Perceptual sources for closed-syllable vowel laxing and derived environment effects

by
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Abstract

This dissertation claims that allowing perceptual factors to play a role in phonology helps make some progress on the understanding of two challenging phenomena: closed-syllable vowel laxing (CSVL), i.e. the tendency for vowels to be lowered and centralized before word-final and preobstruent consonants, and phonologically-derived environment effects (PDEEs), i.e. patterns where a phonological process is blocked unless accompanied by another phonological process. CSVL is challenging because the mechanism that relates vowel quality and the postvocalic context is not obvious. In particular, CSVL cannot be analyzed as a coarticulatory effect driven by vowel shortening. PDEEs are challenging because they imply that a smaller input-output change may be worse than a strictly larger one, in violation of a basic principle of faithfulness.

Part I proposes that CSVL is a strategy to enhance contrasts among postvocalic consonants in contexts where these consonants lack good release cues and are therefore perceptually weak. In particular, laxing is argued to enhance contrasts of place of articulation (e.g. contrasts involving [p], [t], [k]). This hypothesis is supported by the results of a perception experiment showing that, in French, [p], [t], and [k] are generally more distinct after lax mid vowels than after tense mid vowels. An analysis of CSVL is proposed using constraints on contrasts.

Part II proposes that PDEEs follow from the hypothesis that the input-output distance is perceived logarithmically: this predicts that a feature change may be less salient perceptually and therefore represent a smaller violation of faithfulness if accompanied by another feature change. This theory has two desirable consequences: it reconciles the analysis of PDEEs with the idea of a minimal input-output modification bias and it derives a number of perceptual constraints on the features that can interact in PDEEs, therefore providing a restrictive account of the typology.

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Part I

A theory of closed-syllable vowel laxing
Chapter 1

Introduction

1.1 Background

Phonotactic restrictions on permissible sequences of vowels and consonants are well known in phonology and have a phonetic basis in most cases (Kawasaki-Fukumori, 1992; Flemming, 2001). For instance, languages often ban consonant-vowel sequences consisting of a nasal consonant followed by an oral vowel. This restriction is found in Nupe (Niger-Congo): nasal vowels generally contrast with oral vowels (1-a), but the contrast is neutralized after nasal stops (1-b), where only nasal vowels can occur (Hyman, 1975 via Flemming, 2001). This restriction can be interpreted as resulting from a phonetic assimilation of the oral vowel to the adjacent nasal stop: [ma] is not attested because the nasal feature of [m] always spreads on a following [a].

(1) An example of phonetically-motivated phonotactic restriction on vowel-consonant sequences: Nupe.

   a. [bã] ‘to break’ - [ba] ‘to cut’
   b. [mã] ‘to give birth’ - *[ma]

The first part of this thesis focuses on a phonotactic restriction involving vowel-consonant sequences whose phonetic motivation is not obvious: closed-syllable vowel laxing, and the related pattern of open-syllable vowel tensing. Closed-syllable vowel
laxing describes the phonotactic restriction that bans tense vowels, i.e. vowels like [i u e o], in closed syllables. For instance, in Indonesian as spoken by speakers with a Javanese background, high and mid vowels must be lax before word-final consonants (2) (van Zanten, 1989).

(2) Vowel laxing before word-final consonants in Indonesian.

\[ \text{tit[ik]/*tit[ik]} \quad \text{‘dot’} \]

Open-syllable vowel tensing describes the phonotactic restriction that bans lax vowels, i.e. vowels like [i u e o], in open syllables. For instance, in the same variety of Indonesian, high and mid vowels must be tense word-finally (3).

(3) Vowel tensing in word-final position in Indonesian.

\[ \text{tit[i]/*tit[r]} \quad \text{‘bridge’} \]

The syllable-based terminology is not used in a technical sense but only as a convenient way to group segmental contexts in which tense and lax vowels occur. In Southern French for instance, the split between the contexts favoring tense mid vowels and the contexts favoring lax mid vowels broadly corresponds to the traditional distinction between open and closed syllables (Coquillon and Turcsan, 2012; Ey-chenne, 2014; Storme, 2017). Tense mid vowels occur in absolute word-final position (_#) and before consonants followed by vowels (_CV), glides (_CGV), or liquids (_CLV) (4-a). Lax mid vowels occur before word-final consonants (_C#) and before consonants followed by obstruents (_CO) (4-b). The former set of contexts corresponds to open syllables and the latter set to closed syllables, according to research on syllabification by French speakers (Goslin and Frauenfelder, 2000).

(4) Southern French

a. Mid-vowel tensing in open syllables.
b. Mid-vowel laxing in closed syllables.

- C#  sec  [sek]  ‘dry’
- CO  hectare  [ektas]  ‘hectar’

However, there is no claim that the sets of contexts favoring tense vs. lax vowels will always exactly correspond to the distinction between open and closed syllables in the technical sense. For instance, in some Southern French varieties, there is an exception to the generalization that mid vowels are tense in open syllables: in open syllables before schwa, mid vowels must be lax (5) (Eychenne, 2014; Storme, 2017).

(5) Mid-vowel laxing in open syllables before schwa in some Southern French varieties

saugrenu [sogʁəny]/*[sogənɔ̃] ‘absurd’

The syllable-based terminology is useful to describe the patterns succinctly and it is probably why it is so widely used in the literature dealing with patterns of vowel laxing and tensing. In this thesis, open syllables and closed syllables will generally be used as shortcuts to refer to contexts where vowels are in word-final position (_#) or before prevocalic consonants (_CV) vs. before word-final consonants (_C#) or before preobstruent consonants (_CO).

Closed-syllable laxing and open-syllable tensing are puzzling because the mechanism that relates vowel quality and syllable structure (or, in nonsyllabic terms, the postvocalic context) in VC sequences is far from obvious. Botma and Van Oostendorp (2012) propose vowel shortening as a mechanism relating laxing and syllable structure. This proposal is attractive because (i) vowels are often shorter in closed than in open syllables (Maddieson, 1985) and (ii) vowel quality depends on vowel duration, with shorter vowels being more coarticulated with adjacent segments (Lindblom, 1963).
However, there is a basic problem with an attempt to relate laxing and syllable structure via duration. Vowel shortening is generally characterized by raising (i.e. a decrease of the vowel’s first formant value), due to the increased degree of coarticulation with adjacent consonants: consonants generally have a more constricted articulation than vowels and therefore greater coarticulation results in vowel raising (Lindblom, 1963). However, vowel laxing is characterized by lowering (increase of the vowel’s first formant value), at least for nonlow vowels. This is illustrated in Figure 1-1 with Indonesian (data from speaker J1 in van Zanten, 1989, p. 72): tense vowels [i e u o] have lower first formant (F1) values than their lax counterparts [i e u o].

Raising of /a/ to [o] in closed syllables is often reported, for instance in Klamath (Barker, 1964 via Blevins, 1993), and can be treated as a coarticulatory effect, assuming that it is accompanied by vowel shortening. However, the lowering of nonlow vowels in closed syllables attested in languages like Indonesian clearly goes against the expected coarticulatory effect.

Laxing is also characterized by centralizing: lax vowels [i e u o] have less extreme
second formant (F2) values than their tense counterparts [i e u o] (see Figure 1-1).\(^1\) However, centralization is not expected to follow automatically from vowel shortening either. The patterns of vowel assimilation to a neighbouring consonant are expected to vary by consonant and by vowel but not to involve a general centralization (Lindblom, 1963). For instance, a front vowel (with a high F2 target) strongly coarticulated with a following [p] (with a low F2 target) should shift towards the center of the vowel space and become less front. However, if strongly coarticulated with a following [k] (with a very high F2 target), it should shift towards the periphery of the vowel space and become more front. Across-the-board centralization in closed syllables is mysterious from a purely coartculatory perspective.

*Closed-syllable vowel laxing* and *open-syllable vowel tensing* cannot be ruled out as phonetically unnatural phonological patterns because they are widespread cross-linguistically. They are reported in genetically diverse language families, including Austronesian (Blust, 2013, pp. 263-265), Germanic (Botma and Van Oostendorp, 2012), Niger-Congo (Lindau-Webb, 1987), and Romance (Féry, 2003) (see appendix A for a small, nonexhaustive survey). This suggests that they must be underlied by a single mechanism with a basis in universal principles of speech production or perception, like most other crosslinguistically widespread phonotactic restrictions. However, as reviewed above, the nature of this mechanism still remains mysterious.

One additional difficulty comes from the fact that languages with closed-syllable laxing vary as to which vowels they lax and before which coda consonants. In some languages, closed-syllable vowel laxing is very general. For instance, in the variety of Indonesian described earlier, all nonlow vowels are realized as lax [i u e œ] word-finally before all consonants (van Zanten, 1989). In other languages, vowel laxing is limited to specific vowels or/and to specific consonantal contexts. Sri Lanka Malay (Austronesian) has a six vowel inventory /i e ø a o u/ but closed-syllable vowel laxing only applies to mid vowels /e o/ (Nordhoff, 2009). In Chamorro (Austronesian), vowel laxing is quite general in its application. However, the phoneme /o/ is lowered and

---

\(^1\)F2 centralization is particularly strong for the lax front vowels [i e] with respect to their tense counterparts [i e].
centralized to [o] only before coda velars [k ɣ] (Topping, 1973, p. 21). Before other coda consonants, there is no laxing. This is illustrated in (6).

(6) Laxing of [o] before velars only: Chamorro.

/oppe/ ['oppi] ‘respond’
/toktuk/ ['taktuk] ‘hug’
/hotni/ ['hotni] ‘thread needle’

Other similar restrictions on the vowels that lax and the contexts triggering laxing can be found in appendix A.

A comprehensive theory of closed-syllable vowel laxing and open-syllable vowel tensing should both provide a mechanism relating vowel quality and the postvocalic context (or, in syllabic terms, syllable structure) and account for the cross-linguistic variation. This thesis will mainly focus on the former question but also provide some preliminary thoughts on the latter one.

1.2 Proposal

This thesis proposes an analysis according to which closed-syllable vowel laxing and open-syllable vowel tensing are patterns of contrast enhancement: enhancement of consonant contrasts and enhancement of vowel contrasts, respectively. Vowel laxing is proposed to be a strategy helping listeners recover the identity of postvocalic consonants, in particular the place of articulation of these consonants (e.g. labial vs. dental vs. velar). Laxing happens in contexts where informative cues signaling the postvocalic consonant’s place of articulation are independently missing and as a way to compensate for this absence. This analysis relies on two hypotheses. Vowel laxing happens before consonants lacking good release place cues (H1). Lax vowels provide better closure place cues in VC than tense vowels: consonant place contrasts are more distinct after lax vowels than after tense vowels (H2).

(H1) Laxing happens before consonants with weak release place cues.
(H2) Consonant place contrasts are more distinct after lax vowels than after tense vowels.

⇒ Laxing happens before consonants with weak place cues as a way to enhance poorly cued place contrasts.

Vowel tensing is proposed to follow from a default preference for good vowel contrasts. In the absence of any pressure from the consonantal context, vowels are realized as tense rather than lax because tense vowels are more distinct from each other than lax vowels (H3).

(H3) Tense vowels are more distinct from each other than lax vowels.

⇒ Tense vowels are preferred by default for better vowel dispersion.

The following sections present some basic motivations for these three hypotheses.

1.2.1 The role of consonant place contrasts

This section provides preliminary evidence for interpreting the contexts where vowel laxing happens as contexts where postvocalic consonants have weak release place cues (H1). It also motivates the hypothesis that lax vowels provide better closure cues to C-place contrasts in VC than tense vowels (H2).

(H1) Laxing happens before consonants with weak release place cues

There are multiple acoustic events which contribute to the identification of a consonant's place of articulation. They include formant transitions in adjacent segments with formant structure: release transitions (i.e. transitions occurring in the segment following the consonant) and closure transitions (i.e. transitions occurring in the segment preceding the consonant). They also include internal cues like the spectrums of the stop bursts (for oral stops), of the nasal resonances (for nasal stops) and of the frication noises (for fricatives) (Cooper et al., 1952; Delattre, Liberman, and Cooper, 1955; Dorman, Studdert-Kennedy, and Raphael, 1977; Dorman and Raphael, 1980).
The availability and quality of these cues typically differ in contexts which favor tense vowels vs. contexts which favor lax vowels. The evidence suggests that coda consonants (i.e. word-final consonants and preobstruents consonants) have weaker place cues than onset consonants. This evidence is reviewed in the following paragraphs.\(^2\)

The availability of *release transitions* for a consonant depends on the nature of the following segment. Release transitions can be expressed in this segment only if it has a formant structure. Word-final consonants (C#) are not followed by any segment within the same word and therefore lack release transitions by definition. Preobstruents consonants (CO) also lack release transitions because obstruents do not have formant structure. The two major contexts favoring vowel laxing in VC sequences (namely VC# and VCO or, in other words, coda contexts) are therefore contexts where release transitions signaling C-place are missing.

Release transitions have been shown to be particularly important for place identification (see Walley and Carrell, 1983 for stops, Malécot, 1956 for nasals, Harris, 1958 for low amplitude fricatives like [θ f]). As a consequence, contexts favoring laxing are typically contexts where a major cue to the place of the postvocalic consonant is missing.

The availability and quality of *internal cues* also differ in onset and coda positions. Onset stops systematically have internal cues whereas coda consonants have internal cues only when they are released (i.e. when their is an audible burst). There is also evidence that released coda stops have weaker bursts than onset stops in English: Redford and Diehl (1999) found that word-initial consonants were longer than word-final consonants and word-initial stops had a larger amplitude than word-final stops.

*Closure transitions* are the only cues that are systematically available for postvocalic coda consonants but not for onset consonants. However, they are weak place cues, at least for major places of articulation. For stops, the release transitions outweigh the closure transitions in place identification: if they provide conflicting cues,

---

\(^2\)The hypothesis that place contrasts are more distinct in onset than in coda has already been proposed as crucial to explain the typology of place neutralization (Steriade, 1999): neutralization of major place contrasts is favored in coda positions cross-linguistically.
listeners identify the place of articulation according to the release transitions (Fujimura, Macchi, and Streeter, 1978).

These differences in the availability of cues have an impact on listeners’ ability to correctly identify place in onset vs. coda positions. For instance, Redford and Diehl (1999) report higher error rate in the identification of word-final released stops [p t k] and fricatives [f s s] as compared to word-initial [p t k f s s] in English.³

(H2) Consonant place contrasts are more distinct after lax vowels than after tense vowels

Not all vowels provide equally informative closure transitions to signal consonant place in VC sequences. The clearest evidence for lax vowels providing better place cues to following consonants than tense vowels comes from Lisker’s (1999) study. Lisker reports data on the percentage of correct place identification in VC sequences in different vowel contexts in English, including after tense and lax vowels. The results about place identification after tense vowels [i u ei ow], lax vowels [i u e o], and low vowels [æ a] are reported in Table 1.1. The column ‘Average’ reports the percentage of correct identification across all three places. Percentages of correct identification equal to or lower than 80% are bolded.

³Not all confusions involve place in their results (e.g. [f]-[p] confusions are frequent), but place confusions increase specifically.
Table 1.1: Percent of correct identification in VC sequences (unreleased stops) in English (Lisker 1999).

<table>
<thead>
<tr>
<th>Context</th>
<th>Average</th>
<th>p</th>
<th>t</th>
<th>k</th>
</tr>
</thead>
<tbody>
<tr>
<td>Front</td>
<td>i_#</td>
<td>79</td>
<td>97</td>
<td>78</td>
</tr>
<tr>
<td></td>
<td>i_#</td>
<td>98</td>
<td>100</td>
<td>95</td>
</tr>
<tr>
<td></td>
<td>ej_#</td>
<td>80</td>
<td>89</td>
<td>54</td>
</tr>
<tr>
<td></td>
<td>e_#</td>
<td>98</td>
<td>95</td>
<td>98</td>
</tr>
<tr>
<td></td>
<td>æ_#</td>
<td>100</td>
<td>97</td>
<td>100</td>
</tr>
<tr>
<td>Back</td>
<td>u_#</td>
<td>74</td>
<td>92</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>u_#</td>
<td>97</td>
<td>100</td>
<td>97</td>
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<td></td>
<td>ow_#</td>
<td>80</td>
<td>93</td>
<td>98</td>
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<tr>
<td></td>
<td>œ_#</td>
<td>95</td>
<td>90</td>
<td>98</td>
</tr>
<tr>
<td></td>
<td>œ_#</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>

Lisker's data show that, overall, place identification is worse after tense vowels than after lax and low vowels. The average percentage of correct identification is never higher than 80% after tense vowels whereas it is never lower than 95% after lax vowels. The results for tense mid vowels [ej] and [ow] must be taken with caution. In languages with laxing, tense vowels do not generally have offglides and are realized as [ɛ] and [o]. Therefore, the results for English tense mid vowels do not necessarily generalize. However, for high vowels, the results are both as expected under (H2) and likely to generalize.

Why would lax vowels provide better cues to following place contrasts than tense vowels? In the following paragraphs, I provide some background on the effect of vowel quality (in particular, vowel backness and vowel height) on the shape of second and first formant transitions into the major places of articulation for consonants (labial, dental, velar) in VC sequences. I show how these results can account for some of Lisker's results and how they lead us to expect that place contrasts should be less distinct after tense than after lax vowels generally.

**F2 transitions.** Vowels adjacent to labial consonants are generally characterized by a
relatively low F2 value. Vowels adjacent to alveolar or dental consonants are generally characterized by a relatively high F2 value. Vowels adjacent to velars are generally characterized by a relatively high F2 value (at least for front vowels). However, the exact shape of the transition depends on the specific vowel context, in particular for [k]. [k] has the most variable F2 realization, followed by [p] and by [t] in this order (Stevens, Sharon, and Matthies 1999). Transitions are more or less similar depending on the vowel context and this acoustic similarity correlates well with perceptual results about place confusability (Ohala and Ohala, 2001). The F2 closure transitions from [i a u] to [p t k] are schematized in Figure 1-2.

![Figure 1-2: Schematized F2 VC transitions with V={i, a, u} and C = {labial, dental, velar}. Labials: dotted. Dentals: dashed. Velars: dashed and bold.](image)

In an [u] context, F2 transitions signaling [p] and [k] are very similar: they are
both level (see Figure 1-2a) (Halle, Hughes, and Radley, 1957; Delattre, 1958; Ohala and Ohala, 2001). This probably explains why [p] and [k] are particularly confusable after [u] in different languages (Ohala and Ohala, 2001 on Hindi, Marty, 2012 on French). Lisker’s (1999) results showing that English [k] was particularly hard to identify after [u] are also compatible with this explanation.\(^4\)

When going from [u] to [a] and [i], vowel F2 increases. The shape of the F2 transitions into [p] and [k] also changes (see Figure 1-2a vs. Figures 1-2b and 1-2c): the transition into [p] becomes falling and the transition into [k] becomes raising. As a consequence, the acoustic distance between the phonetic realizations of [k] and [p] increases. Laxing of back vowels involves fronting (or, equivalently, an increase in F2): [u] is more front than [u], and [o] is more front than [o]. This fronting is also expected to result in an increase in the acoustic distance between the transitions signaling [p] and [k], and therefore in a more distinct contrast.

Because of the high F2 target of [i], transitions signaling [p] and [t] are both falling in VC transitions (see Figure 1-2c). As a consequence, [p] and [t] are acoustically more similar after [i] than after [a] or [u]. The slope of the F2 transition into [k] is not as steep after [i] than after [a] (Dorman, Studdert-Kennedy, and Raphael, 1977). As a consequence, [k] and [t] are also acoustically more similar after [i] than after [a]. The acoustic results correlate with the perceptual results: [t] is found to be particularly confusable with [p] and [k] in the context of [i] (Winitz, Scheib, and Reeds, 1972; Lisker, 1999; Ohala and Ohala, 2001).

When going from [i] to less front vowels, vowel F2 decreases and, as a consequence, place contrasts involving [t] are expected to be more distinct. Laxing of front vowels involves backing (or, equivalently, a decrease in F2): [i] is more back than [i] and [e] is more back than [e]. This backing is also expected to result in an increase in the acoustic and perceptual distance between [t] and the two other consonants [p] and [k].

To summarize, as vowels are centralized along F2, place contrasts that are not

\(^4\)The fact that the percentage of correct identification for labial stimuli is not as low as expected probably means that listeners were biased to answer [p] when faced with a signal that was ambiguous between [p] and [k].
very distinct should become more distinct: there is more space to realize distinct F2 transitions in the center of the vowel space than in the periphery. The centralization observed in patterns of closed-syllable vowel laxing is therefore expected to improve the distinctiveness of some place contrasts.

**F1 transitions.** F1 transitions are also expected to be more distinct in lower vowels than in higher vowels (and therefore in lax vowels than in the corresponding tense vowels).

Vowels preceded by labial consonants are characterized by higher average F1 onset frequencies than vowels preceded by alveolar and velar consonants and vowels preceded by alveolar consonants are characterized by higher F1 onset frequencies than vowels preceded by velars (see Stevens, Sharon, and Matthies, 1999). However, these differences are visible in [a] contexts but not in [u] or [i] contexts (see Alwan, Jiang, and Chen, 2011 specifically on [p] vs. [t]). This plausibly follows from the fact that low vowels and consonants have very distinct F1 targets (high F1 targets for low vowels vs. low F1 targets for consonants) whereas high vowels and consonants both have low F1 targets. Lindblom’s (1963) model of coarticulation predicts that consonants will undershoot their formant targets more if adjacent to vowels with very distinct formant targets. In the present context, consonants (which have low F1 targets) will undershoot their targets more in the context of vowels with high F1 targets (i.e. low vowels) than in the context of vowels with low F1 targets (i.e. high vowels). Also, given that [p] has a relatively low resistance to F1 coarticulation, as can be inferred from the variability of its F1 locus (Stevens, Sharon, and Matthies, 1999), undershoot is expected to be stronger for [p]. As a result, the different F1 realizations of consonants are expected to be more distinct in the context of low than high vowels, as schematized in Figure 1-3.5

5Note that the results cited in this paragraph were established for CV transitions, but they can probably be extended to VC transitions.
How do these results about the similarity of F1 transitions in high vs. low vowels relate to laxing? Laxing is characterized by lowering. As vowels are lowered (F1 increases), consonants’ F1 realizations become more distinct. Therefore, if F1 plays a role in the perception of place,\(^6\) laxing should improve place distinctiveness.

To summarize, vowel centralizing should make place contrasts that are not very distinct in the context of peripheral vowels (e.g. \([p]-[k]\) in the context of back vowels and \([p]-[t]\) and \([k]-[t]\) in the context of front vowels) more distinct. Vowel lowering should generally increase the distance between the F1 realizations of consonants differing in place of articulation. Because laxing involves both centralizing and lowering, laxing should result in a general enhancement of postvocalic place contrasts.

### 1.2.2 The role of vowel contrasts

This section provides some basic motivation for the hypothesis that tense vowels are preferred by default because they are more distinct from each other than lax vowels (H3).

\(^6\)The role of F1 is more controversial than the role of F2: see Delattre, Liberman, and Cooper, 1955.
(H3) Tense vowels are more distinct from each other than lax vowels

The first two vowel formants correspond to the main dimensions of the similarity space for vowels: the further apart vowels are along the F1 and F2 dimensions, the more distinct they are (Delattre et al., 1952; Shepard, 1972; Plomp, 1975). The inventory of tense vowels is more dispersed along F1 and F2 than the inventory of lax vowels (see Figure 1-1) and is therefore expected to allow for better vowel discrimination. Focusing on the subinventories /i u a/ (with tense high vowels) and /ɪ u a/ (with lax high vowels), it is clear that the former inventory is better dispersed than the latter inventory: [i] and [u] are further apart from each other along F2 than [ɪ] and [u] and the F1 distances between tense high vowels and [a] are larger than the F1 distances between lax high vowels and [a]. In the inventory /ɪ u ɛ o a/ with lax high and mid vowels, the vowel space is particularly crowded in the low region: [ɛ] and [ɔ] are both close to [a] and relatively close to each other.

1.2.3 Preliminary dispersion-theoretic analysis

I briefly show how closed-syllable vowel laxing and open-syllable vowel tensing can be derived in a dispersion-theoretic framework, using a toy example with three vowels [a u u] and two consonants [p k] ([u] is a tense vowel and [u] is its lax counterpart). The analysis presented in this introduction is just meant to illustrate the basic principles of the proposal and will be refined in a later chapter.

Dispersion Theory is the name given to theories that derive restrictions on possible phoneme inventories and sound combinations from principles of maximal contrast (see Liljencrants and Lindblom, 1972). I use Flemming’s (2002) implementation of Dispersion Theory in Optimality Theory (Prince and Smolensky, 1993). Liljencrants and Lindblom’s (1972) hypothesis that contrast matters in sound patterns is reflected in the hypothesis that the selection of phonological inventories is subject to constraints on contrasts. Constraints on contrasts are paradigmatic constraints that penalize pairs of sounds that occur in a given context based on their perceptual distance. These constraints may be relativized to a context to reflect the observation that

27
perceptual distances between phonemes may vary across contexts. Here, two aspects of the contexts are relevant for place contrasts: whether the vowel is followed (this is what distinguishes open and closed syllables) and whether it has good closure cues (this is what distinguishes tense and lax vowels).

In the toy example with three vowels [a u u] and two consonants [p k], constraints on contrasts evaluate vowel contrasts (1-a) and consonant contrasts relativized to a particular vocalic and syllabic context (1-b). There are two distinct constraints *a-u and *a-u because the perceptual distance between [a] and [u] and between [a] and [o] differ: [a] is more distinct from [u] than from [o]. There are two distinct constraints *up-uk and *up-uk to reflect the hypothesis that the distinctiveness of [p] and [k] varies in coda position after [u] and after [u] (smaller after [u] than after [u]).

(7) Constraints on contrasts

a. Constraints on vowel contrasts
   (i) *a-u
   Penalize minimal pairs that only differ by [a] and [u].
   (ii) *a-u
   Penalize minimal pairs that only differ by [a] and [u].

b. Constraints on place contrasts in coda position (where release transitions are missing)
   (i) *up-uk
   Penalize minimal pairs that only differ by [up] and [uk].
   (ii) *up-uk
   Penalize minimal pairs that only differ by [up] and [uk].

The hypothesis that more distinct contrasts are preferred over less distinct contrasts is reflected in the rankings in (8-a) and (8-b). The constraint penalizing the less distinct [a] ~ [u] contrast outranks the constraint penalizing the more distinct [a] ~ [u] contrast. The constraint penalizing the less distinct [up] ~ [uk] contrast outranks

7One could also add a constraint *ap-ak. However, the two sequences should be very distinct (see Figures 1-2b and 1-3b) and therefore this constraint will be ranked far below *up-uk and *up-ok.
the constraint penalizing the more distinct \([up] \sim [uk]\) contrast.

(8) Rankings implementing the preference for more distinct contrasts

a. Preference for more distinct vowel contrasts

\[ *_{a-u} \gg *_{a-u} \]

b. Preference for more distinct place contrasts

\[ *_{up-uk} \gg *_{up-uk} \]

Tableau (9-a) shows how an inventory with tense \([u]\) in closed syllables is derived when vowel contrasts matter more than place contrasts, i.e. when it is worse to allow \([a]\) and \([u]\) to contrast than to allow \([p]\) and \([k]\) to contrast in coda position after \([u]\) \((*_{a-u} \gg *_{up-uk})\). The candidates that are evaluated by the grammar are sets of VC sequences. Tableau (9-b) shows how an inventory with lax \([u]\) in closed syllables is derived when place contrasts matter more than vowel contrasts, i.e. when it is worse to allow \([p]\) and \([k]\) to contrast in coda position after \([u]\) than to allow \([a]\) and \([u]\) to contrast \((*_{up-uk} \gg *_{a-u})\).

(9) Deriving closed-syllable vowel laxing as a trade-off between vowel dispersion and place dispersion

a. Vowel dispersion constraints outrank place dispersion constraints

<table>
<thead>
<tr>
<th></th>
<th>*_{a-u}</th>
<th>*_{a-u}</th>
<th>*_{up-uk}</th>
<th>*_{up-uk}</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\varepsilon)</td>
<td>ap ak up uk</td>
<td>**</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ap ak up ok</td>
<td>**</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\[ \text{Vowel contrasts} \quad \text{Place contrasts} \]

b. Place dispersion constraints outrank vowel dispersion constraints

<table>
<thead>
<tr>
<th></th>
<th>*_{up-uk}</th>
<th>*_{up-uk}</th>
<th>*_{a-u}</th>
<th>*_{a-u}</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\varepsilon)</td>
<td>ap ak up uk</td>
<td>*</td>
<td></td>
<td>**</td>
</tr>
<tr>
<td></td>
<td>ap ak up ok</td>
<td>*</td>
<td>**</td>
<td></td>
</tr>
</tbody>
</table>
1.3 Goals and outline

The theory of closed-syllable vowel laxing and open-syllable vowel tensing proposed in this thesis is attractive for the following reasons: it provides well-motivated mechanisms to relate vowel quality and the postvocalic consonantal context in VC sequences (i.e. enhancement of place contrasts) and to derive a default preference for tense vowels (i.e. enhancement of vowel contrasts). The success of this theory will depend on whether the following predictions are confirmed for specific patterns attested cross-linguistically:

Prediction 1: all consonants triggering laxing are involved in place contrasts.

Prediction 2: the release cues signaling place contrasts are less distinct in the contexts where preceding vowels are lax than in the contexts where they are tense.

Prediction 3: these place contrasts are more distinct after lax vowels than after tense vowels.

Prediction 4: tense vowels are more distinct from each other than lax vowels.

The main goal of this thesis is to test some of these predictions in French, where mid vowels are lax in closed syllables, according to the loi de position, and develop a basic dispersion-theoretic analysis. Although the French pattern will be the main focus of this thesis, other patterns will also be discussed and a basic account of some aspects of the cross-linguistic variation will be proposed. In particular, I will discuss how to derive the difference between across-the-board laxing vs. laxing before specific consonants.

Chapter 2 presents the results of a study investigating the acoustic correlates of the tense/lax distinction in a Southern French variety. The goal of this chapter is to better understand what the nature of the tense/lax distinction is, and in particular which between vowel duration and vowel quality is primary. As already previewed in this introduction, the quality of lax vowels cannot be derived from tense vowels' formant targets via vowel undershoot and therefore F1 and F2 targets must be specified for lax
vowels. Chapter 2 develops this argument using Southern French as primary source of evidence as well as other languages more anecdotally and provides evidence that the tense/lax distinction does not always involve two different durational targets.

Chapter 3 provides evidence for the four predictions laid out above and focuses more specifically on the hypothesis that closed-syllable vowel laxing is a place contrast enhancement strategy (Prediction 3). The evidence for this prediction comes from an experiment investigating the effect of vowel quality on the distinctiveness of \( [p t k] \) in coda position in French. The results of this experiment show that, for each pair of tense-lax mid vowels, two place contrasts among the three contrasts under consideration are more distinct after the lax mid vowel than after the tense mid vowel. No place contrast is found to be more distinct after the tense mid vowel than after the lax mid vowel. An acoustic study shows that the perceptual improvement after lax vowels correlates with an increase in the distance between the F1 realizations of the relevant consonants in this context, suggesting that vowel laxing is primarily a pattern of vowel lowering in French.

Chapter 4 develops a basic analysis of the patterns of open-syllable vowel tensing and closed-syllable vowel laxing in the framework of Dispersion Theory. In this chapter, I propose that across-the-board laxing and consonant-specific laxing are due to two different types of dispersion constraints. Contextual constraints evaluating the perceptual distance between two segments are used to derive vowel laxing before all consonants involved in a poorly cued contrast (e.g. French). Constraints evaluating the distance between diphones are used to derive vowel laxing only before some of the consonants involved in a poorly cued contrast (e.g. Chamorro).
Chapter 2

Vowel laxing as vowel lowering and centralizing: evidence from the French loi de position

2.1 Introduction

The main goal of this chapter is to better understand what the acoustic correlates of the tense/lax distinction are, and in particular to establish whether vowel quality or duration is primary in this opposition. This chapter investigates the acoustics of mid vowels in a French variety in which mid vowels follow the loi de position. The loi de position is the name given by French phonologists to the allophonic distribution of mid vowels observed in Southern French varieties, in which tense mid vowels [e ø o] are reported to occur in open syllables (1-a) and lax mid vowels [ɛ œ ɔ] in closed syllables (1-b) (Lyche, 2003; Coquillon and Turcsan, 2012; Eychenne, 2014).1

(1) The loi de position in Southern French varieties.
   a. Tense mid allophones occur word-finally.

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1Mid vowels [e ø o] and [ɛ œ ɔ] will be referred as tense vs. lax or close-mid vs. open-mid in this chapter.
b. Lax mid allophones occur before final consonants.
   fète [fet] 'party'
   meute [moet] 'herd'
   botte [bot] ‘boot’

In word-final syllables, French tense mid vowels are characterized by lower F1 values than their lax counterparts, [e] by a higher F2 value than [e], and [o] by a lower F2 value than [ɔ] (Delattre, 1969; Gottfried, 1984; Calliope, 1989; Gendrot and Adda-Decker, 2005; Ménard, Schwartz, and Aubin, 2008). This study aims to better establish the acoustic correlates of the tense and lax distinction in and beyond word-final syllables and to investigate how the *loi de position* interacts with the prosodic and consonantal contexts in which vowels occur. In particular, three important questions that are relevant to the general project about closed-syllable vowel laxing have not been investigated experimentally yet:

(2) Questions about the *loi de position*.

a. Does the *loi de position* hold both in word-final and nonfinal syllables?

b. Is the *loi de position* a pattern of vowel reduction induced by shortening?

c. Do only mid vowels follow the *loi de position*?

The distribution of tense and lax mid vowels in French is relevant from a cross-linguistic perspective, as a case of closed-syllable vowel laxing (Féry, 2003). The tense/lax distinction is often characterized as involving at least one of the three following acoustic dimensions: F1, F2, duration. Lax vowels have typically higher F1 values, more central F2 values, and shorter durations than tense vowels (e.g. van Zanten, 1989 and Adisasmito-Smith, 1999 on Indonesian). However, studies on tense vs. lax vowels do not always provide information about all three dimensions. For instance, acoustic studies of French mid vowels generally focus on vowel quality. As
a consequence, it is not clear whether all three dimensions always play a role and whether the tense/lax distinction primarily affects vowel quality or duration. Also, studies investigating the effect of syllable structure on vowels rarely control for the effect of coarticulation with neighboring consonants. For instance, vowel formants and durations are averaged across consonantal contexts in van Zanten’s (1989) and Adisasmito-Smith’s (1999) studies of Indonesian. The effect of syllable structure is therefore potentially confounded with the effect of the consonantal context.

The present chapter contributes to the research question on the acoustic correlates of the tense/lax distinction by providing a detailed analysis of a closed-syllable laxing language and carefully controlling for coarticulation. In the remainder of this introduction, the relevance of questions (2) for French phonology and for the typology of closed-syllable vowel laxing is motivated.

2.1.1 The loi de position in nonfinal syllables

The existence of distinct tense and lax mid allophones is clear in word-final syllables in Southern French varieties (see Table 1). However, it is still debated whether the loi de position holds beyond these contexts in Southern French (Lyche, 2003, p. 351).

Since vowels are shorter in nonfinal syllables than in word-final syllables in French (Delattre, 1966; O’Shaughnessy, 1984; Bartkova and Sorin, 1987) and shorter vowels are more subject to coarticulation with neighboring consonants (Lindblom, 1963), the loi de position could be overridden by coarticulatory effects in nonfinal syllables. For instance, Tranel (1987) claims that mid vowels are systematically realized as lax before nonfinal coda [y] but can be realized as tense or lax before other nonfinal coda consonants. Vowel-to-vowel coarticulation in V1CV2 sequences has also been claimed to override the effect of syllable structure word-medially in French, with mid vowels in V1 being realized as lax before nonhigh vowels in V2 (Tranel, 1987). However, Nguyen and Fagyal (2008) did not find this effect in Southern French and it will not be further investigated in the present study.
2.1.2 The *loi de position* and vowel duration

Answering question (2-b) is crucial to our understanding of the mechanism relating vowel quality and the syllabic/segmental context in the *loi de position* and more generally in closed-syllable laxing languages. Some phonological accounts take the *loi de position* to be a pattern of vowel reduction, with the relationship between mid-vowel quality and the syllabic/segmental context being mediated via vowel moraicity or duration (Féry, 2003; Lyche, 2003). However, this is still controversial, as some authors hold that the difference between close-mid and open-mid vowels is fundamentally a difference in aperture (Eychenne, 2014, p. 238). The duration-based analysis was also proposed by Botma and Van Oostendorp (2012) to account for the pattern of laxing in closed syllables cross-linguistically.

Lyche (2003) derives the complementary distribution of close-mid and open-mid vowels in Southern French from the following hypotheses: (i) tense mid vowels are bimoraic, (ii) lax mid vowels are monomoraic, and (iii) rimes are bimoraic. By (i) and (iii), tense mid vowels are predicted to occur only as nuclei of open syllables. By (ii) and (iii), lax mid vowels are predicted to occur as syllable nuclei only if a coda consonant provides the second mora needed to form a well-formed rime, namely in closed syllables.

There are several empirical problems with these hypotheses. First, while close-mid rounded vowels have been shown to be longer than their open-mid counterparts in positions where they contrast in Standard French (e.g., *côte* [kot] ‘coast’ vs. *cote* [kot] ‘rate’; see Gottfried and Beddor, 1988), it is unclear whether this durational difference extends to contrastive unrounded mid vowels in Standard French (e.g., *thé* [te] vs. *taie* [te]), and to French varieties where close-mid and open-mid vowels are in complementary distribution.

Second, while lowering of mid vowels is reported to happen across consonant types in word-final closed syllables in *loi de position* dialects, Bartkova and Sorin’s (1987) study of vowel duration in VC# contexts suggests that the effect of C is consonant-specific and can be either a shortening or a lengthening effect depending
on the consonant. This means that rimes probably do not have identical durations across the board and therefore the claim that all rimes are bimoraic is problematic. Hypothesis (iii) can be maintained if moraicity is disconnected from duration (Scheer, 2006), but this move makes the use of moraicity to explain the loi de position less appealing.

Hypotheses (i) and (ii) are also conceptually problematic. The hypothesis of an inherent relationship between vowel shortening and vowel laxing is at odds with the observation that vowels with higher F1 tend to be longer cross-linguistically (Lehiste, 1970). Lax mid vowels have higher F1 values than tense mid vowels in French: if anything, lax mid vowels are expected to be inherently longer than their tense counterparts. Also, this hypothesis is not supported by the evidence available on patterns of vowel undershoot in French. Gendrot and Adda-Decker (2005) found that, on average, French vowels are more centralized along F2 when shorter, but not necessarily lower. The average pattern of F1 undershoot is height dependent: with decreasing duration, high vowels have slightly higher F1 values, tense mid vowels do not vary along F1, and lax mid vowels and [a] have lower F1 values. Since tense mid vowels do not have higher F1 values when they become shorter, it is mysterious why shortening of mid vowels in closed syllables should be accompanied by an increase in F1.

The evidence available on the history of French does not suggest that the syllable-based distribution of mid vowels is related to a distinction in vowel duration (Spence, 1988). For instance, the front rounded mid vowel is always pronounced as [ø] in word-final open syllables regardless of whether the vowel was historically long (e.g., the suffix -eux) or short (e.g., peu ‘few’) and the front unrounded mid vowel is always pronounced as [ɛ] before consonants word-finally regardless of whether it was historically long or short, tense mid or lax mid.

Another reason to doubt that closed-syllable vowel laxing is driven by vowel shortening and assimilation to the following consonant is provided by languages where the lowering observed in closed syllables must be interpreted as blocking a reduction process. In Dupaninga Agta (Austronesian), mid vowels /e/ and /o/ raise to [ɪ] and [ʊ]
in unstressed open syllables (3-a), but raising is blocked in unstressed closed syllables (3-b) (Robinson, 2008, pp. 68-70). Similar patterns where a process of vowel reduction is blocked in closed syllables are found in Latin (Niedermann, 1985, pp. 18-31) and in Bedouin Hijazi Arabic (Al Mozainy, 1981) (see appendix A).

(3) Dupaningan Agta vowel reduction in open syllables.
   a. /o/ raises to [u] in unstressed open syllables.
      /pot-pot-an/ [potputan] 'pluck out'
   b. /o/ does not raise in unstressed closed syllables.
      /mag-pot-pot/ [magpotpot] 'harvest by plucking'

2.1.3 The loi de position and high vowels

A complete typology of closed-syllable vowel laxing should include a description of which vowels it applies to. A quick survey reveals that languages differ in allowing different subsets of their oral vowel inventories to have tense/lax allophones. Some languages are reported to have tense/lax allophones for all their oral vowels. For instance, Kuteb (Niger-Congo) has /ieaou/ vs. /iæou/ (Koops, 2009). In some languages, the tense/lax distinction only applies to vowels of a specific height, for instance to mid vowels only in Selaru (Austronesian; Coward, 1990) and Sri Lanka Malay (Austronesian; Nordhoff, 2009), to nonlow vowels only in Chamorro (Austronesian; Topping, 1973) and Kairiru (Austronesian; Wivell, 1981), to nonmid vowels only in Hiligaynon (Austronesian; Wolfenden, 1971). In other languages, subsets that cannot be characterized only in terms of height have tense/lax allophones: all oral vowels except [y] and [u] in Dutch (Trommelen, 1983), only [i]/[ɪ], [e]/[ɛ], and [o]/[ɔ] in Paluai (Austronesian; Schokkin, 2014), only high vowels and [ɔ]/[ɔ] in Hinuq (Forker, 2013).

French varieties with the loi de position belong to the set of languages with a height restriction on vowel laxing. However, to my knowledge, there is no acoustic study comparing the effect of syllable structure across oral vowels in these varieties. Since Québec French has high vowel laxing in closed syllables, characterized by an increase in F1 and F2 centralization (Martin, 2002; Côté, 2012), one may wonder
how high vowels pattern in other French varieties, and in particular in *loi de position* varieties.

2.1.4 Experiments and hypotheses

In this chapter, I report the results of three production studies that examine whether and how syllable structure affects oral vowel quality and duration across a range of consonantal and prosodic contexts in a variety of French in which mid vowels are reported to follow the *loi de position*. Experiment 1 looks at the realization of oral vowels before onset and coda [s] and [l] in word-medial and word-final positions. Experiment 2 looks at the realization of oral vowels before onset and coda [s] in word-medial and word-final positions. The choice of phonetic correlates of mid vowel quality was guided by prior research on French mid vowels. F1 and F2 are the main dimensions along which close-mid and open-mid vowels have been found to differ. Duration has also been argued to distinguish close-mid and open-mid vowels in the phonological literature.

The main hypotheses which were tested in this study are summarized in (H1) and (H2). (H1) is about the effect of the postvocalic consonantal context on vowel quality. (H2) is about the relationship between vowel quality and duration.

(H1) Closed-syllable vowel laxing applies to mid vowels but not to other vowels in word-final and word-medial positions.

(H2a) (weak) Closed-syllable vowel laxing is accompanied by closed-syllable vowel shortening.

(H2b) (strong) Closed-syllable vowel laxing is synchronically driven by closed-syllable vowel shortening.

(H2b) entails (H2a): for (H2b) to hold, (H2a) must hold and, in addition, the realization of vowels in open and closed syllables must be derivable from a single acoustic target for each vowel via duration-based undershoot. (H2b) will not be tested statistically but through an exploratory analysis of vowel-consonant coarticulation. If (H2b)
holds, it is expected that differences in vowel quality in open vs. closed syllables are entirely predictable from duration. In these analyses, it will also be explored whether variations in the magnitude of the effect of syllable structure on mid-vowel formants across prosodic contexts can be explained as resulting from coarticulation.

Section 2.2 presents the materials and methods used in Experiments 1 and 2. Section 2.3 presents the results. Section 2.4 concludes with a discussion of the results and their consequences for accounts of the loi de position and the typology of closed-syllable vowel laxing.

2.2 Materials and methods

2.2.1 Participants

20 speakers from Clermont-Ferrand, Auvergne (12 males, 8 females; aged 21-76, mean = 48 years, sd = 18 years) participated in Experiment 1 and eight speakers from the same city (6 males, 2 females; aged 19-59, mean = 26 years, sd = 13 years) in Experiment 2. The distribution of mid vowels follows the loi de position in the variety of French spoken in Auvergne. For instance, the name of the central square in Clermont-Ferrand, ‘Jaude’, is typically pronounced as [3d], instead of the more standard [3od]. Participation was voluntary. At the time of the recordings, all participants had been living in the Clermont-Ferrand area for more than twenty years except three of them, who were in their late twenties and were born and lived in Clermont-Ferrand until around the age of 20.

2.2.2 Stimuli and recordings

Participants in Experiment 1 were recorded pronouncing each of the seven oral vowels V in [i y u e/ɛ o/ɔ o/ɔ a] in Syllable|Consonant|Position = 8 conditions, with Syllable = {open, closed}, Consonant = {u, l}, and Position = {medial, final}. [u] and [l] were chosen because they are typical coda consonants in French and have different F1 and F2 targets: a higher F1 target and a lower F2 target for [u] than for
Medial syllables were used rather than initial syllables for the nonfinal syllable condition because they are shorter (Bartkova and Sorin, 1987) and thus provide a wider range of durations together with word-final syllables. Nonce words were used as stimuli in order to have a better control over the segmental context and to have a fully crossed design. Based on previous research, the prevocalic consonant is not expected to interact with the *loi de position*. Therefore, a unique consonant, [k], was used in prevocalic position.

The nonce words had the following shapes: \([\text{bakV}\{\text{i,l}\}\text{a}]\) (medial open syllable), \([\text{bakV}\#\{\text{i,l}\}\text{a}]\) (final open syllable), \([\text{bakV}\{\text{i,l}\}\text{ta}]\) (medial closed syllable), \([\text{bakV}\{\text{i,l}\}\#\text{ta}]\) (final closed syllable). The following spelling conventions were adopted: \([i]: <i>, [y]: <u>, [u]: <ou>, [e]: <ê>\) in open syllables, \(<e>\) in closed syllables, \([\text{o}/[\text{o}]\]: <eu>, [o]/[o]: <o>, [a]: <a>, [k]: <qu> before front vowels, <c> before back vowels.

The nonce words were introduced as place names in the following carrier sentences: \(\text{La ville de } _\text{- vendait le sel}\) (medial open/closed syllable conditions), \(\text{La ville de } _\text{- rachetait le sel}\) (final open syllable condition), \(\text{La ville de } _\text{- taxait le sel}\) (final closed syllable condition). Each stimulus was repeated five times by each speaker, yielding a total of \(20*5*7*8=5600\) vowels.

Participants in Experiment 2 were recorded pronouncing each of the seven oral vowels \([i\ y\ u\ c\ v\ o\ v\ a\] \(\text{in } |\text{Syllable}|^*|\text{Consonant}|^*|\text{Position}| = 4\) conditions, with \(|\text{Syllable}| = \{\text{open, closed}\}\), \(|\text{Consonant}| = \{s\}\), and \(|\text{Position}| = \{\text{medial, final}\}\). \([s]\) was chosen because \([sC]\) clusters are hetero-syllabic in French (Goslin and Frauenfelder, 2000) but have properties that set them apart from other hetero-syllabic clusters. In particular, they can occur in word-initial position in French. Also, they do not trigger laxing of preceding high vowels in Québec French (Côté, 2012). This raises the question of how they behave with respect to the *loi de position* in European French.

Nonce words were used as stimuli for the same reasons as in Experiment 1. The nonce words had the following shapes: \([\text{bakVs}a]\) (open medial syllable), \([\text{bakV}#\text{sa}]\) (open final syllable), \([\text{bakV}st\text{a}]\) (medial closed syllable), \([\text{bakV}#\text{sa}]\) (final closed syllable). The same spelling conventions were used as in Experiment 1. Nonce words
were introduced as place names in the following carrier sentences: *Les gens de _ vivaient dans les montagnes* (medial open/closed syllable conditions), *Les gens de _ s'adonnaient à l'opium* (final open syllable condition), *Le pays de _ abondait de diamants* (final closed syllable condition). Each stimulus was repeated three times by each speaker, yielding a total of \(8 \times 3 \times 7 \times 4 = 672\) vowels.

The recordings were made in a quiet room in Clermont-Ferrand with a table-mounted Shure SM58 connected to a computer via a Shure X2u XLR-to-USB signal adapter. The recordings were made using the Audacity software, with 44 kHz/16 bit sampling. The distance (approximatively 30 cm) and orientation of the participants to the microphone was held constant across all recording sessions.

### 2.2.3 Phonetic analyses

The recordings were first automatically segmented using the McGill Prosodylab text-to-speech aligner (Gorman, Howell, and Wagner, 2011). The segmentation was manually corrected to correspond to the criteria chosen in the study. All acoustic analyses were performed using the Praat software (Boersma and Weenink, 2017). Measures of vowel duration included the vocalic segment only and not the initial burst associated with consonant release. The end of the vowel was identified by the last periodic oscillation when the vowel was followed by an aperiodic sound (e.g., [s]) and by a change in intensity or formant trajectory otherwise (e.g., with [l] and some instances of [u]). Measurements of vowel first and second formants were made at vowel midpoint using a Praat script. The ceiling of the formant search range was set to 5500 Hz for female speakers and 5000 Hz for male speakers. Among the 5600 vowels recorded in Experiment 1, 99 were excluded from the analysis, either because they were misread (e.g., *bacura* was sometimes read as [bakura] instead of the expected [bakyra]) or formants could not be measured reliably. For one speaker, word-medial [i] tended to palatalize the preceding consonant and was not realized as a full vowel. For a handful of vowels, the formant measure at vowel midpoint was not reliable and another point close to the vowel midpoint was chosen instead. Among the 672 vowels recorded in Experiment 2, 11 were excluded from the analysis for the same reasons.
2.2.4 Statistical analyses

R (R Core Team, 2017) and lme4 (Bates, Maechler, and Bolker, 2014) were used to perform linear mixed effects analyses of the relationship between the response variables (F1, F2, Duration) and the categorical predictors (Height, Syllable, Position, Consonant) and their interactions in Experiments 1 and 2. The logarithm of vowel duration was used as dependent variable in the models instead of duration because duration was logarithmically distributed. In all models, the response variables were normalized by speaker (using the R function `scale`), as it helped model convergence. P-values were obtained using the lmerTest package (Kuznetsova, Brockhoff, and Christensen, 2015).

Height (a variable with 3 levels: high, mid, low) was used instead of Vowel (a variable with 7 levels) in the models. This is motivated by the hypotheses which are explicitly about height. This is also motivated by the finding that vowels of the same height have very similar F1 values within speakers in French (Ménard, Schwartz, and Aubin, 2008) and are expected to have similar durations since vowel duration is highly correlated with F1 (Lehiste, 1970; Escudero et al., 2009). Post hoc comparisons showed that the effects on F1 and duration which held for a group of vowels with the same height also held for each vowel individually, confirming that vowels of the same height are affected similarly by syllable structure.

For F2, separate models were run on three subsets of the data, {i, e/e, a}, {y, ø/œ, a}, and {u, o/ɔ, a}. This was done because the effect of syllable on F2 is expected to go in different directions for front unrounded vowels (lowering of F2) and back rounded vowels (raising of F2). In a single F2 model with Height as a variable, the two effects would cancel each other out and it would be impossible to assess the presence of any effect.

In the F1 and F2 models, the formants of high vowels in open syllables before word-medial [l] (Experiment 1) and word-medial [s] (Experiment 2) served as the baseline for comparison. This choice was motivated by the hypothesis that the effect of Syllable is the smallest in that context (see section 1.1) and to allow for a direct
comparison between high and mid vowels. In the duration model in Experiment 1, the duration of high vowels in open syllables before word-final [ү] was taken as the baseline. This choice was motivated by the post hoc observation that there is no significant effect of syllable on vowel duration in open syllables before word-final [ү] and therefore this context provides a natural baseline for comparison.

There were two external sources of nonindependence in the data: data came from different speakers and each nonce word was repeated several times by each speaker. One approach is to control for these effects by having by-subject and by-subject/by-repetition random intercepts and random slopes for all the predictors and their interactions (Barr et al., 2013). However, the models with full random effect structures did not converge. The random structure was chosen so as to both control for the effects of theoretical interest (in particular the effect of Syllable on Height) and to allow for model convergence. The by-speaker random effect structure included subject-specific intercepts and random slopes for the effect of Consonant, Position, Syllable, Height, and the interaction of Syllable and Height.

The effect of repetition is expected to mainly affect vowel duration, if subjects speak faster as the experiment proceeds, and secondarily vowel formants, as a consequence of duration-induced vowel undershoot. However, models allowing for different speakers to have different mean vowel durations and formant values across the different repetitions were not found to improve model fit as compared to models without these effects. Therefore, no by-subject/by-repetition random effect was included in the models.

2.3 Results

2.3.1 Experiment 1

Figure 2-1 summarizes the distribution of the seven oral vowels over the F1xF2 space in final/medial open/closed syllables across speakers in Experiment 1. The results are comparable with previous studies for word-final syllables. In addition, the vowel space
is smaller word-medially than word-finally (Delattre, 1969; Gendrot and Adda-Decker, 2005; Meunier and Espesser, 2011), attracted to the top left corner before medial [l] and to the bottom right corner before medial [r], in accordance with previous studies on the influence of [l] and [r] on neighbouring vowels (Delattre, 1969; Chafcouloff, 1985).

Figure 2-1: Mean vowel F1 and F2 in Hz (with standard deviations) in final/medial open/closed syllables before [l]/[r] across speakers

**F1.** The results for F1 are shown in Figure 2-2. The output of the statistical model for the syllable effect is shown in Table 2.1. High and mid vowels have significantly higher F1 values in closed than in open syllables in all contexts except word-medially before [l] for high vowels. The effect of syllable is larger for mid vowels than for high vowels in all contexts. The effect of syllable is modulated by the coda consonant and by word-position: it is smaller in word-medial than in word-final position, and before [l] than before [r]. The low vowel patterns differently from high and mid vowels: its F1 value is not increased in closed syllables.
Figure 2-2: Vowel F1 (in Hz) in final/medial open/closed syllables before [l]/[u] across speakers. Inside each plot, the boxes indicate the inter-quartile range (IQR), the range between the first and third quartile. The horizontal line indicates the median. The whiskers indicate the range, up to 1.5 times the IQR away from the median. Dot outside the whiskers lie more than 1.5 times the IQR away from the median and are potential outliers.
Table 2.1: Effect of syllable on vowel F1 (F1 values centered by subject). The effect Syllable (in the first row) indicates the increase in F1 for high vowels in closed syllables compared to open syllables word-medially before [l]. Interactions in subsequent rows show how the effect of syllable differs in the context appearing as the rightmost element in the interaction and in the corresponding baseline context. Significant effects are boldfaced.

F2. The results for F2 are shown in Figure 2-3. Only peripheral mid vowels [e] and [o] have systematically different F2 values in open and closed syllables. Tables 2.2 and 2.3 show the effect of syllable on [e] and [o] across the four contexts. The baselines in Tables 2.2 and 2.3 are high vowels [i] and [u], respectively. Front unrounded mid vowels have significantly lower F2 realizations and back rounded mid vowels have significantly higher F2 realizations in closed syllables than in open syllables across medial and final positions before [l] and [u]. The distances between allophones are larger word-finally than word-medially.
Figure 2-3: Vowel F2 (in Hz) in final/medial open/closed syllables before [l]/[u] across speakers.

<table>
<thead>
<tr>
<th></th>
<th>Estimate</th>
<th>Standard Error</th>
<th>t value</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Syllable</td>
<td>-0.05</td>
<td>0.05</td>
<td>-1.15</td>
<td>0.26</td>
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<tr>
<td>Syllable:Mid</td>
<td>-0.16</td>
<td>0.05</td>
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<td>&lt;0.01</td>
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<td>Syllable:Position</td>
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<td>0.04</td>
<td>0.48</td>
<td>0.63</td>
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<td>Syllable:Position:Mid</td>
<td>-0.16</td>
<td>0.05</td>
<td>-3.04</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Syllable:Consonant</td>
<td>-0.04</td>
<td>0.04</td>
<td>-0.96</td>
<td>0.34</td>
</tr>
<tr>
<td>Syllable:Consonant:Mid</td>
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<td>0.05</td>
<td>-0.76</td>
<td>0.45</td>
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<tr>
<td>Syllable:Position:Consonant</td>
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<td>0.05</td>
<td>-1</td>
<td>0.32</td>
</tr>
<tr>
<td>Syllable:Position:Consonant:Mid</td>
<td>0.12</td>
<td>0.07</td>
<td>1.58</td>
<td>0.11</td>
</tr>
</tbody>
</table>

Table 2.2: Effect of syllable on peripheral high and mid front unrounded vowels’ F2 (F2 values centered by subject). The estimate in the first row (Syllable) indicates the increase in [i]’s F2 in closed syllables compared to open syllables word-medially before [l].
Table 2.3: Effect of syllable on peripheral high and mid back rounded vowels’ F2 (F2 values centered by subject). The estimate in the first row (Syllable) indicates the increase in [u]’s F2 in closed syllables compared to open syllables word-medially before [l].

<table>
<thead>
<tr>
<th></th>
<th>Estimate</th>
<th>Standard Error</th>
<th>t value</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Syllable</td>
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<td>0.05</td>
<td>1.7</td>
<td>0.1</td>
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<td><strong>Syllable:Mid</strong></td>
<td>0.28</td>
<td>0.06</td>
<td>4.74</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Syllable:Position</td>
<td>0.08</td>
<td>0.05</td>
<td>1.78</td>
<td>0.08</td>
</tr>
<tr>
<td><strong>Syllable:Position:Mid</strong></td>
<td>0.22</td>
<td>0.06</td>
<td>3.46</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Syllable:Consonant</td>
<td>0.02</td>
<td>0.05</td>
<td>0.41</td>
<td>0.68</td>
</tr>
<tr>
<td>Syllable:Consonant:Mid</td>
<td>-0.06</td>
<td>0.06</td>
<td>-0.92</td>
<td>0.36</td>
</tr>
<tr>
<td>Syllable:Position:Consonant</td>
<td>-0.11</td>
<td>0.06</td>
<td>-1.75</td>
<td>0.08</td>
</tr>
<tr>
<td>Syllable:Position:Consonant:Mid</td>
<td>0.06</td>
<td>0.09</td>
<td>0.69</td>
<td>0.49</td>
</tr>
</tbody>
</table>

**Duration.** Figure 2-4 shows the effect of syllable on vowel duration across the four contexts. The model output is shown in Table 2.4. Vowels are consistently shorter in closed syllables than in open syllables except in word-final position before [i]. The shortening effect is the largest in medial position before [i]. In word-medial position, the shortening effect is larger on nonhigh vowels than on high vowels.
Figure 2-4: Vowel duration (in ms) in final/medial open/closed syllables before [l]/[v] across speakers.
Syllable | Estimate | Standard Error | t value | p-value |
--- | --- | --- | --- | --- |
Syllable | -0.57 | 0.06 | -9.5 | <0.01 |
Syllable:Mid | 0.1 | 0.06 | 1.75 | 0.08 |
Syllable:Low | 0.1 | 0.08 | 1.28 | 0.2 |
Syllable:Position | 0.25 | 0.05 | 4.59 | <0.01 |
Syllable:Position:Mid | -0.33 | 0.08 | -4.26 | <0.01 |
Syllable:Position:Low | -0.39 | 0.11 | -3.58 | <0.01 |
Syllable:Consonant | 0.5 | 0.05 | 9.13 | <0.01 |
Syllable:Consonant:Mid | 0.12 | 0.08 | 1.57 | 0.12 |
Syllable:Consonant:Low | -0.12 | 0.11 | -1.13 | 0.26 |
Syllable:Position:Consonant | -1.05 | 0.08 | -13.6 | <0.01 |
Syllable:Position:Consonant:Mid | 0.15 | 0.11 | 1.35 | 0.18 |
Syllable:Position:Consonant:Low | 0.09 | 0.15 | 0.58 | 0.56 |

Table 2.4: The effect of syllable on vowel duration (log ms centered by subject). Syllable (in the first row) indicates the increase in duration for high vowels when going from open to closed syllables word-finally before [l]. The estimate is negative in this context, which indicates that high vowels are shortened.

Summary. Mid vowels are lower and peripheral mid vowels are more central in closed than in open syllables across the four contexts in Experiment 1, in accordance with (H1). High vowels were also found to have higher F1 values in closed syllables than in open syllables, except word-medially before [l]. However, this effect is smaller than for mid vowels and it does not affect high vowels' F2, contrasting with the Québec French pattern of high vowel laxing where both F1 and F2 are affected and the effect of syllable structure is larger.

Vowels are generally shorter in closed syllables than in open syllables, in accordance with H2, except word-finally before [s]. The fact that word-final [s] patterns differently could be due to a difficulty to measure vowel duration in this context. In Standard French, the rhotic tends to be realized as a voiced fricative word-finally and as a voiceless fricative word-initially (Laëtifer, 1987 via Fougeron, 2007). The presence of voicing word-finally would tend to make vowel duration harder to measure.
(consistent with the higher variability for this condition in Figure 2-4) and would likely result in closed-syllable measurements including more of the following consonant than open-syllable measurements (where the following consonant is word-initial and voiceless). This could help explain why this particular condition is different from the others in durational terms. An inspection of the spectrograms revealed that this hypothesis is plausible: word-final [ɪ] tends to be voiced and word-initial [ɻ] voiceless, resulting in a clearer boundary between the vowel and the following [ɹ] with word-initial [ɪ] than word-final [ɻ].

In the next section, I explore whether the different realizations of mid vowels in open vs. closed syllables and across prosodic and consonantal contexts can be analyzed as resulting from coarticulation, assuming fixed F1 and F2 targets for mid vowels across the board. Although small F1 differences were found for high vowels in open vs. closed syllables in most contexts, it will be assumed that high vowels have the same F1 target in open and closed syllables.

**Exploratory analysis of coarticulation.** If variations in the realizations of mid vowels in open vs. closed syllables are driven by closed-syllable vowel shortening (at least in the contexts where closed-syllable vowel shortening is clear, i.e. in all contexts except word-finally before [ɹ]), it is expected that differences in vowel quality should disappear when duration is controlled for. In a given consonantal and prosodic context, close-mid and open-mid allophones should converge to the same vowel target as duration increases and the relation between duration and vowel quality should be continuous and monotonic across the two sets of allophones. If variations in the realizations of vowels across prosodic contexts result from vowel undershoot, word-medial and word-final vowels should converge to the same target in a given consonantal context and the relation between duration and vowel quality should also be continuous and monotonic across the two sets of allophones. If variations in the realizations of vowels across consonantal contexts also result from vowel undershoot, pre-[ɹ] and pre-[ɻ] vowels should converge to the same target as duration increases. Also, vowels' F1 and F2 realizations are expected to become closer to the F1 and F2 targets of the following consonant as vowel duration decreases. The targets for [ɹ] and [ɻ] were not
estimated, but [ə] is known to have a higher F1 target and a lower F2 target than [l] (Delattre, 1959; Chafcouloff, 1985).

Figure 2-5 shows how vowel F1 varies as a function of vowel height, vowel duration, vowel position in the word, and the following consonant. Mid vowels in open syllables and in closed syllables are distinguished as close-mid vs. open-mid.

![Figure 2-5: Vowel F1 as a function of vowel duration, vowel height, vowel position, and following consonant. F1 and Duration are scaled by speaker. The lines indicate the trends for each level of height. Vowels in medial syllables are shown in dark gray, and vowels in final syllables are shown in light gray.](image)

The relationship between vowel duration and vowel quality for mid vowels across syllable types is not consistent with an undershoot account: close-mid and open-mid vowels clearly point to different F1 targets as vowel duration increases and the two sets do not lie on a continuum. This speaks against (H2b) and suggests that mid vowels have not only different F1 realizations but also different F1 acoustic targets in open and closed syllables.

However, the relationship between vowel duration and vowel F1 across prosodic
and consonantal contexts is consistent with an undershoot account, where vowels have the same F1 targets across consonantal and prosodic contexts. Vowels are shorter in word-medial than in word-final syllables. Vowel F1 converges toward a smaller value before [l] than before [u] as vowel duration decreases and this trend is visible among medial vowels and among final vowels and for each height. This is compatible with a coarticulatory effect since [l] has a lower F1 target than [u]. Also, vowels with F1 targets further away from the consonant target are more coarticulated (the slope is steeper) than vowels with closer F1 targets: [a] undershoots more its target in the [l] context and high vowels undershoot more their targets in the [u] context. This is also consistent with a coarticulatory effect of [l] and [u] on vowel F1. Vowel F1 converges to the same value for each level height across consonants, suggesting that there is a single vowel F1 target for each height level in both cases. These facts suggest that mid-vowel allophones are closer to each other in nonfinal syllables because they are more affected by coarticulation.

Figure 2-6 shows how vowel F2 varies as a function of vowel identity, vowel duration, and the following consonant. To improve readability, only the linear trends (with standard errors) are shown.
Figure 2-6: Vowel F2 as a function of vowel duration, vowel identity, and following consonant. F2 and Duration are scaled by speaker. To improve readability, only the linear trends (with standard errors) are shown.

As for F1, the relationship between vowel duration and vowel F2 for peripheral mid vowels across syllable types is not consistent with an undershoot account: peripheral close-mid and open-mid vowels clearly point to different F2 targets as vowel duration increases and the two sets do not lie on a continuum. This also speaks against (H2b) and suggests that peripheral mid vowels have not only different F2 realizations but also different F2 acoustic targets in open and closed syllables.

However, the relationship between vowel duration and vowel F2 across consonantal and prosodic contexts is consistent with an undershoot account. As vowel duration decreases, vowel F2 converges to a larger value with [l] than with [u], except for [a], whose F2 value varies in a similar way in the two contexts. As in the case of F1, excluding [a], slopes are generally steeper for vowels which are further away from the consonantal target everything else being equal. For instance, the slope for [u] is steeper than the slope for [i] in the [l] context and the slope for [i] is steeper than the
slope for [u] in the [s] context. This is consistent with a coarticulatory effect of [l] and [s] on vowel F2, at least for nonlow vowels. Vowel F2 converges to the same value for each vowel across consonants, suggesting that there is a single vowel F2 target for each vowel in both cases.

### 2.3.2 Experiment 2

Figure 2-7 summarizes the distribution of the seven oral vowels over the F1 x F2 space in final/medial open/closed syllables across speakers in Experiment 2. The general distribution of the vowels in the acoustic space is comparable with the results in the pre-[l] context in Experiment 1: vowels with high F1 values or low F2 values word-finally show less extreme formant realizations word-medially.

![Figure 2-7: Mean vowel F1 and F2 in Hz (with standard deviations) in final/medial open/closed syllables before [s] across speakers.](image)

**F1.** The results for F1 are shown in Figure 2-8. The output of the statistical model is shown in Table 2.5. Mid vowels have higher F1 values in closed than in open
syllables before [s] both word-medially and -finally, and the distance between mid-vowel allophones in open and closed syllables is larger word-finally. High vowels have higher F1 values in closed syllables than in open syllables only word-finally and the effect is smaller than for mid vowels. As in Experiment 1, the low vowel patterns differently from high and mid vowels: its F1 value is not increased in closed syllables.

Figure 2-8: Vowel F1 (in Hz) in final/medial open/closed syllables before [s] across speakers.
Table 2.5: Effect of syllable on vowel F1 (F1 values centered by subject). The estimate in the first row (Syllable) indicates the increase in high vowels' F1 in closed syllables compared to open syllables word-medially. Interactions in subsequent rows show how the effect of syllable differs in the context appearing as the rightmost element in the interaction and in the corresponding baseline context.

<table>
<thead>
<tr>
<th></th>
<th>Estimate</th>
<th>Standard Error</th>
<th>t value</th>
<th>p-value</th>
</tr>
</thead>
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<tr>
<td>Syllable</td>
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<td>-0.79</td>
<td>0.44</td>
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<td>Syllable:Mid</td>
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<td>5.46</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Syllable:Low</td>
<td>0.06</td>
<td>0.22</td>
<td>0.27</td>
<td>0.79</td>
</tr>
<tr>
<td>Syllable:Position</td>
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</tr>
<tr>
<td>Syllable:Position:Mid</td>
<td>0.14</td>
<td>0.1</td>
<td>1.38</td>
<td>0.17</td>
</tr>
<tr>
<td>Syllable:Position:Low</td>
<td>-0.39</td>
<td>0.14</td>
<td>-2.75</td>
<td>0.01</td>
</tr>
</tbody>
</table>

F2. The results for F2 are shown in Figure 2-9. Only peripheral mid vowels have significantly different F2 values in open and closed syllables. The outputs of the statistical models for front unrounded and back rounded vowels are shown in Table 2.6 and Table 2.7, respectively. Peripheral mid vowels have significantly more central F2 realizations in closed than in open syllables across medial and final positions. The F2 realizations of other vowels are not significantly affected by syllable structure. The F2 distance between [e] and [ɛ] is significantly larger word-finally than word-medially.
Figure 2-9: Vowel F2 (in Hz) in final/medial open/closed syllables before [s] across speakers.

<table>
<thead>
<tr>
<th>Syllable</th>
<th>Estimate</th>
<th>Standard Error</th>
<th>t value</th>
<th>p-value</th>
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<tbody>
<tr>
<td>Syllable</td>
<td>-0.05</td>
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<td>-0.73</td>
<td>0.47</td>
</tr>
<tr>
<td>Syllable:Mid</td>
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<td>-2.58</td>
<td>0.02</td>
</tr>
<tr>
<td>Syllable:Low</td>
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<tr>
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<tr>
<td>Syllable:Position:Low</td>
<td>0.11</td>
<td>0.1</td>
<td>1.12</td>
<td>0.26</td>
</tr>
</tbody>
</table>

Table 2.6: Effect of syllable on peripheral high and mid front unrounded vowels’ F2 (F2 values centered by subject). The estimate in the first row (i.e., Syllable) indicates the increase in [i]’s F2 in closed syllables compared to open syllables word-medially.
Table 2.7: Effect of syllable on peripheral high and mid back rounded vowels' F2 (F2 values centered by subject). The estimate in the first row (Syllable) indicates the increase in [u]'s F2 in closed syllables compared to open syllables word-medially.

**Duration.** The results for duration are shown in Figure 2-10. No vowel was found to have a significantly different duration in open and closed syllables word-medially or word-finally. A likelihood ratio test was performed and showed that adding syllable structure as a fixed effect does not significantly improve model fit ($\chi^2 = 13.47$, df=14, p=0.49).
Figure 2-10: Vowel duration (in ms) in final/medial open/closed syllables before [s] across speakers.

**Summary.** Mid vowels have consistently higher F1 values and peripheral mid vowels have consistently more central F2 values in closed than in open syllables before [s], in accordance with (H1). Mid vowels are never shorter in closed than in open syllables, against (H2a). Because (H2b) entails (H2a), these results speak also against (H2b). These results are consistent with the results of Experiment 1, with the following difference: coda [s] does not trigger vowel shortening in word-medial or in word-final syllables. As in Experiment 1, the F1 and F2 distances between close-mid and open-mid allophones tend to be larger word-finally than word-medially. In the next section, I explore whether these variations can be analyzed as resulting from coarticulation.

**Exploratory analysis of coarticulation.** As a dental fricative, [s] is expected to have a relatively small F1 target and a relatively high F2 target. Figure 2-11 shows how vowel F1 varies as a function of vowel height, vowel duration, and vowel position in the word before [s].
The relationship between vowel duration and vowel F1 for mid vowels across syllable types is not consistent with an undershoot account: close-mid and open-mid vowels clearly point to different F1 targets as vowel duration increases and the two sets do not lie on a continuum. This speaks specifically against (H2b).

However, the relationship between vowel duration and vowel F1 across word-medial and word-final positions is consistent with an undershoot account. Vowels are shorter in medial than final syllables. F1 values converge toward a relatively low value and become more similar with decreasing duration. This trend is visible among final and medial syllables. [a] undershoots more its target than other vowels. These results are consistent with a pattern of undershoot. This is consistent with vowels having the same F1 target across word-medial and word-final contexts.

Figure 2.3.2 shows how vowel F2 varies as a function of vowel identity and vowel duration in the word before [s].
F2 as a function of vowel height and duration before [s]. F2 and Duration are scaled by speaker.

As vowel duration decreases, F2 values converge to a high region in F2. Slopes are generally steeper for vowels with more extreme formant values (e.g. for [o] and [u]). This is consistent with a coarticulatory effect of [s] on vowel F2. This is consistent with vowels having the same F2 target across word-medial and word-final contexts.

2.4 General discussion

2.4.1 Acoustic correlates of the tense/lax mid distinction

One of the major results of this study is that mid-vowel lowering and centralizing do not entail mid-vowel shortening in French. This is at odds with phonological accounts of the loi de position as a phenomenon of vowel reduction. These accounts further assume that there is an inherent relation between shorter duration and laxing, understood as an increase in F1 and F2 centralizing. However, the patterns of vowel
undershoot observed in French by Gendrot and Adda-Decker (2005) and in the present study cast a doubt on this connection. The present study showed that the patterns of undershoot vary by consonant, as expected under Lindblom's (1963) model, and do not necessarily involve an increase in F1 (this only happens with [u]). Also, tense and lax mid vowels do not converge to the same acoustic targets as vowel duration increases.

The results are compatible with tense and lax mid vowels having different F1 and F2 targets, but not necessarily different durational targets, at least in French varieties obeying the *loi de position*. [ø] and [œ] were not found to have different F2 targets. This is consistent with other studies which only report an effect of syllable structure on the F2 of peripheral mid vowels. High vowels were found to have a higher F1 value in closed syllables than in open syllables, except in word-medial positions before dental segments ([s] and [l]). This is also the context where the F1 distances between mid-vowel allophones were the smallest. This suggests that the *loi de position* also affects high vowels. However, the effect on high vowels is smaller than for mid vowels and does not affect F2. Syllable structure was found to have a very different effect on [a] vs. nonlow vowels. In particular, [a] was sometimes found to have a lower F1 value in closed than in open syllables. This happens in particular in contexts with closed-syllable vowel shortening in Experiment 1, suggesting that the raising of the low vowel in closed syllables can be due to vowel undershoot.

The *loi de position* can probably not be reduced to an increase in F1 while analyzing the centralizing of F2 for peripheral mid vowels as a by-product of this increase, due to the bell shape of the vowel space. The space of vowels which can be produced by the human vocal tract is assumed to display a front-back asymmetry (Liljencrants and Lindblom, 1972). If F2 centralizing followed from an increase in F1 alone, the F2 distance between [o] and [œ] would probably be smaller than the F2 distance between [e] and [ɛ]. But the centralizing effect does not appear to be asymmetric between front

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2Standard French has close-mid/open-mid vowel contrasts in penultimate syllables before schwa and these contrasts involve duration, with [o] and [ɔ] being longer than [a] and [œ] respectively (Gottfried and Beddor, 1988). Therefore durational targets must be specified for close-mid and open-mid vowels in this variety of French.
2.4.2 Vowel duration

The results suggest that vowel duration is determined by vowel height, with duration(high) < duration(mid) < duration(low), and by the context in which vowels occur. The effect of the context appears to be largely independent of vowel height: vowels are shorter in word-medial than in word-final positions and vowels are shortened before coda liquids (setting aside the case of the word-final rhotic) but not before coda [s]. These findings are consistent with previous research on the role of height (Lehiste, 1970; Escudero et al., 2009), word-position (Delattre, 1969; O'Shaugnessy, 1984), and coda-consonant manner (Katz, 2012) on vowel duration. Katz (2012) showed a similar asymmetry between liquids and obstruents in English: English vowels followed by a liquid-voiced obstruent cluster (e.g., [dilb]) are shorter than those followed by a singleton liquid (e.g., [dil]) but this cluster-driven compression does not obtain for similar pairs containing obstruents (e.g., [dis] vs. [disp]) in place of the liquid.

2.4.3 Coarticulation

Another important result of this study is that the open-mid/close-mid distinction holds across different consonantal contexts and both word-medially and word-finally. Together with Nguyen and Fagyal's (2008) finding that vowel coarticulation does not override the effect of the loi de position in Southern French, the results of this study suggest that coarticulation is in general not strong enough to neutralize the allophonic distribution of close-mid and open-mid vowels.

The exploratory analysis of coarticulation suggests that it is likely that the differences in the allophonic distances between mid-vowel allophones in medial and final syllables can be explained in terms of vowel undershoot. It is possible that differences across consonants are to be explained this way as well. As long as consonants have different F1 and F2 targets and different effects on vowel duration, it is expected that
patterns of vowel undershoot will vary across consonants. For instance, the F1 target for [l] appears to be between the F1 targets for close-mid and open-mid vowels whereas the F1 target for [u] appears to be similar to the target for open-mid vowels. This alone could explain why F1 distances between close-mid and open-mid allophones are smaller before [l] than [u] word-medially: in the case of [l], both close-mid and open-mid vowels are moving closer to each other when assimilating to [l], whereas in the case of [u], only the close-mid vowels will shift towards the open-mid vowels. Another fact that could explain the difference between [l] and [u] word-medially is the overall longer duration of vowels before medial onset [u] than medial onset [l].

The patterns of coarticulation described in this study might be responsible for the uncertainty reported in the phonological literature as to whether the loi de position holds word-medially. Because F1 and F2 distances between close-mid and open-mid vowels are generally smaller word-medially, the allophonic distribution should be harder to detect by ear in that context. Also, I found that close-mid vowels and open-mid vowels may have similar realizations in different consonantal contexts due to coarticulation: for instance, the F1 of open-mid vowels before coda [l] was found to be similar to the F1 of close-mid vowels before onset [u] (see Figure 2-2). Failing to carefully control for the consonantal context when assessing the close-mid vs. open-mid quality of a word-medial vowel might therefore lead to overlook the actual effect of syllable on mid vowels.

Another language shows evidence for cooccurrence of closed-syllable vowel laxing and vowel lowering due to coarticulation: Thao (Austronesian; Blust, 2013, p. 264, Blust, 2003, pp. 26-27). In this language, a tense high vowel preceding or following an [r] is realized as a tense mid vowel (4-a) and a high vowel in closed syllables is realized as lax in closed syllables (4-b). When high vowels are in closed syllables and adjacent to [r], the two processes cumulate: high vowels are realized as lax mid vowels [e] or [o] (4-c).

(4) A language with vowel lowering due to coarticulation and closed-syllable vowel laxing: Thao
a. High vowel lowering preceding or following /r/
   /rima/  [rema]  ‘five’
   /iruf/  [erof]  ‘saliva’

b. High vowel laxing in closed syllables
   /fifnan/  [fifnan]  ‘milky water left over after washing rice’

c. High vowel laxing and lowering in closed syllables with r environment
   /ripnu/  [repnu]  ‘five’

2.4.4 Consequences for the typology of closed-syllable vowel laxing

The patterns of vowel reduction documented in the present study and elsewhere (e.g. Gendrot and Adda-Decker, 2005) do not point towards an inherent relationship between shortening and laxing (understood as F1 raising and F2 centralizing). As vowel duration decreases, vowel formants assimilate more to the consonantal context. Because most consonants have high F1 targets, like [l] and [s], vowel reduction for mid vowels in closed syllables should not result in an increase in F1 in most coda contexts. Assuming that patterns of coarticulation are qualitatively similar across languages and roughly follow Lindblom’s (1963) model, this means that laxing is unlikely to be due to shortening, even in languages in which closed-syllable laxing is always accompanied by closed-syllable shortening.

2.5 Conclusion

The primary goal of this chapter was to better establish the role of F1, F2, and duration in the close-mid/open-mid distinction in a French variety in which mid vowels follow the loi de position. The results indicate that mid vowels are consistently lower and peripheral mid vowels more central in closed syllables than in open syllables, but not shorter. Allophonic distances between close-mid and open-mid vowels vary in different prosodic and consonantal contexts and these variations are compatible with an undershoot analysis. From a typological perspective, the results indicate
that closed-syllable vowel laxing cannot be generally conceived as a pattern of vowel reduction and that vowel quality can be affected by syllable structure independently of vowel duration.
Chapter 3

Vowel laxing as a strategy to enhance place contrasts: evidence from the French *loi de position*

3.1 Introduction

The preceding chapter (i) has established that vowel laxing in closed syllables in French involves vowel lowering (increase in F1) and vowel centralizing (centralizing along F2) but not necessarily shortening and (ii) has argued against an analysis of patterns of laxing as vowel reduction. These results imply that duration cannot be the mechanism relating vowel quality and syllable structure in the patterns of closed-syllable vowel laxing and open-syllable vowel tensing.

In the introduction, it was proposed that closed-syllable vowel laxing and open-syllable vowel tensing are patterns of contrast enhancement. Vowel laxing was proposed to happen before consonants with weak place cues as a way to enhance poorly cued place contrasts. Vowel tensing was proposed to follow from a default preference for good vowel contrasts: in the absence of any pressure from the consonantal context, vowels are realized as tense rather than lax because tense vowels are more distinct from each other than lax vowels. This account relies on the three hypotheses repeated
(H1) Laxing happens before consonants with weak release place cues.

(H2) Consonant place contrasts are more distinct after lax vowels than after tense vowels.

⇒ Laxing happens before consonants with weak place cues as a way to enhance poorly cued place contrasts.

(H3) Tense vowels are more distinct from each other than lax vowels.

⇒ Tense vowels are preferred by default for better vowel dispersion.

The goal of this chapter is to apply this theory to French and, in particular, provide evidence for (H2). In chapter 1, (H2) was motivated using evidence from English, where, on average, place contrasts were found to be more distinct after lax high vowels than after tense high vowels (Lisker, 1999). In this chapter, the focus will be on mid vowels. Lisker's (1999) results about the confusability of place contrasts after English tense mid vowels do not necessarily generalize to other languages as English tense mid vowels have offglides whereas other languages (including French) generally do not.

Lisker's (1999) study has another limitation. The data about the effect of vowel quality on postvocalic place contrasts are presented as percentages of correct identification. Percentages of correct identification are hard to interpret because they do not provide information about the specific consonants that are hard to distinguish or about listeners' bias to give a particular response. In this chapter, this limitation will be addressed by using Luce's (1963) Biased Choice Model, which makes it possible to get estimates for perceptual distances between specific sounds and estimates for response bias from confusion matrices.

As discussed in chapter 2, laxing only applies to mid vowels in the Southern French variety under study and it is reported to apply before all coda consonants. As a consequence, the current theory makes the following predictions:
Prediction 1: all consonants triggering laxing are involved in place contrasts.

Prediction 2: the release cues signaling place contrasts are less distinct in the contexts where preceding mid vowels are lax than in the contexts where they are tense.

Prediction 3: these place contrasts are more distinct after lax vowels than after tense vowels.

Prediction 4: tense vowels are more distinct from each other than lax vowels.

In the remainder of this introduction, preliminary evidence for Predictions 1, 2, and 4 is provided and Prediction 3 is discussed. The study testing Prediction 3 is presented after the introduction.

Prediction 1: all consonants triggering laxing are involved in place contrasts

The consonants that occur in word-final position in French are shown in Table 3.1. Mid vowels are realized as lax before all these consonants when they are in word-final position. Two consonants occur elsewhere in French and are not attested word-finally: the glides [w] and [q] (in parentheses in Table 3.1).

<table>
<thead>
<tr>
<th></th>
<th>Labial</th>
<th>Dental</th>
<th>Postalveolar</th>
<th>Palatal</th>
<th>Velar</th>
<th>Uvular</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stop</td>
<td>p</td>
<td>b</td>
<td>t</td>
<td>d</td>
<td>k</td>
<td>g</td>
</tr>
<tr>
<td>Nasal</td>
<td>m</td>
<td>n</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fricative</td>
<td>f</td>
<td>v</td>
<td>s</td>
<td>z</td>
<td>j</td>
<td></td>
</tr>
<tr>
<td>Approximant</td>
<td></td>
<td>l</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Glide</td>
<td>(w, q)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3.1: French consonants

Because mid vowels are lax before all the word-final consonants in Table 3.1, the current theory predicts that all these consonants should be involved in place contrasts (see Prediction 1 above). Is this plausible?
For each manner of articulation, there are several places of articulation. For instance, word-final stops are labial, dental, or velar; word-final nasals are labial, dental or palatal, etc. There are two exceptions: there is only one approximant and one glide that can occur word-finally (i.e. [l] and [j]). However, although these two consonants are not involved in place contrasts in the traditional sense in coda position, they are likely to be confusable with each other because French [l] is clear (i.e. with a relatively high F2 target; Chafcouloff, 1985). One of the dimensions that may play a role in the confusion is F2, i.e. one of the main acoustic correlates of place (Delattre, Liberman, and Cooper, 1955). Some languages provide indirect evidence that clear [l] and [j] are confusable. In Cibaeño (a dialect of Dominican Spanish), the phonemes /l/ and /j/ are neutralized and realized as [j] in some environments (Guitart, 1981). Data about phonological neutralization may be used as indirect evidence about perceptual similarity: phonemes that neutralize are typically phonemes that are similar (see Flemming, 2017 among others). To my knowledge, no language neutralizes dark [l] (characterized by a low F2; see Recasens and Espinosa, 2005) and [j]. This is expected if what drives the neutralization of clear [l] and [j] is F2 similarity: [j] is more similar to clear [l] along F2 than to dark [l].

**Prediction 2: vowel laxing happens before consonants with weak release place cues**

Because mid vowels are lax before the consonants in Table 3.1 when these consonants are in word-final or preobstruent position but tense otherwise, the current theory predicts that the consonants’ release cues are less informative about place of articulation in word-final or preobstruent position than in other contexts (see Prediction 2 above). Is this plausible?

C-place contrasts are less distinct perceptually word-finally than prevocally for released stops, fricatives, and nasals (Redford and Diehl, 1999; Repp and Svastiskula, 1988). Glides and liquids provide release transitions that can cue the place of articulation of a preceding consonant (Flemming, 2007; Bakst and Katz, 2014) whereas obstruents do not.
Clear [l] and [j] are neutralized word-finally (1-a) but not prevocally (1-b) in some languages.

(1) Cibaeño (Dominican Spanish dialect) (Guitart, 1981)
   a. papel [papej] ‘paper’
   b. papeles [papeles] ‘papers’

Because contexts that favor contrast neutralization are typically contexts where contrasts are less distinct perceptually (Flemming, 2017), this suggests that clear [l] and [j] are less distinct word-finally than prevocally.

It is less clear which place contrast involving [s] is less distinct word-finally and before obstruents than in other contexts. [s] was found to be less distinct from the null segment word-finally and before [t] than prevocally (Storme, in press). These results support the hypothesis that there is an onset vs. coda perceptual asymmetry for [s] but they do not provide evidence about a specific place contrast involving [s] that is less distinct in coda than in onset. Data from loanword adaptations suggest that [s] could be confusable with [k] in coda position: coda [s] is adapted as [k] in Vietnamese (2) (Kang, Pham, and Storme, 2016). Therefore, the contrast between [k] and [s] may be relevant. More work is needed to answer this question.

(2) Adaptation of French coda [s] and [k] as [k] in Vietnamese
   a. corset [kɔʁse] > côc xe [kɔːk̚seː] ‘bra’
   b. biftek [biʃtek] > bìp ték [biʃˈtek] ‘beef steak’

In some Southern French varieties, mid vowels are also lax in open syllables before schwa (3-a). This is not the case in all French varieties: in Standard French for instance, mid vowels are tense in open syllables before schwa (3-b).

(3) a. hôtelier [ɔtɔlje] ‘hotel-adj’ (in some Southern French varieties)
    b. hôtelier [ɔtɔlje] ‘hotel-adj’
In Storme (2017), I propose that the special behavior of schwa is due to its short duration. This proposal is based on the observation that speakers who lax mid vowels in open syllables before schwa have shorter schwās than speakers who do not. In this paper, I hypothesized that short schwās trigger laxing of preceding mid vowels in VCw sequences because short schwās provide shorter and therefore less informative release transitions than longer vowels.

**Prediction 4: tense vowels are more distinct from each other than lax vowels**

The current theory predicts that mid tense vowels are more distinct from each other than lax mid vowels (see Prediction 4 above). Lax mid vowels are more central along F2 than tense mid vowels and, as a consequence, lax vowels are acoustically closer to each other than tense vowels (see chapter 2). Because F2 is one of the main dimensions of the similarity space for vowels, tense mid vowels should be perceptually more distinct than lax mid vowels.

**Prediction 3: place contrasts are more distinct after lax vowels than after tense vowels**

To my knowledge, no study has investigated the effect of tense mid vs. lax mid vowels on postvocalic place contrasts in French (see Prediction 3). Some studies have investigated the effect of vowel height and backness on place contrasts in French and provide preliminary evidence for the hypothesis that (some) place contrasts are more distinct when consonants are adjacent to lower and more central vowels. Benoit, Mohamadi, and Kandel (1994) report higher percentages of correct identification of consonants [b v z ɹ l] in nonce words of the shape VCVCV when V=[a] than when V=[i] or [y]. Marty (2012) reports smaller perceptual distance between burstless [k] and burstless [p] word-finally after back rounded vowels [u o] than after front vowels [e a i].

also finds that the vowel effect depends on the presence of a burst: there is no vowel effect if the burst is present. This is potentially problematic for the hypothesis...
that vowel laxing is an enhancement strategy in French. French final stops are released. Why should laxing be attested in a language where final stops are released if the presence of the burst neutralizes the vowel effect? Vowel quality may still play a role in natural speech: bursts are masked by noise whereas vowel formants are more robust to noise (e.g. Alwan, Jiang, and Chen, 2011). Vowel enhancement may play a role in noisy conditions.

To test whether mid-vowel laxing improves postvocalic place contrasts, a perception experiment was conducted. Section 3.2 describes the results of an acoustic study comparing the F1 and F2 realizations of [p t k] in coda position after the ten French oral vowels. Section 3.3 describes the results of a perceptual study using the same stimuli to investigate the effect of vowel quality on the perceptual distinctiveness of place contrasts.

### 3.2 Acoustic study

This section presents a study of the first and second formant transitions from the ten French oral vowels [i y u e o ð ø o ð o a] into the three voiceless stops [p t k]. The goal of this study is to determine whether the vowel context affects the acoustic similarity of these transitions and, more specifically, whether the transitions into coda [p t k] are acoustically more distinct following lax mid vowels [C ð o] than following tense mid vowels [e ø o].

#### 3.2.1 Methods

Two Standard French native speakers (a female and a male) were recorded uttering CVC2 nonsense syllables, with V in [i y u e ø o ð ø o ð o a] and C1 and C2 in [p t k]. Each of the 90 syllables was repeated three times by each speaker, yielding a total of 540 syllables. All syllables were phonotactically licit syllables for those speakers, except for the C1eC2 syllables. In Standard French, tense rounded mid vowels [Ø] and [ø] are licit in word-final closed syllables (e.g. *côté* [kot] and *meute* [møt]) but the unrounded tense mid vowel [e] is not. In order to control that CeC syllables were not uttered
with extra care due to their special phonotactic status, acoustic measurements were made to verify that their formant values and durations were sensible.

Recordings were done in a sound-attenuated booth, using a head-mounted Shure SM35-XLR microphone connected to a computer via a Shure X2u XLR-to-USB signal adapter. The recordings were made using the Audacity software, with 44 kHz/16 bit sampling. The distance (approx. 5 cm) to the microphone was held constant across the recording session. Vowels were manually segmented using Praat. Measures of vowel duration included the vocalic segment only and not the initial burst associated with consonant release. The end of the vowel was identified by the last periodic oscillation.

In order to test the hypothesis about the effect of the vowel context on the distinctiveness of place contrasts, measurements of F1 and F2 were made at the vowel offset, defined as the point located five milliseconds before the end of the vowel. The distances between the formant measures at the vowel offset before [p], [t], and [k] were taken as measures of the acoustic distinctiveness of place contrasts in the different vowel contexts. Measurements of F1 and F2 were also made at vowel midpoint to verify that the vowels were pronounced as expected based on previous research on French. All acoustic analyses were performed using the Praat software (Boersma and Weenink 2017). The ceiling of the formant search range was set to 5500 Hz for the female speaker and to 5000 Hz for the male speaker.

The formant frequencies were transformed in order to better correspond to the auditory frequencies. The Hertz values were transformed into Bark values using the following formula from Schroeder et alii (1979) ($x$ corresponds to the frequency in Hertz and $y$ to the frequency in Bark). The formant frequencies were also normalized by speaker (using the R function `scale`).

$$y = 7 \times \ln \left( \frac{x}{650} + \sqrt{1 + \left( \frac{x}{650} \right)^2} \right)$$

R (R Core Team, 2017) and lme4 (Bates, Maechler, and Bolker, 2014) were used to perform linear mixed effects analyses of the relationship between the response
variables (F1, F2) and the categorical predictors (Height, Backness, C2) and their interactions. The details of the models will be provided in the next section with the results.

### 3.2.2 Results

Figure 3-1 summarizes the distribution of the ten oral vowels over the F1 x F2 space across speakers and consonantal contexts.

![Figure 3-1: Mean vowel F1 and F2 (in Hz) with standard deviations across speakers and consonantal contexts.](image)

The results are generally compatible with previous studies on the realization of oral vowels in final syllables. One difference is that [ɛ] appears to have a slightly higher F1 value than [œ] and [o], whereas these vowels have been found to have roughly the same F1 values in other studies (Ménard, Schwartz, and Aubin, 2008). The F1 realization of [ɛ] is aligned with the F1 realizations of the other tense mid vowels, as expected. [ɛ] and [o] appear to have quite extreme F2 realizations: their F2 realizations are similar
to those of the corresponding high vowels [i] and [u]. Extreme F2 values for the tense mid vowels are found in other studies as well (see Experiment 2 in section 2.3.2). The difference between tense mid and lax mid vowels is as expected: [e] is more front and higher than [ɛ], [ɔ] is more back and higher than [ɔ], [œ] is higher than [œ] but the two vowels do not appear to have very different F2 realizations.

Durations were also measured in order to verify that they are sensible too. The durations of the ten oral vowels across the different consonantal contexts are shown in Table 3.2 with the standard deviation. As found in other studies of Standard French vowels, the stressed tense rounded mid vowels [o ø] are longer than their lax counterparts [ɛ œ] (Gottfried and Beddor, 1988). In absolute word-final position, [e] and [ɛ] contrast in Standard French but no durational difference between the two vowels has been reported in this position. The fact that no durational difference between [e] and [ɛ] was found here either suggests that [e] was not produced with extra care despite its marked phonotactic status in this position.

<table>
<thead>
<tr>
<th>Vowel</th>
<th>Mean duration (ms)</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>i</td>
<td>88</td>
<td>21</td>
</tr>
<tr>
<td>y</td>
<td>96</td>
<td>19</td>
</tr>
<tr>
<td>u</td>
<td>98</td>
<td>20</td>
</tr>
<tr>
<td>e</td>
<td>113</td>
<td>16</td>
</tr>
<tr>
<td>ø</td>
<td>126</td>
<td>21</td>
</tr>
<tr>
<td>o</td>
<td>127</td>
<td>21</td>
</tr>
<tr>
<td>e</td>
<td>112</td>
<td>14</td>
</tr>
<tr>
<td>œ</td>
<td>115</td>
<td>21</td>
</tr>
<tr>
<td>ɔ</td>
<td>116</td>
<td>13</td>
</tr>
<tr>
<td>a</td>
<td>118</td>
<td>14</td>
</tr>
</tbody>
</table>

Table 3.2: Vowel duration (in ms) averaged across speakers, contexts, and repetitions.

Figure 3-2 shows, for each post-vocalic consonant, the average F1 and F2 values at the end of the vowel across speakers, vowels, items, and repetitions. The results are qualitatively similar to Stevens et alii’s (1999) results on English. F1 is higher before
[p] than before [t] and [k], and higher before [t] than [k]. There is more variability before [p]. F2 is lower before [p] than before [t] and [k]. There is more variability before [k]. Overall, there is a lot of overlap across vowels.

Figure 3-2: Mean vowel F1 and F2 (in Hz) with standard deviations five milliseconds before the end of the vowel before [p t k].

**Acoustic distances along F1.** Figure 3-3 shows how F1 measured at the vowel offset varies as a function of the vowel and the following consonant.
To test the effect of vowel height on the acoustic distinctiveness of postvocalic consonants' F1 realizations, a linear mixed effects model was fit to the transformed F1 data. The fixed effects included Height (a variable with three levels: high, tense mid, lax mid), Backness (a variable with three levels: front unrounded, front rounded, back rounded), and C2 (a variable with three levels: [p t k]) and all their interactions. The variables Height and Backness define the nine vowels [i y u ø o e ø e ø]. Because there is only a single low vowel [a] in French, it is not possible to define a full model including low vowels and the interaction of Height and Backness. For this reason, [a] was excluded from the statistical analysis. The random effect structure included a by-speaker/by-repetition random intercept and a by-speaker/by-repetition random slope for C2. More complex models that were able to converge were not found to improve model fit according to likelihood ratio tests.

The variables were coded as follows. [t] was taken as the baseline for the variable C2. This choice is motivated by the observation that [t] has a F1 locus intermediary between [p] and [k]. High vowels were taken as the baseline for the variable Height.
The variable Backness was sum coded.

The output of the statistical model for the fixed effects is shown in Table 3.3. Before high vowels, the F1 realizations of [p t k] are not significantly different. Before tense mid vowels, the F1 locus of [k] is slightly lower than the F1 locus of [t] but this effect does not reach significance. Before lax mid vowels, the F1 locus of [k] is lower and the F1 locus of [p] is higher than the F1 locus of [t]. However, the effect of laxing on the [k]-[t] distance is probably entirely driven by [e], as indicated by the interaction terms Low-mid:Back:k and Low-mid:FrontUnrounded:k. To summarize, F1 realizations of [p t k] are not significantly different after high and tense mid vowels. They are all distinct after [e] and the F1 locus of [p] is distinct from the F1 realizations of [t] and [k] after [æ ə].
<table>
<thead>
<tr>
<th></th>
<th>Estimate</th>
<th>Std. Error</th>
<th>t value</th>
<th>p value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Intercept) t</td>
<td>-0.771372</td>
<td>0.047537</td>
<td>-16.227</td>
<td>4.14e-09 ***</td>
</tr>
<tr>
<td>k</td>
<td>0.016494</td>
<td>0.049920</td>
<td>0.330</td>
<td>0.743341</td>
</tr>
<tr>
<td>p</td>
<td>-0.049317</td>
<td>0.070251</td>
<td>-0.702</td>
<td>0.498252</td>
</tr>
<tr>
<td>High-mid:k</td>
<td>-0.110945</td>
<td>0.067040</td>
<td>-1.655</td>
<td>0.098649 .</td>
</tr>
<tr>
<td>Low-mid:k</td>
<td>-0.198789</td>
<td>0.067040</td>
<td>-2.965</td>
<td>0.003187 **</td>
</tr>
<tr>
<td>High-mid:p</td>
<td>0.012466</td>
<td>0.067040</td>
<td>0.186</td>
<td>0.852573</td>
</tr>
<tr>
<td>Low-mid:p</td>
<td>0.406235</td>
<td>0.067040</td>
<td>6.060</td>
<td>2.91e-09 ***</td>
</tr>
<tr>
<td>Back:k</td>
<td>0.082555</td>
<td>0.067040</td>
<td>1.231</td>
<td>0.218811</td>
</tr>
<tr>
<td>FrontUnrounded:k</td>
<td>-0.072080</td>
<td>0.067040</td>
<td>-1.075</td>
<td>0.282876</td>
</tr>
<tr>
<td>Back:p</td>
<td>0.019712</td>
<td>0.067040</td>
<td>0.294</td>
<td>0.768865</td>
</tr>
<tr>
<td>FrontUnrounded:p</td>
<td>0.040632</td>
<td>0.067040</td>
<td>0.606</td>
<td>0.544766</td>
</tr>
<tr>
<td>High-mid:Back:k</td>
<td>0.022031</td>
<td>0.094808</td>
<td>0.232</td>
<td>0.816356</td>
</tr>
<tr>
<td>Low-mid:Back:k</td>
<td>0.161434</td>
<td>0.094808</td>
<td>1.703</td>
<td>0.089316 .</td>
</tr>
<tr>
<td>High-mid:FrontUnrounded:k</td>
<td>-0.025272</td>
<td>0.094808</td>
<td>-0.267</td>
<td>0.789934</td>
</tr>
<tr>
<td>Low-mid:FrontUnrounded:k</td>
<td>-0.213179</td>
<td>0.094808</td>
<td>-2.249</td>
<td>0.025032 *</td>
</tr>
<tr>
<td>High-mid:Back:p</td>
<td>-0.111637</td>
<td>0.094808</td>
<td>-1.178</td>
<td>0.239626</td>
</tr>
<tr>
<td>Low-mid:Back:p</td>
<td>-0.014227</td>
<td>0.094808</td>
<td>-0.150</td>
<td>0.880786</td>
</tr>
<tr>
<td>High-mid:FrontUnrounded:p</td>
<td>0.142347</td>
<td>0.094808</td>
<td>1.501</td>
<td>0.133958</td>
</tr>
<tr>
<td>Low-mid:FrontUnrounded:p</td>
<td>-0.039396</td>
<td>0.094808</td>
<td>-0.416</td>
<td>0.677952</td>
</tr>
</tbody>
</table>

Table 3.3: Summary of the fixed effects for F1 (baseline: high vowels)

**Acoustic distances along F2.** Figure 3-4 shows how F2 measured at the vowel offset varies as a function of the vowel and the following consonant.

To test the effect of vowel height on the acoustic distinctiveness of postvocalic consonants' F2 realizations, linear mixed effects models were fit to the transformed F2 data. Different models were fit for each level of the Backness variable (front unrounded, front rounded, and back rounded), excluding the low vowel for the same reasons as in the F1 model. For the three models, the random effect structure included a by-speaker random intercept, a by-speaker random slope for Height, and a by-
Figure 3-4: Vowel F2 before [p t k] five milliseconds before the end of the vowel.

speaker random slope for C2. More complex models that were able to converge were not found to improve model fit according to likelihood ratio tests.

Table 3.4 shows the output of the statistical model for the front unrounded vowels [i e ɛ]. The baseline is the F2 of [e] before [t]. After [e], the F2 realizations of [t] and [k] are significantly different but not the F2 realizations of [t] and [p]. After [i], the distance between the F2 realizations of [t] and [k] is decreased compared to after [e]. This means that the F2 realizations of [p t k] are generally more similar after [i] than after [e]. After [e], the distance between the F2 realizations of [p] and [t] (and as a consequence of [p] and [k]) is increased compared to after [ɛ]. This means that the F2 realizations of [p t k] are generally more distinct after [ɛ] than after [i] and [ɛ].
Table 3.4: Summary of the fixed effects for F2: front unrounded vowels (baseline: [e])

<table>
<thead>
<tr>
<th></th>
<th>Estimate</th>
<th>Std. Error</th>
<th>t value</th>
<th>p value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Intercept) t</td>
<td>1.00202</td>
<td>0.13350</td>
<td>7.506</td>
<td>0.04211 *</td>
</tr>
<tr>
<td>k</td>
<td>0.58518</td>
<td>0.11481</td>
<td>5.097</td>
<td>0.01030 *</td>
</tr>
<tr>
<td>p</td>
<td>-0.04894</td>
<td>0.14724</td>
<td>-0.332</td>
<td>0.77224</td>
</tr>
<tr>
<td>High:k</td>
<td>-0.32396</td>
<td>0.11671</td>
<td>-2.776</td>
<td>0.00573 **</td>
</tr>
<tr>
<td>Low-mid:k</td>
<td>0.03464</td>
<td>0.11671</td>
<td>0.297</td>
<td>0.76679</td>
</tr>
<tr>
<td>High:p</td>
<td>-0.03921</td>
<td>0.11671</td>
<td>-0.336</td>
<td>0.73706</td>
</tr>
<tr>
<td><strong>Low-mid:p</strong></td>
<td>-0.23878</td>
<td>0.11671</td>
<td>-2.046</td>
<td>0.04134 *</td>
</tr>
</tbody>
</table>

Table 3.5 shows the output of the statistical model for the back rounded vowels [u o o]. The baseline is the F2 of [o] before [p]. After [o], the F2 realizations of [p] and [t] are significantly different but not the F2 realizations of [p] and [k]. There is no significant effect of height on the distances between the F2 realizations of [p t k] after back vowels. This means that the F2 centralization observed in [o] does not affect the distinctiveness of F2 transitions into [p t k].

<table>
<thead>
<tr>
<th></th>
<th>Estimate</th>
<th>Std. Error</th>
<th>t value</th>
<th>p value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Intercept) p</td>
<td>-1.47920</td>
<td>0.05839</td>
<td>-25.335</td>
<td>&lt; 2e-16 ***</td>
</tr>
<tr>
<td>k</td>
<td>-0.12689</td>
<td>0.09265</td>
<td>-1.369</td>
<td>0.195114</td>
</tr>
<tr>
<td>t</td>
<td>0.98955</td>
<td>0.14724</td>
<td>6.721</td>
<td>0.023534 *</td>
</tr>
<tr>
<td>High:k</td>
<td>0.01837</td>
<td>0.11671</td>
<td>0.157</td>
<td>0.875034</td>
</tr>
<tr>
<td>Low-mid:k</td>
<td>0.21638</td>
<td>0.11671</td>
<td>1.854</td>
<td>0.064396</td>
</tr>
<tr>
<td>High:t</td>
<td>-0.10547</td>
<td>0.11671</td>
<td>-0.904</td>
<td>0.366646</td>
</tr>
<tr>
<td><strong>Low-mid:t</strong></td>
<td>-0.14762</td>
<td>0.11671</td>
<td>-1.265</td>
<td>0.206583</td>
</tr>
</tbody>
</table>

Table 3.5: Summary of the fixed effects for F2: back vowels (baseline: [o])

Table 3.6 shows the output of the statistical model for the front rounded vowels [y o o]. The baseline is the F2 of [y] before [k]. After [a], the F2 realizations of [k] and [t] are significantly different but not the F2 realizations of [p] and [k]. The distances
between [p t k]'s F2 realizations are not significantly different after [ø] and after [y]. However, the distance between the F2 realizations of [t] and [k] (and therefore of [t] and [p]) decreases significantly after [œ] as compared to after [ø].

<table>
<thead>
<tr>
<th></th>
<th>Estimate</th>
<th>Std. Error</th>
<th>t value</th>
<th>p value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Intercept) k</td>
<td>-0.18855</td>
<td>0.07089</td>
<td>-2.660</td>
<td>0.041755 *</td>
</tr>
<tr>
<td>p</td>
<td>-0.10844</td>
<td>0.09265</td>
<td>-1.170</td>
<td>0.263804</td>
</tr>
<tr>
<td>t</td>
<td>0.46825</td>
<td>0.11481</td>
<td>4.078</td>
<td>0.020298 *</td>
</tr>
<tr>
<td>High:p</td>
<td>-0.16238</td>
<td>0.11671</td>
<td>-1.391</td>
<td>0.164818</td>
</tr>
<tr>
<td>Low-mid:p</td>
<td>-0.18001</td>
<td>0.11671</td>
<td>-1.542</td>
<td>0.123675</td>
</tr>
<tr>
<td>High:t</td>
<td>-0.05304</td>
<td>0.11671</td>
<td>-0.454</td>
<td>0.649748</td>
</tr>
<tr>
<td>Low-mid:t</td>
<td>-0.28426</td>
<td>0.11671</td>
<td>-2.436</td>
<td>0.015250 *</td>
</tr>
</tbody>
</table>

Table 3.6: Summary of the fixed effects for F2: front rounded vowels (baseline: [ø])

**Summary.** For each pair of vowels differing in height, Table 3.7 summarizes whether the acoustic distance between the two consonants in the corresponding row is larger after the lower vowel than after the higher one or does not differ significantly after the two vowels. The symbol ✓ is used when the distance is larger after the lower vowel. The symbol ✗ is used when the distance is larger after the higher vowel. The symbol = is used when the distance is not significantly different after the two vowels. Tables 3.8a and 3.8b zoom in on the mid vowels, which are the only vowels to be involved in tense-lax pairs in French.
Table 3.7: The effect of height on the distances between the F1 and F2 realizations of [p t k]. ✓ means that the distance between the two consonants is larger after the lower of the two vowels. ✓ means that the distance between the two consonants is larger after the higher of the two vowels. = means that the distance between the two consonants does not vary significantly after the two vowels.

Table 3.8: The effect of mid-vowel height on the distances between the F1 and F2 realizations of [p t k].

The distances between the formant realizations of [p t k] generally do not differ after high and tense mid vowels. One exception concerns [i] and [e]: the F2 distance between [k] and the other two consonants was found to be larger after [e] than after [i]. The fact that the F1 realizations of consonants are not significantly different may be due to the relative proximity of high and tense mid vowels along F1.

Mid-vowel laxing was found to generally increase the distance between the F1 realizations of [p t k]. The increase was observed for all pairs after [e] but only for the pairs involving [p] after rounded vowels [o œ]. This difference could be due to the fact that [e] had a higher F1 value than [œ œ] in this study.

Mid-vowel laxing was not found to generally increase the distance between the F2 realizations of [p t k]. This was the case only for [e], after which the distances between [p] and [t] and between [p] and [k] were found to increase as compared to after
[e]. After front rounded vowels, mid-vowel laxing had an unexpected effect on the F2 distances between consonants: the distances involving [t] were found to decrease after the lax vowel as compared to after the tense vowel, although tense and lax front rounded vowels did not appear to have very different F2 targets.

These results suggest that the most consistent effect of mid-vowel laxing is to increase the distances between the F1 realizations of the following coda consonants.

3.3 Perceptual study

Previous studies on French suggest that, as in English (Lisker, 1999) or Hindi (Ohala and Ohala, 2001), vowel quality has an effect on place identification (Benoit, Mohamadi, and Kandel, 1994; Marty, 2012). This section tests how vowel quality affects place identification in coda position specifically, and considering a larger range of oral vowels than in previous studies.

Given that F2 plays an important role in place identification, perceptual distances between [p t k] are expected to generally reflect the acoustic distances between their F2 realizations. For instance, the perceptual distance between [k] and [p] is expected to be smaller after back vowels than after front vowels (Marty, 2012). F1 plays a smaller role in place identification and, as a consequence, the perceptual improvement due to vowel lowering is expected to be smaller in magnitude.

3.3.1 Methods

One third of the stimuli recorded in section 3.2 (from the first repetition) were used to serve as stimuli for the perceptual experiment. The final burst was edited out in order to directly test the effect of vowel transitions on place discriminability. A silence was added before and after each nonce syllable in order to have an approximately equal duration for all stimuli. In order to control for the effect of stimulus intensity on the task, the amplitude of the sound files was equalized and scaled to a maximum peak value equal to one.
85 participants took part in the experiment online. 43 English-speaking participants were recruited through Mechanical Turk and were paid 3.5 dollars for their participation. 42 French-speaking were recruited through the mailing list of the CNRS' Réseaux d'information sur les sciences de la cognition (RISC) and were paid 7 euros for their participation. All participants gave their informed consent.

180 CVC syllables with the final burst edited out were presented in randomized order to the participants. The stimuli were presented as words from an exotic language. Participants were instructed to identify the final consonant among [p t k]. All participants indicated that they wore headphones while taking the test.

For 10 participants (six English-speaking participants and four French-speaking participants), the scores of correct identification were at chance level (approximately 33%) and much lower than for the other participants. Because it was not possible to establish whether these participants did the task carefully, their data were not included in the analysis.

Confusion matrices were built, collapsing across speakers, participants, and C1. These confusion matrices indicates how many times [p], [t] or [k] was identified as [p], [t] or [k] in each of the 10 vowel contexts [i y u ø ø ø ø ø ø ø ø]. The confusion matrices were analyzed using Luce's (1963) Biased Choice Model (BCM). This model is a model of identification tasks. It assumes that the probability of identifying stimulus $s_i$ as belonging to response category $r_j$ is proportional to the similarity between $s_i$ and $s_j$, $η_{ij}$, and a bias, $b_j$, towards response $r_j$. The probability of responding $r_j$ when listening to stimulus $s_i$ is calculated as the product of $η_{ij}$ and $b_j$ divided by the sum of the products of similarity to $s_i$ and bias for all other response categories $r_k$ available to participants.

$$p(r_j|s_i) = \frac{η_{ij}b_j}{∑_{r_k} η_{ik}b_k}$$

Similarity is assumed to range between 0 and 1, 0 corresponding to an infinite perceptual distance between the two relevant stimuli and 1 for identity of the two stimuli. Similarity is assumed to be symmetric. The rate of confusion between two sounds
depends on their similarity and the direction of the confusion depends on the bias.

A BCM was fit to the confusion matrices using Edward Flemming’s R code implementing the BCM as a log-linear model. In this model, the logarithm of the similarity between two sounds can be interpreted as the negative perceptual distance between these two sounds, with -log(0) corresponding to an infinite perceptual distance and -log(1) corresponding to a perfect identity. A contextual parameter was added in the model in order to obtain estimates of consonant similarity after different vowels. Only the estimates of the perceptual distances will be reported in this chapter.

### 3.3.2 Results

Figure 3-5 shows, for each pair of consonants, the perceptual distances between them across all vowel contexts as estimated by the BCM.

![Perceptual distances between [p], [t], and [k] after the ten French oral vowels.](image)

The overall results are consistent with what is known about the role of transitions in signaling place. The distance between [k] and [p] varies a lot as a function of
the identity of the preceding vowel and the distance between \([p]\) and \([t]\) varies much less. This is consistent with the finding that the identification of \([k]\) is the most dependent on vowel transitions and the identification of \([t]\) the least (Cooper et al., 1952; Winitz, Scheib, and Reeds, 1972). This is also consistent with the acoustic results for F2 presented in section 3.2: \([k]\) was found to have the most variable F2 and \([t]\) the least variable F2.

The overall patterns of place distinctiveness correlate with F2, in particular for the contrast between \([k]\) and \([p]\) after nonlow vowels. As nonlow vowels become more front, the perceptual distance between \([p]\) and \([k]\) increases. This is compatible with the idea that F2 is central in the perception of place.

The perceptual distance between \([k]\) and \([t]\) also varies with the vocalic context, and in particular to vowel backness, though to a smaller extent. As vowels become more back (leaving aside \([e]\) for the moment), \(d_{kt}\) slightly increases. This is also consistent with F2 transitions playing an important perceptual role: as vowels become more back, the distance between the F2 realizations of \([t]\) and \([k]\) increases.

Figure 3-6 zooms in on the comparison of tense and lax mid vowels.

90
Figure 3.6: Perceptual distances (d) between [p], [t], and [k] after tense and lax mid vowels.

Table 3.9 shows the effect of vowel height on place distinctiveness after front vowels. The baseline is the post-[e] context. The parameters in the first three rows of Table 3.9 under the column Estimate correspond to the opposite of the distance between the relevant consonants after [e] (see section 3.3.1 for an explanation about why these parameters are negative). The perceptual distance corresponds to the absolute value of these estimates. The interaction terms indicate how the perceptual distance between the different pairs of consonants varies after [e] and [i] as compared to the baseline post-[e] context. A negative interaction corresponds to an increase in the perceptual distance between the two relevant consonants. $d_{kp}$ and $d_{kt}$ were found to be significantly larger after [e] than after [e], but lowering to [e] was not found to increase $d_{pt}$. Raising from [e] to [i] was not found to decrease consonants’ distinctiveness.
<table>
<thead>
<tr>
<th></th>
<th>Estimate</th>
<th>Std. Error</th>
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<th>p value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d_{kp}$</td>
<td>-1.621391</td>
<td>0.106916</td>
<td>-15.165</td>
<td>$&lt; 2e-16$ ***</td>
</tr>
<tr>
<td>$d_{kt}$</td>
<td>-1.145463</td>
<td>0.090536</td>
<td>-12.652</td>
<td>$&lt; 2e-16$ ***</td>
</tr>
<tr>
<td>$d_{pt}$</td>
<td>-1.390733</td>
<td>0.087621</td>
<td>-15.872</td>
<td>$&lt; 2e-16$ ***</td>
</tr>
<tr>
<td>$d_{kp}:i$</td>
<td>-0.122913</td>
<td>0.153893</td>
<td>-0.799</td>
<td>0.424469</td>
</tr>
<tr>
<td>$d_{kp}:e$</td>
<td>-0.749436</td>
<td>0.168364</td>
<td>-4.451</td>
<td>8.54e-06 ***</td>
</tr>
<tr>
<td>$d_{kt}:i$</td>
<td>0.185130</td>
<td>0.126012</td>
<td>1.469</td>
<td>0.141794</td>
</tr>
<tr>
<td>$d_{kt}:e$</td>
<td>-0.959854</td>
<td>0.147299</td>
<td>-6.516</td>
<td>7.20e-11 ***</td>
</tr>
<tr>
<td>$d_{pt}:i$</td>
<td>-0.020529</td>
<td>0.126052</td>
<td>-0.163</td>
<td>0.870625</td>
</tr>
<tr>
<td>$d_{pt}:e$</td>
<td>-0.014994</td>
<td>0.123205</td>
<td>-0.122</td>
<td>0.9031</td>
</tr>
</tbody>
</table>

Table 3.9: The effect of vowel height on place distinctiveness after front unrounded vowels. The baseline is the post-[e] context.

Table 3.10 shows the effect of vowel height on place distinctiveness after front rounded vowels. The baseline is the post-[ø] context. $d_{kp}$ and $d_{pt}$ were found to be significantly larger after [œ] than after [ø], but lowering to [œ] was not found to increase $d_{kt}$. Raising from [ø] to [y] was found to improve $d_{kp}$.

<table>
<thead>
<tr>
<th></th>
<th>Estimate</th>
<th>Std. Error</th>
<th>t value</th>
<th>p value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d_{kp}$</td>
<td>-0.929276</td>
<td>0.091410</td>
<td>-10.166</td>
<td>$&lt; 2e-16$ ***</td>
</tr>
<tr>
<td>$d_{kt}$</td>
<td>-1.213542</td>
<td>0.092328</td>
<td>-13.144</td>
<td>$&lt; 2e-16$ ***</td>
</tr>
<tr>
<td>$d_{pt}$</td>
<td>-1.355742</td>
<td>0.095822</td>
<td>-14.148</td>
<td>$&lt; 2e-16$ ***</td>
</tr>
<tr>
<td>$d_{kp}:y$</td>
<td>-0.309830</td>
<td>0.134646</td>
<td>-2.301</td>
<td>0.021388 *</td>
</tr>
<tr>
<td>$d_{kp}:œ$</td>
<td>-0.355155</td>
<td>0.135109</td>
<td>-2.629</td>
<td>0.008572 **</td>
</tr>
<tr>
<td>$d_{kt}:y$</td>
<td>0.122718</td>
<td>0.129424</td>
<td>0.948</td>
<td>0.343034</td>
</tr>
<tr>
<td>$d_{kt}:œ$</td>
<td>0.178985</td>
<td>0.130344</td>
<td>1.373</td>
<td>0.169697</td>
</tr>
<tr>
<td>$d_{pt}:y$</td>
<td>-0.176198</td>
<td>0.135960</td>
<td>-1.296</td>
<td>0.194991</td>
</tr>
<tr>
<td>$d_{pt}:œ$</td>
<td>-0.372217</td>
<td>0.137065</td>
<td>-2.716</td>
<td>0.006615 **</td>
</tr>
</tbody>
</table>

Table 3.10: The effect of vowel height on place distinctiveness after front rounded vowels. The baseline is the post-[ø] context.
Table 3.11 shows the effect of vowel height on place distinctiveness after back rounded vowels. The baseline is the post-[o] context. $d_{kp}$ and $d_{pt}$ were found to be significantly larger after [o] than after [a], but lowering to [o] was not found to increase $d_{kt}$. Raising from [o] to [u] was found to slightly decrease $d_{kp}$.

<table>
<thead>
<tr>
<th></th>
<th>Estimate</th>
<th>Std. Error</th>
<th>t value</th>
<th>p value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d_{kp}$</td>
<td>-0.598250</td>
<td>0.081776</td>
<td>-7.316</td>
<td>2.56e-13 ***</td>
</tr>
<tr>
<td>$d_{kt}$</td>
<td>-1.404321</td>
<td>0.101444</td>
<td>-13.843</td>
<td>&lt; 2e-16 ***</td>
</tr>
<tr>
<td>$d_{pt}$</td>
<td>-1.450139</td>
<td>0.093662</td>
<td>-15.483</td>
<td>&lt; 2e-16 ***</td>
</tr>
<tr>
<td>$d_{kp}$:0</td>
<td>0.251675</td>
<td>0.113749</td>
<td>2.213</td>
<td>0.026929 *</td>
</tr>
<tr>
<td>$d_{kp}$:a</td>
<td>-0.359958</td>
<td>0.115225</td>
<td>-3.124</td>
<td>0.001784 **</td>
</tr>
<tr>
<td>$d_{kt}$:0</td>
<td>0.050855</td>
<td>0.144270</td>
<td>0.352</td>
<td>0.724465</td>
</tr>
<tr>
<td>$d_{kt}$:a</td>
<td>-0.081679</td>
<td>0.141049</td>
<td>-0.579</td>
<td>0.562536</td>
</tr>
<tr>
<td>$d_{pt}$:0</td>
<td>0.097636</td>
<td>0.130913</td>
<td>0.746</td>
<td>.455784</td>
</tr>
<tr>
<td>$d_{pt}$:a</td>
<td>-0.311110</td>
<td>0.139022</td>
<td>-2.238</td>
<td>0.025231 *</td>
</tr>
</tbody>
</table>

Table 3.11: The effect of vowel height on place distinctiveness after back rounded vowels. The baseline is the post-[o] context.

Summary. The results concerning the difference between tense and lax mid vowels are summarized in Table 3.12, where $\checkmark$ indicates that the perceptual distance between the consonants in the corresponding row is significantly larger after the lax vowel than after the tense vowel in the corresponding column and $\checkmark$ indicates that no significant difference was found. For each tense-lax pair, at least two place contrasts are improved after the lax mid vowel as compared to after the tense mid vowel. The distinctiveness of [k] and [p] is increased after the lax vowel for all tense-lax pairs. The distinctiveness of [p] and [t] is increased after the lax vowel for two of the three tense-lax pairs. The distinctiveness of [k] and [t] is increased after the lax vowel for one of the three tense-lax pairs.
3.4 General discussion

Mid-vowel laxing was found to improve some postvocalic place contrasts in French, as predicted. Because the present study focused on [p t k], one may wonder how the results generalize to other consonants. The results are likely to generalize to these three place contrast across manners of articulation, as they are similarly cued by formant frequencies (Delattre, Liberman, and Cooper, 1955). For the other place contrasts (e.g. [l] and [j]), more investigation is needed. If F1 dispersion plays an important role, the results are likely to generalize to other place contrasts as it should always be the case that F1 distances are larger after lower than higher vowels.

The acoustic study shows that the perceptual improvement after lax vowels correlates with an increase in the distance between the F1 realizations of the relevant consonants in this context. When place contrasts were found to be more distinct after the lax mid vowel than after the tense mid vowel, the acoustic distance between the F1 realizations of the two relevant consonants was also found to be increased but not necessarily the acoustic distance between their F2 realizations. This suggests that vowel lowering rather than vowel centralizing is driving the perceptual improvement. However, it should be kept in mind that this experiment does not provide direct evidence for the role of vowel lowering in the improvement of place contrasts: showing this would require using synthesized stimuli manipulating F1 and F2 independently. A thorough test of this hypothesis is left for further research.

If mid-vowel lowering plays a central role in place contrast enhancement, why does closed-syllable vowel laxing also involve centralizing? One possibility is that

<table>
<thead>
<tr>
<th></th>
<th>e-ε</th>
<th>ø-œ</th>
<th>o-ø</th>
</tr>
</thead>
<tbody>
<tr>
<td>d_{pt}</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>d_{pk}</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>d_{kt}</td>
<td>✓</td>
<td>=</td>
<td>=</td>
</tr>
</tbody>
</table>

Table 3.12: Summary of the results.
centralizing is a by-product of lowering, due to the shape of the vowel space. The vowel space is asymmetric between front and back. In the front, it is not possible to lower without also substantially centralizing. In the back, it is possible to do so (Liljencrants and Lindblom, 1972). This approach of centralizing as a by-product of lowering works well for languages like Indonesian, where lax back mid vowels are less centralized than lax front mid vowels (see chapter 1). As seen in chapter 2, this may not be the right approach for French, as the centralization observed when going from [o] to [o] seems larger than would be required by vowel lowering alone. More work should be done on the interaction of F1 and F2 and on establishing the exact shape of the vowel space in order to make progress on this question.

Lisker’s (1999) study on English does not include an acoustic study of the F1 and F2 transitions in tense high vs. lax high vowels. Therefore it is not possible to conclude whether the perceptual improvement after lax high vowels better correlates with an increase in the distance between the F1 realizations or the F2 realizations of the relevant consonants. Acoustic and perceptual studies of languages with high vowel laxing should be done to test this.

However, the hypothesis that centralizing follows from lowering alone is probably not correct for lax high vowels. In Quebec French, lax high vowels are more centralized than would be required by lowering alone. For instance, if laxing of [u] only involved lowering, one would expect the lax high back allophone to be realized roughly as [o], without centralizing. However, lax [u] is more central than [o] in Quebec French: they have similar F1 values but [u] has a higher F2 value (Martin, 2002, p. 84). This means that, for high vowels, laxing involves centralization but centralization is not a by-product of lowering. This view is compatible with the results of the perception experiment: lowering high vowels from [i] to [e] and from [u] to [o] in French was found not to be enough to improve postvocalic place contrasts. It is conceivable that both lowering and centralizing are necessary to improve place contrasts after high vowels.

The results of this chapter support the general hypothesis that laxing is a strategy to enhance place contrasts. However, it was not found that all place contrasts were
improved after all lax mid vowels. Is it possible to derive laxing before all coda consonants if only some contrasts are improved after lax vowels? This issue is addressed in chapter 4, where phonetically-based grammatical models of vowel laxing and tensing are discussed.
Chapter 4

Towards a dispersion-theoretic analysis of vowel laxing

The preceding chapter has provided evidence for the hypothesis that laxing mid vowels in French generally improves the distinctiveness of postvocalic place contrasts. This chapter sketches an analysis of closed-syllable vowel laxing as a contrast enhancement strategy using Dispersion Theory. Dispersion Theory is the name given to theories that derive restrictions on possible phoneme inventories and sound combinations from principles of maximal contrast (see Liljencrants and Lindblom, 1972; Schwartz et al., 1997; Flemming, 2002). Dispersion Theory was first applied to derive broad cross-linguistic tendencies in the structure of vowel inventories. For instance, it accounts for the prevalence of [a i u] vowel inventories among three-vowel inventories. [a i u] are the most distinct three vowels that can be produced by the human vocal tract, each occupying a different corner of the auditory space of possible vowels. The hypothesis that vowel inventories are structured by a principle of maximal contrast correctly predicts that [a i u] should be frequent. Becker-Kristal’s (2010) survey of vowel formant patterns in 230 languages provides evidence for other basic predictions of this theory.

Dispersion Theory has also been applied beyond vowel inventories to account for some aspects of the structure of consonant inventories (see Boersma and Hamann, 2008; Schwartz et al., 2012) and beyond static phoneme inventories to account
for cross-linguistic tendencies in phonotactic restrictions (Kawasaki-Fukumori, 1992; Flemming, 2004; Flemming, 2017). The present project combines these different approaches and derives the pattern of closed-syllable vowel laxing and open-syllable vowel tensing from the interaction of vowel dispersion and consonant dispersion in context.

The analysis presented here is not meant to be comprehensive but rather to illustrate how dispersion-theoretic principles can help derive some aspects of the typology of closed-syllable vowel laxing, in particular patterns of vowel laxing across consonantal contexts (e.g. Southern French) and patterns of vowel laxing before specific consonants (e.g. Chamorro). Another goal of this chapter is to develop further predictions to be tested in future work.

Section 4.1 illustrates the basics of the analysis using a minimal example with just three possible vowels and two coda consonants and shows that this analysis is able to derive consonant-specific patterns of vowel laxing that are hard to capture in alternative analyses. Section 4.2 expands this minimal example by considering a slightly larger vowel space with five possible vowels and three coda consonants and shows how it is possible to derive vowel laxing in closed syllables across consonantal contexts provided there is a constraint that militates against vowel-consonant covariation across an inventory. Section 4.3 discusses three ways to interpret this constraint: in terms of a set of constraints on consonant-zero contrasts, in terms of an economy constraint, and in terms of a set of special contextual dispersion constraints. Section 4.4 shows how the third of these approaches derives mid-vowel laxing before all major places of articulation in French. Section 4.5 shows that the present analysis also makes predictions about patterns of neutralization: it predicts that neutralization of place contrasts should be observed after tense vowel. Preliminary evidence supporting this hypothesis is provided. Section 4.6 discusses further predictions of the present approach to be tested in the future. Section 4.7 concludes the first part of this thesis.
4.1 A minimal example

This section builds on the minimal example presented in chapter 1. The goal of this section is to show how vowel quality can be determined as the result of a compromise between constraints on vowel dispersion (which favor tense vowels by default) and constraints on consonant dispersion in different vocalic contexts (which favor vowels that provide better cues to place of articulation). We consider an auditory space containing only the three vowels [a u u] and only the two consonants [p k]. Inventories of syllables are evaluated by the constraints on vowel contrasts (1-a) and the constraints on consonant contrasts relativized to a particular vocalic and syllabic context (1-b).

(1) Constraints on contrasts.
   a. Constraints on vowel contrasts.
      (i) *a-u
          Penalize minimal pairs that only differ by [a] and [u].
      (ii) *a-u
          Penalize minimal pairs that only differ by [a] and [u].
   b. Constraints on place contrasts in coda position (where release transitions are missing).
      (i) *up-uk
          Penalize minimal pairs that only differ by [up] and [uk].
      (ii) *up-uk
          Penalize minimal pairs that only differ by [up] and [uk].

The hypothesis that more distinct contrasts are preferred over less distinct contrasts is reflected in the rankings in (2-a) and (2-b). The constraint penalizing the less distinct [a]-[u] contrast outranks the constraint penalizing the more distinct [a]-[u] contrast. The constraint *up-uk outranks *up-uk because [p] and [k] are less distinct after [u] than after [u].

(2) Rankings implementing the preference for more distinct contrasts.
a. Preference for more distinct vowel contrasts.
   \[ *a-u > *a-u \]

b. Preference for more distinct place contrasts.
   \[ *up-uk > *up-uk \]

Tableau (3-a) shows how an inventory with tense [u] in closed syllables is derived when vowel contrasts matter more than place contrasts: /ap ak up uk/ wins against /ap ak up uk/ because syllables [ap] and [ak] are more distinct from [up] and [uk] than from [up] and [uk]. Tableau (3-b) shows how an inventory with lax [u] in closed syllables is derived when place contrasts matter more than vowel contrasts: /ap ak up uk/ wins against /ap ak up uk/ because [up] and [uk] are more distinct than [up] and [uk].

(3) Deriving closed-syllable vowel laxing as a trade-off between vowel dispersion and place dispersion.

a. Vowel dispersion constraints outrank place dispersion constraints.

<table>
<thead>
<tr>
<th></th>
<th>*a-u</th>
<th>*a-u</th>
<th>*up-uk</th>
<th>*up-uk</th>
</tr>
</thead>
<tbody>
<tr>
<td>ap ak up uk</td>
<td>**</td>
<td>*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ap ak up uk</td>
<td>**</td>
<td></td>
<td>*</td>
<td></td>
</tr>
</tbody>
</table>

b. Place dispersion constraints outrank vowel dispersion constraints.

<table>
<thead>
<tr>
<th></th>
<th>*up-uk</th>
<th>*up-uk</th>
<th>*a-u</th>
<th>*a-u</th>
</tr>
</thead>
<tbody>
<tr>
<td>ap ak up uk</td>
<td>*</td>
<td></td>
<td>**</td>
<td></td>
</tr>
<tr>
<td>ap ak up uk</td>
<td>*</td>
<td>**</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

What happens with inventories that avoid the bad place contrast [up]-[uk] and minimize the bad vowel contrast [a]-[u] by covarying vowel quality and place, for instance inventories containing [up] and [uk] sequences and inventories containing [up] and [uk] sequences? There is no constraint yet that penalizes inventories containing these sequences. The constraints penalizing inventories where vowels [u u] and consonants
[p k] covary are shown in (4).

(4) Constraints penalizing vowel-consonant covariation.

   a. *up-uk

   Penalize minimal pairs that only differ by [up] and [uk].

   b. *up-uk

   Penalize minimal pairs that only differ by [up] and [uk].

How should these constraints be ranked? To my knowledge, no experiment has been done which bears on that question. Testing the hypothesis about the impact of vowel-place covariation on the distinctiveness of place contrasts would require a different design than what was used in the experiment presented in chapter 3. In this experiment, listeners were tested on their ability to identify word-final stops in different vocalic contexts but not on their ability to identify both the vowel and the consonant. Testing the hypothesis of covariation would involve running an identification task on whole VC syllables and asking listeners to identify both the vowel and the consonant. It would then be possible to get results about the distance between syllables varying in two segments.

Despite the absence of data bearing on this issue, it seems reasonable to assume that covarying consonant and vowel in VC sequences should result in an enhancement of place: syllables that differ both by the vowel and the following consonant should be more distinct than syllables that differ only by the consonant. In other words, a pattern of covariation should help listeners to recover the final consonant because information about its identity is also provided by the identity of the vowel. According to this reasoning, *up-uk and *up-uk should be outranked by *up-uk and *up-uk, as shown in (5).

(5) Hypothesized ranking of the distinctiveness constraints relative to the [p]-[k] contrast with and without vowel-consonant covariation

*up-uk >> *up-uk >> *up-uk, *up-uk
This kind of covariation is observed in several languages, suggesting that allowing it may be a desirable feature of an analysis of closed-syllable vowel laxing. In Chamorro (Austronesian), the phoneme /o/ is lowered and centralized to [ɔ] only before coda velars [k ơ] (Topping, 1973, p. 21). Before other coda consonants, there is no laxing. This is illustrated in (6).

(6) Laxing of [o] before velars only: Chamorro.

/oppo/ ['oppo] 'respond'
/toktu/ ['toktu] 'hug'
/hotni/ ['hotni] 'thread needle'

A similar pattern is found in Uma Juman (Austronesian), where only velars [k] and [ơ] among coda stops [p t k m n ơ] trigger laxing of [u] to [o] in closed syllables (7) (Blust, 1977, pp. 78-80).

(7) Laxing of [u] before velars: Uma Juman

/tapuluk/ [tapu'lok] 'heap, pile'
/la?uŋ/ [la'?oŋ] 'back'

In English, [p] cannot occur after lax [u] and [k] cannot occur tense [u] (8).¹

(8) English

loop [lu:p] - *loop [lup]
boot [bu:t] - foot [fut]

One possible interpretation of these patterns is as follows: these languages solve the problem of a poor [up]-[uk] or [op]-[ok] contrast by laxing [u] or [o] only before [k]. English shows further evidence for an avoidance of the [up] -[uk] contrast.

Note that covarying vowel and consonant should be superior to the across-the-board laxing strategy for another reason as well: it also makes it possible to maintain

¹There are exceptions to these generalizations. E.g. Tense [u] can occur before [k] in 'Luke' and before [m], e.g. 'whom', 'room' (some dialects).
a high vowel before nonvelar consonants and therefore maintain the best vowel dispersion possible in these contexts.

Tableau (9) shows how covarying vowel height and consonant place is better for dispersion purposes under the ranking in (5).

(9) Covarying vowel height and consonant place

<table>
<thead>
<tr>
<th></th>
<th>*up-uk</th>
<th>*up-uk</th>
<th>*up-uk</th>
<th>*up-uk</th>
</tr>
</thead>
<tbody>
<tr>
<td>up uk</td>
<td>*</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>up uk</td>
<td></td>
<td>*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>up uk</td>
<td></td>
<td></td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>up uk</td>
<td></td>
<td></td>
<td></td>
<td>*</td>
</tr>
</tbody>
</table>

Based on Chamorro, Uma Juman, and English, it seems that there is a preference to lax before velars as opposed to before labials. Why is it so? In the present analysis, the choice between laxing before [k] or laxing before [p] can be governed by the relative ranking of *up-uk and *up-uk. Limiting laxing to prevelar contexts is possible if *up-uk outranks *up-uk, as shown in (10).

(10) Deriving a Chamorro-like language

<table>
<thead>
<tr>
<th></th>
<th>*up-uk</th>
<th>*up-uk</th>
<th>*up-uk</th>
<th>*up-uk</th>
</tr>
</thead>
<tbody>
<tr>
<td>up uk</td>
<td>*</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>up uk</td>
<td></td>
<td>*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>up uk</td>
<td></td>
<td></td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>up uk</td>
<td></td>
<td></td>
<td></td>
<td>*</td>
</tr>
</tbody>
</table>

Is there a perceptual reason for languages to prefer the ranking *up-uk >> *up-uk over the ranking *up-uk >> *up-uk? [up] and [uk] might be more distinct than [uk] and [up]. [k] has a high F2 target whereas [p] has a low F2 target. If [k] occurs after [u] and [p] after [u], the F2 transition from [u] to [p] will be level while the F2 transition from [u] to [k] will be slightly rising and moving away from [p], resulting in a relatively large difference between the F2 loci of [p] and [k]. However, if [k] occurs
after [u] and [p] after [u], the F2 transition from [u] to [k] will be level while the F2 transition from [u] to [p] will be slightly falling and getting closer to [k], resulting in a smaller distance between the F2 loci of the two consonants.

The fact that it is possible to derive partial laxing and make sense of laxing of back vowels before velars is a good feature of the present analysis. Alternative theories of vowel laxing as a pattern of vowel reduction cannot derive this kind of consonant-specific conditioning (unless there is consonant-specific shortening).

However, if covariation is possible and improves place contrasts, then there should be no reason to observe across-the-board laxing. Compared to a strategy of covariation, across-the-board laxing should both reduce place dispersion (because the identity of the vowel does not provide information about the identity of the consonant) and vowel dispersion (because both vowels are laxed and therefore closer to [a]). But, in most languages with laxing in closed syllables, laxing applies across the board. I will go back to the question of how to get both consonant-specific laxing and across-the-board laxing in section 4.3.

### 4.2 Expanding the minimal example

In this section, I expand the minimal example presented in section 4.1. Throughout this section, only inventories without the type of vowel-consonant covariation discussed in section 4.1 will be considered. I will return to this problem in section 4.3.

In section 4.2.1, considering a slightly expanded auditory space with [a i u u] and [k p], I show how the analysis is able to derive across-the-board laxing if (i) laxing improves place contrasts both after high and back vowels and (ii) the type of vowel-consonant covariation discussed in section 4.1 is blocked. In section 4.2.2, considering the same vowel space but consonants [k t], I show that the present analysis cannot derive laxing of a vowel if laxing does not improve any place contrasts for that vowel, and this even under the simplifying assumption that covariation is blocked. In section 4.2.3, expanding the consonant space to [p t k], I show that laxing of a given vowel
is possible before all consonants if laxing improves at least some place contrasts after that vowel.

### 4.2.1 Auditory space: [a i i u u] and [p k]

To see how the analysis works with a more realistic vowel inventory than the one considered in section 4.1, the vowel space [a i i u u] is used in this section. In the experiment, lowering was found to improve the [k]-[p] contrast both for front and back vowels. Focusing on this vowel space and a consonant space with [p k] thus allows us to see how the analysis works when laxing improves place contrasts across vowels. For the moment, vowel inventories allowing for vowel-consonant covariation will not be considered as potential candidates. The goal is to check that the analysis works under the most favorable conditions.

The vowel space contains five possible vowels. There are therefore 10 vowel-to-vowel distances that are relevant to the selection of vowel inventories in that space. Among those, the smallest distances are the distances between [i] and [i] and between [u] and [u]. Based on the logic that less distinct contrasts are more penalized than more distinct contrasts, vowel inventories with three vowels will exclude the pairs [i]-[i] and [u]-[u]. Among the four remaining three-vowel inventories, /a i u/, /a i u/, /a i u/, and /a i u/, only the one with the largest minimal vowel-to-vowel distance will be selected. This inventory is the inventory with tense high vowels /a i u/.

Tableau (11) shows how the inventory with tense high vowels /up uk ip ik ap ak/ is derived as the best inventory according to the ranking of vowel dispersion constraints. All ten vowel dispersion constraints are shown here. The ranking assumed in (11) is not based on perceptual data and therefore does not necessarily reflect the actual relations between these distances in any language, in particular for the two blocks of constraints in the right part of the table (the block of constraints going from *i-u to *i-u and the block containing the three lowest ranked constraints). For convenience, all the constraints that penalize specifically pairs involving [i] and [u] were placed in the middle of the ranking, although some of them might outrank some of the constraints on the right side of the table, *i-a, *u-a, and *i-u. For instance, it is possible that
the distance between [i] and [a] is larger than the perceptual distance between [u] and [a], due to the large F2 difference between [i] and [a], and that therefore *u-a should outrank *i-a. However, [i] will be penalized by other constraint rankings (e.g. *i-a ≫ i-a) so the fact that *u-a may outrank *i-a will not affect the general prediction that /a i u/ is the most dispersed vowel inventory.

(11) Inventory evaluation according to the ranking of vowel dispersion constraints

<table>
<thead>
<tr>
<th></th>
<th>*i-t</th>
<th>*u-t</th>
<th>*i-u</th>
<th>*u-a</th>
<th>*i-u</th>
<th>*u-a</th>
<th>*i-a</th>
<th>*u-a</th>
<th>*i-u</th>
</tr>
</thead>
<tbody>
<tr>
<td>up uk ip ik ap ak</td>
<td>!</td>
<td></td>
<td>!</td>
<td>!</td>
<td>!</td>
<td>!</td>
<td>!</td>
<td>!</td>
<td>!</td>
</tr>
<tr>
<td>up uk ip ik ap ak</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>!</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>up uk ip ik ap ak</td>
<td></td>
<td>!</td>
<td></td>
<td>!</td>
<td>!</td>
<td>!</td>
<td>!</td>
<td>!</td>
<td>!</td>
</tr>
<tr>
<td>up uk ip ik ap ak</td>
<td>!</td>
<td>!</td>
<td></td>
<td>!</td>
<td>!</td>
<td>!</td>
<td>!</td>
<td>!</td>
<td>!</td>
</tr>
<tr>
<td>ip ik ip ik ap ak</td>
<td>!</td>
<td>!</td>
<td>!</td>
<td>!</td>
<td>!</td>
<td>!</td>
<td>!</td>
<td>!</td>
<td>!</td>
</tr>
</tbody>
</table>

In the experiment, the distance between [k] and [p] was found to increase when laxing front and back mid vowels. Assuming that these results extend to high vowels, this translates into a difference in the rankings of *ip-ik vs. *ip-ik and *up-uk vs. *up-uk. Also, [k] and [p] were found to be more confusable after back vowels than after front vowels. Finally, [k] and [p] were found to be more distinct after [a] than after high front and back vowels. Together, these findings establish the ranking of distinctiveness constraints in (12).

(12) Ranking of the distinctiveness constraints relative to the [k]-[p] contrast.

*up-uk ≫ *up-uk ≫ *ip-ik ≫ *ip-ik ≫ *ap-ak

Tableau (13) shows how the inventory with only front vowels /ip ik ip ik ap ak/ is derived as the best inventory according to the ranking of place dispersion constraints in (12).

(13) Inventory evaluation according to the ranking of place dispersion constraints
The inventory with across-the-board laxing /up uk ip ik ap ak/ can be derived as a compromise between the inventory that best satisfies vowel dispersion (/up uk ip ik ap ak/) and the inventory that best satisfies place dispersion (/ip ik ip ik ap ak/). The rankings of vowel dispersion constraints and place dispersion constraints that are needed to derive this inventory are shown in (14).

(14) Ranking deriving the inventory with across-the-board laxing /up uk ip ik ap ak/

a. *i- > *up-uk (eliminates the candidate /ip ik ip ik ap ak/ with better place dispersion)
b. *up-uk > *i-u (eliminates the candidates /up uk ip ik ap ak/ and /up uk ip ik ap ak/ with better vowel dispersion)
c. *ip-ik > *i-u (eliminates the candidate /up uk ip ik ap ak/ with better vowel dispersion)

The ranking *i- > *up-uk in (14-a) favors /up uk ip ik ap ak/ over the inventory with best place dispersion /ip ik ip ik ap ak/: under this ranking, it is preferrable to allow [k] and [p] to contrast after [u] than to allow [i] and [i] to contrast. The ranking *up-uk > *i-u in (14-b) favors /up uk ip ik ap ak/ over the inventories with better vowel dispersion /up uk ip ik ap ak/ and /up uk ip ik ap ak/: under this ranking, it is preferrable to allow [i] and [u] to contrast than to allow [k] and [p] to contrast after [u]. The ranking *ip-ik > *i-u in (14-c) favors /up uk ip ik ap ak/ over the inventory with better vowel dispersion /up uk ip ik ap ak/: under this ranking, it is preferrable to allow [i] and [u] to contrast than to allow [p] and [k] to contrast after [i].
Tableau (15) shows how the rankings in (14) derive the inventory /up uk ip ik ap ak/ as the winner. This vowel inventory represents a compromise between the inventory with best vowel dispersion but worst place dispersion and the inventory with best place dispersion but worst vowel dispersion. In word-final position, only the vowel dispersion constraints are relevant and the winning three-vowel inventory is /i a u/.

(15) Deriving the inventory with across-the-board laxing /up uk ip ik ap ak/

<table>
<thead>
<tr>
<th></th>
<th>*i-</th>
<th>*up-uk</th>
<th>*up-uk</th>
<th>*ip-ik</th>
<th>*i-u</th>
</tr>
</thead>
<tbody>
<tr>
<td>up uk ip ik ap ak</td>
<td>*</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>up uk ip ik ap ak</td>
<td>*</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>up uk ip ik ap ak</td>
<td>*</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ut up uk ip ik ap ak</td>
<td>*</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ip ik ip ik ap ak</td>
<td>*</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4.2.2 Auditory space: [a i u u] and [k t]

This section considers the same vowel space as in the preceding section but a different place contrast: [k]-[t] instead of [k]-[p]. In the experiment, the distance between [k] and [t] was found to increase when lowering front vowels before stops but not when lowering back vowels before stops. It will be possible to show that laxing is not predicted to be possible for a given vowel if it does not improve any place contrasts (in this case, the unique [k]-[t] contrast) after that vowel (in this case, the back high vowel [u]).

The same constraints on vowel dispersion can be used but new constraints must be posited to evaluate [k]-[t] contrasts in different vowel contexts. These constraints are defined in (16).

(16) Constraints on [k]-[t] contrasts in coda position (where release transitions are missing).

a. *ut-uk
Penalize minimal pairs that only differ by [ut] and [uk].

b. *ut-uk

Penalize minimal pairs that only differ by [ut] and [uk].

c. *it-ik

Penalize minimal pairs that only differ by [it] and [ik].

d. *it-ik

Penalize minimal pairs that only differ by [it] and [ik].

e. *at-ak

Penalize minimal pairs that only differ by [at] and [ak].

In the experiment, the distance between [k] and [t] was found to increase when laxing front mid vowels but not when laxing back mid vowels. Assuming that these differences extend to high vowels, this translates into a difference in constraint rankings for *it-ik and *it-ik only: *ut-uk and *ut-uk have the same ranking. Also, [k] and [t] were found to be more confusable after front vowels (at the exception of [e]) than after back vowels. Finally, the distinctiveness of [k] and [t] was found to be roughly equal after [a] and after back vowels. Together, these findings establish the ranking of distinctiveness constraints in (17).

(17) Ranking of the distinctiveness constraints relative to the [k]-[t] contrast.

*it-ik ≫ *it-ik ≫ *ut-uk, *ut-uk, *at-ak

Tableau (18) shows how the candidates differing by tensing/laxing of front and back vowels are evaluated by the ranking in (17). Candidate /ut uk ut uk at ak/ is selected because it performs best on place dispersion by avoiding [k]-[t] contrasts after front vowels.

(18) Inventory evaluation according to the ranking of place dispersion constraints.
Tableau (19) zooms in on a subpart of tableau (18). The candidate with across-the-board laxing /ut uk it ik at ak/ ties with the candidate with laxing of front vowels only /ut uk it ik at ak/. They tie because the distinctness of the [t]-[k] contrast does not differ significantly after [u] and after [u]. When combined with the constraints on vowel dispersion, the candidate with laxing of front vowels only will always beat the candidate with across-the-board laxing because the inventory /i u a/ is more dispersed than the inventory /i u a/. As a consequence, the present approach is unable to derive laxing across vowels if laxing does not also improve place contrasts across vowels.

\[
\begin{array}{|c|c|c|c|c|}
\hline
\text{Tableau} & \text{candidate 1} & \text{candidate 2} & \text{candidate 3} & \text{candidate 4} \\
\hline
\text{ut uk it ik at ak} & * & * & * & * \\
\text{ut uk it ik at ak} & * & * & * & * \\
\text{ut uk it ik at ak} & * & * & * & * \\
\text{ut uk it ik at ak} & * & * & * & * \\
\hline
\end{array}
\]

(19) Deriving the inventory with laxing of front vowels only /ut uk it ik at ak/.

\[
\begin{array}{|c|c|c|c|c|}
\hline
\text{Tableau} & \text{candidate 1} & \text{candidate 2} & \text{candidate 3} & \text{candidate 4} \\
\hline
\text{ut uk it ik at ak} & * & * & * & * \\
\text{ut uk it ik at ak} & * & * & * & * \\
\hline
\end{array}
\]

4.2.3 Auditory space: [a u u] and [p k t]

In this section, considering the vowel space [a u u] and expanding the consonant space to include [p t k], I show that laxing of a given vowel is possible before all consonants if laxing improves some place contrasts after that vowel. The assumption that vowel-consonant covariation is blocked plays a crucial role in this result.

In addition to the constraints already used, the constraints in (20) are required to evaluate [p]-[t] contrasts after back vowels.

\[
\begin{array}{|c|c|c|c|c|}
\hline
\text{Tableau} & \text{candidate 1} & \text{candidate 2} & \text{candidate 3} & \text{candidate 4} \\
\hline
\text{ut uk it ik at ak} & * & * & * & * \\
\text{ut uk it ik at ak} & * & * & * & * \\
\hline
\end{array}
\]

(20) Constraints on [p]-[t] contrasts after back vowels.
a. *up-ut
Penalize minimal pairs that only differ by [up] and [ut].
b. *up-ut
Penalize minimal pairs that only differ by [up] and [ut].

Among back vowels, lowering was found to improve the contrasts involving [p] only. Also, after back vowels, the distinctiveness of the [k]-[p] contrast was the worst, followed by [k]-[t] and by [p]-[t]. These results support the ranking of distinctiveness constraints in (21). *ut-uk and *ut-uk have the same ranking because the contrast between [t] and [k] was not found to be affected by lowering [u] to [u].

(21) Ranking of the distinctiveness constraints relative to the [p]-[k], [p]-[t] and [k]-[t] contrasts after back vowels.
*up-uk > *up-uk > *ut-uk, *ut-uk > *up-ut > *up-ut

If vowel-consonant covariation is not allowed, there are only two candidates with a low vowel and a high vowel combined with [p t k] to consider: /ap at ak ut uk/ and /ap at ak up ut uk/. Other potential candidates, for instance /ap at ak up ut uk/, are excluded because they show vowel-consonant covariation. Tableau (22) shows how those two candidates are evaluated by the ranking of distinctiveness constraints relative to place contrasts in (21).

(22) Inventory evaluation according to the ranking of place dispersion constraints

<table>
<thead>
<tr>
<th></th>
<th>*up-uk</th>
<th>*up-uk</th>
<th>*ut-uk</th>
<th>*ut-uk</th>
<th>*up-ut</th>
<th>*up-ut</th>
</tr>
</thead>
<tbody>
<tr>
<td>ap at ak up ut uk</td>
<td>*</td>
<td>*</td>
<td></td>
<td>*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ap at ak up ut uk</td>
<td>*</td>
<td></td>
<td>*</td>
<td></td>
<td>*</td>
<td></td>
</tr>
</tbody>
</table>

The candidate with across-the-board laxing is favored by the ranking of distinctiveness constraints on place contrasts. Note that this inventory will be favored as long as a single contrast is improved by laxing. In the experiment it was found that two place contrasts were improved by laxing for each pair of tense-lax mid vowels (front unrounded, front rounded, back rounded). As a consequence, the analysis is able to
derive laxing across mid vowels and across places of articulation in French.

The fact that only two candidates are available due to the restriction on covariation plays a big role in this result. In the next section, I discuss how this restriction can be interpreted.

4.3 Interpreting the constraint against vowel-consonant covariation

In the preceding analysis, it was crucial to refer to a restriction against vowel-consonant variation to derive two results: (i) the possibility of vowel laxing before both consonants involved in poorly cued contrast (e.g. \([p]-[k]\) after back vowels, see section 4.1) and (ii) the possibility of vowel laxing before all consonants if some place contrasts are improved by laxing (e.g. laxing of back vowels \([k]\) and \([t]\), see section 4.2.3). However, it was also crucial that this restriction be turned off in order to derive laxing of back vowels before velars only in some languages (see section 4.1). This apparent contradiction can be solved if the restriction against covariation is included in the grammar as a constraint or as a set of constraints: when this constraint (or these constraints) is (or are) ranked high enough with respect to the distinctiveness constraints, patterns of across-the-board laxing are derived and when it (or they) is (or are) ranked low enough with respect to the distinctiveness constraints, consonant-specific conditioning for vowel laxing is derived.

This section deals with the following question: how to interpret the constraint against covariation? Three answers will be considered. First, I will discuss a dispersion-theoretic approach where contrasts between consonants and zero are also relevant. Second, I will consider an approach based on economy, where an economy constraint militates to minimize the number of vowel targets in a given context. Finally, I will propose that it is possible to derive consonant-specific patterns of vowel laxing and across-the-board laxing with two different types of dispersion constraints. Dispersion constraints evaluating pairs of diphones and introduced in the preceding
sections (e.g. *up-uk) derive consonant-specific laxing whereas dispersion constraints evaluating pairs of sounds in a given context (e.g. *p-k/u_) derive across-the-board laxing.

4.3.1 A dispersion-theoretic interpretation

First, I consider an approach that is compatible with Dispersion Theory. This approach consists in positing other constraints on contrasts to disfavor candidate with high vowels followed by stops. One potential candidate is a set of constraints that penalize consonant-zero contrast in different vocalic contexts. In their study of formant release transitions in CV sequences, Delattre, Liberman, and Cooper (1955, p. 771) note that "the first formant must have some degree of rising transition if a consonant is to be heard at all when the second formant is straight". Recast in terms of VC transitions, this statement says that the first formant must have some degree of falling transition if a consonant is to be heard at all when the second formant is straight. The greater the difference in aperture between the vowel and the following consonant, the sharper the falling F1 transition will be and the more audible the consonant should be. The idea that the magnitude of formant trajectories is useful to explain phonotactic restrictions has been defended by Kawasaki-Fukumori (1992).

This approach could help derive laxing of back vowels after both [p] and [k]. In this context, the F2 VC transitions are flat (Delattre, 1958). According to Delattre et al's (1955) reasoning, [p] and [k] should therefore be hard to distinguish from zero, in particular if they are unreleased. Lowering back vowels before both [p] and [k] could be a way to enhance the role of the F1 transition in signaling the presence of these consonants.

The constraints that are needed to deal with the present case are shown in (23).

(23) Constraints on [k]-Ø and [p]-Ø contrasts in coda position (where release transitions are missing).

a. *up-u

Penalize minimal pairs that only differ by [up] and [u].
b. *uk-u  
Penalize minimal pairs that only differ by [uk] and [u].
c. *up-u  
Penalize minimal pairs that only differ by [up] and [u].
d. *uk-u  
Penalize minimal pairs that only differ by [uk] and [u].

According to the hypothesis that consonants are more audible if they are signaled by a falling F1 transition than by a level F1 transition, the constraints penalizing [k]-Ø and [p]-Ø contrasts after tense back vowels should outrank the constraints penalizing these contrasts after lax back vowels, as in (24).

(24) Rankings of the constraints evaluating [k]-Ø and [p]-Ø contrasts in coda position  

<table>
<thead>
<tr>
<th></th>
<th>*up-u</th>
<th>*uk-u</th>
<th>*up-u</th>
<th>*uk-u</th>
</tr>
</thead>
<tbody>
<tr>
<td>u up uk</td>
<td>*</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ūū u up uk</td>
<td></td>
<td>*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>u up uk</td>
<td>*</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>u up uk</td>
<td></td>
<td></td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>ūū u up uk</td>
<td></td>
<td></td>
<td></td>
<td>*</td>
</tr>
</tbody>
</table>

The tableau in (25) shows how these constraints favor an inventory with laxing of back vowels before both [k] and [p].

(25) Deriving laxing across consonant contexts with C - Ø distinctiveness constraints

This approach is a potential alternative to the approach based on place contrasts proposed in this dissertation. Indeed, once these constraints are adopted, it is potentially possible to justify laxing without appealing to constraints on place contrasts.

There are two main issues with this alternative dispersion-theoretic approach.
First, there is less evidence for C-∅ confusability than for place confusability. For instance, in a perceptual study of consonant identification (joint work with Sam Zukoff), we found that listeners were about five times more likely to misidentify [k] as [p] and [p] as [k] than as [k] as ∅ and [p] as ∅, as shown in (26). One possible reason is that the presence vs. absence of a consonant is signaled by other cues, including durational cues. In grammatical terms, this means that the distinctiveness constraints relative to C-∅ contrasts should be lower ranked than the distinctiveness constraints relative to place contrasts and therefore should be less likely to play a role.

(26)  Confusion matrix in context [k/p∅_tana]

<table>
<thead>
<tr>
<th>Response</th>
<th>∅</th>
<th>k</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stimulus</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>∅</td>
<td>406</td>
<td>23</td>
<td>15</td>
</tr>
<tr>
<td>k</td>
<td>17</td>
<td>333</td>
<td>94</td>
</tr>
<tr>
<td>p</td>
<td>29</td>
<td>169</td>
<td>246</td>
</tr>
</tbody>
</table>

Second, this approach potentially derives patterns of open-syllable vowel laxing and closed-syllable vowel tensing. For instance, if the contrast between [p] and ∅ after high back vowels is the most distinct when [p] is preceded by [u] and ∅ is preceded by [u], then it is possible to derive tensing to [u] after [p] and laxing to [u] word-finally, as shown in (27).

(27)  Deriving laxing in open syllables with C-∅ distinctiveness constraints

<table>
<thead>
<tr>
<th></th>
<th>*up-u</th>
<th>*up-u</th>
<th>*up-u</th>
<th>*up-u</th>
</tr>
</thead>
<tbody>
<tr>
<td>u up</td>
<td>*</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>u up</td>
<td></td>
<td></td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>u up</td>
<td></td>
<td></td>
<td></td>
<td>*</td>
</tr>
<tr>
<td>u up</td>
<td></td>
<td></td>
<td></td>
<td>*</td>
</tr>
</tbody>
</table>

There are actually reasons to think that [up] and [u] might be more distinct than the other pairs [up]-[u], [up]-[u], and [up]-[u]. This pair involves two different vowels: therefore, it should be more distinct than pairs [up]-[u] and [up]-[u]. In addition, the
contrast between \([up]\) and \([u]\) could be more distinct than the contrast between \([up]\)
and \([u]\), based on the shape of the F2 transition into \([p]\) starting from \([u]\) vs. starting
from \([u]\). \([p]\) should lower the F2 realization of a preceding \([u]\) in \([up]\), making \([op]\)
quite similar to \([u]\). In the inventory \(/u up/\), the F2 value of \([o]\) is not lowered in the
absence of a following \([p]\) and therefore \([u]\) and \([up]\) remain quite distinct along F2.

This kind of problems cannot arise with the approach based on place contrasts
because there are no constraints that relate the realization of vowels in open syllables
and the realization of vowels in closed syllables. Tense vowels should always be
preferred in open syllables because only vowel dispersion constraints are relevant in
this context.

### 4.3.2 An interpretation based on economy

There is a more radical way to deal with this problem: assuming that there are
constraints that explicitly militate for more symmetric vowel inventories. Positing
a constraint requiring symmetry of vowel inventories could favor say \(/up ok ap ak/\)
over \(/up ok ap ak/: \(/up ok ap ak/\) is more symmetric than \(/up ok ap ak/\) because
the high vowels have the same height in the former inventory but not in the latter
inventory.

The need for such constraints has been argued for in previous works on Dispersion
Theory. Vowel inventories derived with dispersion constraints only (e.g. Liljencrants
and Lindblom, 1972) have been observed to be more asymmetric than attested vowel
inventories (Boersma and Hamann, 2008, p. 224). In their study of the realization
of the height feature by French speakers, Ménard, Schwartz, and Aubin (2008) found
that “speakers tend to align vowels with a similar height along stable F1 values across
rounding and place of articulation” (Ménard, Schwartz, and Aubin, 2008, p. 26):
French speakers tend to use the same F1 target for \([i y u]\), the same F1 target for \([e \phi o]\)
and the same F1 target for \([e \infty o]\). Under dispersion-theoretic principles, this is
unexpected: covarying F1 and F2 is a way to achieve better vowel dispersion.

Different interpretations of this pressure for symmetry have been proposed, ap-
pealing to an efficient use of auditory and/or articulatory features. For instance,
Ménard, Schwartz, and Aubin (2008) argue that the pattern they observed in French is best explained in a theory where both dispersion and gestural economy play a role in shaping vowel inventories, on the assumption that producing the same F1 value requires a similar tongue to roof of the mouth distance across rounding and places of articulation. Alternatively, this could be explained as resulting from feature economy (Clements, 2003), assuming that speakers are inclined to maximize the use of auditory F1 targets.

Could a principle of economy favor inventories like /up uk/ and /up uk/ over /up uk/ and /up uk/? The notion of economy of F1 targets must be relativized to a context though: otherwise, inventory /a u up uk ap ak/ would always be worse than /a u up uk ap ak/. The two inventories tie on economy (there are three levels of height in each: [a u u]) and /a u up uk ap ak/ is better both for vowel dispersion and consonant dispersion: [up] and [ap] are more distinct than [up] and [ap] and [up] and [uk] are more distinct than [up] and [uk], at least according to the analysis of covariation as enhancement. If economy is relativized to a context, it is possible to distinguish /a u up uk ap ak/ and /a u up uk ap ak/. For /a u up uk ap ak/, the subinventories of preonset vowels /a u/ and precoda vowels /a u/ can both be described with two F1 targets. In the case of /a u up uk ap ak/, the subinventory of precoda vowels /a u u/ must be described with three different F1 targets.

Note that, if economy must be relativized to a context, the gestural interpretation becomes more problematic. It is unclear why the context in which vowels occur should be relevant to the count of gestures. This makes more sense if the economy is representational. The idea that representational economy plays a role in phonological grammars can be found in Chomsky and Halle (1968) among others. Suppose that inventories are subject to the constraint that their description has to be economical. The description of the inventory in (28-a) is less economical than the description of the inventory in (28-b) because the context makes specific reference to velars in (28-a) but not in (28-b).

(28)  Economy as representational economy.
In the context of Chomsky and Halle (1968), economy is a criterion relevant to the learner of a language and is not stated directly as a constraint on phonological grammars. However, if learners favor more economical grammars everything else being equal, then the typology of phonological patterns should also be shaped by economy. For current purposes, the constraint banning vowel-consonant covariation will be defined as in (29). This constraint will assign 2+2=4 violation marks to the inventory with laxing before both [p] and [k] /a u up uk ap ak/ (two violation marks for the subinventory of preonset vowels /a u/ and two violations for the subinventory of precoda vowels /a u/) and 2+3=5 violation marks to the inventory with laxing only before [k] /a u up uk ap ak/ (two violations for the subinventory of preonset vowels /a u/ and three violations for the subinventory of precoda vowels /a u u/).

(29)  Economy

Assign as many violations marks as there are different F1 vowel targets in preonset vowel inventories and in precoda vowel inventories.

Tableau (30) shows how the inventory with across-the-board laxing can win if Economy outranks the constraint penalizing laxing before both [p] and [k], *up-uk. For instance, /u up uk/ violates Economy twice because there is one F1 target in each subinventory of precoda and preonset vowels (the F1 target of [u] in both cases). /u up uk/ violates Economy three times because there is one F1 target in the subinventory of preonset vowels (the F1 target of [u]) but two F1 targets in the subinventory of precoda vowels (the F1 targets of [u] and [u]).

(30)  Absence of height-place covariation is better for economy.
There are problems with this approach though. One question is the following: why does economy care about the distinction between preonset vowel inventories and pre-coda vowel inventories specifically? This distinction is conceptually motivated by perceptual factors: onset and coda positions correspond to positions where good cues to place are available vs. missing. It makes sense that distinctiveness constraints refer to this split because the presence or absence of cues affects the distinctiveness of contrasts. However, it is conceptually unclear why these specific contexts matter for economy. For instance, one could imagine that other contexts could be relevant: for instance, the economy constraint could be defined so as to penalize a large number of different F1 vowel targets before each consonant. Also, why should the number of F1 targets be minimized rather than say the number of F2 targets? The approach based on economy leaves open a number of questions.

Another problem is that this approach potentially predicts that laxing a vowel could be required in order to improve a single consonant contrast. Suppose that the economy constraint outranks all distinctiveness constraints referring to place contrasts except for a single one. In order to avoid a badly cued contrast between two consonants and to avoid having too many different F1 targets in precoda position, it will be preferrable to lax a vowel before all coda consonants rather than just before the consonants involved in a poor contrast.

### 4.3.3 Distinguishing two types of dispersion constraints

Tense vowels can be penalized before both consonants involved in a poorly cued contrast (e.g. [u] can be penalized before both [p] and [k]) if contextual distinctiveness constraints are defined such that both segments (e.g. both [p] and [k]) are penalized in
the relevant context (e.g. in the context [u_]) (31-a). This definition differs from the
notion of contextual distinctiveness constraints that was assumed until now, where
pairs of diphones were penalized (31-b).

(31) Two conceptions of contextual distinctiveness constraints

a. *p-k/u_ (preliminary version)
   Penalize any inventory of VC syllables where [p] or [k] occurs after [u].
   (In other words: penalize any inventory containing [up] or [uk])

b. *up-uk
   Penalize any inventory containing [up] and [uk].

The difference between the two constraints is illustrated in (32). The constraint
*up-uk in (31-b) only penalizes inventories where the two diphones [up] and [uk] are
attested. The constraint *p-k/u_ in (31-a) penalizes inventories where any of the two
diphones [up] or [uk] is attested. This constraint will penalize the occurrence of a tense
vowel (here [u]) before any of the two segments involved in a poorly cued contrast:
satisfying this constraint will result in across-the-board laxing (assuming no other
option is available). Satisfying *up-uk will not necessarily result in across-the-board
laxing, as already seen.

(32) How the two distinctiveness constraints penalize candidates.

<table>
<thead>
<tr>
<th></th>
<th>*p-k/u_</th>
<th>*up-uk</th>
</tr>
</thead>
<tbody>
<tr>
<td>up uk</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>up ok</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>up uk</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>up ok</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Using segment distinctiveness constraints like *p-k/u_ to derive across-the-board
laxing differs from an approach using an economy constraint combined with dipphone-
based distinctiveness constraints like *up-uk (see section 4.3.2 for this approach). In
the latter case, the economy constraint can motivate laxing even before consonants
that are not involved in a poorly cued place contrast (see section 4.3.2 for discussion). In the former case, this is not possible: if there is no constraint militating for economy and assuming that laxing is only motivated by place enhancement, then laxing should never be attested beyond the contexts where it is perceptually motivated. Deriving across-the-board laxing with segment-based distinctiveness constraints therefore provides a more restrictive theory. There is another reason to prefer this theory over the economy-based theory: there is no longer any need to stipulate that economy cares about contexts that are defined in perceptual terms (see the definition of the economy constraint in (29)).

Is there a motivation for distinguishing two kinds of distinctiveness constraints? Diphone distinctiveness constraints like *up-uk are just an extension of simple, context-independent segment distinctiveness constraints like *p-k. They are motivated if speakers optimize not only contrasts between sounds but also contrasts between sequences of sounds (see Graff, 2012 for evidence that words are optimized for communicative efficiency).

Contextual distinctiveness constraints like *p-k/u_ make sense if the perceptual distance between the two relevant sounds (here, [p] and [k]) in the relevant context (here u_) is computed with an identification algorithm that does not rely on the identification of the context (here, the identity of the preceding vowel). Given a sequence [up], the contrast between [p] and [k] will be evaluated based on the perceptual distance between [up] and [uk], regardless of whether [uk] is attested in the candidate inventory. In the same way, given a sequence [uk], the contrast between [p] and [k] will be evaluated based on the perceptual distance between [up] and [uk], regardless of whether [u] is attested in the candidate inventory.

Nearey and Shammass (1987) proposed an algorithm classifying stop place based on locus equations that has this property. In this algorithm, identification of stop place can be made independent of the identification of the adjacent vowel.

Locus equations express the n^th-formant realization of a consonant C, Fn(C), as a linear function of the n^th-formant realization of the adjacent vowel, Fn(V), as in (33). Formant realizations of consonants have been shown to be well described by
this relation (Lindblom, 1963).

(33) Locus equation

\[ F_n(C) = \alpha F_n(V) + \beta \]

In Nearey and Shammass's algorithm, the classification of place is based on the proximity between the actual formant value of the consonant and the formant value expected for each place given the vowel realization, \( F_n(V) \), and language-specific locus equations (with language-specific slope \( \alpha \) and intercept \( \beta \)). For instance, a target stop \( C \) is classified as [p] if, among the F2 values expected for [p t k] based on F2(V) and the locus equations for [p t k], the F2 value expected for [p] is the closest to F2(C).

In this algorithm, the identification of stop place is independent of the identification of the vowel context: the algorithm only uses the realization of the adjacent vowel, \( F_n(V) \), to make its decision. The identity of that vowel, \( T_n(V) \) (where \( T_n(V) \) denotes the target formant value of V), does not matter.

If contextual distinctiveness constraints evaluate inventories based on this type of algorithm, they will only compare realizations of two relevant consonants where the formant value of the adjacent vowel is held constant. For instance, given [up] with \( F_2([u]) = 900 \) Hz, a distinctiveness constraint will penalize the contrast between [p] and [k] based on the distance between the two realizations of [p] and [k] after an [u] whose F2 value is equal to 900 Hz. And this regardless of whether [uk] is attested in the inventory under evaluation. As a result, this constraint will penalize both an inventory containing [up] but not [uk] and an inventory containing both [up] and [uk]. Consider a candidate inventory containing [up] and [uk] but not [uk], where [u] has an F2 value of 900 Hz and [u] an F2 value of 1100 Hz. Because of the way the identification algorithm works, there is a contextual distinctiveness constraint *p-k/u_ that will penalize [up] based on its distance to hypothetical [uk], although [uk] is not in the inventory.

The constraint *p-k/u_ in (31-a) needs to be slightly modified though. As it is formulated, it will penalize an inventory containing only [up] or an inventory containing only [uk] (i.e. where the contrast between [p] and [k] is neutralized). But
distinctiveness constraints can be satisfied by neutralization (see section 4.5). The constraint therefore needs to be slightly reformulated in order to penalize contrasts between [p] and [k] rather than just sequences involving [p] or [k].

The reformulation of the constraint as a constraint on contrasts is shown in (34). The resulting constraint is partly blind to the structure of the candidate inventory (e.g. it ignores whether both [p] and [k] are preceded by [u] in the syllable inventory) but not totally (e.g. it takes into account whether both [p] and [k] are attested in the syllable inventory).

(34) *p-k/u_ (final version)
    Penalize any occurrence of [p] or [k] after [u] if both [p] and [k] are attested in the inventory of VC syllables.

The tableau in (35) shows how this constraint evaluates different inventories of syllables: it penalizes inventories where [u] occurs before [p] or [k] provided that both [p] and [k] are attested. In other words, it does not penalize candidates where the contrast is neutralized. In this sense, it is a distinctiveness constraint and differs from a markedness constraint penalizing an inventory containing [up] or [uk] (this constraint is shown as *up ∨ uk in (35)).

(35) Contextual distinctiveness constraints differ from markedness constraints banning specific sound sequences.

<table>
<thead>
<tr>
<th></th>
<th>*p-k/u_</th>
<th>*up ∨ uk</th>
</tr>
</thead>
<tbody>
<tr>
<td>up uk</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>up uk</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>up uk</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>up uk</td>
<td></td>
<td></td>
</tr>
<tr>
<td>up</td>
<td></td>
<td>*</td>
</tr>
<tr>
<td>uk</td>
<td></td>
<td>*</td>
</tr>
</tbody>
</table>
4.4 Analysis of the French *loi de position*

I briefly illustrate how the *loi de position* can be derived using the type of contextual segment distinctiveness constraints introduced in section 4.3.3. To simplify, the vowel space contains seven possible vowels [i e u o o a] and three possible consonants [p t k]. I focus on the laxing of front mid vowels.

The rankings in (36-a) and (36-b) are motivated by the results of the perceptual experiment in chapter 3, where the contrasts between [p] and [k] and between [k] and [t] were found to be more distinct after [c] than after [e]. The ranking in (36-a) favors an inventory containing [ek] and [et] over inventories containing [ek] or/and [et]. The ranking in (36-b) favors an inventory containing [ep] and [ek] over inventories containing [ek] or/and [ep].

(36) Deriving the *loi de position* with segment distinctiveness constraints (front vowels).

   a. *k-t/e_ ≫ *k-t/ε_
   b. *p-k/e_ ≫ *p-k/ε_
   c. *k-t/e_ , *p-k/e_ ≫ *ε-ɔ ≫ *e-ɔ

The constraints *ε-ɔ and *e-ɔ in (36-c) refer to vowel contrasts: tense vowels [e] and [o] are preferred by default over lax vowels [ɛ] and [ɔ] (*ε-ɔ ≫ *e-ɔ) because they are more dispersed along F2. The ranking in (36-c) favors an inventory containing lax vowels [ɛ] and [ɔ] (which is worse than an inventory containing tense vowels for vowel dispersion purposes) over an inventory with [ep], [et], and/or [ek].

Put together, these rankings derive a preference for the inventory containing [ep], [et] and [ek] over inventories containing [ep], [et], and/or [ek]. As desired, it is possible to derive across-the-board laxing.

Generally, this approach predicts that, as long as every consonant is involved in at least one poorly cued contrast after a tense vowel and the corresponding constraint outranks a distinctiveness constraint favoring tense vowels, laxing should be derived before all consonants. Here, all of [p t k] are involved in a place contrast that is less
distinct after [e] than after [i] (see (36-a) and (36-b)) and the vowel distinctiveness constraint penalizing [e] is outranked by the relevant place distinctiveness constraints (see (36-c)). Therefore, laxing is derived before all three consonants [p t k]. The same approach can be applied to other mid vowels as, for all mid vowels (front unrounded, front rounded, back rounded), every consonant was found be involved in at least one contrast that was less distinct after the tense vowel than after the lax vowel (see chapter 3).

Because place contrasts were not found to be more distinct after [e] than after [i] in chapter 3, contextual distinctiveness constraints will assign the same penalty to VC sequences involving [i] and [e]. And [i] will be preferred over [e] for vowel distinctiveness: high vowels are more dispersed along F2 than tense mid vowels (37).

This analysis derives the following property of the loi de position: although mid vowels are lax in closed syllables, high vowels are not lowered to mid in closed syllables.

(37) \( *e-o \gg *i-u \)

Why aren't Southern French high vowels laxed to [i u] in closed syllables, as in québec French? Or in other words, where does the difference between Southern French (which does not lax high vowels) and québec French (which laxes high vowels) come from?

Lisker (1999) found that place contrasts are generally more distinct after lax high vowels than after tense high vowels in VC. In chapter 3, tense mid vowels were not generally improve postvocalic place contrasts as compared to tense high vowels. The results from these two studies suggest that lax high vowels should provide better place cues than both tense high and tense mid vowels. Focusing on the contrast between [p] and [k] and on front vowels, this motivates the ranking in (38).

(38) \( *p-k/i_, *p-k/e_ \gg *p-k/i_ \)

High lax vowels are more central (and therefore should be less distinct) than tense high vowels and tense mid vowels in quebec French (Martin, 2002). This motivates
the ranking of vowel dispersion constraints in (39).

(39)  \[ *i-u \gg *e-o, *i-u \]

The difference between Southern French and Québec French can now be derived as resulting from a difference in the way the two rankings in (38) and (39) interact. The ranking in (40-a), where having good vowel contrasts among high vowels matters more than having good place contrasts after high vowels, derives no laxing of \([i]\) before coda \([p]\) and \([k]\). This corresponds to the situation in Southern French. The ranking in (40-b), where having good place contrasts after high vowels matters more than having good vowel contrasts among high vowels, derives laxing of \([i]\) before \([p]\) and \([k]\). This corresponds to the situation in Québec French.

(40)  
  a. Southern French  
      \[ *i-u \gg *p-k/i_ \]
  b. Quebec French  
      \[ *p-k/i_ \gg *i-u \]

### 4.5 Enhancement and neutralization

Closed-syllable vowel laxing was analyzed as a strategy to enhance poorly cued place contrasts. Are there alternative repairs available to avoid sequences of tense vowels followed by a coda consonant? This section shows how the present analysis predicts that patterns of place contrast neutralization sensitive to vowel height should be attested and provides preliminary evidence that this prediction is correct.

In addition to constraints on contrasts, Flemming (2002) posits a constraint that favors large inventories, MaxContrast. Because the present analysis selects inventories of VC syllables, this constraint is stated in terms of maximizing the number of syllables in an inventory (41).

(41)  \[ \text{MaxContrast} \]
Assign one check mark ✓ for each distinct syllable in an inventory of syllables.

Having more contrasts available is desirable because it increases the information density per sound and therefore allows speakers to have shorter words to convey the same amount of information (Nettle, 1995). This requirement is implemented in terms of a positive constraint that counts the number of contrasts in the candidate inventory (Flemming, 2002; Flemming, 2004). The largest inventory or inventories are selected by this constraint, all others are eliminated. Because MaxContrast may be dominated by other constraints in a specific grammar, MaxContrast will actually select the largest viable inventory.

The constraints on the distinctiveness of contrasts and the constraint on inventory size conflicts because the auditory space in which syllables are selected is finite. Allowing more types of syllables in the inventory will necessarily result in smaller perceptual distances between the members of the syllable inventory and in higher rate of misidentification on the part of listeners.

In the current analysis, this constraint is needed to distinguish two possible strategies in the presence of potentially perceptually weak contrasts: the neutralization strategy and the enhancement strategy. The neutralization strategy gets rid of the problem of a perceptually weak contrast by getting rid of one of the members of the contrast, i.e. by reducing the size of the syllable inventory. The enhancement strategy solves the problem by changing some properties of the syllables in different contexts while keeping the inventory size constant.

I show how different rankings of MaxContrast yield the two different types of repairs discussed here, enhancement (42-a) and neutralization (42-b). When MaxContrast outranks the distinctiveness constraints penalizing [p]-[k] contrasts after high back vowels, the smaller inventory /ap ak up/ is penalized and the inventory that both avoids the bad [up]-[uk] contrast and maintains a large number of contrasting syllables is selected as the winner. When the distinctiveness constraints penalizing [p]-[k] contrasts after high back vowels outranks MaxContrast, the inventories that allow contrasts after high back vowels /ap ak up uk/ and /ap ak up uk/ are elimi-
nated and the inventory that eliminates the contrast in this position by eliminating [up] is selected as the winner.

(42) a. Enhancement of place contrasts

<table>
<thead>
<tr>
<th></th>
<th>MaxContrast</th>
<th>*up-uk</th>
<th>*up-uk'</th>
<th>*a-u</th>
<th>*a-u</th>
</tr>
</thead>
<tbody>
<tr>
<td>ap ak up uk</td>
<td>✔️ ✔️ ✔️ ✔️</td>
<td>*!</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ap ak up uk</td>
<td>✔️ ✔️ ✔️ ✔️</td>
<td>✔️</td>
<td>✔️</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ap ak uk</td>
<td>✔️ ✔️ ✔️ ✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td></td>
</tr>
</tbody>
</table>

b. Neutralization of place contrasts

<table>
<thead>
<tr>
<th></th>
<th>*up-uk</th>
<th>*up-uk</th>
<th>MaxContrast</th>
<th>*a-u</th>
<th>*a-u</th>
</tr>
</thead>
<tbody>
<tr>
<td>ap ak up uk</td>
<td>*!</td>
<td>✔️ ✔️ ✔️ ✔️</td>
<td>✔️ ✔️</td>
<td>✔️</td>
<td></td>
</tr>
<tr>
<td>ap ak up uk</td>
<td>*!</td>
<td>✔️ ✔️ ✔️ ✔️</td>
<td>✔️ ✔️</td>
<td>✔️</td>
<td></td>
</tr>
<tr>
<td>ap ak uk</td>
<td>✔️ ✔️ ✔️ ✔️</td>
<td>✔️ ✔️ ✔️</td>
<td>✔️ ✔️</td>
<td>✔️</td>
<td></td>
</tr>
</tbody>
</table>

The current approach predicts that neutralization of place contrasts after higher vowels should be observed. I do not know of a comprehensive cross-linguistic survey of languages with place neutralization in coda position as a function of the preceding vowel. However, there are certainly languages that show neutralization of place contrasts sensitive to vowel quality and where the vowel effect goes in the expected direction. In Munken, in a corpus of about 250 verbs, Lovegren (2013, p. 95) found no evidence for place contrasts in coda position after high vowels: after high vowels, only the homorganic nasal is available, i.e. [n] after [i] and [ŋ] after [u] (43). The choice of the homorganic consonant can be understood as an effect of another constraint in Flemming’s model: MinimizeEffort. Allowing [n] after [i] and [k] after [u] makes it possible to have V#-VC# contrasts at a minimum effort cost because the production of these vowels and consonants involve similar articulatory gestures.

However, all place contrasts are available before the low vowels [a ə]. This is consistent with the results of the perceptual experiment on French, where place contrasts were found to be improved after [ɛ] and [a] as compared to [i] and [ɛ]. Labial-velar
contrasts are unavailable after [u] but are available after [o] and [ɛ]. This is also consistent with the results of the perceptual experiment of French, where the [p]-[k] contrast as found to be more distinct after lower back than after higher back vowels.

(43) Attested vs. unattested vowel-coda combinations in Munken (corpus of about 250 verbs).

<table>
<thead>
<tr>
<th></th>
<th>m</th>
<th>n</th>
<th>n̄</th>
</tr>
</thead>
<tbody>
<tr>
<td>i</td>
<td>✗</td>
<td>✓</td>
<td>✗</td>
</tr>
<tr>
<td>e</td>
<td>✗</td>
<td>✓</td>
<td>✗</td>
</tr>
<tr>
<td>ɛ</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>u</td>
<td>✗</td>
<td>✗</td>
<td>✓</td>
</tr>
<tr>
<td>o</td>
<td>✓</td>
<td>✗</td>
<td>✓</td>
</tr>
<tr>
<td>ɔ</td>
<td>✓</td>
<td>✗</td>
<td>✓</td>
</tr>
<tr>
<td>ə</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>a</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

In Cantonese, all three place contrasts [p t k] and [m n n̄] are available in coda position after low vowels [a] and [ɛ] but only subsets of those contrasts are available in coda position after higher vowels (Kenstowicz, 2012).

4.6 Further predictions

The characterization of the contexts favoring vowel laxing as contexts where the postvocalic consonant lacks good cues to place potentially predicts that laxing should be more likely before consonants that have weaker internal place cues. Fricatives have stronger internal place cues than oral stops and oral stops have stronger internal place cues than nasal stops (Wright, 2004). The difference in the strength of cues provided by nasals vs. stops vs. fricatives has been argued to be relevant to the typology of regressive place assimilation in prestop position, with place assimilation being more likely for nasals than for stops and for stops than for fricatives (Ohala, 1990; Hura, Lindblom, and Diehl, 1992). Is the typology of closed-syllable vowel
laxing also sensitive to these differences, with vowel laxing being more likely before nasals than before stops and more likely before stops than before fricatives? Also, released stops have stronger internal place cues and are more distinct than unreleased stops (Lisker, 1999; Ohala and Ohala, 2001). Is there evidence that closed-syllable vowel laxing is less likely before released stops than before unreleased stops?

These questions cannot be answered definitely yet, as there is (to my knowledge) no comprehensive survey of closed-syllable vowel laxing languages. Below I mention consonant restrictions that I noted in the literature on languages with closed-syllable vowel laxing. These restrictions are consistent with these predictions. A more systematic survey should be carried out to test these predictions thoroughly.

In Paluai, vowel laxing singles out the nasal stops, in accordance with the hypothesis that place contrasts are the weakest in nasals: /i/ is realized as lax [i] before word-final nasals [m n ñ] (44-a) but as tense [i] before other coda consonants [p t k l j w] (44-b) (Schokkin, 2014).

(44) Laxing of [i] before nasals only: Paluai.

a. [i] laxes to [i] before coda nasals.

/musin/ [musin] ‘soft (of betelnut)’

b. [i] does not lax before coda stops.

/nik/ [nik] ‘fish’

In Québec French, a subset of the fricatives is singled out as the only coda consonants that do not trigger vowel laxing, in accordance with the hypothesis that place contrasts are the strongest in fricatives. High vowels are almost systematically tense before medial coda sibilants (45-a) but optionally lax before other medial coda consonants (45-b). High vowels are necessarily tense before word-final coda voiced fricatives [v z ŋ] (45-c) but necessarily lax before other word-final coda consonants (45-d) (Côté, 2012, pp. 242-244). Differences in vowel duration in different consonantal contexts are ignored in the transcriptions in (45). The difference between voiced and voiceless sibilants word-finally remains to be explained. It could be a way to enhance voicing
contrasts.

(45) Restrictions on laxing before fricatives in Québec French

a. High vowels are tense before medial coda sibilants
   bistro \[bistro]\/*[bistro]\

b. High vowels are optionally laxed before other medial coda consonants
   sultan \[sylt\]/[sylt]\

c. High vowels are tense before word-final coda voiced fricatives \[v z 3]\n   vive \[viv]/*[viv] 'live.SUBJ'

d. High vowels are lax before other final coda consonants
   tube \[tsyb]/*[tsyb] 'tube'

Many languages with closed-syllable vowel laxing have unreleased coda stops. Indonesian is one of them, whose inventory of coda consonants is shown in (46) (Sneddon et al., 2010, pp. 8-10). However, it remains to be shown whether languages with closed-syllable vowel laxing are more likely to have unreleased coda stops compared to languages without closed-syllable vowel laxing.

(46) Inventory of word-final consonants in Indonesian

<table>
<thead>
<tr>
<th>Labial</th>
<th>Alveolar</th>
<th>Velar</th>
<th>Glottal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stops</td>
<td>p'</td>
<td>t'</td>
<td>k'</td>
</tr>
<tr>
<td>Nasals</td>
<td>m</td>
<td>n</td>
<td>η</td>
</tr>
<tr>
<td>Fricatives</td>
<td>f</td>
<td>s</td>
<td>h</td>
</tr>
<tr>
<td>Liquid</td>
<td>l, r</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4.7 Conclusion

Part I of this thesis has proposed to analyze the patterns of closed-syllable vowel laxing and open-syllable vowel tensing as motivated by the conflicting requirements of vowel dispersion and consonant dispersion in VC sequences. The hypothesis that consonant place contrasts are more distinct after lax than tense vowels was supported by the results from previous studies (especially for high vowels) and by the results of the
experiment presented in chapter 3 for mid vowels in French. In chapter 3, for each pair of tense/lax mid vowels, at least two place contrasts were found to be improved after lax vowels. A decrease in confusability was observed specifically in contexts where the distance between the F1 realizations of consonants decreased, suggesting that mid-vowel laxing may primarily involve an enhancement of F1 transitions in French. If this is true, mid-vowel centralizing needs to be explained as a by-product of lowering. Further research is necessary to test whether this is the correct interpretation of the results.

The analysis was formalized using the OT implementation of Dispersion Theory by Flemming (2002) in chapter 4. The analysis derives the tense vs. lax quality of vowels in closed syllables as a compromise between constraints favoring maximal vowel dispersion and constraints favoring maximal consonant dispersion. Consonant-specific laxing and across-the-board laxing were analyzed with two different types of dispersion constraints. Consonant-specific laxing (e.g. Chamorro) was derived with constraints penalizing contrasts between VC diphones. Across-the-board laxing (e.g. French) was derived with contextual constraints penalizing consonant-place contrasts in different vowel contexts. Alternative analyses of across-the-board laxing as motivated by constraints on contrasts between consonant and zero or by a constraint on economy were discussed and shown to be problematic.

We saw preliminary evidence (to be confirmed with a larger and more systematic survey) suggesting that there are specific conditionings on vowel laxing that are consistent with this analysis. Paluai laxes high vowels before nasal codas only and this is consistent with the observation that place cues provided by nasals’ internal cues are particularly weak. Québec French does not systematically lax vowels before fricatives and this is consistent with the observation that place cues provided by the frication noise are robust. Some languages lax back vowels before velars only and this is consistent with the observation that the contrast between labials and velars is specifically hard to perceive in this context. Some languages neutralize place contrasts in coda positions after high vowels and this is consistent with the general idea that languages try to avoid place contrasts in coda position after tense vowels.
This perceptually-based theory is an alternative to duration-based accounts. Although lax vowels are often shorter than tense vowels, the quality of lax vowels cannot be simply derived from the quality of tense vowels via vowel undershoot, as shown in chapter 2. Also, the acoustic study of French presented in chapter 2 revealed that tense and lax mid vowels consistently differ along their formant properties, but not in duration.
Part II

A theory of phonologically-derived environment effects
Chapter 5

Introduction

5.1 Background

Phonologically-derived environment effects (henceforth, PDEEs) describe patterns where a phonological process $P$ applies only if accompanied by another phonological process $P'$ (Kiparsky, 1973; Kiparsky, 1993). PDEEs can be illustrated with Campidanian Sardinian phrase-level lenition, as described by Bolognesi (1998). In Campidanian Sardinian, lenition applies in word-initial position only if accompanied by voicing: intervocalic lenition applies to underlyingly voiceless stops /p t k/ voiced through intervocalic voicing (1-a), but not to underlyingly voiced stops /b d g/ (1-b). The pattern is described as productive by Bolognesi (1998).

(1) Campidanian Sardinian lenition (Bolognesi 1998, pp. 30-40)

a. Word-initial voiceless stops are voiced and lenited intervocally

\footnote{Voicing plus lenition also applies to underlyingly voiceless stops between a vowel and $[r]$, e.g. /su triنتaduzu/ [suоrintaduzu] 'the thirty-two'.}
PDEEs are known to be challenging patterns for both rule-based phonology (SPE; Chomsky and Halle 1968) and classical Optimality Theory (OT; Prince and Smolensky 1993). In SPE, a rule of intervocalic lenition ordered after a rule of intervocalic voicing will lenite both underlying /b d g/ and /p t k/, if no further condition is imposed. In classical OT, the ranking that derives lenition of intervocalic voiceless stops (*VConftV > Ident(cont)) will also derive lenition of underlying voiced stops. In both cases, additional machinery is needed in order to distinguish phonologically-derived environments, in which lenition applies, and nonderived environments, in which lenition does not apply. Various proposals have been made to solve this problem including Kisseberth (1972), Kiparsky (1993), Burzio (2000), McCarthy (2003), Wolf (2008), and Hayes and White (2015) among others.

This thesis focuses on yet another problem that PDEEs raise. This problem is specific to theories assuming a minimal input-output modification bias in phonological grammars, e.g. theories like OT that hold that there is a pressure for the output to be faithful to the input. PDEEs may give rise to alternations called ‘saltations’ (White, 2013; White, 2014; Hayes and White, 2015), i.e. alternations where an underlying string leaps over an intermediary form and this intermediary form does not alternate.
In Campidanian Sardinian, the saltatory alternation involving stops in word-initial position is depicted in (2) for velars: underlying /k/ goes to [y] leaping over [g] whereas underlying /g/ is mapped to itself.

(2) Campidanian Sardinian lenition as saltation

Context: word-initial position between vowels

Saltations have been argued to represent a challenge for the hypothesis that phonological grammars only make the smallest input-output change that is required to solve a phonotactic problem. This hypothesis is central in faithfulness-based theories of phonology, and in particular for the (2009) P-map (perceptibility-map) theory (White, 2013; Hayes and White, 2015). The P-map represents the knowledge that speakers have about the similarity between sounds in a given phonological context. Learners and speakers use this knowledge to establish a priori rankings of the faithfulness constraints in a way that minimizes deviations from the input in response to markedness constraints. Grammars constrained by the P-map fail to derive PDEEs because if they allow large input-output changes (e.g. /k/ → [y]) then they also allow strictly smaller changes (e.g. /g/ → [y]). As will be shown in more details in this thesis, this problem arises even for grammars that have the required machinery to model PDEEs (see Hayes and White, 2015). In response, Hayes and White (2015) propose that PDEEs are not P-map compliant and that the P-map is only a soft bias.

5.2 Proposal

This thesis proposes a theory reconciling the analysis of PDEEs with the hypothesis of a strong minimal modification bias. The proposal is based on the idea that a feature
change might be less noticeable in the context of another feature change, provided that the distance between the input and the output is perceived logarithmically. The intuition behind this proposal can be made concrete with a classic example from the perception of weight: lifting three pounds seems negligible after lifting 30 pounds, but not so much after lifting nothing. Applied to Campidanian Sardinian, this translates as follows: lenition is less noticeable in the context of a change in voicing. This is illustrated in Figure 5-1, where the relation between the input-output physical distance and its perception is assumed to be logarithmic. The same lenition is perceived as smaller in case it is preceded by voicing (Figure 5-1b) than in case it is not preceded by voicing (Figure 5-1a).

![Diagram](image)

**Figure 5-1:** The perception of input-output changes: lenition is less noticeable in the context of a voicing change (Figure 6-1b) than alone (Figure 6-1a).

On the grammatical side, this will allow for a given feature change (e.g. lenition) to be considered as a smaller violation of faithfulness if it is independently accompanied by another feature change (e.g. voicing), thus solving the paradox that PDEEs raise for the minimal modification bias. PDEEs will be derived using context-sensitive faithfulness constraints that penalize a feature change differently depending on whether or not another feature in the same domain has been changed. These constraints will be shown to be equivalent to local conjunctions of faithfulness constraints, which have been proposed independently to derive chain shifts (Kirchner 1998). Therefore, the theoretical innovation will be only minimal.

This theory will also be argued to provide a more restrictive typology of PDEEs
than alternatives. In particular, by referring to the perceptual similarity between the input and the output, it will be possible to constrain in a principled way the features that interact in PDEEs and the domain of this interaction. This theory will be argued to derive the four perceptual conditions on PDEEs in (3).

(3) Perceptual conditions on PDEEs

a. Locality condition
   The two feature changes happen on the same segment.

b. One-dimension condition
   The two feature changes happen along the same perceptual dimension.

c. Monotonocity condition
   The second change is a continuation of the first change along the relevant dimension.

d. Size condition
   The licensing change is at least as large as the licensed change.

The first three conditions in (3-a), (3-b), and (3-c) derive from the general hypothesis according to which, in PDEEs, the second feature change is a continuation of the first change along the same perceptual dimension. The size condition in (3-d) refers to the respective size of the two feature changes. This condition does not directly derive from the core proposal in this paper: a change of any size should make its continuation perceptually smaller. However, it derives from the hypothesis of a strong minimal modification bias. This condition will be shown to be needed in order to avoid deriving problematic patterns where a feature is gratuitously changed without phonotactic improvement. This condition also has a straightforward perceptual interpretation: the larger the licensing change is compared to the licensed change, the smaller the perceptual impact of the licensed change is.

These four conditions apply to the Campidanian Sardinian pattern. The first condition is satisfied because voicing feeds lenition on the same segment. The one-dimension condition is satisfied because voicing and lenition both involve shortening
of the target consonant's closure duration. The monotonicity condition is satisfied because lenition represents a further step of reduction after voicing. The size condition is satisfied because the perceptual distance between a voiceless stop and the corresponding voiced stop is greater than the perceptual distance between the voiced stop and the corresponding voiced approximant. This is illustrated in (4) with perceptual data from English (Wang and Bilger, 1973, pp. 1252-1253): [t] and [d] (4-a) are less mutually confusable than [d] and [ð] (4-b).

(4) Consonant confusions across CV/VC and a range of signal-to-noise ratios.

a. Confusions involving voicing.

<table>
<thead>
<tr>
<th>Response</th>
<th>t</th>
<th>d</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stimulus</td>
<td>t</td>
<td>1765</td>
</tr>
<tr>
<td></td>
<td>d</td>
<td>91</td>
</tr>
</tbody>
</table>

b. Confusions involving continuancy.

<table>
<thead>
<tr>
<th>Response</th>
<th>d</th>
<th>ð</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stimulus</td>
<td>d</td>
<td>1640</td>
</tr>
<tr>
<td></td>
<td>ð</td>
<td>371</td>
</tr>
</tbody>
</table>

5.3 Outline

Chapter 6 presents the theory and its grammatical implementation and shows how it derives a number of constraints on the features that can interact in PDEEs, therefore providing a restrictive account of the typology. The theory's predictions are tested on a PDEE pattern attested in Romanian, where vowel destressing feeds vowel raising. The proposal is also shown to be able to extend to cases where the blocking is both phonologically and morphologically conditioned, provided that phonological representations are allowed to include some phonetic detail.

Chapter 7 focuses on a PDEE pattern attested in Standard French and which is potentially problematic for the theory presented in chapter 6: the licensing change and
the licensed change seem to involve two segments that are not adjacent, in violation of the locality condition. I show how it is possible to analyze this pattern within the present framework by allowing formant transitions to play role in the phonology. I show that the resulting theory not only works but is also superior to two potential alternatives.
Chapter 6

The theory

6.1 Introduction

Section 6.2 introduces in more details the puzzle that PDEEs raise for a theory of faithfulness that is constrained by the P-map. Section 6.3 introduces the proposal based on the logarithmic perception of the input-output distance and its grammatical implementation. Section 6.4 shows that the combination of the present analysis and P-map principles makes it possible to restrict the typology of PDEEs in a principled way and avoid overgeneration issues faced by non-P-map compliant alternatives. Section 6.5 looks at a case study in Romanian and tests predictions introduced in section 6.4 about the perceptual relation between the two feature changes and their respective size. Section 6.6 shows how the analysis accounts for cases where the blocking is both phonologically and morphologically conditioned.

6.2 The puzzle

Section 6.2.1 presents the motivations for the P-map hypothesis. Section 6.2.2 illustrates the problem that PDEEs raise for this hypothesis. Section 6.2.3 shows that the problem cannot be solved by appealing to Comparative Markedness, a markedness-based theory of PDEEs, as this theory fails to derive Campidanian Sardinian lenition.
6.2.1 Motivations for the P-map

The P-map is a theory which predicts that phonological grammars minimize the perceptual deviation from the input in response to markedness constraints. It was initially proposed in the context of OT to account for why some markedness constraints are always satisfied by violating the same faithfulness constraints cross-linguistically. For instance, the constraint against word-final voiced stops is always satisfied by violating faithfulness to voicing, e.g. German Rad /rad/ → [rat] vs. Raden /raden/ → [radan]. Other potential repairs, e.g. consonant-deletion /rad/ → [ra] or vowel-epenthesis /rad/ → [rada], are not attested.

Steriade (2009) explains this type of asymmetry by hypothesizing that speakers favor repairs which involve the smallest perceptual deviation from the input. Changing the voicing feature of a word-final voiced consonant from [+voice] to [-voice] makes it possible to satisfy markedness while keeping the output maximally similar to the input, on the assumption that all other potential repairs, e.g. consonant deletion and vowel epenthesis, constitute more salient changes. Universal differences among the perceptual effects of various changes, e.g. consonant deletion and vowel epenthesis vs. consonant devoicing in (1-a), translate into a universal ranking of faithfulness constraints penalizing larger changes from the input, as in (1-b).

(1) The P-map and word-final devoicing

a. Perceptual similarity

\[ d(C, \emptyset), d(V, \emptyset) > d(C_{[+\text{voice}]}, C_{[-\text{voice}]}) \]

b. OT ranking:

\[ \text{Max}(C), \text{Dep}(V) \gg \text{Ident}(\text{voice}) \]

If the ranking in (1-b) is universal, devoicing is correctly predicted to be the only possible repair to avoid word-final voiced consonants, as shown in (2).

(2) Deriving devoicing as the only repair for word-final voiced consonants
Another motivation for a principle like the P-map comes from the observation that, cross-linguistically, phonemes are more resistant to neutralization in some contexts than in others and this resistance can be understood as related to how perceptually distinct phonemes are in different contexts. A classic example is the case of vowel reduction, which is analyzed with a P-map compliant ranking of positional faithfulness constraints by Beckman (1998). Neutralization of vowel height contrasts may happen in unstressed syllables only, e.g., in Italian, but never in stressed syllables only. This is compatible with the P-map because the perceptual distance between vowels of different heights is typically larger in stressed syllables than in unstressed syllables, due to duration-induced vowel reduction. For instance, mapping [ɛ] to [e] represents a greater perceptual change in stressed syllables than in unstressed syllables. By the P-map, the fact that low and high vowels are more similar in unstressed syllables than in stressed syllables (3-a) translates into a ranking of faithfulness constraints that penalizes the neutralization of height contrasts more in stressed syllables than in unstressed syllables (3-b).

(3) P-map and vowel reduction in unstressed syllables

a. Perceptual similarity
\[ d(V_{\text{[+low]}}, V_{\text{[low]}})/\hat{v} > d(V_{\text{[+low]}}, V_{\text{[low]}})/\check{v} \]

b. OT ranking
\[ \text{Ident(low)}/\check{v} \gg \text{Ident(low)}/\hat{v} \]

If the ranking in (3-b) is universal, the neutralization of height contrasts in stressed syllables is correctly predicted to entail the neutralization of height contrasts in un-
stressed syllables.

6.2.2 The problem for the P-map

In a nutshell, the problem that PDEEs raise for the P-map is the following: if a big input-output change is allowed by a phonological grammar (e.g. /k/ → [γ]), then a strictly smaller change should be allowed too (e.g. /g/ → [γ]).

To illustrate this point, Hayes and White’s (2015) faithfulness-based analysis of Campidanian Sardinian lenition will be used. The problem is not specific to their approach but common to any analysis where the difference between derived and non-derived environments is captured in the ranking of faithfulness constraints. Hayes and White’s (2015) analysis is used because the problem that PDEEs raise for the P-map is particularly easy to see in this framework.

Hayes and White’s analysis is implemented with *Map faithfulness constraints (Zuraw, 2007). In this approach, a constraint of the form *Map(x, y) assesses a violation to a candidate if a segment belonging to natural class x in the input is mapped to a corresponding segment in natural class y in the output. *Map constraints differ from classic Ident(F) faithfulness constraints in two respects: (i) instead of requiring identity of the input and the output along a particular property, they ban mappings from specific input structures to different output structures, e.g. they ban [±voice] to [-voice] mappings, and (ii) they are not restricted to operate on features but can operate on feature combinations. The second property is crucial to derive PDEEs, as PDEEs cannot be modeled using faithfulness constraints restricted to single features (Hayes and White, 2015).

To derive Campidanian Sardinian, Hayes and White (2015) use two *Map faithfulness constraints. *Map(k,γ) bans mappings from voiceless stops to voiced fricatives (‘k’ is used as a placeholder for voiceless stops and ‘γ’ for voiced fricatives). This faithfulness constraint is outranked by two markedness constraints, *VC[cont]V and *VC[voice]V, penalizing intervocalic stops and intervocalic voiceless consonants, respectively. Ranking *VC[cont]V and *VC[voice]V above *Map(k,γ) ensures that voiceless stops are both voiced and lenited intervocally. *Map(g, γ) bans mappings
from voiced stops to voiced fricatives ('g' is used as a placeholder for voiced stops). This faithfulness constraint outranks *VC[cont]V, ensuring that voiced stops are not lenited. The ranking deriving Campidanian Sardinian lenition is shown in (4).

(4) Ranking deriving Campidanian Sardinian lenition according to Hayes and White.

*VC[voice]V, *Map(g, y) >> *VC[cont]V >> *Map(k, y)

Tableaux (5-a) and (5-b) show how this analysis derives the pattern of Campidanian Sardinian lenition.

(5) Hayes and White's analysis of Campidanian Sardinian lenition.

<table>
<thead>
<tr>
<th>/de kuat:ru/</th>
<th>*VC[voice]V</th>
<th>*Map(g, y)</th>
<th>*VC[cont]V</th>
<th>*Map(k, y)</th>
</tr>
</thead>
<tbody>
<tr>
<td>dekuat:ru</td>
<td>*!</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>dexuat:ru</td>
<td>*!</td>
<td>*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>deguat:ru</td>
<td></td>
<td>*!</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>degu:ru</td>
<td></td>
<td>*</td>
<td>*</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>/de goma/</th>
<th>*VC[voice]V</th>
<th>*Map(g, y)</th>
<th>*VC[cont]V</th>
<th>*Map(k, y)</th>
</tr>
</thead>
<tbody>
<tr>
<td>degoma</td>
<td></td>
<td>*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>degoma</td>
<td></td>
<td>*!</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Crucially, the ranking *Map(g, y) >> *Map(k, y) is not P-map compliant: it entails that the combination of a change in voicing and a change in continuancy (/k/ → [y]) represents a smaller violation of faithfulness than a change in continuancy (/g/ → [y]).

If only P-map compliant rankings of faithfulness constraints were allowed, then *Map(k, y) should outrank *Map(g, y). For /k/ to be mapped to [y] intervocically, *VC[cont]V and *VC[voice]V must outrank *Map(k, y). By the P-map, this ranking entails that *VC[cont]V and *VC[voice]V also outrank *Map(g, y). In other words, the
P-map predicts that [k]-[y] alternations entail [g]-[y] alternations.

6.2.3 Comparative Markedness is not the solution

Could a markedness-based theory of PDEEs solve the problem? An alternative to faithfulness-based models of PDEEs was proposed by McCarthy (2003): Comparative Markedness. This theory aims to account for both phonologically-derived environment effects that are studied in this paper and morphologically-derived environment effects.

Comparative Markedness splits each markedness constraint $M$ into two constraints: (i) $M_{\text{Old}}$ penalizes 'old' violations of markedness, i.e. violations that are incurred by the fully faithful candidate (FFC), the candidate obtained by ranking all the faithfulness constraints above all the markedness constraints and (ii) $M_{\text{New}}$ penalizes 'new' violations of markedness, i.e. violations that are not incurred by the FFC. Non-derived environment blocking arises in case (i) $M_{\text{New}}$ outranks $M_{\text{Old}}$ and (ii) a faithfulness constraint is sandwiched between the two markedness constraints.

Comparative Markedness successfully derives the textbook case of derived environment effect: Finnish assimilation across a morpheme boundary (Kiparsky, 1973; Kiparsky, 1993). In Finnish, a morphologically-derived /t-i/ sequence goes to [si] (6-a), but a morpheme-internal /ti/ sequence goes to [ti] (6-b).

(6) Finnish assimilation.

a. Underlying /t-i/ goes to [si].
   /halut-i/ ‘want-PAST’ [halusi]

b. Underlying /ti/ goes to [ti].
   /tila/ ‘room.NOM.SG’ [tila]

The analysis works as follows. The FFC corresponding to underlying /tila/, [tila], violates the markedness constraint against [ti] sequences, *ti. As a result, candidate [tila] violates the constraint that penalizes ‘old’ violations of *ti, *ti$_{\text{Old}}$. If Ident(cont), the faithfulness constraint penalizing changes of continuancy, outranks *ti$_{\text{Old}}$, then
/tila/ goes to [tila]. The FFC corresponding to underlying /halut-i/ does not violate *ti, on the assumption that [t] and [i], which belong to two different morphemes, are not adjacent in FFCs. As a result, [haluti] violates the constraint that penalizes 'new' violations of *ti, *ti\textsubscript{New}. If *ti\textsubscript{New} outranks Ident(\text{cont}), then /halut-i/ does not go to [haluti] but to [halusi]. To summarize, the ranking deriving Finnish assibilation is shown in (7).

(7) Ranking deriving Finnish assibilation according to Comparative Markedness

*ti\textsubscript{New} $\gg$ Ident(\text{cont}) $\gg$ *ti\textsubscript{Old}

The OT tableaux in (8-a) and (8-b) show how /halut-i/ is mapped to [halusi] and /tila/ to [tila]. The assumption that the stem and the suffix are not adjacent in the FFC of /halut-i/ is represented with a blank space between the two in the FFC. The FFC is assumed to be ruled out by a high ranked markedness constraint requiring that the stem and the suffix form a single prosodic word.

(8) Comparative Markedness derives assibilation across a morpheme-boundary and no assibilation morpheme-internally.

\begin{center}
\begin{tabular}{|c|c|c|}
\hline
 & *ti\textsubscript{New} & Ident(\text{cont}) & *ti\textsubscript{Old} \\
\hline
haluti & *! & & \\
\hline
\textsuperscript{\textntilde} halusi & & * & \\
\hline
\end{tabular}
\end{center}

\begin{center}
\begin{tabular}{|c|c|c|}
\hline
 & *ti\textsubscript{New} & Ident(\text{cont}) & *ti\textsubscript{Old} \\
\hline
\textsuperscript{\textntilde} tila & & * & \\
\hline
sila & *! & \\
\hline
\end{tabular}
\end{center}

However, Comparative Markedness fails to derive Campidanian Sardinian lenition because stops will violate the same markedness constraint against intervocalic stops,
*VC_{cont}V_{New}, whether they correspond to a voiceless or a voiced stop underlyingly.

Let us consider the inputs /de#kuat:ru/ and /de#goma/. In both cases, the FFCs do not violate *VC_{cont}V, on the assumption that the word-initial consonant and the preceding vowel, which belong to two different morphemes, are not adjacent in the FFC. As a consequence, the outputs with the voiced stops in intervocalic positions, [deguat:ru] and [degoma], both violate *VC_{cont}V_{New}: they introduce new violations of *VC_{cont}V as compared to their respective FFCs [de kuat:ru] and [de goma]. The assumption that the word-initial consonant and the preceding vowel are not adjacent in the FFC is represented with a blank space between the two in the FFC. Blocking lenition for underlyingly voiced stops requires ranking Ident(cont) above *VC_{cont}V_{New}. Allowing lenition for underlyingly voiceless stops requires ranking Ident(cont) below *VC_{cont}V_{New}. An analysis of Campidanian Sardinian will suffer from a ranking paradox.

The tableaux in (9) show how Comparative Markedness fails to derive Campidanian Sardinian lenition. The FFC is assumed to be ruled out by a high ranked markedness constraint requiring that the proclitic [de] and the following word form a single prosodic word. *VC_{voice}V outranks Ident(voice), producing intervocalic voicing. An analysis assuming the ranking *VC_{cont}V_{New} \gg Ident(voice) \gg *VC_{cont}V_{Old} wrongly predicts that both underlyingly voiced stops and underlyingly voiceless stops should be lenited.

(9) Comparative Markedness fails to derive Campidanian Sardinian lenition

a. /k/ \rightarrow [y]

<table>
<thead>
<tr>
<th>/de#kuat:ru/</th>
<th>*VC_{voice}V</th>
<th>Id(voice)</th>
<th>*VC_{cont}</th>
<th>Id(cont)</th>
<th>*VC_{cont}</th>
</tr>
</thead>
<tbody>
<tr>
<td>FFC=[de kuat:ru]</td>
<td>*</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>dkuat:ru</td>
<td>*!</td>
<td></td>
<td></td>
<td>*</td>
<td></td>
</tr>
</tbody>
</table>
| dkuat:ru | *! | | | | *
| deguat:ru | * | | *! | | |
| dryuat:ru | | * | | * | |

b. /g/ \not\rightarrow [g] but /g/ \rightarrow [y]
To my knowledge, there is no other markedness-based theory of PDEEs aside Comparative Markedness. This leaves us with the following paradox: PDEEs require a faithfulness-based account, and yet faithfulness-based accounts of PDEEs are not P-map compliant.

Hayes and White (2015) resolve this paradox by weakening the P-map: rankings of faithfulness constraints tend to be P-map compliant but are not necessarily so. In the next section, an alternative solution is proposed.

6.3 Proposal

Section 6.3.1 shows how the assumption that the perception of the input-output distance is perceived logarithmically predicts that a feature change will have a different perceptual impact depending on whether or not other features are also changed. Section 6.3.2 provides a grammatical implementation of this idea using context-sensitive faithfulness constraints and shows how the interaction of these faithfulness constraints and classic markedness constraints can derive PDEEs.

6.3.1 Logarithmic perception

This paper proposes an alternative theory of PDEEs that analyzes them as P-map compliant. This theory is based on a well-known result in psychophysics that a change along a physical dimension is perceived logarithmically: the same change along a physical dimension is perceived as smaller if the original stimulus is higher along this dimension. This generalization is known as the Weber-Fechner law.

The Weber-Fechner law is here applied to the perception of the distance between the input and the output. This differs from the normal applications of this law, which usually applies to the perception of physical quantities (e.g. weight, light, duration,
etc.). Here, the relevant dimension is more abstract: it is a difference between physical quantities. The main implication is that the direction of the change does not matter: whether the output is shorter or longer, what matters is how far it is from the input. The Weber-Fechner law has been applied to the perception of geographical distance. Following a tradition that thinks about perceptual similarity in terms of perceptual distance, I assume that the results in the geographical domain extends to the notion of input-output distance in phonology.

If the perception of the distance between the input and the output is logarithmic, it is expected that a change in an input-output pair will be perceived as less noticeable if accompanied by another change. This is illustrated in Figure 6-1, where the relation between the input-output distance and its perception is assumed to be logarithmic. The same lenition is perceived as smaller in case it is preceded by voicing (Figure 6-1b) than in case it is not preceded by voicing (Figure 6-1a).

![Diagram](attachment:image.png)

**Figure 6-1:** The perception of input-output changes: lenition is less noticeable in the context of a voicing change (Figure 6-1b) than alone (Figure 6-1a).

### 6.3.2 Grammatical implementation

In order to distinguish the violation of faithfulness to continuancy in the context of a voicing change vs. in the absence of a voicing change in the same segment, I propose to split Ident(cont) into two context-sensitive constraints. One of them penalizes a change in continuancy if this change is not accompanied by a change in voicing in the same segment. This is the constraint in (10-a). The other constraint penalizes
a change in continuancy if this change is accompanied by a change in voicing in the
same segment. This is the constraint in (10-b). It is important to specify that the
two changes happen in the same segment in order to prevent a change in voicing in
one segment from having an effect on the continuancy of another segment. For now,
the restriction to single segments is stipulated but will be motivated in section 6.4.

(10) Splitting Ident(cont) into two context-sensitive variants:
    a. Ident(cont)/nochange(voice)
       Assign a violation to an input-output segment pair violating Ident(cont)
       if it does not also violate Ident(voice).
    b. Ident(cont)/change(voice)
       Assign a violation to an input-output segment pair violating Ident(cont)
       if it also violates Ident(voice).

More generally, for any two features F and G, constraints of the format
Ident(F)/nochange(G) and Ident(F)/change(G) can be built (11). Later in this chap-
ter, only features that are perceptually connected will be argued to be able to be
related through this type of constraints.

(11) Splitting Ident(F) into two context-sensitive variants:
    a. Ident(F)/nochange(G)
       Assign a violation to an input-output segment pair violating Ident(F) if
       it does not also violate Ident(G).
    b. Ident(F)/change(G)
       Assign a violation to an input-output segment pair violating Ident(F) if
       it also violates Ident(G).

Context-sensitive faithfulness constraints are used to model position faithfulness
(Beckman, 1998), root faithfulness (McCarthy and Prince, 1991) or preservation of
laryngeal contrasts in pre-vocalic positions (Steriade, 2009). The present proposal
extends the notion of context-sensitive faithfulness by allowing the context to be
stated as a relation between the input context and the output context. Alternatively, these constraints can be thought of as faithfulness constraints indexed to a particular phonological process affecting the same segment. In this sense, they are similar to Wolf's (2008) PREC constraints: these constraints assign violations of faithfulness depending on whether a phonological process has applied in a previous evaluation. An important difference has to do with the framework that is assumed: Wolf's (2008) system relies on a representation of the candidates evaluated by the grammar as chains whereas the current analysis is compatible with the classical OT conception of candidates as static phonological forms.

Formally, the constraints in (10) are equivalent to the local conjunctions \( \text{Ident}(\text{cont}) \land \neg \text{Ident} (\text{voice}) \) and \( \text{Ident} (\text{cont}) \land \text{Ident} (\text{voice}) \), respectively. \( \neg \text{Ident} (\text{voice}) \) is an anti-faithfulness constraint (Alderete, 2001). It penalizes a faithful mapping of the voice feature. Local conjunctions of faithfulness constraints \( F \land F' \) have already been proposed to model synchronic chain shifts (Kirchner, 1996; Moreton and Smolensky, 2002). The only innovation is in the possibility to conjoin faithfulness and anti-faithfulness constraints.

Although the constraints are equivalent to local conjunctions of faithfulness constraints, the conditional formulation will be maintained: it better corresponds to the idea that the cost of violating a simple faithfulness constraint may depend on whether or not other simple faithfulness constraints are also violated in the same domain. The constraint names, abbreviations, and equivalences are shown in Table (12).

<table>
<thead>
<tr>
<th>Constraint name</th>
<th>Abbreviation</th>
<th>Equivalent to</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{Ident}(\text{cont})/\text{nochange}(\text{voice}) )</td>
<td>( \text{Id}(\text{cont})/\text{nochange}(\text{voi}) )</td>
<td>( \text{Ident}(\text{cont}) \land \neg \text{Ident}(\text{voice}) )</td>
</tr>
<tr>
<td>( \text{Ident}(\text{cont})/\text{change}(\text{voice}) )</td>
<td>( \text{Id}(\text{cont})/\text{change}(\text{voi}) )</td>
<td>( \text{Ident}(\text{cont}) \land \text{Ident}(\text{voice}) )</td>
</tr>
</tbody>
</table>

Table (13) shows how these constraints assign violations to the input-output segment pairs relevant for Campidanian Sardinian and how they compare to the simple \( \text{Ident}(\text{cont}) \) constraint. \( \text{Ident}(\text{cont}) \) assigns a violation mark to both pairs because both pairs involve a change in continuancy. \( \text{Ident}(\text{cont})/\text{nochange}(\text{voice}) \) assigns a violation mark to the pair \( <\text{g/}, \text{[y]}> \) because this pair violates \( \text{Ident}(\text{cont}) \) but sat-
isfies Ident(voice). Ident(cont)/change(voice) assigns a violation mark to the pair
</k/, [ɣ]> because this pair violates both Ident(cont) and Ident(voice).

(13) Violation profiles of the two context-sensitive faithfulness constraints

\[
\begin{array}{ccc}
\text{Ident(cont)/nochange(voice)} & \text{Ident(cont)/change(voice)} & \text{Ident(cont)} \\
</k/, [ɣ]> & * & * \\
</g/, [ɣ]> & * & * \\
\end{array}
\]

By the P-map, the hypothesis that lenition is less noticeable in the context
of a change in voicing translates into the ranking in (14): the constraint
penalizing a change in continuancy in the context of a change in voicing,
Ident(cont)/change(voice), is outranked by the constraint penalizing a change in con-
tinuancy alone, Ident(cont)/nochange(voice).

(14) A change in continuancy is less noticeable in the context of a change in
voicing:

Ident(cont)/nochange(voice) \gg Ident(cont)/change(voice)

Campidanian Sardinian lenition can be derived by interleaving the markedness con-
straints responsible for voicing and lenition in the ranking in (14). The ranking in
(15-a) derives intervocalic voicing. The ranking in (15-b) derives lenition conditioned
on voicing.

(15) OT ranking for Campidanian Sardinian

a. Intervocalic voicing

*VC[voice]V \gg Ident(voice)

b. Intervocalic voicing conditions lenition

*VC[voice]V \gg Ident(cont)/nochange(voice) \gg *VC[cont]V \gg

Ident(cont)/change(voice)

If the stop is underlyingly voiceless, intervocalic voicing is enforced through the rank-
ing in (15-a). Once a change in voicing has been made, the constraint which is rele-
vant to evaluate violations of faithfulness to continuancy is $\text{Ident(cont)}/\text{change(voice)}$. This constraint is ranked under $\ast \text{VC}_{\text{cont}}V$. Therefore, the voicing change must be accompanied by a change in continuancy. If the stop is underlyingly voiced, nothing motivates a violation of $\text{Ident(voice)}$. As a consequence, the constraint which is relevant to evaluate violations of faithfulness to continuancy is $\text{Ident(cont)}/\text{no change(voice)}$. This constraint outranks $\ast \text{VC}_{\text{cont}}V$. Therefore, lenition does not happen. The analysis derives the desired interaction between the two changes, where lenition applies only if voicing applies. The tableaux in (16) show more concretely how the analysis derives Campidanian Sardinian lenition.

(16) Analysis of Campidanian Sardinian lenition

a. $/k/ \to [\gamma]$

<table>
<thead>
<tr>
<th>/de kuat:ro/</th>
<th>$\ast \text{VC}_{\text{voice}}V$</th>
<th>$\text{Id(voice)}$</th>
<th>$\text{Id(cont)/no change(voi)}$</th>
<th>$\ast \text{VC}_{\text{cont}}V$</th>
<th>$\text{Id(cont)/change(voi)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>d:kuat:ro</td>
<td>$\ast$</td>
<td>$\ast$</td>
<td>$\ast$</td>
<td>$\ast$</td>
<td>$\ast$</td>
</tr>
<tr>
<td>d:xuat:ro</td>
<td>$\ast$</td>
<td>$\ast$</td>
<td>$\ast$</td>
<td>$\ast$</td>
<td>$\ast$</td>
</tr>
<tr>
<td>d:guat:ro</td>
<td>$\ast$</td>
<td>$\ast$</td>
<td>$\ast$</td>
<td>$\ast$</td>
<td>$\ast$</td>
</tr>
<tr>
<td>d:xuat:ro</td>
<td>$\ast$</td>
<td>$\ast$</td>
<td>$\ast$</td>
<td>$\ast$</td>
<td>$\ast$</td>
</tr>
<tr>
<td>$\ast$ d:xuat:ro</td>
<td>$\ast$</td>
<td>$\ast$</td>
<td>$\ast$</td>
<td>$\ast$</td>
<td>$\ast$</td>
</tr>
</tbody>
</table>

b. $/g/ \to [\gamma]$

<table>
<thead>
<tr>
<th>/de gama/</th>
<th>$\ast \text{VC}_{\text{voice}}V$</th>
<th>$\text{Id(voice)}$</th>
<th>$\text{Id(cont)/no change(voi)}$</th>
<th>$\ast \text{VC}_{\text{cont}}V$</th>
<th>$\text{Id(cont)/change(voi)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\ast$ d:gama</td>
<td>$\ast$</td>
<td>$\ast$</td>
<td>$\ast$</td>
<td>$\ast$</td>
<td>$\ast$</td>
</tr>
</tbody>
</table>

| d\:yama | $\ast$                       | $\ast$            | $\ast$                      | $\ast$                        | $\ast$                      |

6.4 Consequences

Sections 6.4.1 and 6.4.2 show how the present analysis combined with P-map principles makes it possible to avoid two problematic predictions of non-P-map compliant alternatives, i.e. the problem of bizarre feature interactions and the problem of gratuitous violations of faithfulness.
6.4.1 Avoiding bizarre feature interactions

This section argues that adopting a P-map compliant account provides a way to constrain the features interacting in PDEEs. The argument is based on a comparison between two PDEEs: the voicing feeds lenition pattern attested in Campidanian Sardinian and the unattested and intuitively bizarre voicing feeds labialization pattern.

Suppose that any feature change can interact in the way hypothesized in PDEE and participate in the kind of context-sensitive faithfulness constraints posited in section 6.3. Then one should expect PDEE patterns of the type voicing feeds labialization described in (17), where labialization applies in word-initial position only if accompanied by voicing. Labialization applies to underlyingly voiceless stops voiced through intervocalic voicing, but not to underlyingly voiced stops. This case also represents a saltation, as illustrated in (18).

(17) A bizarre PDEE pattern: voicing feeds labialization

a. Word-initial voiceless stops in intervocalic position are voiced and labialized

/ku/ [ku]
/a ku/ [agwu]

b. Word-initial voiced stops in intervocalic position are not labialized

/gu/ [gu]
/a gu/ [agu]

(18) Voicing feeds labialization as saltation

\[
\begin{array}{c|c|c}
\text{-round} & \emptyset & \text{+round} \\
\text{+voice} & +voice & +voice \\
\end{array}
\]

This pattern seems intuitively crazier than the pattern observed in Campidanian Sardinian. However, it can be formally derived if [voice] and [place] are allowed to be combined in the context-sensitive faithfulness constraints in (19-a) and (19-b). These
constraints have the same format as the constraints used to derive Campidanian Sardinian lenition. The markedness constraint motivating labialization is shown in (19-c).

(19) Constraints deriving the voicing feeds labialization pattern.

a. \text{Ident} \text{ (place)}/\text{nochange} \text{ (voice)}
   
   Assign a violation to an input-output segment pair violating \text{Ident} \text{ (place)} if it does not violate \text{Ident} \text{ (voice)} (equivalently, if it violates \text{−Ident} \text{ (voice)}).

b. \text{Ident} \text{ (place)}/\text{change} \text{ (voice)}
   
   Assign a violation to an input-output segment pair violating \text{Ident} \text{ (place)} if it violates \text{Ident} \text{ (voice)}.

c. \*[-\text{around}][-\text{around}]
   
   Assign a violation mark to output candidate containing a CV sequence whose elements do not agree in labiality.

The ranking in (20-a) derives intervocalic voicing. The ranking in (20-b) derives labialization conditioned on voicing.

(20) OT ranking deriving the voicing feeds labialization pattern

a. Intervocalic voicing
   
   \*\text{VC}_{i-\text{voice}}V \gg \text{Ident} \text{ (voice)}

b. Intervocalic voicing conditions labialization
   
   \*\text{VC}_{i-\text{voice}}V \gg \text{Ident} \text{ (place)}/\text{nochange} \text{ (voice)} \gg \*[-\text{around}][-\text{around}] \gg \text{Ident} \text{ (place)}/\text{change} \text{ (voice)}

If the stop is underlyingly voiceless, intervocalic voicing is enforced through the ranking in (20-a). Once a change in voicing has been made, the constraint that is relevant to evaluate violations of faithfulness to place becomes \text{Ident} \text{ (place)}/\text{change} \text{ (voice)}. This constraint is ranked under \*[-\text{around}][-\text{around}], as shown in (20-b). Therefore, the voicing change must be accompanied by a change in place. If the stop
is underlyingly voiced, Ident(voice) is not violated by the winner. In this case, the constraint which is relevant to evaluate violations of faithfulness to place is Ident(place)/nochange(voice). This constraint outranks *[around][−around], as shown in (20-b). Therefore, labialization does not happen. The analysis derives the problematic interaction between the two changes, where labialization applies only if voicing applies. This is illustrated in the tableaux in (21).

(21) Analysis deriving the voicing feeds labialization pattern

\[
\begin{array}{|c|c|c|c|c|}
\hline
& \text{/k/} & \rightarrow & [g^w] \\
\hline
/\text{a ku}/ & *\text{VC}_{[\text{voice}]}V & \text{Id(voice)} & \text{Id(place)/no change(voice)} & *[\text{around}] & \text{Id(place)/ change(voice)} \\
\hline
\text{aku} & *! & & & * & \\
\hline
\text{ak}^*u & *! & & & * & \\
\hline
\text{agu} & * & & & *! & \\
\hline
\text{ag}^*u & * & & & * & \\
\hline
\end{array}
\]

This problem does not only arise under the present proposal but under any faithfulness-based account that does not constrain feature interactions. It arises in the *Map approach of because any pair of segments can be related by *Map constraints. The tableaux in (22) show that the *Map approach also derives the problematic voicing feeds labialization pattern.

(22) *Map derives the voicing feeds labialization pattern

\[
\begin{array}{|c|c|c|c|c|}
\hline
& \text{/g/} & \rightarrow & [g^w] \\
\hline
/\text{a gu}/ & *\text{VC}_{[\text{voice}]}V & \text{Id(voice)} & \text{Id(place)/no change(voice)} & *[\text{around}] & \text{Id(place)/ change(voice)} \\
\hline
\text{ag}^*u & * & & & *! & \\
\hline
\end{array}
\]
The problem also arises with Burzio's (2000) Sequence Faithfulness. In this approach, PDEEs arise from the existence of faithfulness constraints requiring preservation of entire segments or even sequences. The problematic pattern is also derived by this approach, as shown in (23). Faith(g) is the crucial constraint in Burzio's theory: it penalizes any change in the mapping from underlying /g/ to its output correspondent.

(23) Sequence Faithfulness derives the voicing feeds labialization pattern

If perception plays a role in PDEE, as is expected under a P-map approach, it will not necessarily be the case that any feature change will license any other feature change. The intuition behind the proposal in this paper is that a first change may license
a further change if the second change can be conceived of as a continuation of the first one along the same perceptual dimension. This predicts several properties for features interacting in PDEEs.

For the second feature change to be a continuation of the first one, the two changes have to affect the same phonological entity, i.e. the same segment - assuming that features are properties of segments. This derives the *locality condition* on the feature interaction. The locality condition is not built in Burzio's (2000) Sequence Faithfulness and, as noted by Wolf (2008), this predicts pathological patterns with long distance feature interactions. The present analysis will be able to derive PDEEs involving two adjacent segments by exploiting the fact that perceptual cues signaling a segment's features may be distributed in adjacent segments (see the analysis of Sanskrit ruki in section 6.6 and see chapter 7). In Hayes and White (2015), *Map constraints are restricted to apply to segments only but this locality condition is stipulated and not derived.

The approach presented here also predicts that the two changes must happen along a common perceptual dimension. This derives the *one-dimension condition* on the feature interaction. Finally, for the second change to be a continuation of the first one, both changes must go in the same direction along the relevant perceptual dimension. This derives the *monotonicity condition* on the two changes.

In Campidanian Sardinian lenition, these three conditions are met, as already previewed in chapter 5. The *locality condition* is satisfied because the two changes happen to the same segment: voicing of the word-initial segment licenses lenition of the same word-initial segment only. The *one-dimension condition* is satisfied because closure durations are generally longer for voiceless stops than for voiced stops (see Lisker, 1957 on English), and for voiced stops than for voiced continuants (see Marotta, 2001, p. 32 on Tuscan Italian spoken in Pisa). There is potentially another dimension that is relevant: intensity. Voiceless stops have less intensity than voiced stops and voiced stops have less intensity than voiced approximants (Katz, 2016). Intervocalic voicing will result in a shortening of the closure duration and in an increase of the segment's intensity. Lenition will result in a further step of reduction
and increase in intensity. The *monotonicity condition* is also satisfied. Because these conditions are met, the lenition will be perceived as less salient as a continuation of the voicing change affecting intervocalic voiceless stops than if it were the only change affecting intervocalic voiced stops.

The feature changes interacting in the imaginary *voicing feeds labialization* pattern most likely do not meet all of these conditions. In a classic paper, Miller and Nicely (1955) suggest that the perception of place and voicing are relatively independent. As a consequence, a change in place and a change in voicing should happen along different perceptual dimensions. More recently, this view has been challenged and voice and place have been found to interact perceptually (see Benki, 2001 and Chodoroff and Wilson, 2014 among others). However, they probably do not interact in a way that suggests that labialization of velars before [u] may be the continuation of a perceptual change initiated by voicing. Labialized consonants are characterized by slightly lower F1 values, lower F2 values than their plain counterparts in an [a] context and by a lower center of gravity for the burst (see Rose, 1979 on Nootkan, Gordon, Barthmaier, and Sands, 2002 on Montana Salish, and Ladefoged and Maddieson, 1996, pp. 358-360 on Ponapean). Voicing of intervocalic voiceless velars is expected to affect the consonant’s closure duration (by shortening it) and the consonant’s F1 onset frequency (by lowering it). Chodoroff and Wilson (2014) found that the center of gravity was lower for voiced labial and alveolar bursts than for their corresponding voiceless bursts but they did not find a consistent effect for velars. Therefore, the only dimension along which labialization and voicing can be considered as adding up monotonically in the *voicing feeds labialization* pattern is F1. However, in an [u] context, F1 is already very low and is therefore unlikely to play any crucial perceptual role. Also, F2 is probably a more important cue for the contrast between labialized and plain stops than F1. But voicing does not manipulate this dimension. As a consequence, labialization is unlikely to be perceived as a continuation of the change in voicing.

To summarize, having P-map principles play a role in PDEEs provides a way to restrict the typology. Theories that do not impose constraints on PDEEs potentially
predict many interactions that are not attested and that seem intuitively bizarre, like the *voicing feeds labialization* pattern. In sections 6.5 and 6.6, two attested PDEE patterns will be discussed and shown to also satisfy the conditions laid out in this section.

Formally, bizarre patterns like the *voicing feeds labialization* case can be ruled out by preventing the grammar from projecting faithfulness constraints of the Ident(F)/change(G) and Ident(F)/nochange(G) type for features F and G that do not interact perceptually in the expected way.

Hayes and White (2015) argue that it is possible to constrain the typology of saltations in a non-P-map compliant account via diachronic explanations. They propose that saltations are never the result of a single regular sound change but always involve interactions of regular sound changes or external influences, such as loanword adaptation and hypercorrection. However, without a constrained theory of the diachrony, it is unclear how all kinds of unattested and intuitively unnatural patterns can be ruled out. For instance, it is not very difficult to imagine a scenario similar to the ones they hypothesize for actual saltations and derive the *voicing feeds labialization* pattern.

One scenario they consider as the diachronic source for PDEEs is ‘interposition by borrowing’. Consider a language A without native contrastive voiced stops (24-a). In this language, /k/ goes to [g] intervocally (24-b) and to [gʷ] intervocally before rounded vowels (24-c).

(24) Language A

a. /k/, */g/

b. /k/ → [g]/V_ V-round

c. /k/ → [gʷ]/V_ +round

Loanwords are introduced in language A from a language B with contrastive voiceless and voiced stops (25-a). In this language, voiceless stops and voiced stops are always realized faithfully, in particular intervocally, (25-b) and (25-c).
Suppose now that the speakers of language A treat foreign /k/s from language B like their native /k/s but adopt the foreign treatment of underlying /g/s, with which they are unfamiliar. The resulting language displays the problematic voicing feeds labialization pattern: /k/ alternates [g\textsuperscript{w}] intervocically before rounded vowels (26-a) whereas /g/ does not (26-b).

Language A after contact with language B

a. /k/ → [g\textsuperscript{w}]/V_V+round
b. /g/ → [g]/V_V+round

6.4.2 Avoiding gratuitous violations of faithfulness

Another problem with an approach of PDEE that is not constrained by the P-map is that it allows for gratuitous violations of faithfulness in response to a single markedness constraint: it predicts that it should be harmonically improving to do two changes in response to a single markedness constraint rather than just the only change that should be necessary. This problem arises both with the context-sensitive faithfulness constraints and with the *Map approach, as shown in (27-a) and (27-b), respectively. In the example in (27), the two analyses predict that it should be better to both lenite and devoice rather than just lenite in order to satisfy a markedness constraint against intervocalic stops. This pattern is problematic because intervocalic devoicing is highly marked cross-linguistically.

Problematic prediction: two changes are better than one in response to a single markedness constraint

a. Context-sensitive faithfulness constraints
If a principle like the P-map plays a role, a ranking of faithfulness constraints that generally minimizes change is preferred. There is such a ranking. If Ident(voice) is at least as high as the highest ranked of the two context-sensitive faithfulness constraints Ident(cont)/nochange(voice) and I(cont)/change(voice), then this effectively predicts that the two changes must be motivated by two markedness constraints. Tableau (28) shows how requiring that Ident(voice) ranks at least as high as Ident(cont)/change(voice) blocks intervocalic devoicing.

(28) How minimizing change helps with PDEEs.

<table>
<thead>
<tr>
<th>aga</th>
<th>Ident(voice)</th>
<th>Ident(cont)/nochange(voice)</th>
<th>VC[cont]V</th>
<th>Ident(cont)/change(voice)</th>
</tr>
</thead>
<tbody>
<tr>
<td>❑ aga</td>
<td>❑ *</td>
<td>❑ *</td>
<td>❑ *</td>
<td>❑ *</td>
</tr>
<tr>
<td>❑ aya</td>
<td>❑ *</td>
<td>❑ *</td>
<td>❑ *</td>
<td>❑ *</td>
</tr>
<tr>
<td>❑ axa</td>
<td>❑ *</td>
<td>❑ *</td>
<td>❑ *</td>
<td>❑ *</td>
</tr>
</tbody>
</table>

There is therefore a general way to derive PDEEs without predicting gratuitous violations of faithfulness: it must be the case that the faithfulness constraint referring to the feature involved in the first change (Ident(voice) in Campidanian Sardinian) must outrank the faithfulness constraint referring to the feature involved in the second change (Ident(cont) in Campidanian Sardinian). This condition is stated in (29)
for Campidanian Sardinian.

(29) Condition on PDEEs (Campidanian Sardinian).

If \( \text{Ident}(\text{cont})/\text{nochange}(\text{voice}) \succ \text{Ident}(\text{cont})/\text{change}(\text{voice}) \), then \( \text{Ident}(\text{voice}) \) outranks or has the same ranking as \( \text{Ident}(\text{cont}) \).

The constraint in (29) can be stated for the more general case, using \( F \) and \( G \) for features that satisfy the conditions laid out in section 6.4.1 (30).

(30) Condition on PDEEs (general case).

If \( \text{Ident}(F)/\text{nochange}(G) \succ \text{Ident}(F)/\text{change}(G) \), then \( \text{Ident}(G) \) outranks or has the same ranking as \( \text{Ident}(F) \).

The implication in (29) (and the more general version in (30)) has a perceptual interpretation. By P-map, (29) implies that the difference between changing continuancy alone vs. changing continuancy with voicing is significant only if changing voicing is at least as big a change as changing continuancy. This intuitively makes sense: the larger the first change with respect to the second one, the less noticeable the second one will be. This is illustrated in Figure 6-2, where voicing represents a larger acoustic change in Figure 6-2a than in Figure 6-2b. As a result, the second change represents a perceptually smaller change in Figure 6-2a than in Figure 6-2b.

![Figure 6-2: The perception of input-output changes: lenition is less noticeable in the context of a large voicing change (Figure 6-2a) than in the context of small voicing change (Figure 6-2b).]
The condition in (29) is a slightly stronger statement: it imposes that the first change has to be at least as large as the second one in order for PDEEs to be derived. In other words, this condition sets a threshold on how small the conditioned change should be with respect to the conditioning change in order to be reduced enough to deserve a separate faithfulness constraint.

Going back to the case of Campidanian Sardinian, there is evidence supporting the hypothesis that voicing a voiceless stop represents a larger perceptual change than leniting a voiced stop. The evidence does not come from Campidanian Sardinian as there is (to my knowledge) no available phonetic data on the lenition pattern in the language. The evidence comes from Wang and Bilger’s (1973) identification study of English voiced/voiceless fricatives/stops (also reported by White, 2017). Following White, I used the confusion matrices in Tables 2 and 3 in Wang and Bilger (1973), where the target consonants appeared in CV and VC contexts, and summed the values across CV and VC contexts and across all signal-to-noise ratios. The perceptual distances in (31) were calculated feeding the confusion matrices to Luce’s (1963) Biased Choice Model.

(31) Perceptual distances between voiced stops and fricative and of voiceless and voiced fricatives across CV and VC contexts in Wang and Bilger (1973).

<table>
<thead>
<tr>
<th>Feature</th>
<th>Sound pairs</th>
<th>Perceptual distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>voicing</td>
<td>[p] and [b]</td>
<td>2.74±.07</td>
</tr>
<tr>
<td></td>
<td>[f] and [v]</td>
<td>2.48±.07</td>
</tr>
<tr>
<td></td>
<td>[t] and [d]</td>
<td>2.85±.07</td>
</tr>
<tr>
<td></td>
<td>[θ] and [ð]</td>
<td>1.68±.07</td>
</tr>
<tr>
<td>continuancy</td>
<td>[b] and [v]</td>
<td>1.25±.04</td>
</tr>
<tr>
<td></td>
<td>[p] and [f]</td>
<td>1.53±.05</td>
</tr>
<tr>
<td></td>
<td>[t] and [θ]</td>
<td>1.91±.06</td>
</tr>
<tr>
<td></td>
<td>[d] and [θ]</td>
<td>1.37±.05</td>
</tr>
</tbody>
</table>

The results in (31) show that, in general, consonants differing just in voicing are more dissimilar than consonants differing just in continuancy. One exception is the pair of
[θ] and [ð]: the perceptual distance between [θ] and [ð] is smaller than the perceptual distance between [t] and [θ]. However, the pairs that are relevant for Campidanian Sardinian show the expected relationship. The distance between [p] and [b] is more than twice as large as the distance between [b] and [v]. Although Campidanian Sardinian has [β] rather than [v], the two sounds should be quite similar. The distance between [t] and [d] is also larger than the distance between [d] and [ð]. These results are compatible with the hypothesis that changing voicing is a greater violation of faithfulness than changing continuancy.

Campidanian Sardinian has another phonologically-derived environment effect, where intervocalic voiced geminates /b: d: g:/ are optionally mapped to [β ð γ] leaping over [b d g] whereas /b d g/ stay intact (Bolognesi, 1998; Hayes and White, 2015). The relevant perceptual dimension is closure duration again. Contextual intervocalic voicing shortens the closure duration of geminates, making them more similar to nongeminate voiced stops. Once this first step of shortening has happened, it is possible to further shorten the closure duration at a small perceptual cost while satisfying a markedness constraint against intervocalic voiced stops.

The analysis presented here could also extend to the Manga dialect of Kanuri, which shows a pattern of lenition similar to Campidanian Sardinian: intervocalic /t/ is mapped to [ð] leaping over [d] whereas /d/ is mapped to itself (Hayes and White, 2015). The same analysis can be proposed for this language as for Campidanian Sardinian, except that the nonderived environment effect is limited to [t].

6.5 Testing the predictions: the case of Romanian vowel reduction

This section tests three predictions of the present approach to PDEEs on another case study: (i) the two features involved in PDEEs share a perceptual cue, (ii) the two changes can be considered as adding up monotonically along this dimension, and (iii) the first change along this dimension is at least as large the second change. The case
study is Romanian vowel reduction, as described by Steriade (2015), where vowel
destressing conditions reduction. Romanian vowel reduction was chosen as a case
study because it represents a pattern of PDEE that is attested in other languages,
including Armenian (Khanjian, 2009) and Palauan (Zuraw, 2003). The analysis of
Romanian vowel reduction is presented in section 6.5.1 and the predictions are tested
in section 6.5.2. Section 6.5.3 discusses the Armenian pattern of vowel reduction.

6.5.1 Analysis of Romanian vowel reduction

In Romanian, stem low vowels which lose stress under affixation are reduced to [ʌ]
(32-a) whereas low vowels which are unstressed in the base are not reduced under
affixation (32-b). As a consequence, [a] alternates with [ʌ] whereas [a] does not.

(32) Romanian vowel reduction

a. Base low vowels which lose stress under affixation are raised
   barba 'beard' /'bɑrba/ [b'arba] 'beard'
   /'bɑrba-'os/ [b'ar'bos] 'bearded'
   sanie 'sled' /'sanie/ [s'anie] 'sled'
   /'sanie-'utʃA/ [sa'nietʃA] 'sled-DIM'

b. Low vowels that are not stressed in the base are not raised under
   affixation
   masină 'machine' /ma'ʃina/ [ma'ʃina] 'machine'
   /ma'ʃina-'utsA/ [maʃin'utsA] 'machin-DIM'
   Roman place name /'roman/ [ˈroman]
   /'roma-'ʃkan/ [romaʃkan] 'Roman-inhabitant'

Steriade (2015) provides arguments against non-PDEE analyses of this pattern. First,
it is not the case that raising is blocked only in positions where secondary stress is
expected. In [roma-'ʃkan], no secondary stress is expected to fall on the second, pre-
tonic syllable and yet [a]-raising is blocked. Second, suffixation triggers raising of low
vowels only if it shifts stress away from them. The suffix [-nik] exceptionally fails to
attract stress. In that case, base [a] does not lose stress and does not raise either,
e.g. [o'bráz] ‘cheek’ ~ [o'bráz-nik] ‘cheeky’. Under further affixation, stress shifts and raising applies, e.g. [obrz-nitʃ-je] ‘impudence’. Third, the pattern is not specific to particular suffixes: the same diminutive suffix occurs with and without [a]-raising in the base (e.g., /'sanie-utʃA/ [sAni-'utfA] vs. /maʃ'inA-utʃA [maʃin-'utfA]). The derived environment effect is productive.

Romanian vowel reduction involves a saltation, as depicted in (33): /'a/ in the base goes to [a] over [a] in the derivative whereas /a/ in the base is mapped to itself in the derivative.

(33) Romanian vowel reduction as saltation

Under the current analysis, this pattern can be understood as follows. Vowel duration is the perceptual dimension common to [stress] and [low]. Destressing of the stressed low vowel in the stem results in shortening of the low vowel. In the context of this first change, a further reduction to [A] is made possible because it represents a relatively smaller durational change compared to the shortening induced by destressing. This second change is motivated by a markedness constraint against unstressed low vowels. In the absence of destressing, reducing the low vowel to [A] represents a more noticeable durational change: the cost of making that change is larger than the cost of not satisfying the markedness constraint against unstressed low vowels. As a consequence, no reduction happens and unstressed /a/ in the base is mapped to itself in the derivative.

Formally, the pattern is derived with the constraints in (34).

(34) Constraints deriving Romanian vowel reduction.

a. Ident(low)/nochange(stress)
Assign a violation to an input-output segment pair violating Ident(low) if it does not also violate Ident(stress).

b. Ident(low)/change(stress)
Assign a violation to an input-output segment pair violating Ident(low) if it also violates Ident(stress).

c. Ident(stress)
Assign a violation mark to an input-output segment pair if the two segments disagree on stress.

d. *[+low, -stress]
Assign a violation mark to an output low vowel which does not carry stress.

The analysis assumes a cyclic derivation: the base with stress is the input to derivative formation. The Romanian pattern can be derived with the rankings in (35). The ranking in (35-a) causes stress to shift to the right from the base to the suffix. The ranking in (35-b) derives vowel reduction conditioned by destressing. The ranking in (35-c) corresponds to the condition required to prevent gratuitous violations of faithfulness (see section 3.2).

(35) OT ranking for the Romanian grammar for derivatives

a. Destressing
StressRight $\gg$ Ident(stress)

b. Destressing conditions reduction
StressRight $\gg$ Ident(low)/nochange(stress) $\gg$ *[+low,-stress] $\gg$
Ident(low)/change(stress)

c. Condition on the relative ranking of Ident(stress) and Ident(low)
Ident(stress) is at least as high as Ident(low)/nochange(stress).

If destressing of the low vowel is not needed because the low vowel was already unstressed in the base, the constraint which is relevant to evaluate violations of faithfulness to the [low] feature is Ident(low)/nochange(stress). This constraint outranks
+[low,-stress]. Therefore, the winner is among the candidates without reduction of /a/ to [A]. If the low vowel is stressed in the base, stress shift is enforced through the ranking in (35-a). Once a change in stress has been made, the constraint that is relevant to evaluate violations of faithfulness to [low] becomes Ident(low)/change(stress). This constraint is ranked under *[+low,-stress]. Therefore, the stress shift away from underlying /'a/ must be accompanied by a change in [low]. This derives the desired interaction between the two changes, where reduction applies only if destressing applies.

The tableaux in (36) show more concretely how the analysis derives Romanian vowel reduction. It is assumed that both the stem and the suffix bear stress in the input but this is crucial for the base only. To simplify the analysis, candidates that are not relevant to the nonderived environment effect are not considered. Other constraints are needed in addition to explain why there is just one stress per word, why stress cannot fall on word-final [A] and why vowel hiatuses are not tolerated.

(36) Analysis of Romanian vowel reduction

a. /'a/ → [A]

<table>
<thead>
<tr>
<th>/'barbA-'os/</th>
<th>StressR</th>
<th>Id(stress)</th>
<th>Id(low)/no change(stress)</th>
<th>*[+low, -stress]</th>
<th>Id(low)/change(stress)</th>
</tr>
</thead>
<tbody>
<tr>
<td>'barbos</td>
<td>*!</td>
<td>*</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>bar'bos</td>
<td>*</td>
<td></td>
<td>*[!+]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>barbos</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

b. /a/ → [a]

<table>
<thead>
<tr>
<th>/ma'finA-'utfA/</th>
<th>StressR</th>
<th>Id(stress)</th>
<th>Id(low)/no change(stress)</th>
<th>*[+low, -stress]</th>
<th>Id(low)/change(stress)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ma'finutfA</td>
<td>!*</td>
<td>*</td>
<td></td>
<td></td>
<td>!</td>
</tr>
<tr>
<td>ma'finutfA</td>
<td>*</td>
<td>*</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ma'fjniutfA</td>
<td>*</td>
<td></td>
<td></td>
<td></td>
<td>*</td>
</tr>
</tbody>
</table>

6.5.2 Acoustic study

To test the predictions of the present theory of PDEE, one female Romanian native speaker was recorded uttering words with vowels varying along the two features in-
volved in Romanian vowel reduction, \([+\text{low}] / [-\text{low}]\) and \([+\text{stress}] / [-\text{stress}]\). She read a list of 90 monomorphemic words or nonce-words twice. The four vowels \(['a], [a], ['\Lambda], \) and \([\Lambda]\) appeared in 15 different consonantal contexts. The stressed vowels appeared in two different word types: monosyllables and disyllables. This yielded a total of 60 instances of ['a], 60 instances of ['\Lambda], 30 instances of [a], and 30 instances of [\Lambda]. Words were uttered in a carrier sentence.

Recordings were done in a sound-attenuated booth, using a head-mounted Shure SM35-XLR microphone connected to a computer via a Shure X2u XLR-to-USB signal adapter. The recordings were made using the Audacity software, with 44 kHz/16 bit sampling. The distance (approx. 5 cm) to the microphone was held constant across the recording session. Vowels were manually segmented using Praat. Measures of vowel duration included the vocalic segment only and not the initial burst associated with consonant release. The end of the vowel was identified by the last periodic oscillation when the vowel was followed by an aperiodic sound and by a change in intensity or formant trajectory otherwise.

Figure 6-3 shows the logarithm of vowel duration for the four vowels. Vowel duration was logged because duration is perceived logarithmically. Data are pooled across consonantal contexts, word types and repetitions. All four vowels appear to have different mean durations, with \(['a]\) being the longest vowel and \([\Lambda]\) the shortest.
A linear regression was fit to the data, with the logarithm of vowel duration as dependent variable and [low] and [stress] as predictors. [a] served as the baseline for comparison. Table (37) shows the output of the statistical model.

(37) Effect of raising and destressing on vowel duration (baseline: stressed [a], logged duration). Significant effects are bolded.

<table>
<thead>
<tr>
<th></th>
<th>Estimate</th>
<th>Std. Error</th>
<th>t value</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Intercept)</td>
<td>4.99633</td>
<td>0.02856</td>
<td>174.937</td>
<td>&lt;2e-16</td>
</tr>
<tr>
<td>low</td>
<td>-0.21194</td>
<td>0.04073</td>
<td>-5.204</td>
<td>5.39e-07</td>
</tr>
<tr>
<td>stress</td>
<td>-0.31143</td>
<td>0.05120</td>
<td>-6.082</td>
<td>7.19e-09</td>
</tr>
<tr>
<td>low:stress</td>
<td>-0.02914</td>
<td>0.07177</td>
<td>-0.406</td>
<td>0.685</td>
</tr>
</tbody>
</table>

Both features [low] and [stress] have a significant effect on vowel duration. This is compatible with the idea that the features interacting in PDEE share a common perceptual cue, provided that these durational differences also play a role in the perception of the categories. Both vowel raising and destressing involve shortening.

The interaction of [low] and [stress] is not significant and this was confirmed by an
anova. This means that the effect of destressing on vowel duration is not significantly different in [+low] vowels in [-low] vowels. This means that the difference in duration between stressed ['a] and [ʌ] can be considered as the sum of the durational difference between ['a] and [a] and the difference between ['a] and [ʌ]. This is compatible with the hypotheses that reducing from [a] to [ʌ] can be considered as a continuation of the change from ['a] to [a] along the dimension of duration.

Finally, the main effects of [stress] and [low] on vowel duration were compared using the R package multcomp. The effect of destressing on vowel duration was found to be slightly larger than the effect of raising, in accordance with the hypothesis that the first change must be at least as large as the second change.

\begin{center}
\begin{tabular}{lcccr}
\hline
& \text{Difference between shortening induced by destressing and raising} & & & \\
& \text{Estimate} & \text{Std. Error} & \text{t value} & \text{p-value} \\
\hline
\text{low-stress} & 0.09950 & 0.05147 & 1.933 & 0.0548 \\
\hline
\end{tabular}
\end{center}

6.5.3 Armenian vowel reduction

Armenian shows a similar pattern of vowel reduction to Romanian: base high vowels which lose stress through affixation are reduced to zero (39-a) or alternate with schwa (39-b)-(39-c) whereas vowels which are unstressed in the base and remain so in derivatives stay intact (39-d) (Khanjian, 2009).

\begin{enumerate}
\item Destressed high vowels are generally reduced to zero:
  \hspace{1cm} /makʰur/ \, \text{‘clean’} \, [makʰur] \\
  \hspace{1cm} /makʰur-’el/ \, \text{‘to clean’} \, [makʰr’el] \\
\item Destressed high vowels are reduced to schwa to avoid illicit clusters:
  \hspace{1cm} /kʰ’in/ \, \text{‘price’} \, [kʰ’in] \\
  \hspace{1cm} /kʰ’in-’el/ \, \text{‘rich’} \, [kʰ’on-’el] \\
\item Post-[r] stressed high vowels alternate with pre-[r] schwa:
  \hspace{1cm} /əstʰr’ug/ \, \text{‘slave’} \, [əstʰr’ug] \\
  \hspace{1cm} /əstʰr’ug-atsadz/ \, \text{‘enslaved’} \, [əstʰɔŋ-atsadz]
\end{enumerate}
d. Unstressed high vowels are not reduced:

/irig'\textsuperscript{un}/ ‘night’ [irig\textsuperscript{un}]

/irig'\textsuperscript{un}-at\textsuperscript{h}em / ‘nighttime’ [irignat\textsuperscript{h}em]

e. Destressed non-high vowels are not reduced:

/d'on/ ‘holiday’ [d'on]

/d'on-'el/ ‘to celebrate’ [don-'el]

The analysis is similar to Romanian. The two changes (vowel shortening and vowel deletion) happen along the dimension of duration. Destressing of the stressed high vowels in the stem results in vowel shortening. In the context of this first change, a further reduction to zero is allowed because it is perceptually less noticeable and makes it possible to satisfy a markedness constraint against short vowels. In the absence of a stress change, reducing to zero is perceived as too large a change and, as a consequence, high vowels remain intact. The cases of alternation with schwa are explained as responses to other markedness constraints: markedness constraint against illicit clusters and markedness against [ra] sequences (see Khanjian, 2009 for more details).

Note that the assumption that the first change has to be at least as large as the second one does not seem realistic under the assumption that perception is logarithmic: the perceptual distance between short [i] and zero should be infinite. I assume that perception is not logarithmic at the extremes. This problem is a general problem that has been raised about the Weber-Fechner law.

6.6 Phonologically- and morphologically-derived environment effects

Blocking in morphologically-nonderived and phonologically-nonderived environments are normally treated as a unified phenomenon (Kiparsky, 1993). Finnish assibilation and Sanskrit ruki are reported processes that show both kinds of blocking simultaneously. Can the present theory extend to morphologically-derived environment effects (MDEEs)?
Because the analysis of Finnish assibilation as a phonologically-derived environment effect has been challenged (Hammond, 1992), I focus on Sanskrit ruki. This pattern is interesting because it is \textit{a priori} challenging for the present analysis, as (i) the two changes affect two different segments and (ii) the derived environment blocking is both phonologically and morphologically conditioned. I show how MDEEs can be in principle analyzed like PDEEs, under the conditions in (40).

\begin{enumerate}
\item Conditions to analyze MDEEs like PDEEs
\begin{enumerate}
\item Phonological representations include some phonetic detail (e.g. Flemming, 2008).
\item Different perceptual dimensions may integrate to form a single perceptual dimension (Kingston et al., 2008).
\end{enumerate}
\end{enumerate}

Via the condition in (40-a), morphological concatenation has a phonological effect, and this effect might feed a further phonological process. The condition in (40-b) will be necessary to relate different perceptual cues signaling a single contrast (e.g. a consonant’s closure cues and internal cues). I illustrate how the analysis works with Sanskrit ruki.

The data comes from Whitney (1889, pp. 61-64), Kiparsky (1973, pp. 61-66), and Kiparsky (1982, pp. 75-82) and the analysis of the pattern as a derived environment effect from Kiparsky. In Sanskrit, the dental noted as $s$ becomes the sound noted as $\tilde{s}$ after $[r\ u\ k\ i]$ in morphologically-derived environments (41-a) and in phonologically-derived environments (41-b), but not otherwise (41-c). Most of the sounds noted as $\tilde{s}$ come from ruki contexts. However there are a few words with underlying $s$ (41-d).

\begin{enumerate}
\item Sanskrit ruki
\begin{enumerate}
\item Assimilation after $[r\ u\ k\ i]$ across a morpheme boundary
\begin{itemize}
\item bibʰarṣi /bi-bʰar-ṣi/ [bibʰarṣi] \textquoteleft you carry\textquoteright
\item vakṣyati /uak-ṣja-ti/ [uakṣjati] \textquoteleft he will say\textquoteright
\item agniṣu /agni-ṣu/ [agniṣu] \textquoteleft fire-DAT.PL\textquoteright
\end{itemize}
\item Assimilation after $[r\ u\ k\ i]$ in environments derived by the application of
\end{enumerate}
\end{enumerate}
zero grade ablaut

ušṭá /uošt-tá/ [uʃtá] ‘shone, dwelt’
jakṣati /dža-g’as-anti/ [džakṣati] ‘ate’ (3d pl)
siṣṭa /ca-g-ta/ [siṣṭa] ‘taught’

c. No assimilation after [r u k i] in non-derived environments

pustaka [puštaka] ‘book’
barsa [baarša] ‘tip’
kisalaya [kisalaja] ‘sprout’

d. A few words have underlying $\breve{s}$

bāspa [bašpa] ‘fear’

This pattern is challenging for the present theory because the triggering phonological process in (41-b) (the zero ablaut) affects the stem vowel while the triggered phonological process (retroflexion) affects the postvocalic stem consonant. It is also challenging because the triggered phonological process is fed both by ablaut and morphological concatenation. An analysis in terms of phonologically-derived environment seems to only be able to apply the ablaut case in (41-b): it is left as a coincidence why the same process of retroflexion happens in morphologically-derived environments (41-a).

The proposal is the following: morphological concatenation and vowel deletion both feed retroflexion in (41-a) and (41-b) because both processes result in the creation of new formant closure transitions that were absent in the input. This change affecting the consonant’s closure transitions then feeds total assimilation of the consonant. Note that this reasoning assumes that the input is specified phonetically and that faithfulness constraints can refer to transitions which are not contrastive (see the condition in (40-a)). The assumption of a phonetically-enriched input to phonology is common in works following the program of phonetically-based phonology (see Flemming, 2008 and McCarthy, 2009).

I follow Flemming’s (2003, pp. 366-368) analysis of ruki as a progressive assimilation. The sibilant assimilates to a [-anterior] apical after back and retroflex segments: these segments lower the F3 locus of the following dental sibilant, making it more similar to a retroflex (Steriade, 2001). The reason why retroflexion happens after [i]
is a bit mysterious. Flemming (2003) proposes that the sound noted as $s$ actually corresponds to two allophones, a [+anterior] apical $[s]$ after $[i]$ and a [-anterior] apical $[s]$ after $[ruk]$. This type of allophony is attested in other languages like Wargamay and Walmatjari. In what follows, I focus on the better understood case of assimilation after $[ruk]$.

In order to formalize the present analysis, the formant locus of consonants must be represented in phonological representations. I propose to distinguish two dental sibilant allophones in terms of their closure properties. When preceded by a segment with a low F3, the allophone of $[s]$ has a low F3 locus and the transition between this segment and $[s]$ is characterized by a sharply rising F3. This allophone will be noted as $[F3s]$, where $[F3]$ denotes a low F3 locus at the onset of the consonant. When preceded by a segment that does not have a low F3, the F3 locus of the sibilant will not be as low and the F3 transition will not be as sharp. This allophone will be noted as $[F3^\#]$, where $[F3]$ materialized as a high F3 locus at the onset of the consonant. The allophone $[F3s]$ is the default allophone because a dental consonant has a high F3 target. For instance, the morpheme /si/ in bibharsi ‘you carry’ is realized as $/F3^\#s/$ underlyingly.

We are now in a position to be able to characterize the licensing change as a change affecting the closure properties of the dental sibilant. When the $[a]$ preceding the dental sibilant in the input /ua$F3^\#$-tá/ in (41-b) is deleted, the dental sibilant comes in contact with $[u]$. The underlying allophone $[F3s]$ with a high F3 locus is replaced with the allophone $[F3s]$ with a low F3 target through coarticulation with the preceding $[u]$. The same change happens in morphologically derived environments in (41-a). The only difference is that the new transition is not created via vowel deletion but via morphological concatenation.

The change affecting the sibilant’s closure transitions then feeds a total assimilation of the sibilant: $[F3s]$ becomes the retroflex $[F3s]$. This second change is motivated by a markedness constraint against consonants with conflicting place cues (low F3 closure transitions vs. frication noise with a high center of gravity). This constraint can also be interpreted as a constraint disfavoring poor dental-retroflex contrasts, i.e.
[F3$\text{s}$]-[F3$\text{g}$] contrasts that are not cued by distinct enough closure transitions. If the closure transition is already similar to that of a retroflex sibilant in the input, assimilation of the frication noise in the output is blocked because it represents a larger change comparatively.

The ruki pattern can be analyzed as a saltation, depicted in (42).

(42) Sanskrit ruki as a saltation

Formally, the interaction of vowel deletion and retroflexion after [r u k] is derived with the markedness constraints in (43). Ablaut (43-a) regulates the alternation between full-grade and zero-grade ablaut. *X_{F3}\text{F3}\text{C}$ in (43-b) is the markedness constraint that triggers the conditioning change: this constraint is responsible for the lowering of the dental sibilant’s F3 locus after segments with low F3 targets. *F3$\text{s}$ in (43-c) is the markedness constraint that triggers the second change (the full assimilation to a retroflex).

(43) Markedness constraints needed to derive the Sankrit ruki

a. Ablaut

Assign a violation mark to a candidate with full-grade ablaut in a past participle.

b. *X_{F3}\text{F3}\text{C}$

Assign a violation mark to a candidate containing a consonant with a high F3 locus following a segment with a low F3 target.

c. *F3$\text{s}$

Assign a violation mark to any dental sibilant realized with a low F3 locus.
The faithfulness constraints in (44) are needed to derive the interaction of the two changes. C\textsubscript{clos} is a variable that refers to C’s closure allophones, F\textsubscript{3}C and F\textsubscript{3}C in the present case. C\textsubscript{fric} is a variable that refers to different ways of realizing a consonant’s frication noise, here as a dental frication noise [s] (with high center of gravity) or as retroflex frication noise [s] (with lower center of gravity). Ident(C\textsubscript{clos}) in (44-a) penalizes the mapping from /F\textsubscript{3}s/ to [F\textsubscript{3}s]. It conflicts with *X\textsubscript{F}\textsubscript{3}F\textsubscript{3}C in (43-b). Ident(C\textsubscript{fric})/nochange(C\textsubscript{clos}) in (44-b) and Ident(C\textsubscript{fric})/change(C\textsubscript{clos}) in (44-c) are the faithfulness constraints that derive the interaction between the two changes affecting the sibilant’s closure transitions and frication noise.

(44) Faithfulness constraints needed to derive the Sankrit ruki

a. Ident(C\textsubscript{clos})
   Assign a violation mark for any input-output consonant pairs such that C\textsubscript{clos}\textsubscript{1} ≠ C\textsubscript{clos}\textsubscript{0}.

b. Ident(C\textsubscript{fric})/nochange(C\textsubscript{clos})
   Assign a violation mark for any input-output consonant pairs such that C\textsubscript{fric}\textsubscript{1} ≠ C\textsubscript{fric}\textsubscript{0} and C\textsubscript{clos}\textsubscript{1} = C\textsubscript{clos}\textsubscript{0}

c. Ident(C\textsubscript{fric})/change(C\textsubscript{clos})
   Assign a violation mark for any input-output consonant pairs such that C\textsubscript{fric}\textsubscript{1} ≠ C\textsubscript{fric}\textsubscript{0} and C\textsubscript{clos}\textsubscript{1} ≠ C\textsubscript{clos}\textsubscript{0}

The ranking in (45) derives the ruki pattern.

(45) Constraint ranking deriving the ruki pattern

Ablaut, *X\textsubscript{F}\textsubscript{3}F\textsubscript{3}C \gg Ident(C\textsubscript{clos}), Ident(C\textsubscript{fric})/nochange(C\textsubscript{clos}) \gg *F\textsubscript{3}s \gg Ident(C\textsubscript{fric})/change(C\textsubscript{clos})

Ablaut and *X\textsubscript{F}\textsubscript{3}F\textsubscript{3}C outranked the faithfulness constraint requiring segment’s closure transitions to be identical in the input and in the output, Ident(C\textsubscript{clos}). This motivates the licensing change. The ranking *F\textsubscript{3}s \gg Ident(C\textsubscript{fric})/change(C\textsubscript{clos}) licenses a further change affecting the frication noise in case the closure transitions have
been changed. When the closure transitions have not been changed, the ranking \( \text{Ident(Cfric)/nochange(C_clos)} \gg *F3\bar{g} \) prevents the assimilation from happening.

The tableaux in (46) show how the analysis derives retroflexion in phonologically-derived environments (46-a) and in morphologically-derived environments (46-b) and blocking in non-derived environments (46-c). The analysis in (46-a) is simplified to focus on the phonologically-derived environment effect: as is, this analysis does not derive the assimilation of [t] to the preceding retroflex [s] in [uF3stā]. Deriving this assimilation would require additional constraints.

(46) Analysis of Sanskrit ruki

a. /uF3stā/ → [uF3stā]

<table>
<thead>
<tr>
<th>a</th>
<th>Ablaut</th>
<th>*X(_{F3})C</th>
<th>(\text{Id(C_clos)})</th>
<th>(\text{Id(Cfric)/no})</th>
<th>*F3\bar{g}</th>
<th>(\text{Id(Cfric)/change(C_clos)})</th>
</tr>
</thead>
<tbody>
<tr>
<td>uF3stā</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>uF3stā</td>
<td>*!</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>uF3stā</td>
<td></td>
<td>*</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>*uF3stā</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>*</td>
</tr>
</tbody>
</table>

b. /bi-bF3arF3si/ → [bibF3arF3si]

<table>
<thead>
<tr>
<th>bi-bF3arF3si</th>
<th>*X(_{F3})C</th>
<th>(\text{Id(C_clos)})</th>
<th>(\text{Id(Cfric)/nochange(C_clos)})</th>
<th>*F3\bar{g}</th>
<th>(\text{Id(Cfric)/change(C_clos)})</th>
</tr>
</thead>
<tbody>
<tr>
<td>bibF3arF3si</td>
<td></td>
<td></td>
<td></td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>bibF3arF3si</td>
<td>*</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
| *bibF3arF3si | * | | | | *

Does the ruki pattern analyzed this way satisfy the four conditions on PDEEs? The locality condition is satisfied because the formant change feeds retroflexion on the
same segment (the dental sibilant).

Do the two changes satisfy the one-dimension condition and the monotonicity condition? The two changes seem to affect different dimensions, i.e. the closure transitions into the sibilant and the sibilant’s frication noise. This is potentially problematic for the current hypothesis. This is where the hypothesis that different perceptual cues may integrate (Kingston et al., 2008) plays a role (see the condition in (40-b)). Kingston et al. (2008) suggest that rather than paying attention to every individual property in the acoustic signal, the auditory system might perceive acoustically related cues as a single ‘intermediate perceptual property’. Specifically, they found evidence for the perceptual integration of multiple properties associated with low frequency spectral continuity into a single ‘low frequency’ property (f0 and F1). The same ‘low frequency’ property may be involved in Sanskrit. Coarticulation lowers the F3 locus of the sibilant. Assimilation lowers the center of gravity of the sibilant. Understood this way, the two changes also satisfy the monotonicity condition: they both involve lowering along the integrated frequency dimension.

Is the size condition satisfied? Usually, closure transitions do not play a major role in cueing place compared to consonants’ internal cues and release transitions (see chapter 3 and references therein). However, closure transitions are an important cue for the dental-retroflex contrast (Steriade, 2001). The fact that Sanskrit uṣṭā is realized as [uṣṭā] with retroflexion of the whole [št] cluster testifies to that: the place of articulation of the cluster is determined based on its left context, and not based on its right context, as is usually the case. The fact that coarticulation with [u] can have such effects suggest that the closure cues are the major cue to the dental-retroflex contrast and outweigh the other cues.

6.7 Discussion and conclusion

This chapter has proposed a new theory of phonologically-derived environment effects in which the minimal input-output modification bias plays a role. This theory was argued to be superior to accounts in which this bias does not play a role because
it provides a more restrictive account of the typology. Phonologically-derived environment effects were argued to arise as a consequence of the fact that perception is logarithmic: the same input-output change is perceived as smaller if it is the continuation of an independent input-output change than if it is implemented alone and, as a consequence, a given feature change may represent a smaller violation of faithfulness in the context of another feature change than alone. Formally, the account relies on independently motivated machinery: local conjunction of faithfulness constraints and anti-faithfulness constraints.

I conclude with a brief discussion of how the current analysis can be reconciled with the claim that PDEEs are typologically rare. Although there is no comprehensive cross-linguistic survey of PDEEs, PDEEs seem relatively rare compared to patterns that can be described with simple faithfulness constraints (Hayes and White, 2015). In the current approach, this typologically marked status can have two sources. First, there are quite severe constraints on the type of features or features' cues that can interact. In the presence of such constraints, it is expected that the typology of PDEEs should be restricted. Second, the faithfulness constraint that was crucial to model PDEEs (Ident(F)/nochange(G)) is formally complex. Therefore, the marked status of PDEEs can also be analyzed as deriving from an anti-complexity bias. If learners favor simpler grammars, they will tend to favor grammars that do not involve local conjunctions of faithfulness constraints. As a result, the linguistic typology will be biased toward the type of alternations that can be modeled with classical OT faithfulness constraints. Finally, another reason why they might be rare is if the two context-sensitive constraints are generally close to each other. Suppose that the perceptual difference between a feature in the presence vs. absence of another feature change is generally small. In grammatical terms and assuming that ranking distances reflect perceptual distances, then the ranking distance between two context-sensitive constraints will be small and hence there will not be much room for inserting a markedness constraint between the two.
Chapter 7

A case study:
phonologically-conditioned cyclicity
in Standard French

7.1 Introduction

Chapter 6 has proposed a theory of phonologically-derived environment effects (PDEEs) in which a phonological process is allowed to feed another phonological process provided that the second process can be construed as a continuation of the first one on the same segment and along the same perceptual dimension. This chapter argues that an intriguing pattern of phonologically-conditioned cyclicity in Standard French can be analyzed as a PDEE and shows how it can be handled by the theory of PDEEs presented in chapter 6. This pattern is interesting because (i) the conditioning change and the conditioned change seem to happen on two different segments and (ii) it is not clear a priori whether there is a single perceptual dimension that unites the changes. This is potentially problematic for the theory of PDEEs presented in chapter 6.

Standard French has a pattern of phonologically-conditioned cyclicity, where the cyclic or regular behavior of stems is dependent on the phonological shape of the suffix.
Because this pattern crucially involves the realization of mid vowels, it is necessary to briefly describe how mid vowels behave morpheme-internally in Standard French. In unstressed (=non-final) syllables, mid vowels are realized as close-mid [e ø o] in open syllables (1-a) and as open-mid [æ œ ɔ] in closed syllables (1-b). The syllable-based distribution of mid vowels is known as the *loi de position*. In stressed (=final) closed syllables, the front unrounded mid vowel is realized as open-mid [e] (1-c), according to the *loi de position*. However, in stressed closed syllables before some consonants (e.g. before [l]), close-mid and open-mid rounded vowels contrast (1-d), in violation of the *loi de position*.

1. The *loi de position* in morpheme-internal syllables in Standard French.
   a. état [eta] ‘state’
   b. colmater [kolmate] ‘plug’
   c. fête [fent] ‘party’
   d. seul [søl] ‘alone’ ~ veule [vøl] ‘weak’
   vol [vol] ‘flight’ ~ drôle [drol] ‘funny’

Because the distribution of mid vowels differs in unstressed syllables and in stressed syllables and stress shifts from the stem-final syllable to the affix under suffixation, mid-vowel alternations are expected to be found in stems with a mid vowel in the stem-final syllable, e.g. in derivatives based on *fête* [fent] ‘party’ like *fêtard* ‘partier’.

Mid-vowel alternations are indeed found in derivatives in Standard French. However, mid-vowel alternations are blocked in particular environments: mid vowels are realized *regularly* and according to the *loi de position* if the suffix starts with a *vowel* (2-a) but *cyclically* if the suffix starts with a *stop* (2-b).\

2. Phonologically-conditioned cyclicity in Standard French
   a. Regular application of the *loi de position* before vowel-initial suffixes.

---

1The judgements reported in this section were checked with seven Standard French speakers. I also checked that the generalizations were productive using nonce words. A single example is used to illustrate each generalization but the generalizations are supported by many more words. Also, they apply to all three series of mid vowels [e]/[ɛ], [o]/[ɔ], and [ø]/[ɔ].
fêtard /fɛt-aʁ/ ‘partier’ [fɛtaʁ] (regular application)
*[^fɛtaʁ] (cyclic application)

b. Cyclic application before stop-initial suffixes.

drôlement /dʁoːl-mɛ/ ‘funny’-ADV *[^dʁolmɛ] (regular application)
[^dʁolmɛ] (cyclic application)

In (2-a), the mid vowel in the stem is realized as close-mid, as expected for a mid vowel in unstressed open syllable according to the loi de position (see (1-a)). In (2-b), the mid vowel in the stem is realized as close-mid in a closed syllable, in violation of the loi de position, which requires mid vowels to be open-mid in this context (see (1-b)).

To get a sense of why this pattern may be treated as a PDEE, it is useful to think about what distinguishes (2-a) and (2-b) in syllable-based terms - although I will ultimately argue against this interpretation. In syllable-based terms, the PDEE can be characterized as follows: the loi de position applies to stem mid vowels if the stem-final consonant is resyllabified (3-a) but does not apply otherwise (3-b). In (3-a), the base-final coda consonant is resyllabified as an onset in the derivative and this resyllabification feeds the loi de position in the preceding mid vowel. In (3-b), the base-final coda consonant is not resyllabified in the derivative and the loi de position does not apply to the preceding mid vowel.

(3) Syllable-based analysis

a. The loi de position applies in derivatives if the base-final consonant and the stem-final consonant are syllabified differently.

fêtard /fɛt-aʁ/ [fɛtaʁ] ‘partier’

b. The loi de position does not apply in derivatives otherwise.

drôlement /dʁoːl-mɛ/ [dʁolmɛ] ‘funny’-ADV

Note that this analysis requires treating the input to derivative formation as already syllabified. In other words, it requires a cyclic evaluation where the syllabified base serves as input. This is the reason why the inputs in (3) are shown as /fɛt-aʁ/ and
/dsol.-mā/, with a syllable boundary, and not as /fet-as/ and /dsol-mā/, without syllable boundary.

The syllable-based analysis makes it clear why the Standard French pattern is challenging for the analysis of PDEEs proposed in chapter 6. As indicated above, this theory requires the two changes interacting in PDEEs to apply to the same segment and to involve the same perceptual dimension. In the Standard French case, the two changes do not seem to involve the same segment: resyllabification applies to the stem-final consonant whereas the loi de position applies to the mid vowel in the stem-final syllable. Moreover, resyllabification and vowel raising seem to involve very different perceptual dimensions: the first change involves a consonantal property (syllabic affiliation) whereas the second change involves vowel height.

The goal of this chapter is twofold: (i) to propose an analysis of the Standard French pattern that is compatible with the perceptual theory of PDEEs and (ii) to compare it to the syllable-based analysis sketched above and to another alternative in which the Standard French pattern is not analyzed as a PDEE.

Section 7.2 presents the analysis and discusses the French pattern in light of the conditions on PDEEs presented in chapter 6. Section 7.3 shows that this analysis is better suited to capture the difference between glide-initial suffixes (which trigger regular application) and liquid-initial suffixes (which trigger cyclic application) than the syllable-based analysis. The argument in this section is based on the results of two perception experiments and a small experiment based on a syllabification task. Section 7.4 discusses another alternative and shows that the present analysis better captures the difference between CL-final stems built with vowel-initial suffixes (which trigger regular application) and C-final stems combined with LV-initial suffixes (which trigger cyclic application). Section 7.5 discusses the special case of suffixes starting with an alternating [ə] (or schwa) and concludes.
7.2 Proposal

The crucial ingredient that will make it possible to connect the changes affecting the consonant and the preceding mid vowel is the concept of formant transitions. Formant transitions are frequency shifts visible in sonorous segments preceding or following a consonant and which serve as cues to the place of articulation of this consonant (Dorman and Raphael, 1980). In a nutshell, the proposal is that a change affecting the release cues of the stem-final consonant (realized in the suffix-initial segment) feeds a change affecting its closure transitions (realized in the stem mid vowel). Vowel-initial suffixes modify the release cues of the stem-final consonant by adding release formant transitions that were absent in the isolated base. Stops do not have formant structure: as a consequence, stop-initial suffixes do not affect as dramatically the release cues of the stem-final consonant.

Although the idea is simple, formalizing it requires some work because formant transitions are not usually treated as phonological entities, but as phonologically irrelevant phonetic detail. This section proposes a formalization of formant transitions as phonological representations. These phonological representations may be accessed by grammatical constraints (in particular by the type of faithfulness constraints defined in chapter 6 to derive PDEEs). By integrating phonetic aspects of representations into phonological representations, the present proposal follows previous works in phonetically-based phonology such as Flemming (2001). By allowing faithfulness constraints to access phonetic detail of the base of derivation in particular, it is in line with Steriade’s (2000) approach to cyclicity.

Section 7.2.1 proposes a cue-based interpretation of the conditioning change in the Standard French PDEE. Section 7.2.2 proposes a cue-based interpretation of the conditioned change. Section 7.2.3 shows how the two changes interact. Section 7.2.4 formalizes this interaction in OT using the model of PDEEs developed in chapter 6. Section 7.2.5 discusses this analysis in light of the conditions on PDEEs presented in chapter 6.

2See also the analysis of Sanskrit ruki in chapter 6.
7.2.1 A cue-based interpretation of the conditioning change

In the syllable-based analysis, the conditioning change is analyzed in terms of resyllabification. Here, I argue instead that it should be analyzed in terms of the presence vs. absence of release transitions.

Consonant allophones are distinguished in terms of their release properties: consonants have C\textsuperscript{rel}-allophones with different release properties. In prevocalic position, consonants have C\textsuperscript{rel}-allophones with release transitions (Delattre, Liberman, and Cooper, 1955), noted \( c' \). In word-final and prestop positions, consonants have C\textsuperscript{rel}-allophones without release transitions, noted \( c \).

The consonant allophones in bases and derivatives can be characterized in terms of their release properties. The base-final C\textsuperscript{rel}-allophone, \( C_B^{rel} \), and the corresponding stem-final C\textsuperscript{rel}-allophone in the derivative, \( C_D^{rel} \), are identical along their release properties when the suffix starts with a stop (4-a) (they both lack release transitions). However, when the suffix starts with a vowel, \( C_B^{rel} \) and \( C_D^{rel} \) differ: \( C_B^{rel} \) lacks release transitions whereas \( C_D^{rel} \) has release transitions (4-b). In dynamic terms, the release properties of \( C_B \) are changed under suffixation with a vowel-initial suffix but are not under suffixation with a stop-initial suffix.

(4) Cue-based characterization of the conditioning change.

a. Before stop-initial suffixes:
\[ C_D^{rel} = C_B^{rel} = c' \]

b. Before vowel-initial suffixes:
\[ C_D^{rel} = c' \neq C_B^{rel} = c' \]

The conditioning change in the Standard French PDEE can then be characterized as follows. If the C\textsuperscript{rel}-allophone changes under suffixation, then the loi de position applies (5-a). If the C\textsuperscript{rel}-allophone does not change under suffixation, then the loi de position does not apply (5-b).

\[ \text{The symbol } ' \text{ is often used to mark an unreleased stop (without burst) rather than a stop without release transitions. Here, it specifically means 'absence of release transitions'. French final stops have release bursts but they do not have release transitions.} \]
(5) Cue-based analysis of the PDEE (preliminary version).
   a. The *loi de position* applies in derivatives if $C_{D}^{\text{rel}} \neq C_{B}^{\text{rel}}$.
      fêtard /fět-aʁ/ [fɛtaʁ] 'partier'
   b. The *loi de position* does not apply in derivatives if $C_{D}^{\text{rel}} = C_{B}^{\text{rel}}$.
      drôlement /dʁol-mɑ̃/ [dʁolmɑ̃] ‘funny’-ADV

One could stop here and leave the theory at this stage, with the syllable-based theory in (3) and the cue-based theory in (5) as perfect parallels. However, the theory of PDEEs presented in chapter 6 is constrained and requires the two changes to be related. Nothing in the statement of (5) (or of (3)) draws any connection between the changes affecting the stem-final consonant and the stem mid vowel.

7.2.2 A cue-based interpretation of the conditioned change

I propose that the requirement that the quality of mid vowels match in the base and in the derivative when $C_{D}^{\text{rel}} = C_{B}^{\text{rel}}$ follows indirectly from a requirement that the stem-final consonant’s closure allophones, $C_{\text{clos}}$, match in the base and in the derivative in this context. This requirement will entail a requirement to have matching vowel qualities because of cooccurrence constraints on vowel and closure formant transitions.

I focus on the first formant (F1) closure transitions, which I suggested are the most relevant transitions in the opposition between close-mid and open-mid vowels in French (see part I). Before consonants with low F1 targets, there are two possible broad shapes for F1 transitions: level and falling. I propose to distinguish consonant allophones in terms of their closure properties, $C_{\text{clos}}$. $C_{\text{clos}}$-allophones characterized by level F1 transitions are noted as $\_c$. The horizontal arrow represents a level F1 transition. It is subscript because it is a transition from a low F1 value to a low F1 value. $C_{\text{clos}}$-allophones characterized by falling F1 transitions are noted as $\searrow c$. The arrow represents a movement from a high F1 value to a low F1 value.

I now assume the two constraints in (6) on the relation between the height of a vowel (high vs. low) and the shape of the closure transitions that can be realized in that vowel (level vs. falling). The constraint in (6-a) says that a F1 closure transition
is level if and only if it is realized in a high vowel. Assuming that there are only two types of F1 transitions (level and falling), this constraint is equivalent to the constraint in (6-b), which says that a F1 closure transition is falling if and only if it is realized in a low or low-mid vowel.

(6) Constraint on vowel height and F1 closure transition.
   a. $C_{\text{clos}} = \rightarrow c \iff V$ is high.
   b. Equivalently, $C_{\text{clos}} = \leftarrow c \iff V$ is low or low-mid.

To make this constraint more concrete, let us consider a high-mid vowel [e] and a low-mid vowel [ɛ] and the closure transitions into [t]. Among the four possible vowel-transition combinations e→t, e↓t, e→t, and e↓t, only two are available due to the constraint in (6): the two combinations in (7-a) do not violate this constraint, however the two combinations in (7-b) violate this constraint, by allowing a level F1 transition to be realized in a low vowel and a falling F1 transition to be realized in a high vowel.

(7) a. Licit vowel-transition combinations: e→t, e↓t
   b. Illicit vowel-transition combinations: *e→t, *e↓t

What is the basis for the constraint in (6)? Falling transitions from a vowel with a low F1 target (=a high vowel) to a consonant with a low F1 target are impossible because it is not possible to realize a clearly falling F1 transition between two segments with similar F1 targets. Level transitions from a vowel with a high F1 target (=a low vowel) to a consonant with a low F1 target are banned because it is not possible to realize a level F1 transition between segments with very different F1 targets.

Given this constraint on vowel-transition combinations, the nature of the cyclic effect can be recharacterized in terms of matching closure allophones in the base and in the derivative instead of matching vowel qualities. Before stop-initial suffixes, the closure transitions are required to match (8-a). This entails a vowel quality match due to the constraint in (6). Before vowel-initial suffixes, the closure transitions are not required to match.
(8) Cue-based characterization of the conditioned change.

a. Before stop-initial suffixes:
   \[ C_{D}^{\text{clo}} = C_{B}^{\text{clo}} \text{ whether } C_{B}^{\text{clo}} = \rightarrow c \text{ or } \leftarrow c \]

b. Before vowel-initial suffixes:
   \[ C_{D}^{\text{clo}} = \rightarrow c \text{ whether } C_{B}^{\text{clo}} = \rightarrow c \text{ or } \leftarrow c \]

7.2.3 A cue-based interpretation of the interaction of changes

The blocking of the *loi de position* can now be characterized as follows. If the stem-final consonant allophone is not changed along its release properties under suffixation \( C_{D}^{\text{rel}} = C_{B}^{\text{rel}} \), then it is not changed along its closure properties \( C_{D}^{\text{clo}} = C_{B}^{\text{clo}} \), even if this must entail a violation of the *loi de position*.

The final version of the cue-based analysis of the Standard French PDEE is presented in (9). Regular application of the *loi de position* happens when \( C_{D}^{\text{rel}} \neq C_{B}^{\text{rel}} \); in this case, the change of the release transitions licenses a change of the closure transitions and mid vowel quality is determined by the *loi de position* (9-a). Cyclic application happens when \( C_{D}^{\text{rel}} = C_{B}^{\text{rel}} \); in this case, the release transitions have not been changed and therefore a further change affecting the closure transitions is blocked, even if it entails a violation of the *loi de position*.

(9) Cue-based analysis of the PDEE (final version).

a. Regular application: if \( C_{D}^{\text{rel}} \neq C_{B}^{\text{rel}} \), \( C_{D}^{\text{clo}} \) and \( C_{B}^{\text{clo}} \) are not required to match. \( C_{B}^{\text{clo}} \) and the *loi de position* must apply.

   *fêtard* /fe\ˈtard/ [fe\_\text{tard}] ‘partier’

b. Cyclic application: if \( C_{D}^{\text{rel}} = C_{B}^{\text{rel}} \), \( C_{D}^{\text{clo}} \) and \( C_{B}^{\text{clo}} \) are required to match, even if it entails violating the *loi de position*.

   * drôlement /dzo\_l\text{ˈman}/ [dzo\_l\text{ˈman}]/*dzo\_l\text{ˈman} ‘funny’-ADV

I illustrate how the analysis works on a concrete example, using /fet-a\text{-}ɛfr/ to illustrate the behavior of derivatives with vowel-initial suffixes and /dzo\_l\text{-}ɛfr/ to illustrate the behavior of derivatives with stop-initial suffixes.

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When the vowel-initial suffix /-au/ combines with the base /fc\t'/, the [t']-allophone in the base is replaced with the [t'-allophone in the derivative [fc\t'au], due to a pressure to coarticulate consonants and vowels in CV sequences. This change affecting [t]'s release transitions licenses a further change affecting [t]'s closure transitions and motivated by the loi de position: the closure transitions in the base-final consonant and in the corresponding stem-final consonant in the derivative are no longer required to match, and [e] is raised to [e] to satisfy the loi de position, with as a result of this raising a replacement of [\t'] with [\t'] (10). The replacement of [\t'] with [\t'] after [e] is motivated by a constraint that penalizes falling F1 transitions in close-mid vowels, [e\t].

(10) Deriving regular application before vowel-initial suffixes

\[
\begin{align*}
&\text{fc} \at \text{\t'-au} \\
&\begin{bmatrix} 
C_{\text{rel}} = \text{\t'} \\
C_{\text{clos}} = \text{-\t'} 
\end{bmatrix} \\
&\begin{bmatrix} 
C_{\text{rel}} = \text{\t'} \\
C_{\text{clos}} = \text{-\t'} 
\end{bmatrix} \\
&\begin{bmatrix} 
C_{\text{rel}} = \text{\t'} \\
C_{\text{clos}} = \text{-\t'} 
\end{bmatrix}
\end{align*}
\]

When the stop-initial suffix /-må/ combines with the base /di\o\_l'/, the base-final [l'] allophone remains intact along its release properties in the derivative, due to the absence of formant structure in [m]. In the absence of change of the release properties of [l], a change affecting the closure transitions would be perceptually too salient and is therefore blocked. To maintain level F1 transitions, the lowering of [o] to [\o] is blocked, in violation of the loi de position (11).

(11) Deriving cyclic application before stop-initial suffixes

\[
\begin{align*}
&\text{di\o\_l'} \text{-må} \\
&\begin{bmatrix} 
C_{\text{rel}} = \text{l'} \\
C_{\text{clos}} = \text{-\l'} 
\end{bmatrix} \\
&\begin{bmatrix} 
C_{\text{rel}} = \text{l'} \\
C_{\text{clos}} = \text{-\l'} 
\end{bmatrix} \\
&\begin{bmatrix} 
C_{\text{rel}} = \text{l'} \\
C_{\text{clos}} = \text{-\l'} 
\end{bmatrix}
\end{align*}
\]
7.2.4 OT analysis

I show how this pattern can be derived using the type of faithfulness constraints introduced in chapter 6. The four markedness constraints in (12) are needed. *C'V requires consonants to be coarticulated with a following vowel: in other words, it requires release transitions to occur between a consonant and a following vowel. This constraint motivates the replacement of the base-final Crel-allophone lacking release transitions with a stem-final Crel-allophone with release transitions before a vowel-initial suffix. *V_{low} \rightarrow C \text{ in (12-b) and } *V_{+low} \rightarrow C \text{ in (12-c) are the two constraints on vowel-transition combinations: they require F1 closure transitions to be level in high vowels and falling in low vowels, respectively. LdP is a name-holder for two markedness constraints that are perceptually motivated in part I: a constraint that requires mid vowels to be tense (or close-mid) in open syllables and a constraint that requires mid vowels to be lax (or open-mid) in closed syllables (see section 7.4 for an alternative analysis where LdP is split into two constraints).}

(12) Markedness constraints

a. *C'V

Assign a violation mark to a candidate in which consonants are not realized with release transitions in a following vowel.

b. *V_{low} \rightarrow C

F1 closure transitions are level in high vowels.

c. *V_{+low} \rightarrow C

F1 closure transitions are falling in low vowels.

d. LdP

Mid vowels are close-mid before prevocalic consonants and open-mid before prestop consonants.

The faithfulness constraints that conflict with these markedness constraints in derivatives are shown in (13). These faithfulness constraints are BD-correspondence constraints (Kenstowicz, 1996; Benua, 1997) because they regulate the mapping from the
base (B) to the corresponding stem in the derivative (D). Ident-BD(C_{rel}) in (13-a) requires consonant allophones to be identical in the base and in the derivative along their release properties: it represents a pressure against consonant-vowel coarticulation and therefore conflicts with \*C\'+V. Ident-BD(C_{clos}) requires consonant allophones to be identical in the base and in the derivative along their closure properties. It conflicts with \*V_{low}\C and \*V_{+low-C}. Ident-BD(low) in (13-c) requires vowels to have the same specification for the [low] feature in the base and in the derivative. It conflicts with LdP.

(13) Simple faithfulness constraints
   a. Ident-BD(C_{rel})
      Assign a violation mark if C_{D}^{rel} \neq C_{B}^{rel}.
   b. Ident-BD(C_{clos})
      Assign a violation mark if C_{D}^{clos} \neq C_{B}^{clos}.
   c. Ident-BD(low)
      Assign a violation for any unfaithful mapping of the [low] feature.

Because /\acute{e}t'-au/ is mapped to [fe\_\tilde{a}u\_], all three faithfulness constraints must be outranked by the corresponding markedness constraints \*C\'+V, \*V_{low}\C, and LdP, as in (14). The ranking in (14-a) ensures that the stem-final consonant and the vowel-initial suffix are coarticulated: /t'-a/ \rightarrow [\tilde{a}]. The ranking in (14-b) ensures that the mid vowel in the base is raised to [e] before [ta]: /\acute{e}t-a/ \rightarrow [eta]. The ranking in (14-c) ensures that vowel raising results in a flattening of the closure F1 transition into [t]: /\varepsilon\_\acute{t}/ \rightarrow [e\_\_t].

(14) Rankings
   a. \*C\'+V \gg Ident-BD(C_{rel})
   b. LdP \gg Ident-BD(low)
   c. \*V_{low}\C \gg Ident-BD(C_{clos})

Because the constraint \*V_{+low-C} is never violated either, one can posit the additional
ranking in (15).

(15) \[ *V+\text{low} \rightarrow C \gg \text{Ident-BD}(C_{\text{clos}}) \]

To block the application of the *loi de position* when the C_{rel}-allophones are identical in the base and in the derivative, Ident-BD(C_{clos}) must be split into two context-sensitive versions, as per the recipe presented in chapter 6. Ident-BD(C_{clos})/nochange(C_{rel}) in (16-a) penalizes a change of the stem-final consonant's closure transitions if its release transitions have not been modified. Ident-BD(C_{clos})/change(C_{rel}) in (16-b) penalizes changing both the stem-final consonant's release and closure transitions in the derivative.

(16) Faithfulness constraints modeling the PDEE

a. Ident-BD(C_{clos})/nochange(C_{rel}) \quad (= \text{Ident-BD}(C_{clos}) \& \neg \text{Ident-BD}(C_{rel}))
   
   Assign a violation mark if \( C_{D,\text{rel}} = C_{B,\text{rel}} \) and \( C_{D,\text{clos}} \neq C_{B,\text{clos}} \).

b. Ident-BD(C_{clos})/change(C_{rel}) \quad (= \text{Ident-BD}(C_{clos}) \& \text{Ident-BD}(C_{rel}))
   
   Assign a violation mark if \( C_{D,\text{rel}} \neq C_{B,\text{rel}} \) and \( C_{D,\text{clos}} \neq C_{B,\text{clos}} \).

As described in chapter 6, these faithfulness constraints and Ident-BD(C_{rel}) must be ranked as in (17). According to the hypothesis that a feature change is perceived as more salient if implemented alone than in the context of another feature change, Ident-BD(C_{clos})/nochange(C_{rel}) outranks Ident-BD(C_{clos})/change(C_{rel}). The faithfulness constraint relative to the conditioning change, Ident-BD(C_{rel}), is at least as high as the faithfulness constraint relative to the conditioned change, Ident-BD(C_{clos})/nochange(C_{rel}), due to the requirement that the conditioning change be at least as large as the conditioned change.

(17) Ranking of the faithfulness constraints deriving the PDEE

Ident-BD(C_{rel}), \quad \text{Ident-BD}(C_{clos})/\text{nochange}(C_{rel}) \gg \text{Ident-BD}(C_{clos})/\text{change}(C_{rel})

To derive application of the *loi de position* when the release transitions are changed
and the cyclic preservation of height in all other circumstances, the constraint LdP must be ranked between the two context-sensitive constraints, as in (18). This ranking is the crucial ranking in the analysis.

(18) Ranking deriving the distribution of regular vs. cyclic application

\[ \text{Ident-BD}(C^{\text{clo}}) / \text{nochange}(C^{\text{rel}}) \gg \text{LdP} \gg \text{Ident-BD}(C^{\text{clo}}) / \text{change}(C^{\text{rel}}) \]

The tableau (19) shows how this analysis correctly derives regular application of the \textit{loi de position} with vowel-initial suffixes. The ranking \(*C'V \gg \text{Ident-BD}(C^{\text{rel}})\) in (14-a) rules out the candidate without CV coarticulation [fe \text{\`a}z]. Because the C^{\text{rel}}-allophone in the derivative has been changed through coarticulation, the constraint that is relevant to evaluate violations of faithfulness to closure transitions is \text{Ident-BD}(C^{\text{clo}}) / \text{change}(C^{\text{rel}}). This constraint is outranked by the markedness constraint favoring close-mid vowels in open syllables (via the ranking (18)) and by the markedness constraint favoring level F1 transitions in close-mid vowels (via the ranking in (14-c)). Therefore, the candidate with the three changes [fe \text{\`a}z] is selected as the winner.

(19) Deriving regular application with vowel-initial suffixes:

\[
\begin{array}{|c|c|c|c|c|}
\hline
fe \text{\`a}z & *C'V & \text{Ident-BD}(C^{\text{rel}}) & \text{*V low } \times C & \text{LdP} & \text{Ident-BD}(C^{\text{clo}}) / \text{change}(C^{\text{rel}}) \\
\hline
fe \text{\`a}z & *! & & & & \\
\hline
fe \text{\`a}z & * & & & & \\
\hline
fe \text{\`a}z & * & & & & \\
\hline
\text{\textit{e}} & \text{\textit{e} \text{\`a}z} & * & & & \\
\hline
\end{array}
\]

The tableau (20) shows how this analysis correctly derives cyclic application with stop-initial suffixes. *C'V is not violated by the most faithful candidate: because [m] does not provide release transitions, no transition that was not present in the input needs to be added. As a result, the winner candidate satisfies \text{Ident-BD}(C^{\text{rel}}). Because \text{Ident-BD}(C^{\text{rel}}) is satisfied, the constraint that is relevant to evaluate violations of faithfulness to closure transitions is \text{Ident-BD}(C^{\text{clo}}) / \text{nochange}(C^{\text{rel}}). This constraint

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outranks LdP (see the ranking in (18)). Therefore, the candidate that satisfies the *loi de position* with a falling F1 transition [dɔʁ'ɔl'mâ], is ruled out. The candidate that satisfies both the *loi de position* and faithfulness to closure transitions, [dɔʁ-ɔl'mâ], is ruled out because [ɔ-] is penalized by *V+low→C (via the ranking in (15)). As a consequence, the winner is the candidate without any change: [dɔʁ-ɔl'mâ].

(20) Deriving cyclic application with stop-initial suffixes:

<table>
<thead>
<tr>
<th>dɔʁ-ɔl'mâ</th>
<th>*C′V</th>
<th>Ident-BD(C′rel)</th>
<th>*V+low→C</th>
<th>Ident-BD(C′clsh)/nochance(C′rel)</th>
<th>LdP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>*</td>
</tr>
<tr>
<td>dɔʁ-ɔl'mâ</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>*</td>
</tr>
<tr>
<td>dɔʁ-ɔl'mâ</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>*</td>
</tr>
</tbody>
</table>

7.2.5 Conditions on PDEEs

In chapter 6, four conditions on PDEEs were discussed: the *locality condition*, the *one-dimension condition*, the *monotonicity condition*, and the *size condition*. The four conditions are repeated in (21). Does the analysis of the Standard French pattern proposed above obey these conditions?

(21) Conditions on the feature changes interacting in PDEE

a. Locality condition

   The two changes happen on the same segment.

b. One-dimension condition

   The two changes happen along the same dimension.

c. Monotonicity condition

   The second change is a continuation of the first change.

d. Size condition

   The first change is at least as large as the second change.

The analysis of the Standard French pattern satisfies the *locality condition* because the two changes affect the same segment, namely the stem-final consonant following
the mid vowel. Release transitions outweigh closure transitions in place perception: if release and closure transitions provide conflicting cues, listeners identify the place of articulation according to the release transitions (Fujimura, Macchi, and Streeter, 1978). Given this asymmetry, it is plausible that adding release transitions to a consonant represents a greater perceptual change than modifying its closure transitions, in accordance with the *size condition*.

It is a bit harder to see how the two changes satisfy the *one-dimension condition* and the *monotonicity condition*. How can levelling the F1 closure transitions going into a consonant (i.e. going from \( \text{c} \) to \( \rightarrow \text{c} \)) be considered as a continuation of adding release transitions to that consonant (i.e. going from \( \text{c}' \) to \( \text{c}'' \)) along the same dimension? Both closure and release transitions provide cues to a consonant’s place of articulation. However, it is not clear that place of articulation represents a single dimension. Rather, the two changes seem to involve a temporal redistribution of the cues: in the unsuffixed form, cues to place are located in the closure transitions and in the consonant’s internal cues whereas in the suffixed form, these cues are located in the release transitions and in the consonant’s internal cues. However, this differs from the notion of perceptual dimension introduced in chapter 6. I leave for further research the task to discover whether the Standard French pattern can be conciled with these two conditions or whether the theory of PDEEs presented in chapter 6 needs to be weakened.

7.3 Comparing the syllable-based and cue-based approaches: glide-initial vs. liquid-initial suffixes

Until now, no direct argument was provided in favor of the cue-based analysis or the syllable-based analysis. In this section, I argue that the cue-based analysis can better account for the behavior of glide-initial and liquid-initial suffixes than the syllable-based analysis.

In unstressed (=non-final) syllables, mid vowels are realized as close-mid [e ø o]
both before CL clusters (22-a) and CG clusters (22-b).

(22) The loi de position in morpheme-internal syllables in Standard French: more data

a. étrange [etʁɑ̃] 'weird'

b. s’Étioler [sɛtjo] ‘wither’

However, the two types of clusters behave differently across a morpheme boundary. Mid vowels are realized regularly and according to the loi de position if the suffix starts with a glide [j w] (23-a) but cyclically if the suffix starts with a liquid [l r] (23-b).

(23) Phonologically-conditioned cyclicity in Standard French: more data

a. Regular application of the loi de position before glide-initial suffixes.
   fêtesons /fe̞tɛʒ/ ‘party’-1.PL.IMPF [fetj5] (regular application)
   *[fe̞tj3] (cyclic application)

b. Cyclic application before liquid-initial suffixes.
   fétersons /fe̞tɛʁɔ̃/ ‘party’-1.PL.FUT *[fe̞tɛʁɔ̃] (regular application)
   [fe̞tɛʁɔ̃] (cyclic application)

Under the syllable-based analysis, glide-initial suffixes trigger regular application if CG clusters are syllabified as onset clusters across a morpheme boundary (24-a). Liquid-initial suffixes trigger cyclic application if CL clusters span two different syllables across a morpheme boundary (24-b).

(24) Syllable-based account: hypothesis about the syllabification of CG vs. CL clusters.

a. C-G clusters are syllabified as onset clusters.
   fêtesons /fe̞tɛʒ/ [feₜj5] ‘party’-1.PL.IMPF

b. C-L clusters span two different syllables.
   fétersons /fe̞tɛʁɔ̃/ [feₜɛʁɔ̃] ‘party’-1.PL.FUT

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In a syllable-based analysis, segments are ordered along a sonority hierarchy. The ability for a consonant $C_2$ to be syllabified with a preceding consonant $C_1$ and form an onset cluster depends on $C_2$'s position along the hierarchy: the more sonorous $C_2$ is, the more likely it is to be syllabified with $C_1$. Because glides are more sonorous than liquids along this hierarchy, they are more likely to form an onset cluster with a preceding consonant cross-linguistically. As a consequence, under a syllable-based theory, glides and liquids may behave differently with respect to syllabification and the hypothesis in (24) is plausible.

However, in French, glides and liquids are not syllabified differently morpheme-internally: both CG and CL clusters are syllabified as onset clusters (25) (Goslin and Frauenfelder, 2000).

(25) Syllabification of CG and CL clusters morpheme-internally.

a. étrange [e.tʁẫ] ‘weird’
b. s’étéoler [se.tjo.le] ‘wither’

For the syllable-based hypothesis to work, it must therefore be the case that syllabification differs morpheme-internally and across a morpheme boundary. This is why the hypothesis in (24) refers specifically to clusters across a morpheme boundary. To my knowledge, the hypothesis that, across a morpheme boundary, CL clusters are syllabified as heterosyllabic clusters and CG clusters as tautosyllabic has never been tested. Section 7.3.1 presents the results of a syllabification task testing this hypothesis.

Under the cue-based analysis, glide-initial suffixes trigger regular application if the stem-final consonant’s release-allophones [c'] and [œ] alternate word-finally and before glides (26-a). Liquid-initial suffixes trigger cyclic application if the same release-allophone [c'] occurs word-finally and before liquids (26-b).

(26) Cue-based account: hypothesis about the release properties of preglide consonants vs. preliquid consonants.
a. Consonant release-allophones alternate word-finally and before glides.

fétons /fe\t^-j\d/  [fe\t\d] ‘party’-1.PL.IMPF

b. Consonant release-allophones do not alternate word-finally and before liquids.

fêterons /fe\t^-u\d/  [fe\t\u] ‘party’-1.PL.FUT

In phonetic terms, the difference between glide-initial and liquid-initial suffixes is expected if glides affect the release properties of a preceding consonant more than liquids do. Both glides and liquids have formant structure and therefore provide release transitions to a preceding consonant (Wright, 2004; Flemming, 2007; Bakst and Katz, 2014). However, glides are acoustically more similar to vowels than liquids are, and therefore potentially provide more robust release transitions to a preceding consonant. Glides [j w] might also have a greater coarticulatory effect on the burst/frication noise/nasal murmur of a preceding consonant than liquids [l u], due to their place features. French glides have extreme F2 loci or are rounded: [j] has a high F2 locus, similar to that of [i], [w] is rounded and has a low F2 locus, similar to that of [u], and [u] is rounded too and quite front. French [l] is clear, i.e. with a relatively high F2 target. However, the F2 target of [l] is not as high as that of [j] (Chafcouloff, 1985). French [u] has a low F2 target (Delattre, 1959; Gendrot, 2014), like [w]. However, [w] is rounded whereas [u] is not. As consequence, glides might have a greater impact on the release cues (understood as the internal cues plus the release transitions) of a preceding consonant than liquids.

There is evidence for a perceptual effect of vowels with extreme F2 values on burst perception in French. Bonneau (2000) showed that French listeners are able to identify vowels from stop bursts only in CV sequences, with C = {p, t, k} and V = {i, a, u}. The percentage of correct identification was particularly high before high vowels [i] (with [t]-burst and [k]-burst in particular) and [u] (with [k]-burst in particular) as compared to before [a]. This suggests that vowels with extreme F2 values [i] and [u] (and by extension [j] and [w]) have a strong coarticulatory effect on a preceding consonant.
Although this study is relevant, it does not directly answer whether glides affect the release properties of a preceding consonant more than liquids do. In particular, [l] and [s] are not as central as [a] along F2 and therefore may have a greater coarticulatory effect on the burst of a preceding consonant. Section 7.3.2 presents the results of a perception experiment that directly tests whether there is a greater perceptual similarity between preliquid consonants and word-final consonants than between preglide consonants and word-final consonants.

### 7.3.1 Testing the syllable-based hypothesis

Are CG and CL clusters syllabified differently across a morpheme boundary? To answer this question, a small experiment based on a syllabification task was conducted. As in other works on syllabification (see Goslin and Frauenfelder, 2000 for instance), participants' syllable judgements are assumed to faithfully reflect the syllable structure that is relevant to phonotactics.

Seven Standard French speakers were asked to syllabify four phonetically transcribed sentences containing CL and CG clusters morpheme-internally and CL and CG clusters across a morpheme boundary (the participants were familiar with International Phonetic Alphabet). The CL cluster was [ts] and the CG cluster was [tʃ]. In the four conditions, the target cluster was preceded by the nasal vowel [ã]. A nonmid vowel was chosen because nonmid vowels are not subject to alternations in derivatives. The vowel [ã] can be followed by onset consonants (27-a) and by coda consonants (27-b). Therefore the choice of [ã] is not expected to bias the participants in any particular direction.

(27)  [ã] occurs in open and closed syllables.

a. manteau [mã.to] ‘coat’

b. pente [pã.ʃ] ‘slope’

The participants were not aware of the purpose of the experiment. They did not report any difficulty to syllabify the target clusters.
The results of the syllabification test are shown in (28). CG and CL clusters were almost systematically syllabified as onset clusters, regardless of the presence of a morphological boundary. One participant syllabified morpheme-internal [tj] as heterosyllabic.

(28) Results

<table>
<thead>
<tr>
<th>Tautosyllabic</th>
<th>Heterosyllabic</th>
<th>Item</th>
</tr>
</thead>
<tbody>
<tr>
<td>tʃ</td>
<td>7/7</td>
<td>0/7</td>
</tr>
<tr>
<td>t-ʃ</td>
<td>7/7</td>
<td>0/7</td>
</tr>
<tr>
<td>tj</td>
<td>6/7</td>
<td>1/7</td>
</tr>
<tr>
<td>t-ʃ</td>
<td>7/7</td>
<td>0/7</td>
</tr>
</tbody>
</table>

Crucially, the cluster [tʃ] was not found to be syllabified as heterosyllabic across a morpheme boundary. This is problematic for the syllable-based account.

7.3.2 Testing the cue-based hypothesis

This section presents the results of two perception experiments testing whether word-final consonants are perceptually more similar to their preliquid counterparts than to their preglide counterparts. The two experiments are based on a discrimination task.

Methods

Stimuli. The hypothesis was tested using the three following consonants: [t], [k], and [ʃ]. Different places and manners of articulation were chosen to test whether the hypothesized effect is general. The effect of glides [j] and [w] was compared to the effect of liquids [l] and [ʁ].

The nonsense words in (29) were used to build the stimuli used in the experiments. Three vowels were used in the pre-consonantal contexts: [a], [i], [u].

(29) Words

a. Preliquid condition: {a, i, u}{f, t, k}{l, ű}a (18 words)
b. Preglide condition: {a, i, u}{f, t, k}{j, w}a (18 words)
c. Word-final condition: al{a, i, u}{f, t, k}

The nonsense words were read once by a male native French speaker in pseudo-random order. The stimuli were recorded with a head-mounted microphone in a sound-attenuated booth.

Bursts and frication noises were extracted from the speech signal using Praat (Boersma and Weenink, 2017), with all cuts made at zero crossings. In the preglide contexts, the portion of noise spanning from the end of the vowel to the onset of voicing was extracted. In the preliquid contexts, the end of the burst or frication noise was identified with a drop in intensity or a change in the distribution of energy over the frequency range. In the word-final context, the whole portion of noise was extracted. Sometimes, some low intensity random fluctuations appeared at the end of the consonant. They were not included.

Two sets of stimuli were built based on the original recordings. In one set, the stimuli were edited in order to control for the effect of both intensity and duration on similarity. The durations of the bursts and frication noise were kept constant within each of the nine conditions (three vowels x three consonants). Long bursts and frication noises were cut at zero crossings to have the same duration as the shortest bursts and frication noise within each condition (in general, bursts and frication noises were shorter before liquids). The amplitude of the burst and frication was equalized within each of the nine conditions. In the second set, only the intensity was controlled for.

Two sets of stimuli were built for the following reasons. Because the hypothesis is specifically about the effect of glide-initial vs. liquid-initial suffixes on the realization of place cues, it is desirable to control for the effect of duration on similarity judgements. However, the judgement of place similarity by actual listeners might also depend on the duration of the segment: some coarticulatory effects might only be perceivable over the whole duration of the segment.

For each set of stimuli, the bursts and frication noises were spliced with the same vowel in each of the nine conditions in order to neutralize the effect of vowel similarity
in the task. This resulted in \(|\{a, i, u\}^*\{f, t, k\}^*\{#, w, j, l\}| = 45\) VC syllables.

For each of the two sets of stimuli, ABX triplets were constructed using these 45 syllables: A and B standing for the preliquid or preglide VC syllable in each of the nine conditions and X standing for the word-final VC syllable in each of the nine conditions. Four comparisons were considered ([j] vs. [l], [j] vs. [u], [w] vs. [l], [w] vs. [u]), and two orders were considered (ABX, BAX), yielding a total of 72 triplets for each set of stimuli. For instance, there was a triplet /ak(la) ak(ja) ak/ (where the first [ak] was extracted from [akla], the second one from [akja], and the last one was just [ak]). The VC syllables were separated by a one second interval in each triplet.

**Participants.** Two perception experiments were run online. Experiment 1 used the stimuli where both intensity and duration were edited. Experiment 2 used the stimuli where only intensity was edited.

42 English-speaking participants were recruited online to participate in Experiment 1. The same number of participants were recruited online to participate in Experiment 2. Among them, 19 were English speakers and 23 were French speakers. The English-speaking participants were recruited on Mechanical Turk and paid three dollars for their participation. The French-speaking participants were recruited through the mailing list of the CNRS’ Réseaux d’information sur les sciences de la cognition and participated on a voluntary basis.

**Task.** The triplets were presented in randomized order. The task was the following: for each triplet, the participants had to choose whether the first or the second syllable was most similar to the last one. Participants were asked to wear headphones while taking the test.

There was a training phase with four triplets. Three catch items were used to check that participants did the experiment carefully. One participant in Experiment 1 and two participants in Experiment 2 failed on all catch items. As a consequence, their data were removed from the analysis, resulting in a dataset of 41 listeners for Experiment 1 and a dataset of 40 listeners for Experiment 2.

**Analysis.** To analyze the results, a mixed-effects logistic regression was run using R (R Core Team, 2017) and lme4 (Bates et al., 2015). The dependent variable was
binary: participants had to choose among the preliquid and the preglide consonant which was more similar to the word-final consonant. The model predicts participants’ probability of answering ‘liquid’ as a function of the liquid-glide pair \((<l, w>, <l, j>, <w, w>, <w, j>)\), the consonant ([f], [t], [k]), and their interaction. In order to control for variations across speakers and items (and language background in Experiment 2), the random effect structure included a by-subject random intercept, a by-vowel random intercept ([a], [i], [u]), and, in Experiment 2, a by-language random intercept (English vs. French). Models with more complex random effect structure did not converge.

**Results**

Figure (30) shows the proportion of ‘liquid’ responses as a function of the liquid-glide pair and the consonant pooled across vowels and participants in Experiment 1. The output of the statistical model is shown in (31). The intercept indicates the logodds of answering ‘liquid’ in the [f] condition and for the liquid glide pair <l,w>. A significant positive estimate corresponds to an increase in the probability of answering ‘liquid’. For instance, the first bar in (30) indicates that listeners judged [af] extracted from [afla] more similar to [af] than [af] extracted from [afja].

(30) Proportion of ‘liquid’ responses as a function of liquid-glide pair and consonant in Experiment 1.
Word-final [f] is significantly more similar to preliquid [f] than to preglide [f], except for the liquid-glide pair <u, w>. The effect of [j] on [f] is overall larger than the effect of [w]. For [t] and [k], the results are different. [t] and [k] are more similar word-finally

| Model output for Experiment 1. | Estimate | Std. Error | z value | Pr(>|z|) |
|-------------------------------|----------|------------|---------|----------|
| (Intercept) C=f, Pair=lw      | 0.35892  | 0.16855    | 2.130   | 0.03321  * |
| Pair=lj                       | 0.81229  | 0.19987    | 4.064   | 4.82e-05 *** |
| Pair=rj                       | 0.57607  | 0.19418    | 2.967   | 0.00301  ** |
| Pair=rw                       | -0.13761 | 0.18542    | -0.742  | 0.45800  |
| C=k                           | 1.15892  | 0.21127    | 5.485   | 4.13e-08 *** |
| C=t                           | 1.21457  | 0.21348    | 5.689   | 1.27e-08 *** |
| Pair=lj:C=k                   | -2.15999 | 0.29045    | -7.437  | 1.03e-13 *** |
| Pair=rj:C=k                   | -2.00847 | 0.28641    | -7.013  | 2.34e-12 *** |
| Pair=rw:C=k                   | 0.16516  | 0.29886    | 0.553   | 0.58050  |
| Pair=lj:C=t                   | -2.13034 | 0.29225    | -7.289  | 3.11e-13 *** |
| Pair=rj:C=t                   | -2.01328 | 0.28810    | -6.988  | 2.79e-12 *** |
| Pair=rw:C=t                   | 0.05487  | 0.29892    | 0.184   | 0.85435  |
and before liquids than before \[w\]. However, there is no significant difference between liquids and \[j\].

The results show a strong effect of \[j\] on \[f\] and a strong effect of \[w\] on \[t\] and \[k\] and support part of the hypothesis that word-final consonants are more similar to their corresponding preliquid counterparts than to their corresponding preglide counterparts. The fact that \[j\] (a consonant with a high F2 target) strongly affects the labial consonant (a consonant with a low F2 target) and \[w\] (a consonant with a low F2 target) strongly affects the velar and dental consonants (consonants with high F2 targets) is expected: coarticulation is expected to be stronger for segments with antagonistic F2 targets (Lindblom, 1963).

Word-final \[f\] was also found to be more similar to \[f\] before \[l\] than to \[f\] before \[w\]. This suggests that glides also affect consonants that are not as dissimilar to them in terms of place and raises the possibility that the design of Experiment 1 did not allow us to detect more subtle coarticulatory effects. Because bursts and frication noises were experimentally shortened in preglide positions, it is possible that only the strongest coarticulatory effects that start early in the consonant were allowed to be detected.

In Experiment 2, duration was not edited in order to test whether effects that could not be detected at the beginning of the preglide consonants could be perceived when considering the whole consonant duration. Figure (32) shows the proportion of 'liquid' responses as a function of the liquid-glide pair and the consonant. The data are pooled across vowels and participants.

(32) Proportion of 'liquid' responses as a function of liquid-glide pair and consonant in Experiment 2.
On average, preliquid consonants were found to be about ten times more likely than preglide consonants to be judged as more similar to word-final consonants ($\beta=2.32\pm0.38$, $z=6.16$, $p=7.51\times10^{-10}$). Likelihood ratio tests were performed to compare the model with liquid-glide pair, consonant, and their interaction as fixed effects to simpler models including only one of the two main effects or no interaction. The full model was found to better fit the data significantly. To check that the effect holds in each context, models were run taking each combination of liquid-glide pair and consonant as baseline. For each combination of liquid-glide pair and consonant, pre-liquid consonants were found to be more likely to be judged as more similar to word-final consonants than pre-glide consonants.

These results support the hypothesis: consonants were consistently found to be more similar word-finally and before liquids than word-finally and before glides.

### 7.3.3 Discussion

Although the test of the syllable-based hypothesis was a pilot study, the results are not very encouraging for this hypothesis. The fact that the syllable-based analysis
fails to derive the correct distribution is maybe not so surprising, given the claim that syllables are not relevant to phonotactics (Ohala, 1992; Steriade, 1999).

The results of Experiments 1 and 2 support the hypothesis that there is a greater similarity between word-final consonants and their preliquid counterparts than between word-final consonants and their preglide counterparts. The results in Experiment 1 are compatible with the idea that place cues in particular are affected by glides: the fact that [j] strongly affects the labial consonant and [w] strongly affects the dental and velar consonants is compatible with an effect of glides on consonant place. In Experiment 2, consonant duration was not controlled for and differences in duration might explain part of the results. Place of articulation probably still played an important role: the differences that were found in Experiment 1 carry over to Experiment 2 (although they are much smaller). Impressionistically, the effects of glides on bursts and frication noises in the stimuli used in Experiment 2 can be characterized as effects on place: consonants [t k f] sound more acute before [j] more grave before [w].

Glides [j] and [w] should affect other consonants' internal place cues similarly, as place is signaled similarly across consonants, i.e. by variations in the distribution of energy over the frequency range. [q] was not included in the experiment because it is a rare phoneme compared to the others and it never occurs in suffixes. Although the F2 value of [q] is not as high as that of [i], [q] is rounded and is therefore expected to have a significant coarticulatory effect on the consonants. An investigation of [q] is left for further research.

Formally, a new markedness constraint must be posited to trigger the change from the word-final c' allophone to c' before glide-initial suffixes. This markedness constraint is defined in (33). The rest of the analysis remains the same.

(33) *C'G

Assign a violation mark to a candidate in which a consonant is not coarticulated with a following glide.

The tableaux in (34) and (35) show how the cue-based analysis derives the asymmetry
between liquid- and glide-initial suffixes. In order to satisfy *C’G, the stem-final consonant allophone is changed in derivatives built with glide-initial suffixes. This change then licenses a change of the stem-final consonant’s closure transitions. This change is motivated by the loi de position. With liquid-initial suffixes, *C’G is not violated: as a consequence, the stem-final does not need to be changed and no change affecting the closure transitions of the stem-final consonant is allowed.

(34) Deriving regular application with glide-initial suffixes:

<table>
<thead>
<tr>
<th>Fe\t:ja</th>
<th>*C’G</th>
<th>Ident-BD(Crel)</th>
<th>*V:low \u03c0C</th>
<th>LdP</th>
<th>Ident-BD(C\text{close})/ change(Crel)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe\t:ja</td>
<td>*!</td>
<td></td>
<td></td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>Fe\t:j5</td>
<td></td>
<td></td>
<td></td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>Fe\t:j5</td>
<td></td>
<td></td>
<td></td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>Fe\t:j5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(35) Deriving cyclic application with liquid-initial suffixes:

<table>
<thead>
<tr>
<th>Fe\t:ja</th>
<th>*C’G</th>
<th>Ident-BD(Crel)</th>
<th>*V:low \u03c0C</th>
<th>Ident-BD(C\text{close})/ nochange(Crel)</th>
<th>LdP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe\t:ja</td>
<td>*!</td>
<td></td>
<td></td>
<td></td>
<td>*</td>
</tr>
<tr>
<td>Fe\t:ja</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>*</td>
</tr>
<tr>
<td>Fe\t:ja</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

7.4 A markedness-based alternative

In this section, I explore an alternative analysis that does not suffer from the same problem as the syllable-based analysis. This analysis is a more radical alternative to the cue-based analysis because it does not involve analyzing the French pattern as a PDEE: instead, LdP is split into several markedness constraints. Some of these constraints outrank Ident-BD(low) and others are outranked by Ident-BD(low), giving rise to phonologically-conditioned cyclicity.

This account is based on a characterization of the split between the contexts favoring regular application and cyclic application in terms of the base mid vowel. The pattern of phonologically conditioned cyclicity can also be characterized as follows:
stem open-mid vowels may raise in derivatives, but stem close-mid vowels are always realized faithfully.

7.4.1 The alternative

Let us start by splitting LdP into the two constraints in (36): *CloseMid/_CS in (36-a) penalizes close-mid vowels occurring before prestop consonants and *Open-Mid/_CV in (36-b) penalizes open-mid vowels occurring before prevocalic consonants. Splitting LdP into two such constraints is compatible with the analysis in part I where tensing in open syllables and laxing in closed syllables are considered as two different processes (vowel contrast enhancement vs. place contrast enhancement).

(36) Splitting LdP into two markedness constraints.
   a. *CloseMidV/_CS
      Assign a violation mark for every tense mid vowel occurring before a prestop consonant.
   b. *OpenMidV/_CV
      Assign a violation mark for every lax mid vowel occurring before a prevocalic consonant.

In this analysis, the basic split between vowel-initial and stop-initial suffixes can be characterized as in (37): vowel-initial suffixes trigger regular application because *OpenMid/_CV is never violated in derivatives (37-a) whereas stop-initial suffixes trigger cyclic application because *CloseMid/_CS may be violated in derivatives (37-b).

(37) Markedness-based analysis of the French pattern.
   a. The constraint against open-mid vowels before prevocalic consonants is never violated in derivatives.
      fêtard  /fet-au/  [fetaʁ]  ‘partier’
   b. The constraint against close-mid vowels before prestop consonants may
be violated in derivatives.

drôlement /dʁol-mã/  [dʁol.mã]  ‘funny’-ADV

The difference between the two types of suffixes is derived assuming the ranking in (38).

(38) Ranking.

*OpenMidV/_CV ≫ Ident-BD(low) ≫ *CloseMidV/_CS

Tableaux in (39) and (40) show how this analysis correctly derives mid-vowel raising before vowel-initial suffixes and cyclic application before stop-initial suffixes.

(39) Deriving mid-vowel raising with vowel-initial suffixes:

<table>
<thead>
<tr>
<th>fet-aur</th>
<th>*OpenMidV/_CV</th>
<th>Ident-BD(low)</th>
<th>*CloseMidV/_CS</th>
</tr>
</thead>
<tbody>
<tr>
<td>fetax</td>
<td>*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>fetaur</td>
<td>*</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(40) Deriving cyclic application with stop-initial suffixes:

<table>
<thead>
<tr>
<th>dəsol-mã</th>
<th>*OpenMidV/_CV</th>
<th>Ident-BD(low)</th>
<th>*CloseMidV/_CS</th>
</tr>
</thead>
<tbody>
<tr>
<td>dəsolmã</td>
<td></td>
<td></td>
<td>*</td>
</tr>
<tr>
<td>dəsolmã</td>
<td></td>
<td></td>
<td>*</td>
</tr>
</tbody>
</table>

The analysis can also account for the difference between glide-initial suffixes and liquid-initial suffixes. Open-mid vowels before CG clusters are penalized by the markedness constraint in (41-a) and open-mid vowels before CL clusters are penalized by the markedness constraint in (41-b).

(41) Splitting LdP into two markedness constraints

a. *OpenMidV/_CGV
   Assign a violation mark for every lax mid vowel occurring before CGV.

b. *OpenMidV/_CLV
   Assign a violation mark for every lax mid vowel occurring before CLV.

The ranking in (42) derives mid-vowel raising before glide-initial suffixes (43) and
cyclic application before liquid-initial suffixes (44). The ranking is compatible with the analysis of the *loi de position* in part 1. If glides provide more informative release cues to consonant place than liquids, then it is expected that it is preferrable to lower mid vowels before CLV than before CGV, as assumed in (42).

(42) Ranking.

\[ *\text{OpenMidV}/\_\text{CGV} \gg \text{Ident-BD(low)} \gg *\text{OpenMidV}/\_\text{CLV} \]

(43) Deriving mid-vowel raising with glide-initial suffixes:

<table>
<thead>
<tr>
<th></th>
<th>f'rtj5</th>
<th>*OpenMidV/_CGV</th>
<th>Ident-BD(low)</th>
<th>*OpenMidV/_CLV</th>
</tr>
</thead>
<tbody>
<tr>
<td>f'rtj5</td>
<td>*</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>*f'rtj5</td>
<td></td>
<td>*</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(44) Deriving cyclic application with liquid-initial suffixes:

<table>
<thead>
<tr>
<th></th>
<th>f'etjua</th>
<th>*OpenMidV/_CGV</th>
<th>Ident-BD(low)</th>
<th>*OpenMidV/_CLV</th>
</tr>
</thead>
<tbody>
<tr>
<td>*f'etjua</td>
<td></td>
<td>*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>f'etjua</td>
<td></td>
<td></td>
<td></td>
<td>*</td>
</tr>
</tbody>
</table>

7.4.2 A problem: CL-V vs. C-LV derivatives

The markedness-based analysis is attractive because it does not require appealing to phonetically-detailed phonological representations: the distribution of regular vs. cyclic application in derivatives can be captured by referring only to the [low] specification of stem mid vowels.

However, the markedness-based analysis fails to derive the difference between derivatives combining CL-final stems and V-initial suffixes and derivatives combining C-final stems and LV-initial suffixes: in the former case, stem mid vowels are realized regularly (45-a) whereas, in the latter case, they are realized cyclically (45-b), as already seen.

(45) Phonologically-conditioned cyclicity in Standard French: more data

a. Regular application of the *loi de position* in CL-final stems with V-initial suffixes.

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métrique /mɛtr-ik/ ‘metric’ [metsik] (regular application)
* [metsik] (cyclic application)
b. Cyclic application in C-final stems with LV-initial suffixes.
   fêterons /fct-yɔ/ ‘party’-1.PL.FUT *[fetsɔ] (regular application)
   [fetsɔ] (cyclic application)

In the markedness-based analysis, CLV sequences are treated identically whether they come from underlying C-LV or CL-V sequences. Deriving cyclic application in (45-b) requires ranking Ident-BD(low) above *OpenMidV/_CLV. But deriving regular application in (45-a) requires ranking Ident-BD(low) below *OpenMidV/_CLV. Tableau (46) shows how the markedness-based analysis fails to derive raising in derivatives combining CL-final stems and vowel-initial suffixes assuming the ranking in (42).

(46) The analysis fails to derive raising in CL-V:

<table>
<thead>
<tr>
<th></th>
<th>*OpenMidV/_CG</th>
<th>Ident-BD(low)</th>
<th>*OpenMidV/_CL</th>
</tr>
</thead>
<tbody>
<tr>
<td>mɛtr-ik</td>
<td>*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>metsik</td>
<td>*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>metsik</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

7.4.3 Analyzing CL-V derivatives with the PDEE theory

The analysis of the French pattern as a PDEE can derive the difference between /fct-yɔ/ [fetsɔ] and in /mɛtr-ik/ [metsik] if consonants have specific release allophones before word-final liquids. This allophone will be noted as c’ (47-a). It is distinct from the allophone c’, which occurs word-finally and before prevocalic liquids (47-b), and the allophone c’, which occurs before vowels and glides (47-c).

(47) a. Consonant allophones before word-final liquids: c’
   mètre /mɛˈtɛʁ/ ‘meter’

b. Consonant allophones word-finally and before prevocalic liquids: c’
   fête /fɛˈtɛ/ ‘party’
   fêterons /fɛˈtɛrɔ/ ‘party’-fut.1.pl

c. Consonant allophones word-finally and before prevocalic liquids: c’
   fêtard /feˌtɛʁ/ ‘partier’
   fétions /feˌtjɔ̃/ ‘party’-impf.1.pl

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Under affixation with a vowel-initial suffix, the allophone c' is replaced with the allophone that occurs before prevocalic liquids, c'. For instance, the underlying sequence /t'ik/ in *métique* /me t'ik/ is realized as [t'ik] in [me t'ik]. This change then licenses a further change affecting the closure transitions of the preliquid consonant, according to the logic described earlier: (i) the mid vowel is raised to satisfy the loi de position and (ii) raising is not blocked because, once the release properties of the postvocalic consonant have been changed, its closure transitions are no longer required to match in the base and in the derivative. Hence, /me t'ik/ is realized as [me t'ik]. According to this analysis, the cluster [tu] is pronounced identically in *métique* [me t'ik] and *fétérone* [fe t'ik]. As said above, the present analysis does not require these clusters to have different realizations, contrary to the markedness-based analysis.

How reasonable is the assumption that consonants have specific release allophones before word-final liquids? This assumption is reasonable if C in CL# is subject to more compression than C in C# and in CLV: under this condition, C will be shorter in CL# than in C# and in CLV. As a result of this shortening, the C-burst or frication noise will be more coarticulated with the following liquid and therefore less informative about the place of the consonant. If L is also subject to compression in CL#, the formant transitions that it provides to C might not be salient enough to compensate for the coarticulatory effect of L on C. This approach predicts that place contrasts should be particularly affected before word-final liquids. Although I do not have evidence yet for the existence of distinct consonant allophones word-finally and before word-final liquids, the hypothesis seems plausible. It could be tested using the method presented in section 7.3.2.

Formally, a new markedness constraint must be posited to trigger the change from the preliquid c' allophone to c' when a CL-final stem is concatenated with a vowel-initial suffix. This markedness constraint is defined in (48).

(48) *C"LV

Assign a violation mark to a candidate in which a consonant has reduced
release cues before a prevocalic liquid.

The rest of the analysis remains the same. Tableau (49) shows how this analysis derives regular application in derivatives combining CL-final stems and vowel-initial suffixes.

(49) Deriving regular application before CL-V:

<table>
<thead>
<tr>
<th>mc \t'ik</th>
<th>*C'LV</th>
<th>Ident-BD(C^ref)</th>
<th>*V_{low} \x C</th>
<th>LdP</th>
<th>Ident-BD(C^clop)/change(C^rel)</th>
</tr>
</thead>
<tbody>
<tr>
<td>mc \t'ik</td>
<td>*!</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>mc \t'ik</td>
<td></td>
<td>*</td>
<td></td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>fe \t'ik</td>
<td></td>
<td>*</td>
<td></td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>ze \t'ik</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>mc \t'ik</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

7.5 Discussion and conclusion

7.5.1 The case of alternating [ø]

In this section, I discuss a further datapoint that is problematic for all three theories presented so far. In derivatives, mid vowels are realized regularly and according to the loi de position if the suffix starts with a vowel (50-a), as already seen, but cyclically if the suffix starts with an alternating [ø] (50-b). [ø] is alternating because it is predictable from the context: it occurs only to break an illicit consonantal cluster, here [tj]. This is the reason why it is not represented in the underlying form of [fetøøjɔ] in (50-b).

(50) Phonologically-conditioned cyclicity in Standard French: more data

a. Regular application before vowel-initial suffixes.
   fètons /fet-3/ 'party'-PRES.1.PL [fet3] (regular application)
   *[fet3] (cyclic application)

b. Cyclic application before alternating [ø].
   fèterions /fet-øj5/ 'party'-COND.1.PL *[fetøj5] (regular application)
   [fetøj5] (cyclic application)
The alternating [ơ] occurring in *étéri*ons is sometimes called schwa and transcribed as [ə]. However, I find this terminology confusing since this vowel is not phonetically different from nonalternating [ơ] (Malécot and Choilet, 1977; Fougeron, Gendrot, and Bürki, 2007; Bürki et al., 2011). In Storme (2017), I showed that the vowel corresponding to graphic e is longer in Standard French than in Southern French. Based on this finding, I propose to transcribe so-called Standard French schwas as [ơ] and Southern French schwas as actual schwas, [ə].

To derive the asymmetry between alternating [ơ] and the other vowels, the three theories must make some problematic assumption. The syllable-based account needs to assume that alternating [ơ] is not syllabified with a preceding consonant (51-a). The cue-based theory needs to assume that consonants before alternating [ơ] are realized without release transitions (51-b). The markedness-based theory needs to assume that a markedness constraint banning close-mid vowels before alternating [ơ] outranks the general markedness constraint banning close-mid vowels before other vowels (51-c).

(51) Deriving cyclicity before schwa.

a. Syllable-based PDEE theory.

[fct.ơřj5]

b. Cue-based PDEE theory.

[fct'ơřj5]

c. Markedness-based theory.

*CloseMidV/ _C#alternating ⇒ *CloseMidV/ _CV

The assumption in (51-a) is problematic because there is no evidence that alternating [ơ]s are syllabified differently from other vowels. I syllabify [fctơřj5] as [fe.tơ.řj5].

The assumption in (51-b) is problematic because there is no evidence that release transitions are realized differently in alternating [ơ] and in other vowels. When testing for the similarity of consonant before glides or liquids and word-finally, I included a few triplets containing three [t]s extracted from [tơ], [ta], and [t#]. I found that

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listeners were more likely to judge [t#] as more similar to [t] extracted from [ta] than to [t] extracted from [ts]. These results are probably due to the fact that [ø] is rounded and rounds [t] via coarticulation. But if [t] and [ø] are coarticulated, then the hypothesis in (51-b) cannot be maintained.

Assuming that the constraints banning close-mid vowels in specific phonological environments are motivated by a need to improve place contrasts in these contexts (see part 1), the ranking in (51-c) is problematic: there is no reason to think that place contrasts should be less distinct before nonalternating [ø] than before other vowels in Standard French. In Storme (2017), I have argued for the ranking in (51-c) for Southern French. But this is more plausible for Southern French than for Standard French because, in Southern French (at least based on the results of my study), the vowel corresponding to graphic e is an actual schwa and systematically triggers lowering of preceding mid vowels (52-a). In Standard French, [ø] does not trigger lowering of a preceding mid vowel when it is not alternating (52-b).

   a. saugrenu [sɔɡœ̃ny]  Southern French
   b. saugrenu [sɔɡœ̃ny]  Standard French

I propose that the specific behavior of alternating [ø] in these derivatives is due not to its phonetic properties but to its alternating status. As noted above, the presence of this vowel is predictable in derivatives: it occurs only to break illicit consonant clusters. For instance, the nominal suffixes [-øi] and [-i] alternate in (53) and this alternation is predictable: [ø] is needed to break a problematic cluster in (53-a), but is not needed in (53-b).

(53) a. espièglerie /espjɛgl-øi/ [espjɛgløi] ‘mischievousness’
    b. déchetterie /dɛʃɛt-øi/ [dɛʃɛtøi] ‘center for waste recycling’

Given this variation, it is possible to derive the phonological effect observed in deriva-
tives with alternating [ø] as morphologically-mediated: consonant-initial suffixes generally trigger cyclicity and the behavior of the variants with alternating [ø] is modeled after the more frequent consonant-initial variants.

7.5.2 Conclusion

In this chapter, I analyzed an intriguing case of phonologically-conditioned cyclicity in Standard French as a PDEE and showed how it can be handled by the theory of PDEEs presented in chapter 6, provided that phonological representations may include some phonetic detail. The analysis was argued to be superior to two alternatives: an alternative analysis of the PDEE as involving resyllabification and an alternative markedness-based theory that does not appeal to PDEEs. The syllable-based analysis was argued to be problematic because it does not capture the difference between glide- and liquid-initial suffixes. The markedness-based analysis was argued to be problematic because it does not capture the difference between CL-final stems combined with V-initial suffixes and C-final stems combined with LV-initial suffixes. The cue-based PDEE analysis was shown to be able to better handle these data. Finally, the behavior of stems concatenated with an alternating [ø] was proposed to be morphologically motivated.

This chapter has also introduced a way to formalize the role of closure transitions and release cues in the phonological grammar. The core idea is to allow the grammar to access different consonant allophones that differ along their release or closure properties. Hypotheses about the distributions of these allophones can be tested. For instance, I hypothesized that consonants have special allophones before word-final liquids. This hypothesis was crucial to derive the behavior CL-V derivatives. Although it is still speculative, it could be tested experimentally, using the method presented in section 7.3.2.
Appendix A

Closed-syllable vowel laxing: survey

This appendix presents a small, nonexhaustive survey of languages showing a preference for lax (or low) vowels in closed syllables and/or for tense (or high) vowels in open syllables.¹ For each language, the following information are given: the vowel inventory, the vowels involved in tense/lax pairs (or in high/low pairs), and a description of the distribution of tense and lax vowels. When the source provides specific information about consonants that occur word-finally, this information is given.

<table>
<thead>
<tr>
<th>Language</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arabic</td>
<td></td>
</tr>
<tr>
<td>Bedouin Hijazi Arabic</td>
<td>Inventory: /i a u/</td>
</tr>
<tr>
<td></td>
<td>Processes:</td>
</tr>
<tr>
<td></td>
<td>• /a/ → [i] or [i] or [u] in nonfinal open syllables</td>
</tr>
<tr>
<td></td>
<td>• /a/ → [a] in nonfinal closed syllables</td>
</tr>
<tr>
<td>Austronesian</td>
<td></td>
</tr>
<tr>
<td>Bario Kelabit</td>
<td>Inventory: /i u a e o a/</td>
</tr>
<tr>
<td>(Blust, 2013, p. 264)</td>
<td>Tense/Lax pairs: i/i, u/u</td>
</tr>
<tr>
<td></td>
<td>Final codas: /p t k ? b d g m n ŋ h l r/</td>
</tr>
<tr>
<td></td>
<td>Processes:</td>
</tr>
<tr>
<td></td>
<td>• /i/, /u/ → [i], [u] in final syllables before /p t k b d g m n ŋ l/</td>
</tr>
<tr>
<td>Chamorro</td>
<td>Inventory: /i e æ u o a/</td>
</tr>
</tbody>
</table>

¹Hinuq (Nakh-Daghestanian) was not included in the survey because, although there seems to be a correlation between vowel quality and syllable structure, the distribution of the tense and lax allophones is not very clear (Forker, 2013, pp. 23-24).
<table>
<thead>
<tr>
<th>Language</th>
<th>Description</th>
</tr>
</thead>
</table>
| (Topping, 1973)              | Tense/Lax pairs: /i, u, e, o/ ²  
|                              | Final codas: /ptk? m n η f s w/ (Topping, 1973, pp. 27, 36)  
|                              | Processes:  
|                              | - /i, /e, /u/ → [i], [e], [u] before coda consonants  
|                              | - /o/ → [o] before coda [k] and [g]  |
| Dupaninga Agta (Robinson, 2008) | Inventory: /i e a o u/ (Robinson, 2008, pp. 68-70)  
|                              | Tense/Lax pairs: i/e, u/o  
|                              | Final codas: /ptkbdgmnηl/r/ (Robinson, 2008, p. 58)  
|                              | Processes:  
|                              | - /e o/ → [i u] in unstressed open syllables after suffixation  |
| Hiligaynon (Wolfenden, 1971) | Inventory: /i e a o u/ (Wolfenden, 1971, p. 13)  
|                              | Tense/Lax pairs: i/i, u/u (a/u) ³  
|                              | Final codas: /ptkbdgmnηsrljwjr/ (Wolfenden, 1971, pp. 17-24)  
|                              | Processes:  
|                              | • /i u a/ → [i u] in closed syllables  
|                              | • /a/ → [u] in closed syllables  |
| Indonesian (Javanese background) | Inventory: /i e a o u/  
| (van Zanten, 1989)            | Tense/Lax pairs: i/i, u/u (a/u) ³  
|                              | Final codas: /ptkrmnnηsrlf/ (Sneddon et al., 2010, pp. 8-10)  
|                              | Processes:  
|                              | • /i u e o/ → [i u e η] in closed syllables  |
| Kairiru (Wivell, 1981)       | Inventory: /i e a o u/  
|                              | Tense/Lax pairs: i/i, u/u (a/u) ³  
|                              | Final codas: /p′t′k′f, β m n η j /tj r/l/ (Wivell, 1981, pp. 12-23)  
|                              | Processes:  
|                              | • /i u e o/ → [i u e η] in closed syllables  
|                              | (Wivell, 1981, pp. 23-25)  |
| Long Semado (Blust, 2013, p. 264) | Inventory: /i u a e o a/  
| (Blust, 2016)                 | Tense/Lax pairs: i/i, u/u  
|                              | Final codas: /ptk? bdgmnηh/l/r/  
|                              | Processes:  

²Topping mentions higher allophones for /e/ and /o/ occurring in open unstressed syllables and transcribes them as [i] and [u]. Arguably, they correspond to reduced variants of /e/ and /o/.

³Raising of /a/ is most probably due to vowel shortening.
<table>
<thead>
<tr>
<th>Language</th>
<th>Description</th>
</tr>
</thead>
</table>
| Paluai (Schokkin, 2014) | * /i u/ → [i:u] in final syllables before /p t k b d g m n ŋ l/  
Inventory: /i i e u u o u/ (Schokkin, 2014, pp. 30-35)  
Tense/Lax Pairs: i/i, e/e, o/o  
Final codas: /p t k m n ŋ l j w/  
Processes:  
• /i/ → [i] before final nasals  
• /e o/ → [e: o] before non glide codas  
• /e/ → [e] before coda [w], /o/ → [o] before coda [j] |
| Sri Lanka Malay (Nordhoff, 2009) | * Inventory: /i e a o u/  
(Inventory: /i e u u o u/ (Schokkin, 2014, pp. 30-35)  
Tense/Lax Pairs: i/i, e/e, o/o  
Final codas: /p t k m n ŋ l j w/  
Processes:  
• /i u/ → [i u] in closed syllables |
| Thao (Blust, 2003) | * Inventory: /i (e) u (o) a/  
(Inventory: /i e a a o u/ (Schokkin, 2014, pp. 30-35)  
Tense/Lax Pairs: i/i, u/u  
Final codas: /p t k q m n f s j w r/  
Processes:  
• /i u/ → [i u] in closed syllables |
| Uma Juman Kayan (Blust, 1977) | * Inventory: /i e a a o u/  
(Inventory: /i e a a o u/ (Schokkin, 2014, pp. 30-35)  
Tense/Lax Pairs: i/i, u/o  
Final codas: /p t k ŋ m n ŋ v r l h j/  
Processes:  
• /i u/ → [o] before word-final [k ŋ h l r ?]  
• /i/ → [e] before word-final [h l r ?]  
• /i/ → [io] before word-final [k ŋ] |
| Germanic Dutch | * Inventory: /i y u i e o ø o æ o ø æ a /4  
(formant measurements: Pols, Tromp, and Plomp, 1973)  
Tense/Lax Pairs: i/i, e/e, ø/æ, o/o (æ/æ) (Trommelen, 1983, p. 65)  
Constraints:  
• no lax vowels word-finally and before a vowel (Kager, 1990)  
• no tense vowels before non coronal consonant clusters |
| Penutian |  
4The inventory does not include diphthongs. |
<table>
<thead>
<tr>
<th>Language</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Klamath</strong></td>
<td>Inventory: /i(:) e(:) a(:) u(:)/</td>
</tr>
<tr>
<td>(Barker, 1964)</td>
<td>Tense/Lax pairs: i/t, u/u (a/o)</td>
</tr>
<tr>
<td></td>
<td>Processes:</td>
</tr>
<tr>
<td></td>
<td>• /i u/ → [i u] in closed syllables</td>
</tr>
<tr>
<td></td>
<td>(/a/ → [o] in closed syllables)</td>
</tr>
<tr>
<td><strong>Niger-Congo</strong></td>
<td>Inventory: /i e -e i a o u/</td>
</tr>
<tr>
<td>Kuteb</td>
<td>Tense/Lax pairs: i/i, u/u e/e, o/o (a/v)</td>
</tr>
<tr>
<td>(Koops, 2009)</td>
<td>Final codas: /b r g m n η/ (Koops, 2009, p. 37)</td>
</tr>
<tr>
<td></td>
<td>Processes:</td>
</tr>
<tr>
<td></td>
<td>• /i u e o/ → [i u e o] in closed syllables</td>
</tr>
<tr>
<td></td>
<td>(/a/ → [v] in closed syllables)</td>
</tr>
<tr>
<td><strong>Romance</strong></td>
<td>Inventory: /i y u e o e o e o a o a/</td>
</tr>
<tr>
<td>French (Quebec)</td>
<td>Tense/Lax pairs: i/ï(t), y/ y(ï), u/u(ï)</td>
</tr>
<tr>
<td>(Côté, 2012, pp. 242-244)</td>
<td>Processes:</td>
</tr>
<tr>
<td></td>
<td>• /i u/ → [i u] in closed syllables</td>
</tr>
<tr>
<td></td>
<td>(obligatory word-finally, optionally word-finally)</td>
</tr>
<tr>
<td></td>
<td>But before coda [v z 3], high vowels are long and tense</td>
</tr>
<tr>
<td>French (Southern)</td>
<td>Inventory: /i y u e o e o e o a o a/</td>
</tr>
<tr>
<td>(Coquillon and Turcsan, 2012)</td>
<td>Tense/Lax pairs: e/c, o/o</td>
</tr>
<tr>
<td></td>
<td>Final consonants: /p t k b d g m n η f s f v z 3 l u j/</td>
</tr>
<tr>
<td></td>
<td>Processes:</td>
</tr>
<tr>
<td></td>
<td>• /e e o/ → [c e o] in closed syllables and before schwa</td>
</tr>
<tr>
<td>Latin</td>
<td>Inventory: /i(ï) u(ï) e(ï) o(ï) a(ï)/</td>
</tr>
<tr>
<td>(Niedermann, 1985)</td>
<td>High/low pairs: i/e</td>
</tr>
<tr>
<td></td>
<td>Processes:</td>
</tr>
<tr>
<td></td>
<td>• /a/ → [i] in noninitial open syllables</td>
</tr>
<tr>
<td></td>
<td>(e.g. con-fac-io → conficio)</td>
</tr>
<tr>
<td></td>
<td>• /a/ → [e] in noninitial closed syllables</td>
</tr>
<tr>
<td></td>
<td>(e.g. con-fac-tus → confectus)</td>
</tr>
</tbody>
</table>

5lengthening before [e]
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