nasalization contrast is top-ranked, above having long [nasal] transitions, so short transitions result.

(15) MAINTAIN V [NASAL] CONTRAST >>
LONG [NASAL] TRANSITIONS,
MAX [NASAL] TRANSITIONS

Finally, in Malay nasality is extended from a nasal up to the next consonantal segment (Piggott 1992):

| | | | | |
|---|---|---|---|---|
| (16) | mãkan | ‘eat’ | mə̃laran | ‘forbid’ |
| | mã̃jãn | ‘stalk’ | mãʔãp | ‘pardon’ |

This results from a ranking along the lines shown in (17). MAX [NASAL] TRANSITIONS is ranked above the constraint against nasalizing non-consonantal segments *[NASAL, -CONS], so [nasal] is freely extended across such segments. Consonantal segments block the spread of nasality because *[NASAL, +CONS] is ranked above maximizing the duration of [nasal] transitions.

(17) *[NASAL, +CONS] >> MAX [NASAL] TRANS >> *[NASAL, -CONS]

Again this is only an outline of an analysis. The constraint against nasalizing consonants should presumably be replaced by constraints requiring the maintenance of voicing and nasalization contrasts in consonants. However, these three languages serve to illustrate the range of possibilities for durational extension of consonant transitions.

## 7. Doubly-conditioned assimilation: Cantonese vowel fronting

We can now formulate the analysis of Cantonese vowel fronting in terms of the constraint ranking in (18). The relative auditory distinctiveness of relevant auditory contrasts is given in (19), where superscript [$^y$] is used to indicate a long [+high F2] transition. This ordering is based on the assumption that a contrast is more distinct if the difference is maintained over a longer duration.

(18) LONG [+HIGH F2] TRANSITIONS >>
MINDIST$_{F2}$ = y-$^y$u,
MAINTAIN F2 CONTRAST >>
MINDIST$_{F2}$ = y-u,
MAX [+HIGH F2] TRANSITIONS

(19) Auditory distinctiveness: y-u > y-$^y$u > y-$^y$u$^y$

The highest-ranked constraint is LONG [+HIGH F2] TRANSITIONS, so partial fronting of a back vowel must apply, even though this results in a vowel contrast which is not maximally distinct (MINDIST$_{F2}$ = y-u is violated). Full fronting is required by MAX [+HIGH F2], but this outcome is blocked because it results in neutralization of the distinction between [u] and [y], in violation of higher-ranked MAINTAIN F2 CONTRAST (20).

When the back vowel is flanked by coronals, as in (21), [+high F2] must be extended from both consonants. The resulting very short period of low F2 is insufficient to meet the minimum distance requirements, so the front-back contrast among the rounded vowels is neutralized.

(20)

| | LONG [+HIGH F2] TRANSITIONS | MINDIST$_{F2}$ = y-$^y$u | MAINTAIN F2 CONTRAST | MINDIST$_{F2}$ = y-u | MAX [+HIGH F2] TRANSITIONS |
|---|---|---|---|---|---|
| tu -ty | *! | | | | * |
| > $t^y$u -ty | | | | * | * |
| ty | | | *! | | |

(21)

| | LONG [+HIGH F2] TRANSITIONS | MINDIST$_{F2}$ = y-$^y$u | MAINTAIN F2 CONTRAST | MINDIST$_{F2}$ = y-u | MAX [+HIGH F2] TRANSITIONS |
|---|---|---|---|---|---|
| tut -tyt | *!* | | | | * |
| $t^y$ut -tyt | *! | | | * | * |
| $t^y$u$^y$t -tyt | | *! | | * | * |
| > tyt | | | * | | |

In this analysis, the required assimilation of vowels to coronals is partial, as indicated by the lack of categorical fronting adjacent to a single coronal. The categorical fronting results from the requirement that contrasts be auditorily distinct. If partial assimilation were allowed to accumulate, the resulting contrast between front vowels and fronted back vowels would be relatively indistinct. To avoid this situation, the contrast is neutralized, resulting in categorical assimilation. In this way coarticulatory effects result in the neutralization of a contrast and so must be part of the phonology.

Cantonese vowel fronting is not an isolated case. Any instance of doubly-conditioned assimilation leads to the same conclusion. Another example is the raising of low vowels between two high vowels in Woleiaian (Sohn 1975, 29ff.; Suzuki, this volume) (22). In this case, an analysis in terms of cumulative partial assimilation is further supported by the fact that raising does not apply to long vowels (23). This outcome is expected given that the greater duration of a long vowel means that even long transitions at the onset and offset of the vowel will leave a sufficient duration unaffected to maintain a contrast with a mid vowel.

| | | | | |
|---|---|---|---|---|
| (22) | ita-ʃḙ | 'our name' | ite-i | 'my name' |
| | kailḙ | 'strong' | malʉ keilḙ | 'strong man' |
| (23) | i taai | 'I...no longer' | nigaausapḙ | 'area below eye' |

Other examples include Acehnese (Durie 1985) in which high back unrounded [ɯ] is rounded when flanked by labials.

Finally, it is important to note that there are two factors involved in the neutralization of F2 contrasts in Cantonese: The degree of assimilation conditioned by a single coronal consonant, and the minimum distance constraints on vowel F2 contrasts. The difference between Cantonese and a comparable language in which coronals do not condition fronting could lie in either of these factors. That is coronals might have a greater fronting effect in Cantonese, or Cantonese might place higher requirements on the minimum F2 distance adequate for a vowel contrast, or a combination of the two. In this analysis, we have hypothesized that both factors are involved, i.e. that coronals have 'long' [+high F2] transitions, and that Cantonese places fairly stringent distinctiveness requirements on F2 contrasts. However, this should not be taken as a strong prediction that coronals condition an exceptional degree of fronting in adjacent vowels. All that is required for an analysis along the proposed lines to be tenable is that F2 in back vowels is raised more between coronals than in other environments, and thus that F2 contrasts are more prone to neutralization in this environment. This is a safe assumption.

## 8. Sanskrit Ruki

The Sanskrit Ruki rule provides a rather different type of case in which coarticulation conditions the distribution of contrasts. In Ruki, dental [s] becomes retroflex [ʂ] in the environments shown in (24) (Whitney 1896). This results in the alternations in the form of the locative plural suffix shown in (25). This alternation is neutralizing, since [s] and [ʂ] contrast in other environments.

(24) s → ʂ / r, u, k, i _

(25) Locative plural suffix /-su/:

| | | | |
|---|---|---|---|
| jaː-su | ‘progeny’ | svasr̩-ʂu | ‘sister’ |
| marut-su | ‘wind’ | çatru-ʂu | ‘enemy’ |
| ap-su | ‘water’ | vaːk-ʂu | ‘voice’ |
| | | agni-ʂu | ‘fire’ |

The analysis of Ruki presents two related questions: What the conditioning environments have in common, and the basis of their connection to retroflexion. From an articulatory point of view, the environments do not appear to have anything in common, and [u, k, i] have nothing in common with the retroflexion they condition. The answer proposed here is that it is hard to maintain a distinction between [s] and [ʂ] following [r, u, k, i] due to coarticulation with these sounds. As a result, the contrast is neutralized (cf. Venneman 1972). That is, coarticulation of /s/ with each of these sounds results in sounds which are articulatorily distinct, but all of which are acoustically similar to retroflex [ʂ], so the distinction cannot be maintained in this environment.

The expected results of these articulatory assimilations are shown with approximate transcriptions in (26). The transcriptions are approximate in that they do not indicate the partial character of the assimilations. Retroflex [r] conditions retroflexion of the sibilant while the back rounded vowel [u] results in a rounded sibilant. The change from [s] to [ʃ] before the high front vowel [i] is a common pattern of palatalization. The same change would be conditioned by [k] because its back tongue position results in retraction of the fricative. As Whitney suggests, velars in Sanskrit were probably backed since they contrasted with palatals (op. cit., p. 15).

(26)
s → ʂ / r _
s → $s^w$ / u _
s → ʃ / k _
s → ʃ / i _

The results of these coarticulations, [ʂ, $s^w$, ʃ], are all similar: they are sibilants with a concentration of fricative noise in a similar frequency range, lower than that of [s]. This is basically because each has a larger front cavity than the dental, either through lip-rounding or tongue-tip retraction. The sounds [$s^w$, ʃ] are too similar to retroflex [ʂ] to maintain an adequate contrast, so they neutralize to the retroflex. Note that this case differs from Cantonese vowel fronting in that the coarticulation is not perceptually motivated. We assume that in this case coarticulation is motivated by minimization of effort, in that slower articulatory movements involve less effort.

We can formalize this analysis in terms of the constraint ranking in (27). The sounds /s/ and /ʂ/ contrast in Noise Frequency (NF), and the relative magnitudes of contrasts on this dimension are given in (28). The constraint COARTICULATE is a simplified formulation of the effort minimization constraints that favour sustaining the articulation of one segment into following segments. This constraint favours the assimilations outlined above.

(27) COARTICULATE, ‘Coproduce /s/ with preceding segment’
MINDIST$_{NF}$ = s-ʂ >>
MAINTAIN NF CONTRAST

(28) s-ʂ > ʃ-ʂ, $s^w$-ʂ

The tableau in (29) shows the case of the /s-ʂ/ contrast following [u]. Satisfying COARTICULATE requires rounding the /s/ which violates the minimum distance requirement on the contrast. The contrast is thus neutralized.

(29)

| | COARTICULATE | MINDIST$_{NF}$ = s-ʂ | MAINTAIN NF CONTRAST |
|---|---|---|---|
| us -uʂ | *! | | |
| $us^w$ -uʂ | | *! | |
| > uʂ | | | * |

The COARTICULATE constraint that motivates Ruki requires partial assimilations of the kind usually dismissed as coarticulation, but due to the minimum distance requirement on the contrast between /s/ and /ʂ/ the outcome is a neutralizing process. So according to this analysis coarticulatory processes condition the distribution of contrasts, and therefore must be included in the phonology.

## 9. Summary

We have seen that the theory of contrast provides no grounds for excluding phonetic detail from phonological representations. The proper criterion for inclusion in phonological representations is relevance to phonological processes. Cases of doubly-conditioned assimilation and Sanskrit Ruki provide evidence that coarticulation is relevant to uncontroversially phonological processes, and therefore must be represented in the phonology. This implies a considerable enrichment of phonological representations because coarticulation involves fine distinctions of quality and sub-segmental durations.

## References

Cheng, L. (1989) “Feature geometry of vowels and co-occurrence restrictions in Cantonese,” ms. MIT, Cambridge.

Cole, J. S. and C. W. Kisseberth (1994) “An optimal domains theory of harmony,” to appear in *FLSM V*.

Durie, M. (1985) *A grammar of Acehnese on the basis of a dilaect of North Aceh*, Foris, Dordrecht.

Flemming, E. S. (1995) *Auditory Representations in Phonology*, Doctoral dissertation, UCLA, Los Angeles, California.

Huffman, M. K. (1988) “Timing of contextual nasalization in two languages,” *UCLA Working Papers in Phonetics* 69.

Kao, D. L. (1971) *Structure of the Syllable in Cantonese*, Mouton, The Hague.

Kaun, A. (1995) *The Typology of Rounding Harmony: An Optimality Theoretic Approach*, Doctoral dissertation, UCLA.

Keating, P. (1984) “Phonetic and phonological representation of stop voicing,” *Language 60*.

Keating, P. (1990) “Phonetic representations in a generative grammar,” *Journal of Phonetics* 18, 321-34.

Keating, P. and A. Cohn (1988) “Cross-language effects of vowels on consonant onsets,” *JASA* 84, Suppl 1, S84.

Lindblom, B. (1986) “Phonetic universals in vowel systems,” in J.J. Ohala and J.J. Jaeger (eds) *Experimental Phonology*, Academic Press, Orlando, Florida.

Lindblom, B. (1990) “Phonetic content in phonology,” *PERILUS* 11.

Magen, H. (1984) “Vowel-to-vowel coarticulation in English and Japanese,” *Journal of the Acoustical Society of America* 75, S41.

Manuel, S. Y. and R. A. Krakow (1984) “Universal and language particular aspects of vowel-to-vowel coarticulation,” *Haskins Status Report on Speech Research* SR-77/78.

Manuel, S. Y. (1990) “The role of contrast in limiting vowel-to-vowel coarticulation in different languages,” *Journal of the Acoustical Society of America* 88, 1286-98.

Martinet, A. (1952) “Function, structure, and sound change”, *Word* 8:1.

McCarthy, J. J. (1994) “The phonetics and phonology of Semitic pharyngeals,” in P. Keating (ed.) *Papers in Laboratory Phonology 3*, CUP, Cambridge.

Öhman, S. E. G. (1966) “Coarticulation in VCV utterances: spectrographic measurements,” *Journal of the Acoustical Society of America* 39, 151-168.

Pierrehumbert, J. (1990) “Phonological and phonetic representation,” *Journal of Phonetics* 18, 375-94.

Piggott, G. (1992) “Variability in feature dependency: The case of nasality,” *Natural Language and Linguistic Theory* 10, 33-78.

de Rijk, R. (1970) “Vowel interactions in Bizcayan Basque,” *Fontes Linguae Vasconum* 2, 149-67.

Sohn, H. (1975) *Woleaian Reference Grammar*, University of Hawaii Press, Honolulu, Hawaii.

Venneman, T. (1972) “Sanskrit ruki and the concept of a natural class,” ms., UCLA.

Whalen, D. H. (1990) “Coarticulation is largely planned,” *Journal of Phonetics* 18, 1-35.

Whitney, W. D. (1896) *A Sanskrit Grammar (3rd ed.)*, Ginn and Co., Boston, Massachusetts.

Wright, J. (1980) “The behavior of nasalized vowels in the perceptual vowel space,” in *Report of the Phonology Laboratory* 5, UC Berkeley, California.

Zipf, G. K. (1949) *Human Behavior and the Principle of Least Effort,* Addison-Wesley, Cambridge, Massachusetts.