Contrast enhancement motivates closed-syllable laxing and open-syllable tensing*

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Abstract

Many languages avoid tense vowels before word-final and preobstruent consonants through vowel laxing and avoid lax vowels word-finally and before prevocalic consonants through vowel tensing. This paper argues that these processes are motivated by contrast enhancement. Vowel laxing is a strategy to enhance the distinctiveness of postvocalic consonant contrasts: it applies before word-final and preobstruent consonants as a way to compensate for the absence of good perceptual cues to consonant place of articulation in these contexts. Vowel tensing is a strategy to enhance the distinctiveness of vowel contrasts. The two strategies conflict to determine vowel quality in vowel-consonant sequences and language variation results from different ways of solving this conflict in grammars with constraints on contrasts. This analysis corroborates the general claim that perceptual contrast, and in particular contrast enhancement, plays a role in shaping phonotactic restrictions (e.g. Flemming 2002).

1 Introduction

This paper focuses on two phonotactic restrictions on the distribution of vowels: a restriction against tense vowels (e.g. [e]) before word-final and preobstruent consonants and a restriction against lax vowels (e.g. [ɛ]) in word-final position and before prevocalic consonants. The most common strategies to avoid these configurations are Closed-Syllable Laxing (CSL) and Open-Syllable Tensing (OST), respectively. CSL avoids tense vowels before word-final and preobstruent consonants through vowel laxing. OST avoids lax vowels word-finally and before prevocalic consonants through vowel tensing. Both processes are attested in Southern French in (1-a) and (1-b) and give rise to tense/lax alternations (1-c) (e.g. Coquillon & Turcsan 2012).

(1) CSL and OST in Southern French

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a. Mid-vowel laxing before word-final and preobstruent consonants
_C# *sec* [s**ɛ**k]/*[s**e**k] 'dry'
_CO *hectare* [**ɛ**ktaʁ]/*[**e**ktaʁ] 'hectar'

b. Mid-vowel tensing word-finally and before prevocalic consonants
_# *sait* [s**e**]/*[s**ɛ**] 'knows'
_CV *écart* [**e**kaʁ]/*[**ɛ**kaʁ] 'gap'

c. Mid-vowel tense/lax alternations
Frédéric [fʁ**e**deʁik] $\xrightarrow[\text{truncation}]{}$ *Fred* [fʁ**ɛ**d]/*[fʁ**e**d]
fête [f**ɛ**t] 'party' $\xrightarrow[\text{suffixation}]{}$ *fêter* [f**e**te]/*[f**ɛ**te] 'to party'

What is the nature of the constraints that drive CSL and OST? Several authors (e.g. Féry 2003; Botma & van Oostendorp 2012) have proposed that restrictions like (1-a) and (1-b) are driven by vowel duration adjustments due to closed-syllable shortening: vowels are shorter before word-final consonants and before consonant clusters than word-finally and before prevocalic consonants (e.g. Maddieson 1985), and vowel laxing is a consequence of shortening. However, vowel shortening should not generally result in vowel laxing: vowels generally RAISE when reduced, due to stronger coarticulation with adjacent consonants (Lindblom 1963), whereas laxing of vowels is generally characterised by LOWERING (e.g. lax [ɛ] is lower than tense [e]). The vowel-reduction analysis of CSL only works straightforwardly for low vowels: laxing of low vowels is described as involving raising (e.g. Dutch lax [ɑ] is higher than tense [a]; Pols et al. 1973).

This paper proposes an alternative analysis according to which CSL and OST for nonlow vowels are motivated by CONTRAST ENHANCEMENT. Lax vowels are argued to allow for more distinct acoustic realisations of postvocalic consonants than their tense counterparts and therefore to increase the perceptual distinctiveness of postvocalic consonant contrasts, in particular contrasts involving PLACE OF ARTICULATION. Vowel laxing is argued to apply before word-final and preobstruent consonants as a way to compensate for the absence of good perceptual cues to consonant place in these contexts. Vowel tensing is argued to correspond to a default preference for more distinct vowel contrasts: tense vowels have more extreme first formant (F1) and second formant (F2) targets than lax vowels and are therefore more distinct from each other. The two enhancement strategies conflict to determine vowel quality in vowel-consonant (VC) sequences: the requirement to have distinct enough C-place contrasts in VC favors V-laxing whereas the requirement to have distinct enough V contrasts favors V-tensing. Language variation results from different ways of resolving this conflict.

Section 2 presents a small survey of languages with CSL and OST and shows why these processes are puzzling from a vowel-reduction perspective. Section 3 presents and motivates the three central hypotheses underlying the analysis of CSL and OST as patterns of contrast enhancement. Section 4 sketches an analysis of the interaction of the two conflicting enhancement strategies in the framework of Dispersion Theory (Liljencrants & Lindblom 1972; Flemming 2002) and shows how this analysis derives CSL and OST. Sections 5 and 6 evaluate the proposal on a case study: the distribution of tense and lax mid vowels in French, known as the *loi de position*. Section 6 uses the French *loi de position* to test the hypothesis which constitutes the real innovation of this account, i.e. that vowel laxing increases the acoustic and perceptual distinctiveness of postvocalic place contrasts. Section

7 expands the analysis presented in section 4, focusing on how to derive consonant-specific CSL vs. across-the-board CSL, and explores the predictions of the enhancement approach to CSL for the typology of place neutralisation.

This analysis represents a significant improvement on previous accounts because it provides a well-motivated mechanism to relate the tense/lax quality of a vowel and its following context. Also, it makes a number of correct typological predictions about the interaction of vowel and consonant properties in VC sequences. If correct, this analysis provides further support for the role of perceptual contrast in driving phonotactic restrictions (Ohala 1990; Kawasaki-Fukumori 1992; Steriade 1997; Flemming 2002; Stanton 2017), and more specifically, for the role of contrast enhancement in phonology (see Flemming 2017 and references therein).

2 Background

CSL and OST are widespread phonological processes cross-linguistically. They are reported in genetically diverse language families, including Austronesian, Germanic, Niger-Congo, and Romance. Sections 2.1 and 2.2 illustrate the patterns of CSL and OST attested in these and other language families based on a small, nonexhaustive survey of 20 languages (see the appendix for a list of the languages surveyed). Section 2.3 describes the acoustic correlates of the tense-lax distinction and argues that CSL cannot be reduced to an effect of vowel reduction for nonlow vowels.

2.1 Crosslinguistic evidence for CSL and OST

In a number of languages, some or all of the vowels transcribed as [i y u e ø o a] (the tense vowels) are allowed to occur word-finally and/or before prevocalic consonants but not before word-final consonants and/or preobstruent consonants. In these contexts, these languages typically only allow some or all of the vowels transcribed as [ɪ ʏ ʊ ɛ œ ɔ ɐ] (the lax vowels). For instance, Kuteb (Niger-Congo; Koops 2009) allows lax vowels [ɪ ʊ ɛ ɔ ɐ] but not tense vowels [i u e o a] to occur before word-final consonants (2). Languages with such restrictions may be called Closed-Syllable Laxing (CSL) languages, where *closed syllable* is used as a shorthand to refer to contexts where vowels are followed by word-final or preobstruent consonants.

(2) An example of CSL language: Kuteb (Niger-Congo; Koops 2009: 21)

[is**ɪ**m]/*[is**i**m]	'back'
[k**ʊ**b]/*[k**u**b]	'bite'
[c**ɛ**b]/*[c**e**b]	'step on'
[ut**ɔ**b]/*[ut**o**b]	'heart'
[ut**ɐ**b]/*[ut**a**b]	'open space'

In a number of languages, lax vowels are allowed to occur before word-final consonants and/or preobstruent consonants but not word-finally and/or before prevocalic consonants. In these contexts, these languages typically only allow tense vowels. For instance, Dutch (Germanic; Kager 1990) allows tense vowels [i e o ø a] but not lax vowels [ɪ ɛ ɔ œ ɑ] to occur word-finally (3). Languages with such restrictions may be called Open-Syllable Tensing (OST) languages, where *open syllable* is used as a shorthand to refer to contexts where vowels are in word-final position or before prevocalic consonants.

(3) An example of OST language: Dutch (Germanic; Kager 1990: 242)

[tɑks**i**]/*[tɑks**ɪ**]	‘taxi’
[sl**e**]/*[sl**ɛ**]	‘sledge’
[mik**a**]/*[mik**ɑ**]	‘mica’

In some languages, both restrictions described in (2) and (3) apply and, therefore, tense and lax vowels are in allophonic distribution. For instance, in the Javanese variety of Indonesian described in van Zanten (1989), both CSL and OST apply in word-final syllables: high and mid vowels are realised as lax [ɪ ʊ ɛ ɔ] before word-final consonants and as tense [i u e o] word-finally. (The process of harmony of the first vowel to the last one in (4) is orthogonal.)

(4) An example of language with CSL and OST: Indonesian (Javanese speaker)

a. Closed-Syllable Laxing in word-final syllables

titik	[tɪt**ɪ**k]/*[tit**i**k]	‘dot, drop’
tutup	[tʊt**ʊ**p]/*[tut**u**p]	‘closed’
tetes	[tɛt**ɛ**s]/*[tet**e**s]	‘drop’
totok	[tɔt**ɔ**k]/*[tot**o**k]	‘full-blooded, newcomer’

b. Open-Syllable Tensing in word-final syllables

titi	[tit**i**]/*[tɪt**ɪ**]	‘wooden bridge’
tutu	[tut**u**]/*[tʊt**ʊ**]	‘to coo’ (of a pigeon)
bebe	[beb**e**]/*[bɛb**ɛ**]	‘dress’
toto	[tot**o**]/*[tɔt**ɔ**]	‘sweepstakes’

In other cases, only CSL or only OST applies and, therefore, tense and lax vowels contrast in some but not all contexts. Standard French allows [e] and [ɛ] to contrast word-finally but not before word-final consonants (Féry 2003): CSL applies to front mid vowels word-finally but not OST (5-a). Conversely, Dutch allows contrasts between tense and lax vowels before word-final single consonants but not word-finally: OST systematically applies word-finally but CSL does not (5-b) (see 2.2 for a slightly more complex picture of the Dutch facts). The fact that only CSL or only OST may apply to vowels in a language suggests that CSL and OST are distinct processes motivated by different constraints.

(5) a. An example of CSL-only pattern: Standard French front mid vowels (Romance; Tranel 1987)

_#	[e]-[ɛ]	[s**ɛ**]	‘knows’
		[s**e**]	‘his/her-PLUR’
_C#	[ɛ]-*[e]	[s**ɛ**k]/*[s**e**k]	‘dry’

b. An example of OST-only language: Dutch (Germanic; Botma & van Oostendorp 2012)

_#	[a]-*[ɑ]	[mik**a**]/*[mik**ɑ**]	‘mica’
_C#	[a]-[ɑ]	[r**a**m]	‘window’
		[r**ɑ**m]	‘ram’

2.2 Vowel-specific and consonant-specific CSL

Languages with CSL may differ in the extent to which CSL applies. In some languages, CSL is very general. For instance, in Kuteb, all vowels are reported to be lax before all word-final consonants and preobstruent consonants (Koops 2009). In other languages, CSL applies only to some vowels or before some consonants. Because the size of the sample used in this survey is rather small, it is not possible to draw definitive conclusions about which vowels or consonants favor CSL crosslinguistically. However, a complete theory of CSL should at least provide a rationale for why the application of CSL may depend on these factors.

In some languages, CSL is limited to specific vowels, in particular to vowels of a specific HEIGHT. For instance, Sri Lanka Malay (Austronesian) has a six-vowel inventory /i e ə a o u/ but CSL only applies to mid vowels /e o/ (Nordhoff 2009). In Québec French, CSL only applies to high vowels (Côté 2012).

CSL may also be limited to specific consonantal contexts. MANNER OF ARTICULATION matters in some languages. In Paluai, high-vowel laxing singles out the nasal stops: /i/ is realised as lax [ɪ] before word-final nasals [m n ŋ] (6-a) but as tense [i] before other coda consonants [p t k l j w] (6-b) (Schokkin 2014).

(6) Laxing of [i] before nasals only: Paluai.
  a. Laxing before word-final nasal stops
    [mus**ɪ**n]/*[mus**i**n] 'soft (of betelnut)'
  b. No obligatory laxing before word-final oral stops.
    [n**i**k] 'fish'

In Québec French, high-vowel laxing is quite general but is systematically blocked before a subset of fricatives. High vowels are optionally lax before medial preobstruent consonants (7-a), unless the following consonant is [s]: in this case, high vowels are tense (7-b). High vowels are necessarily lax before word-final consonants (7-c), unless the following consonant is a voiced fricative [v z ʒ]: in this case, high vowels are tense (7-d) (Côté 2012: 242-244).

(7) Restrictions on laxing before fricatives in Québec French
  a. High vowels are optionally laxed before medial preobstruent consonants...
    sultan [s**y**ltã]/[s**ʏ**ltã]
  b. Unless the following consonant is [s]
    bistrot [b**i**stro]/*[b**ɪ**stro] 'bar'
  c. High vowels are lax before word-final consonants...
    tube [ts**ʏ**b]/*[ts**y**b] 'tube'
    vif [v**ɪ**f]/*[v**i**f] 'lively'
  d. Unless the following consonant is a voiced fricative [v z ʒ]
    vive [v**i**v]/*[v**ɪ**v] 'live.SUBJ'

The PLACE OF ARTICULATION of the postvocalic consonant may also be relevant as to whether or not CSL applies. Several languages lax back vowels only before word-final or preobstruent velars. In Chamorro (Austronesian; Topping 1973), vowel laxing is quite general in its application. However, the phoneme /o/ is lowered and centralised to [ɔ] only before coda velars [k ŋ] (8-a). Before other places of articulations (e.g. labial and dental),

/o/ is realised as tense [o] (8-b). A similar pattern is found in Uma Juman (Austronesian; Blust 1977), where only word-final velars [k] and [ŋ] among word-final stops [p t k m n ŋ] trigger lowering of [u] to [o].

(8) Chamorro (Austronesian; Topping 1973: 21)
   a. Laxing of [o] before word-medial preobstruent velars
      [ˈt**ɔ**ktʊk]/*[ˈt**o**ktʊk] ‘hug’
   b. No laxing of [o] before word-medial preobstruent labials and dentals
      [ˈ**o**ppɪ]/*[ˈ**ɔ**ppɪ] ‘respond’
      [ˈh**o**tni]/*[ˈh**ɔ**tni] ‘thread needle’

Dutch illustrates a more complex pattern, where CSL is conditioned by an interaction of PLACE OF ARTICULATION and CLUSTER SIZE. CSL does not apply before word-final single consonants (9-a) but applies before word-final clusters (9-b), unless the two consonants are dental: in this case, CSL does not apply (9-c) (Trommelen 1983: 67-69; Botma & van Oostendorp 2012).

(9) Restrictions on Dutch CSL
   a. Tense and lax vowels contrast before word-final consonants
      _C# [a]-[ɑ] [r**a**m] ‘window’
      [r**ɑ**m] ‘ram’
   b. CSL applies before word-final clusters...
      _CC# *[a]-[ɑ] *[r**a**mp]/[r**ɑ**mp] ‘disaster’
   c. Unless the two consonants are dental
      _$C_{[+\text{dental}]}C_{[+\text{dental}]}$# [e]-[ɛ] [b**e**ld] ‘idea’
      [g**ɛ**ld] ‘money’

2.3 Acoustic correlates of the tense/lax distinction

The evidence reviewed in sections 2.1 and 2.2 suggest that CSL and OST are common processes. This raises the following quesions. What is the source of those processes? Why are they common whereas Closed-Syllable Tensing (CST) and Open-Syllable Laxing (OSL) are not? Answering these questions requires investigating the phonetics of the tense-lax distinction and how it interacts with the context in which vowels occur.

Acoustically, laxing of nonlow vowels is characterised by LOWERING and CENTRALISING along F2, e.g. Agwagwune (Niger-Congo; Lindau-Webb 1987), English (Lindau 1978), Dutch (Pols et al. 1973), Québec French (Martin 2002), Southern French (Storme 2017b), Indonesian (Austronesian; van Zanten 1989), a.o. Laxing of low vowels is characterised by RAISING, e.g. in Dutch (Pols et al. 1973), in Klamath (Penutian; Blevins 1993), and in Kuteb (Koops 2009). Laxing of nonlow vowels is illustrated in Figure 1 for a variety of Indonesian with CSL and OST: lax allophones [ɪ ɛ ʊ ɔ] have higher F1 targets and less extreme F2 targets than their tense counterparts [i e u o] (van Zanten 1989).

Tense and lax vowels often differ in duration, with lax vowels being shorter than tense vowels (Lindau 1978). Because tense vowels are typically banned in contexts where vowel duration is shorter (see Maddieson 1985 on closed-syllable shortening), it is tempting to try and derive vowel quality differences from differences in vowel duration (see Botma & van

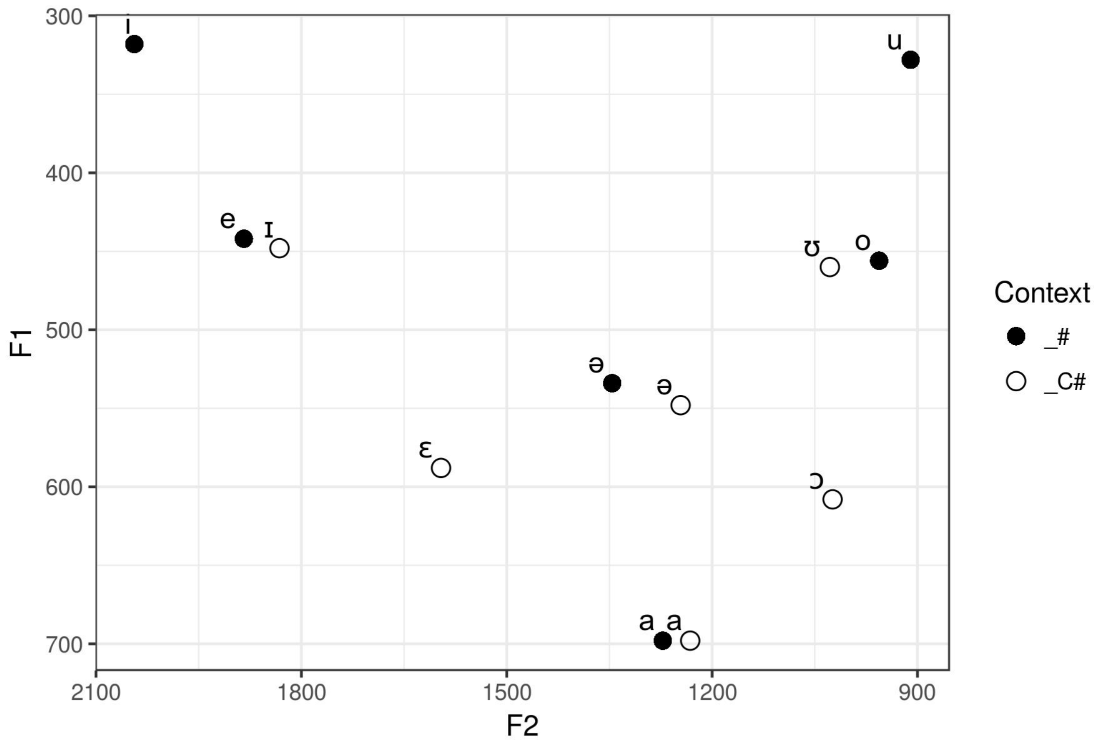


Figure 1: Indonesian vowel inventory word-finally and before word-final consonants (data from Javanese speaker J1 in van Zanten 1989: 72).

Oostendorp 2012 for instance). However, as previewed in the introduction, the tense/lax distinction (understood as a difference along F1 and F2) most likely does not follow from a difference in duration, at least for nonlow vowels: nonlow vowels should raise and not lower when reduced (Lindblom 1963).

The vowel-reduction account also fails to explain why there is a preference for tense vowels word-finally and before prevocalic consonants. Indeed, vowel lengthening should not generally result in raising. Lindblom's theory of coarticulation predicts that vowel lengthening should result in less coarticulation with adjacent consonants: as a vowel becomes longer, its formant realisations should get more faithful to its formant targets. If this vowel is /ɛ/, lengthening will result in a higher F1 realisation (see Gendrot & Adda-Decker 2005 for evidence in French and German): a longer /ɛ/ should not become more similar to [e].

Another reason to doubt that CSL is driven by vowel shortening is provided by languages where the lowering observed before preobstruent consonants must be interpreted as blocking a reduction process. In Dupaninga Agta (Austronesian), mid vowels /e/ and /o/ raise to [i] and [u] in unstressed syllables before prevocalic consonants (10-a), but raising is blocked in unstressed syllables before consonant-obstruent clusters (10-b) (Robinson 2008: 68-70). Similar patterns where a process of vowel reduction is blocked before consonant-obstruent clusters are found in Latin (Niedermann 1985: 18-31) and in Bedouin Hijazi Arabic (Al Mozainy 1981).

(10) Dupaningan Agta vowel reduction

a. /o/ raises to [u] in unstressed syllables before prevocalic consonants.
/pot-p**o**t-an/ [ˈpotp**u**tan] ‘pluck out’
b. /o/ does not raise in unstressed syllables before preobstruent consonants.
/mag-pot-p**o**t/ [magˈpotp**o**t] ‘harvest by plucking’

If the tense or lax quality of a vowel does not follow from adjustments of its duration, could the long or short duration of a vowel follow from its being tense or lax? Some authors have argued for this hypothesis, on the assumption that producing a peripheral vowel requires more time than producing a central vowel because the tongue must move further away from its neutral position (e.g. Botma et al. 2012). However studies on vowel duration find that greater vowel duration correlates with greater vowel aperture but not with greater peripherality (Lehiste 1970; Escudero et al. 2009).

Another analysis of the relation between tensing and duration is proposed by Storme (2017b), based on the results of an acoustic study on Southern French (where both CSL and OST apply). The results suggest that the tense/lax quality of a vowel and its duration are determined by different causal mechanisms: (i) tense and lax mid vowels are specified as having different F1 and F2 targets but not different durational targets and (ii) vowel duration is determined by the prosodic/consonantal context. Lax vowels are generally shorter than tense vowels because they happen to occur in contexts that often trigger vowel shortening (e.g. before liquid-obstruent clusters), but not necessarily so (e.g. before sibilant-obstruent clusters; see Katz 2012).

Another question concerns the relation between lowering of nonlow vowels and centralising. F1 and F2 are not independent, due to the shape of the F1xF2 space: for instance, a larger range of F2 values is available for lower F1 values than for higher F1 values (Liljencrants & Lindblom 1972). As it is not possible to lower peripheral vowels without also centralising them, one may wonder whether centralising should be analysed as a by-product of lowering. However, this is unlikely to be the case in languages like Québec French, where high vowels are more centralised before final consonants than would be expected by lowering alone: lax high vowels [ɪ ʏ ʊ] have approximately the same F1 targets as tense mid vowels [e ø o], but they have more central F2 targets (Martin 2002: 84). This suggests that laxing cannot generally be reduced to lowering alone, with centralising as a side-effect (but see section 6.2 on Southern French).

3 Hypotheses

Section 2 has provided crosslinguistic evidence for CSL and OST. If the constraints that underly these patterns are not motivated by duration, what are they? This paper proposes that CSL and OST for nonlow vowels are motivated by contrast enhancement, i.e. by constraints that require contrasts to be distinct enough perceptually. This proposal relies on three general hypotheses (H1)-(H3). (H1) explains why it might be desirable to lax vowels before consonants. (H2) explains why laxing is particularly desirable before word-final and preobstruent consonants. (H3) underlies the default preference for tense vowels over lax vowels.

(H1) Contrasts between consonants with different places of articulation are more distinct after lax vowels than after tense vowels.

(H2) Place contrasts are more distinct prevocalically than word-finally and before obstruents.

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

This section provides preliminary acoustic or perceptual evidence for these hypotheses and shows how they can account for some specific asymmetries observed in the typology of CSL in section 2.2.

3.1 Laxing enhances postvocalic place contrasts

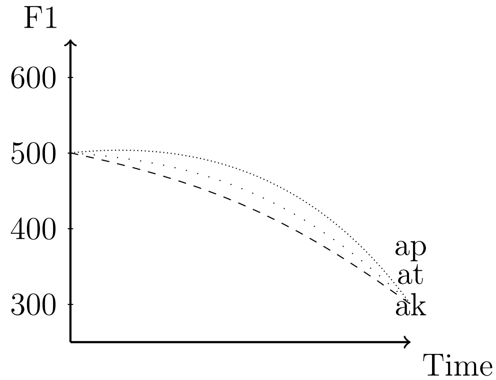
In what follows, the formant value measured right before consonant's closure or after relase is referred to as the consonant's formant realisation. Consonants have different formant realisations depending on the vowel context: through coarticulation, formant realisations of consonants track the formant realisations of adjacent vowels (Lindblom 1963; Sussman et al. 1997). For instance, the last measurable F1 value before closure in VC should be higher if the preceding vowel has a high F1 target (e.g. [a]) than if it has a low F1 target (e.g. [i]), due to the effect of the jaw opening gesture necessary to produce [a]. Because tense and lax vowels differ by F1 and F2, the F1 and F2 realisations of a consonant in VC should differ if V is tense or lax. This section explains how F1 and F2 realisations of the three major places of articulation (labial, dental, velar) at closure should vary after tense and lax vowels and how these variations should generally correspond to greater acoustic and perceptual distinctiveness of place contrasts after lax than after tense vowels.

3.1.1 F1 realisations

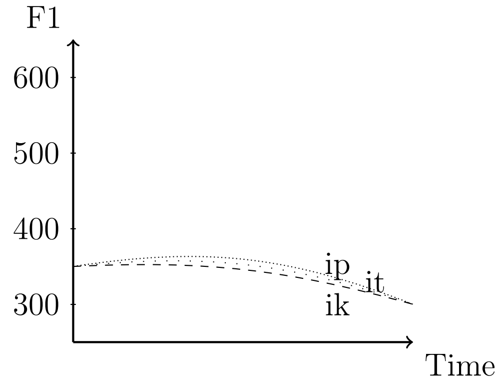
Acoustic theory predicts that the F1 realisation of a consonant should vary as a function of the speed of the articulator movement involved in producing that consonant: in CV, the F1 transition (which tracks the opening of the mouth) is faster if the articulator moves faster, and therefore F1 should be higher at formant onset (Stevens 1998: 335-338). Because the three major places of articulation are produced with different articulators (the lips for labials, the tip of the tongue for dentals, the tongue body for velars) and these articulators have different speeds, this predicts different F1 onset frequencies as a function of place. The movement is the slowest for velars and therefore velars' F1 onset frequency should be the lowest, everything else being equal.[1] The movement is the fastest for labials and therefore labials' F1 onset frequency should be the highest.

Although Stevens' results are based on CV, they should extend to VC if F1 transitions pattern roughly symmetrically in CV and VC: F1 is likely to be higher at the last measurable point before closure for F1 transitions with a higher rate of change. The expected difference in the F1 transitions going from [a] to the three major places of articulation in VC is schematized in Figure 2a. This figure transposes Stevens' simulation results for CV to VC. In all three cases, the movement starts from the same high F1 value (corresponding to the F1 realisation

[1] In his simulation, Stevens (1998: 335-338) actually derives a lower onset F1 frequency for dentals because dentals have a shorter VOT than velars and, as a consequence, the raise in F1 can be heard earlier.



(a) Low vowels



(b) High vowels

Figure 2: Schematized F1 VC transitions into [p t k] after low and high vowels.

of [a] at vowel midpoint) and ends at the same low F1 value (corresponding to the consonant's closure). But the movement is the fastest with [p] and the slowest with [k], [t] being in the middle.

Figure 2b shows how F1 transitions should behave after high vowels. After high vowels, the target for the consonant closure in VC should be reached fast by the three different articulators, because the mouth is almost closed when articulating [i]. Therefore there should be less distinct F1 transitions as a function of place in this context: F1 transitions into [p t k] are less distinct after high vowels (Figure 2b) than after low vowels (Figure 2a).

In accordance with this hypothesis, there is evidence from natural speech that F1 realisations of labials and alveolars are more distinct acoustically before low than before high vowels. Looking at the F1 realisations of /p t b d f s v z/ at release before /a i u/ in English, Alwan et al. (2011: 201) found that labial stops and labial fricatives had significantly higher F1 onset frequencies than alveolar stops and fricatives before [a] but not before [u] or [i]. They also found that the perceptual contrast between labials and alveolars was overall more robust to noise after [a] than after [i] or [u].

Because lax nonlow vowels have higher F1 targets than their tense counterparts (see section 2.3), they should allow for more distinct F1 realisations of postvocalic consonants (see section 6 for French).

3.1.2 F2 realisations

The coarticulatory effect of the F2 realisation of a vowel, F2(V), on the F2 realisation of an adjacent consonant, F2(C), has been well studied, in particular in CV sequences. Many studies (see Sussman et al. 1993 and citations therein) have found that F2(C) after release can be well characterised as a linear function of F2(V) measured at vowel midpoint (the *locus equation*), where the slope k characterizes the consonant's resistance to coarticulation (a higher slope corresponds to less coarticulation resistance) and the intercept c relates to the place where the consonant is articulated (a lower intercept corresponds to a place of articulation located more back in the mouth).

$$F2(C) = k * F2(V) + c$$

Although most studies have focused on CV, there is also evidence that locus equations can apply to VC sequences, although the fit is not as good as for CV (Sussman et al. 1997). The locus equations for [b], [d], and [g] in VC sequences (Sussman et al. 1997) can be used to reason about place distinctiveness as a function of the preceding vowel context. Although these locus equations were established for English voiced stops specifically, they should generalize across manners and modes of articulation (Delattre et al. 1955) and broadly across languages (Sussman et al. 1993).

For each pair of stops involving [b], [d], and [g], Figures 3a through 3c plot the locus equations for the two members of the pair and the difference Δ between the two lines. This difference is a measure of the F2 distinctiveness of each contrast as a function of vowel F2. [g] has two different locus equations after front and back vowels: they correspond to two different allophones of /g/ (palatal and velar) that cannot be subsumed under a single locus equation.

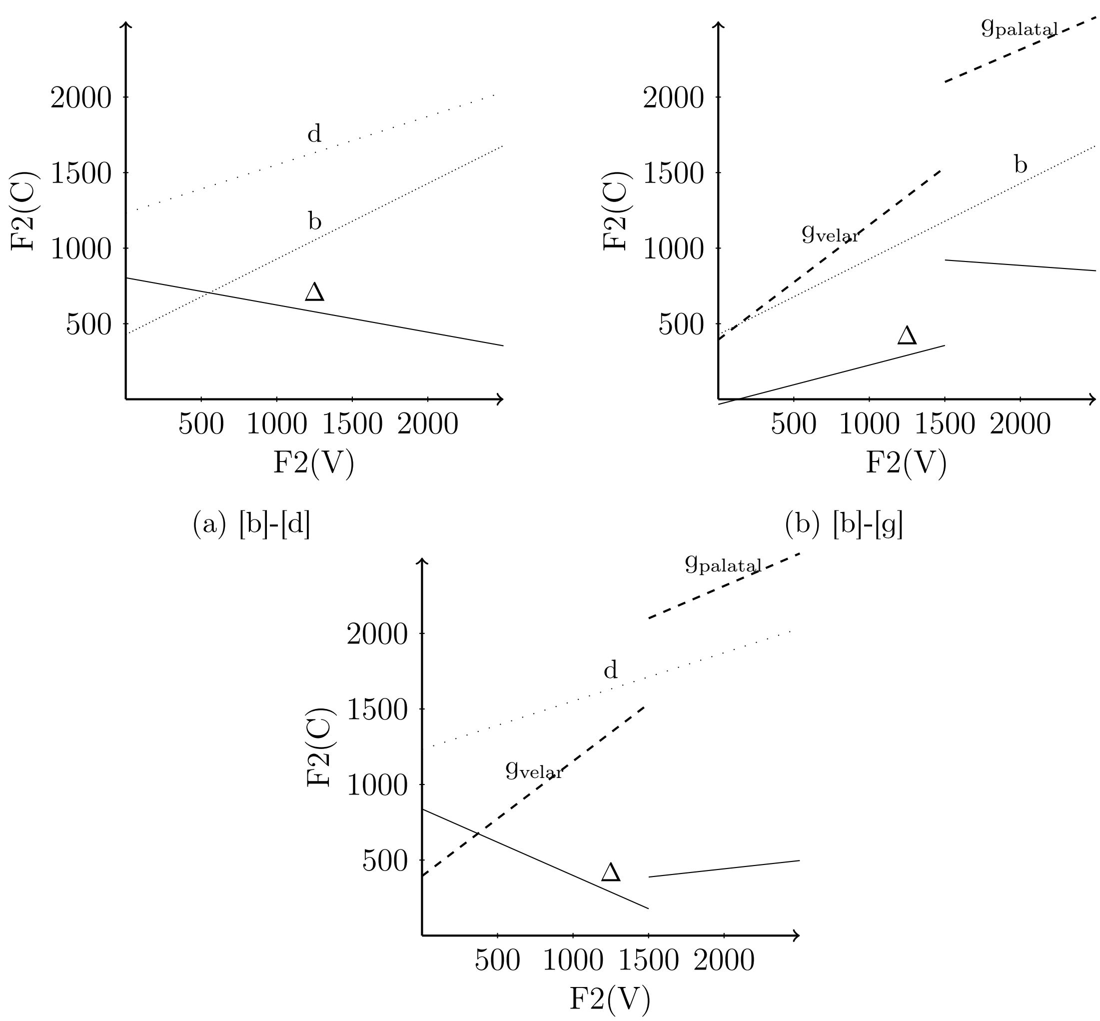
Based on these results, there are two contrasts that should be improved by laxing (i.e. centralising) the preceding vowel: the labial-dental contrast after front vowels (see Figure 3a) and the labial-velar contrast after back vowels (see Figure 3b). The labial-dental contrast is particularly difficult to perceive in an [i]-context (Winitz et al. 1972; Ohala & Ohala 2001; Alwan et al. 2011) and the labial-velar contrast is particularly difficult to perceive in an [u]-context (Halle et al. 1957; Delattre 1958; Winitz et al. 1972; Ohala & Ohala 2001; Marty 2012). Ohala & Ohala (2001) found that, among the three contrasts involving labials, velars, and dentals after [a], [i], and [u] in Hindi, these specific contrasts are the most confusable.

There are two cases where centralising should result in less distinct F2 offsets: the dental-velar and dental-labial contrasts after back vowels (see Figures 3c and 3a). The fact that some languages do not lax back vowels before dentals (see section 2.2) is compatible with this prediction. However, centralising of back vowels before dentals is unlikely to result in very bad dental-velar and dental-labial contrasts: Ohala & Ohala (2001) found that these contrasts remain quite distinct perceptually even after [a], more distinct at any rate than [p]-[t] after [i] and [p]-[k] after [u]. In languages that lax back vowels before all three places of articulation, the perceptual benefit obtained by centralising back vowels before velars and labials is likely to exceed the perceptual loss caused by centralising back vowels before dentals (see section 7.1 for a more thorough discussion).

3.1.3 Perceptual evidence

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. The results are reported in Table 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.

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



(a) [b]-[d]

(b) [b]-[g]

(c) [d]-[g]

Figure 3: F2(C) as a function of F2(V) and the resulting acoustic F2 difference for [b], [d], and [g] in VC sequences. Data from Sussman et al. (1997).

	Context	Average	p	t	k
Front	i_#	**79**	97	**78**	**53**
	ɪ_#	98	100	95	100
	ej_#	**80**	89	**54**	**56**
	ɛ_#	98	95	98	100
	æ_#	100	97	100	95
Back	u_#	**74**	92	100	**31**
	ʊ_#	97	100	97	95
	ow_#	**80**	93	98	**72**
	ɔ_#	95	90	98	95
	ɑ_#	100	100	100	100

Table 1: Percent of correct identification in VC sequences (unreleased stops) in English (Lisker 1999).

whereas it is never lower than 95% after lax vowels.[2] Contrasts involving [k] are particularly less distinct after tense than lax vowels. After tense front vowels, both [k] and [t] have percent of correct identification that are below 80%. These results are slightly different from other studies (e.g. Ohala & Ohala 2001) which found that the contrast between [p] and [t] was the most affected in this context. However, Winitz et al. (1972) also report high [k]-[t] confusability in the context of [i] in English (in [ki]-[ti] specifically). After tense back vowels, only [k] has a percent of correct identification that is below 80%. [k]-[p] confusability is likely to drive this result. 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] (see Marty 2012).

As discussed in section 2.2, some languages specifically lax back vowels after word-final or preobstruent [k]. Under the enhancement analysis of laxing, this is not surprising: the [k]-[p] contrast is particularly confusable after back vowels, in particular after [u]. In Lisker's study, laxing of [u] has the most dramatic perceptual effects, with the percentage of correct identification of [k] jumping from 31% after [u] to 95% after [ʊ].

3.1.4 Interim summary

Lowering should improve the F1 distinctiveness of postvocalic place contrasts generally. Centralising should improve specifically the F2 distinctiveness of contrasts that are perceptually very weak after peripheral vowels (i.e. labial-dental contrasts after front vowels and labial-velar contrasts after back vowels). As a combination of lowering and centralising, laxing should increase the distinctiveness of place contrasts. In accordance with these acoustic predictions, Lisker's study suggests that place contrasts are generally less confusable after lax than after tense vowels.

[2]The results for tense mid vowels [ej] and [ow] do not necessarily generalize to languages where tense mid vowels that lack offglides.

3.2 Laxing happens before consonants lacking informative place cues

The hypothesis that word-final and preobstruents consonants lack good place cues is well-known in phonology because it underlies phonetically-based accounts of the typology of place neutralization (Steriade 1997; Jun 2004). The evidence for this hypothesis is reviewed in section 3.2.1. Section 3.2.2 shows that the hypothesis that laxing happens before consonants lacking good place cues may account for why the application of CSL sometimes depends on the postvocalic consonant's manner of articulation (see section 2.1).

3.2.1 Word-final and preobstruent consonants vs. prevocalic consonants

The place of articulation of a consonant is cued by transitional and internal cues (Cooper et al. 1952; Delattre et al. 1955; Dorman et al. 1977; Dorman & Raphael 1980). Transitional cues refer to 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). Internal cues refer to the stop burst (for oral stops), nasal resonances (for nasal stops) and the frication noise (for fricatives).

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 formant structure (Wright 2004). Word-final consonants are not followed by any segment within the same word and therefore lack release transitions by definition. Preobstruents consonants also lack release transitions because obstruents do not have formant structure. Release transitions have been shown to be particularly important for place identification (see Walley & Carrell 1983 for stops, Malécot 1956 for nasals, Harris 1958 for low amplitude fricatives like [θ f]). The two major contexts favoring vowel laxing are therefore contexts where a major cue to the place of the postvocalic consonant is missing.

The availability and quality of INTERNAL CUES also differ in word-final and preobstruent positions vs. in prevocalic positions. Prevocalic stops systematically have internal cues whereas word-final and preobstruent stops have internal cues only when they are released (i.e. when there is an audible burst). There is also evidence that released stops and fricatives have weaker internal cues word-finally than prevocalically. For instance, Redford & Diehl (1999) found longer durations and larger amplitudes for prevocalic vs. word-final stops and fricatives in English.

CLOSURE TRANSITIONS are the only cues that are not systematically available for prevocalic 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 (see Ohala 1990 and references therein): if they provide conflicting cues, listeners identify the place of articulation according to the release transitions (e.g. Fujimura et al. 1978). Sussman et al. (1997) also found that F2 locus equations are less acurate to model VC transitions than CV transitions, as manifested by a significant decrease in the R-squared statistics (a measure of goodness-of-fit for linear regressions) when going from CV to VC. They suggest that this fact should result in perceptually less informative transitions in VC than in CV: if F2 locus equations are used by listeners to classify place of articulation (e.g. Nearey &

Shammass 1987; Sussman et al. 1991), the classificiation should be less reliable in VC than in CV.

Perceptual studies on the distinctiveness of place contrasts prevocalically vs. word-finally support these predictions. 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 ʃ] as compared to word-initial [p t k f s ʃ] in English.[3] Repp & Svastiskula (1988) also found that this asymmetry extends to nasals (in particular the [m]-[n] contrast in English).

3.2.2 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. Nasal stops have weaker internal place cues than oral stops and oral stops have weaker internal place cues than fricatives (Wright 2004; Jun 2004). The fact that Paluai laxes /i/ only before nasal stops and Québec French does not lax high vowels only before fricatives (see section 2.2) is compatible with the enhancement hypothesis: place features need the most perceptual enhancement in nasals and the least in fricatives. The preliminary typology of CSL presented in section 2.2 nicely mirrors that of place neutralization, where regressive place assimilation in prestop position is more likely to target nasal stops than oral stops and oral stops than fricatives (Ohala 1990; Hura et al. 1992; Jun 2004). More typological work is needed to confirm this parallel.

The fact that CSL does not apply before word-final single consonants in Dutch (see section 2.2) but generally does before word-final clusters is also compatible with the hypothesis that laxing is favored in contexts where cues to place are less distinct. Coarticulation with the following consonant in a $C_1C_2\#$ cluster is likely to weaken C_1's internal place cues and make it less perceptible than word-finally in $C_1\#$. The reason why dental clusters behave differently is not entirely clear. A possible factor is the fact that dentals benefit less from the information provided by formant transitions than labials and velars (Winitz et al. 1972: 1313). This would explain why laxing may be limited to labials and velars.

3.3 Tensing as enhancing vowel contrasts

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). Laxing (i.e. lowering and centralising) of nonlow vowels involves a shrinking of the acoustic distances between vowels both along F1 and F2: [a] is closer to [ɪ] than to [i] along both F1 and F2 and [i] and [u] are closer along F2 than [ɪ] and [ʊ]. Generally, everything else being equal, an inventory of tense vowels is more dispersed along F1 and F2 than an inventory of lax vowels. For instance, in Indonesian (see Figure 1), the inventory /ɪ ʊ ɛ ɔ a/ occupies a subregion of the F1xF2 space occupied by the inventory /i u e o a/. As a consequence, an inventory with tense vowels should allow for better vowel contrasts than an inventory with lax vowels.

[3] Not all confusions involve place in their results (e.g. [f]-[p] confusions are frequent), but place confusions increase specifically.

4 Analysis

This section shows how the combination of the hypotheses outlined in section 3 and Dispersion Theory, a framework that derives typological predictions about phonological patterns from considerations of communicative efficiency, correctly predicts the broad typological asymmetry between the contexts favoring vowel tensing and laxing.

4.1 Constraints on contrasts and constraint rankings

CONSTRAINTS ON CONTRAST, or DISTINCTIVENESS CONSTRAINTS, are paradigmatic constraints that penalize pairs of sounds that occur in a given context based on their perceptual distance (Flemming 2002). These constraints implement an idea central to Dispersion Theory (see Liljencrants & Lindblom 1972) according to which restrictions on possible phoneme inventories derive from principles of maximal contrast. Constraints on contrasts differ from traditional markedness constraints because they evaluate inventories rather than single forms. In the OT implementation of Dispersion Theory, the hypothesis that a more distinct contrast *a-b* should be preferred over a less distinct contrast *c-d* is captured in an OT-ranking penalizing *c-d* more than *a-b*: $*c\text{-}d \gg *a\text{-}b$. Constraints on contrasts may be relativized to a context to reflect the observation that perceptual distances between phonemes and, accordingly, phonological inventories may vary across contexts.

In the present case, hypotheses about the quality of C-place contrasts and vowel contrasts in VC sequences translate into universal OT-rankings of the corresponding distinctiveness constraints. In what follows, [p]-[k] is used as an example of place contrast and [e]-[ɛ] as an example of tense-lax pair. The hypothesis that [p]-[k] is universally more distinct after [ɛ] than after [e] (see section 3.1) translates into a fixed ranking where the constraint penalizing the [p]-[k] constrast after [e], *p-k/e_, outranks the constraint penalizing it after [ɛ], *p-k/ɛ_ (11-a). The hypothesis that the [p]-[k] contrast is universally more distinct prevocalically than word-finally (see section 3.2) translates into a fixed ranking where the constraint penalizing this contrast word-finally, *p-k/_#, outranks the constraint penalizing it prevocalically, *p-k/_V (11-b).

(11) a. OT-ranking following from the hypothesis that [p]-[k] is more distinct after [ɛ] than after [e]
*[p]-[k]/e_ ≫ *[p]-[k]/ɛ_
b. OT-ranking following from the hypothesis that [p]-[k] is more distinct prevocalically than word-finally
*[p]-[k]/_# ≫ *[p]-[k]/_V

The two OT-rankings in (11-a) and (11-b) can be combined in a single OT-ranking reflecting the distinctiveness of place contrasts as a function of both the quality of the preceding vowel (tense vs. lax) and the presence or absence of release transitions (e.g. word-final consonant vs. prevocalic consonant). The effect of the presence or absence of release transitions on place distinctiveness should dominate the effect of the preceding vowel because it involves a more radical difference: [p]-[k] should be less distinct word-finally after [ɛ] (ɛ_#) than prevocalically after [e] (e_V) because the presence of release transitions into a following vowel should outweigh the perceptual benefit of laxing the preceding vowel (see Fujimura et al. 1978 on the perceptual asymmetry between release and closure transitions). Therefore, the two rankings in (11-a) and (11-b) should combine and form the OT-ranking in (12). This ranking assumes the simplest hypothesis about how the preconsonantal and postconsonantal contexts interact perceptually: laxing is assumed to enhance place contrasts both before prevocalic and word-final consonants.

(12) Universal OT-ranking of distinctiveness constraints relative to place contrasts after front vowels

$$\underbrace{\text{*p-k/e\_\#} \gg \text{*p-k/ɛ\_\#}}_{\text{*p-k/\_\#}} \gg \underbrace{\text{*p-k/e\_V} \gg \text{*p-k/ɛ\_V}}_{\text{*p-k/\_V}}$$

The hypothesis that contrasts among tense vowels are more distinct than contrasts among lax vowels (see section 3.3) translates into a universal OT-ranking where contrasts among lax vowels are more penalized than contrasts among tense vowels. In order to evaluate vowel contrasts, an additional tense-lax pair (e.g. [o]-[ɔ]) must be considered. The constraint penalizing the less distinct [ɛ]-[ɔ] contrast, *ɛ-ɔ, outranks the constraint penalizing the more distinct [e]-[o] contrast, *e-o (13).

(13) Universal OT-ranking of distinctiveness constraints relative to vowel contrasts
*ɛ-ɔ ≫ *e-o

Because [o]-[ɔ] was added in the analysis, additional constraints and rankings relative to the distinctiveness of [p]-[k] after back vowels must be considered. Assuming that [p]-[k] is more distinct after [ɔ] than after [o] (see section 3.1), the ranking in (14) is obtained. This ranking is completely parallel to the ranking in (12).

(14) Universal OT-ranking of distinctiveness constraints relative to place contrasts after back vowels

$$\underbrace{\text{*p-k/o\_\#} \gg \text{*p-k/ɔ\_\#}}_{\text{*p-k/\_\#}} \gg \underbrace{\text{*p-k/o\_V} \gg \text{*p-k/ɔ\_V}}_{\text{*p-k/\_V}}$$

4.2 Language types

Among languages where tense and lax vowels are not allowed to contrast, four language types must be considered: languages with Open-Syllable Tensing and Closed-Syllable Tensing (schematically, OST-CST), languages with Open-Syllable Tensing and Closed-Syllable laxing (OST-CSL), languages with Open-Syllable Laxing and Closed-Syllable Tensing (OSL-CST), and languages with Open-Syllable Laxing and Closed-Syllable Laxing (OSL-CSL). They are shown in (15) together with the types of sequences they each allow. The first four sequences (e.g. /ep op ek ok/ in OST-CST) represent the vowel-consonant sequences that can occur at the end of a word in the language. The last four sequences (e.g. /epV opV ekV okV/ in OST-CST) represent the vowel-consonant sequences that can occur before a vowel in the language (V stands for any vowel). (The simplifying assumption that vowels are all tense or all lax before prevocalic consonants and before word-final consonants will be relaxed in section 7.1. For now, an inventory with laxing only before word-final [k], e.g. /ep op ɛk ɛk epV opV ekV okV/, is not considered as a possible candidate.)

(15) Four possible language types

Name	Inventory	Abbreviation
OST-CST	ep op ek ok epV opV ekV okV	{e-o}{p-k} {e-o}{p-k}V
OST-CSL	ɛp ɔp ɛk ɔk epV opV ekV okV	{ɛ-ɔ}{p-k} {e-o}{p-k}V
OSL-CST	ep op ek ok ɛpV ɔpV ɛkV ɔkV	{e-o}{p-k} {ɛ-ɔ}{p-k}V
OSL-CSL	ɛp ɔp ɛk ɔk ɛpV ɔpV ɛkV ɔkV	{ɛ-ɔ}{p-k} {ɛ-ɔ}{p-k}V

The last column in (15) presents a more compact representation of the inventory of sound sequences in the second column: /{e-o}{p-k}/ is a shorthand for /ep op ek ok/. This representation also makes it easier to identify the sounds that contrast in the inventory.

Tableaux (16-a) and (16-b) show the evaluations of [p]-[k] after front vowels and after back vowels respectively. Distinctiveness constraints assign violations to inventories depending on whether they contain the corresponding contrast in the relevant context or not. For instance, the subinventory /e{p-k} e{p-k}V/ violates *p-k/e_# once because it contains the two sequences [ep] and [ek].

(16) Ranking evaluating consonant-place dispersion in syllable inventories

a. Evaluation of place contrasts after front vowels

		*p-k/e_#	*p-k/ɛ_#	*p-k/e_V	*p-k/ɛ_V
CST-OST	e{p-k} e{p-k}V	*		*	
CSL-OST	ɛ{p-k} e{p-k}V		*	*	
CST-OSL	e{p-k} ɛ{p-k}V	*			*
CSL-OSL	ɛ{p-k} ɛ{p-k}V		*		*

b. Evaluation of place contrasts after back vowels

		*p-k/o_#	*p-k/ɔ_#	*p-k/o_V	*p-k/ɔ_V
CST-OST	o{p-k} o{p-k}V	*		*	
CSL-OST	ɔ{p-k} o{p-k}V		*	*	
CST-OSL	o{p-k} ɔ{p-k}V	*			*
CSL-OSL	ɔ{p-k} ɔ{p-k}V		*		*

Tableau (17) shows the evaluations of vowel contrasts in the four inventories. Inventory /{e-o}{p-k} {e-o}{p-k}V/ violates *e-o four times because there are four contexts where the contrast between [e] and [o] is attested in the inventory: before word-final and prevocalic [p] and before word-final and prevocalic [k].

(17) Ranking evaluating vowel dispersion in syllable inventories

		*ɛ-ɔ	*e-o
CST-OST	{e-o}{p-k} {e-o}{p-k}V		****
CSL-OST	{ɛ-ɔ}{p-k} {e-o}{p-k}V	**	**
CST-OSL	{e-o}{p-k} {ɛ-ɔ}{p-k}V	**	**
CSL-OSL	{ɛ-ɔ}{p-k} {ɛ-ɔ}{p-k}V	****	

4.3 Predicted typology

Which of the four types a given language belongs to will depend on how the rankings relative to place dispersion and vowel dispersion interact in this language. If the constraint that militates against the weak [ɛ]-[ɔ] contrast, *ɛ-ɔ, is top-ranked, the language with vowel tensing across contexts (CST-OST) is selected as the optimal language (18). This language maximizes vowel dispersion at the expense of place dispersion. To simplify, only the constraints evaluating [p]-[k] after front vowels are shown in tableaux (18)-(20).

(18) Enhancing vowel contrasts at the expense of place contrasts

		*ɛ-ɔ	*p-k/e_#	*p-k/e_V
☞ CST-OST	{e-o}{p-k} {e-o}{p-k}V		*	*
CSL-OST	{ɛ-ɔ}{p-k} {e-o}{p-k}V	**		*
CST-OSL	{e-o}{p-k} {ɛ-ɔ}{p-k}V	**	*	
CSL-OSL	{ɛ-ɔ}{p-k} {ɛ-ɔ}{p-k}V	****		

If *ɛ-ɔ is outranked by the constraint penalizing place contrasts word-finally after tense vowels (e.g. *p-k/e_#) but outranks the constraint penalizing place contrasts prevocalically after tense vowels (e.g. *p-k/e_V), the language with CSL and OST is selected as the winner (19). This language realises a compromise between maximizing vowel dispersion and place dispersion.

(19) Compromise between vowel contrasts and place contrasts

		*p-k/e_#	*ɛ-ɔ	*p-k/e_V
CST-OST	{e-o}{p-k} {e-o}{p-k}V	*		*
☞ CSL-OST	{ɛ-ɔ}{p-k} {e-o}{p-k}V		**	*
CST-OSL	{e-o}{p-k} {ɛ-ɔ}{p-k}V	*	**	
CSL-OSL	{ɛ-ɔ}{p-k} {ɛ-ɔ}{p-k}V		****	

If *ɛ-ɔ is outranked by all constraints penalizing place contrasts after tense vowels (e.g. *p-k/e_# and *p-k/e_V), the language with vowel laxing across contexts (CSL-OSL) is selected as the winner (20). This language maximizes place dispersion at the expense of vowel dispersion.

(20) Enhancing place contrasts at the expense of vowel contrasts

		*p-k/e_#	*p-k/e_V	*ɛ-ɔ
CST-OST	{e-o}{p-k} {e-o}{p-k}V	*	*	
CSL-OST	{ɛ-ɔ}{p-k} {e-o}{p-k}V		*	**
CST-OSL	{e-o}{p-k} {ɛ-ɔ}{p-k}V	*		**
☞ CSL-OSL	{ɛ-ɔ}{p-k} {ɛ-ɔ}{p-k}V			*****

The language with Closed-Syllable Tensing and Open-Syllable Laxing (CST-OSL) does not win under any ranking. It is harmonically bound by CSL-OST: it ties with CSL-OST for vowel dispersion (17) but it is worse than CSL-OST for place dispersion (16). In other words, the current analysis predicts that there should be no independent processes of Closed-Syllable Tensing (CST) and Open-Syllable Laxing (OSL): if a language tenses a vowel before a coda consonant C it should also tense this vowel before onset C (21-a) and if a language laxes a vowel before onset C it should also lax this vowel before coda C (21-b).

(21) Predicted implicational generalizations

a. Closed-syllable tensing (CST) entails open-syllable tensing (OST).
b. Open-syllable laxing (OSL) entails closed-syllable laxing (CSL).

This is a welcome result because there is no reported cross-linguistically robust phonological process like Closed-Syllable Tensing (a process by which vowels are tensed specifically before word-final and preobstruent consonants) and Open-Syllable Laxing (a process by which vowels are laxed specifically in word-final position and before prevocalic consonants).

5 Case study: the French *loi de position*

The theory of CSL and OST proposed in section 4 is attractive because it provides a well-motivated mechanism to explain interactions between the tense/lax quality of a vowel and the postvocalic context. However, the ultimate success of this theory will depend on whether the following predictions are confirmed for specific patterns attested cross-linguistically:

Prediction 1: tense vowels are more distinct from each other than lax vowels.

Prediction 2: all consonants triggering laxing are involved in place contrasts.

Prediction 3: the internal cues and/or 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 4: these place contrasts are more distinct after lax vowels than after tense vowels.

This section evaluates these predictions by focusing on a specific case study, the French *loi de position*. The test of Prediction 4 is left for section 6 because it is more involved.

5.1 *Loi de position*: basic facts

The *loi de position* is the name given by French phonologists to the tendency observed in many French varieties to realise mid vowels as tense [e ø o] word-finally and before prevocalic consonants and as lax [ɛ œ ɔ] before word-final consonants and before preobstruent consonants (Lyche et al. 2012). This section focuses on varieties where the *loi de position* defines a strict complementary distribution, e.g. in Southern French varieties (Coquillon & Turcsan 2012). In these varieties, CSL and OST apply categorically: mid vowels are systematically tense word-finally and before prevocalic consonants (22-a) and lax before word-final consonants and consonant-obstruent clusters (22-b). Tense/lax alternations driven by OST and CSL are observed, e.g. in suffixed forms (23-a) and in truncated forms (23-b) (see the introduction for examples with front unrounded mid vowels).

(22) a. Mid-vowel tensing word-finally and before prevocalic consonants

_#	*lieu*	[lj**ø**]/*[lj**œ**]	'place'
	mot	[m**o**]/*[m**ɔ**]	'word'
_CV	*heureux*	[**ø**ʁø]/*[**œ**ʁø]	'happy'
	otage	[**o**taʒ]/*[**ɔ**taʒ]	'hostage'

b. Mid-vowel laxing before word-final consonants and consonant-obstruent clusters

_C#	*saute*	[s**ɔ**t]/*[s**o**t]	'jumps'
_CO	*obtus*	[**ɔ**pty]/*[**o**pty]	'obtuse'

(23) Mid-vowel tense/lax alternations

a. Lax → Tense

gueule	[gœl]	'mouth'	$\xrightarrow[\text{suffixation}]{}$	*gueulant*	[g**ø**lã]/*[g**œ**lã]	'shouting'
gomme	[gɔm]	'rubber'	$\xrightarrow[\text{suffixation}]{}$	*gommer*	[g**o**me]/*[gɔme]	'to erase'

b. Tense → Lax

mobylette	[m**o**bilɛt]	'moped'	$\xrightarrow[\text{truncation}]{}$	*mob*	[mɔb]/*[m**o**b]

Prevocalic consonant-glide clusters (CGV) and prevocalic consonant-liquid clusters (CLV) behave like prevocalic consonants (CV): they are preceded by tense mid vowels (24-a). French has three glides [j ɥ w] and two liquids [l ʁ]. However, word-final consonant-liquid clusters (CL#) behave differently: they are preceded by lax mid vowels (24-b). (Word-final CG clusters are not attested in French.)

(24) a. Mid-vowel tensing before prevocalic CG and CL clusters

_CGV	*évier*	[**e**vje]/*[**ɛ**vje]	'sink'
	étoile	[**e**twal]/*[**ɛ**twal]	'star'
_CLV	*éclat*	[**e**kla]/*[**ɛ**kla]	'radiance'
	écran	[**e**kʁã]/*[**ɛ**kʁã]	'screen'

b. Mid-vowel laxing before word-final CL clusters

_CL#	*siècle*	[sj**ɛ**kl]/*[sj**e**kl]	'century'
	maigre	[m**ɛ**gʁ]/*[m**e**gʁ]	'skinny'

Mid vowels occuring as first element of a vowel-vowel sequence are realised as tense (25).

(25) Mid-vowel tensing in hiatus

_V	*béat*	[b**e**a]/*[b**ɛ**a]	'happy'
	boa	[b**o**a]/*[b**ɔ**a]	'boa'

Finally, in some Southern varieties, consonants before schwa behave differently from consonants before other vowels: they are preceded by lax mid vowels (26) (Eychenne 2014).

(26) Mid-vowel laxing before preschwa consonants in some varieties

éperon	[**ɛ**pəʁɔ̃]/*[**e**pəʁɔ̃]	'spur'
hôtelier	[**ɔ**təlje]/*[**o**təlje]	'hotel-ADJ'

5.2 Prediction 1: Tensing as enhancement of vowel backness contrasts

In the present analysis, vowel tensing is hypothesized to be motivated by vowel contrast enhancement, with tense vowels being more distinct than lax vowels. The acoustic dimension along which front rounded, front unrounded, and back mid vowels contrast is F2. Many studies show that French peripheral lax mid vowels [ɛ ɔ] are more central along F2 than peripheral tense mid vowels [e o] while the central tense and lax vowels [ø] and [œ] have similar F2 targets (Delattre 1968; Gottfried 1984; Calliope 1989; Gendrot & Adda-Decker 2005; Storme 2017b). As a consequence, lax vowels should be closer to each other along F2 and less distinct perceptually than tense vowels. To check this, the data in Storme (2017b) (Experiment 1) was used. These data document the acoustic realisations of mid vowels in

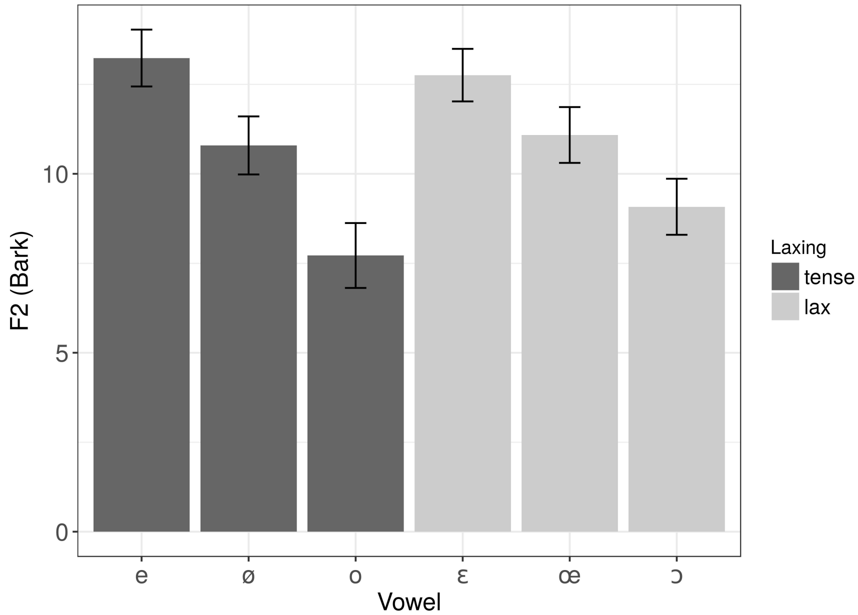


Figure 4: Tense and lax mid vowels' F2 in Barks (mean and standard deviation).

the speech of 20 French speakers from the center of France (a variety with CSL and OST applying to mid vowels). Figure 4 shows the average F2 for tense mid vowels [e ø o] and lax mid vowels [ɛ œ ɔ] as measured at vowel midpoint. Original formant frequencies in Hz were Bark-transformed in order to better correspond to auditory frequencies (Schroeder et al. 1979).

To assess whether or not lax vowels were closer to each other than tense vowel, a linear mixed effects model was fit to the data (using R and the package lme4; R Core Team 2017 and Bates et al. 2014), with fixed effects for Laxing (tense vs. lax), Backness (front unrounded vs. front rounded vs. back) and random intercepts for Speaker, Word-position, Consonantal context, and Repetition. As expected, F2 distances were found to be significantly smaller among lax than tense mid vowels. The [ɛ]-[œ] distance was found to be 0.77 ± 0.06 Barks smaller than [e]-[ø] (t=-13.248, p<2e-16). The [ɔ]-[œ] distance was found to be 1.07 ± 0.06 Barks smaller than [o]-[ø] (t=18.573, p<2e-16). P-values were obtained using the lmerTest package (Kuznetsova et al. 2015).

5.3 Prediction 2: All consonants triggering laxing are involved in place contrasts

The present analysis predicts that, in VC sequences where V is lax, C should be involved in a place contrast. Because mid vowels are realised as lax before all consonants occuring word-finally and before obstruents in Southern French, this predicts that all the consonants occuring in these positions should be involved in place contrasts. The consonants that occur in word-final position in French are shown in Table 2. Most of these consonants also occur word-medially before obstruents (Dell 1995). Two exceptions are the glides [w ɥ], which occur neither word-finally nor before obstruents.

	Labial	Dental	Postalveolar	Palatal	Velar	Uvular
Stop	p b	t d			k ɡ	
Nasal	m	n		ɲ		
Fricative	f v	s z	ʃ ʒ			ʁ
Approximant		l				
Glide	(w, ɥ)			j		

Table 2: French consonants

French stops, nasals, and fricatives are involved in place contrasts. [l] and [j] are not involved in place contrasts in the traditional sense, but they are likely to be confusable with each other because French [l] is clear (i.e. with a relatively high F2 target; Chafcouloff 1985). 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 realised 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).

5.4 Prediction 3: Vowel laxing happens before consonants with weak release place cues

The present analysis predicts that if a consonant C triggers laxing of a preceding vowel in a context C_1 and tensing of a preceding vowel in a context C_2, then cues to C-place are weaker in C_1 than in C_2 (see section 4.3). The predictions about the strength of C-place cues that follow from this hypothesis are shown in Table 3.

Hypothesis	Tensing contexts (provide better C-place cues)	Laxing contexts (provide worse C-place cues)
	_CV	_C#
	_CLV	_CO
	_CGV	_CL#
		_Cə

Table 3: Predictions about the strength of cues to C-place

CV vs. C#, CO. Evidence for the hypothesis that C has better place cues in CV than in C# and CO was reviewed in section 3.2. However, because this evidence bears on major place of articulations (labial, dental, velar), one may wonder whether it extends to other places of articulation attested in French. Clear [l] and [j] are neutralized word-finally (27-a) but not prevocalically (27-b) in some languages, suggesting that clear [l] and [j] might be less distinct word-finally than prevocalically.

(27) Cibaeño (Dominican Spanish dialect; Guitart 1981)

a. *papel* [papej] 'paper'

b. *papeles* [papeles] ‘papers’

It is less clear which place contrast involving [ʁ] is less distinct word-finally and before obstruents than in other contexts. [ʁ] was found to be less distinct from the null segment word-finally and before [t] than prevocalically (Storme in press), in accordance with the hypothesis of a contextual asymmetry in the perception of [ʁ]. Data from loanword adaptations suggest that [ʁ] could be confusable with [k] in nonprevocalic position: [ʁ] is adapted as [k] in Vietnamese in this position (28) (Kang et al. 2016). Therefore, the contrast between [k] and [ʁ] may be relevant. More work is needed to test whether this is the case.

(28) Adaptation of French coda [ʁ] and [k] as [k] in Vietnamese
   a. *corset* [kɔʁse] > *coóc xê* [kɔːk̚se˧] ‘bra’
   b. *biftek* [biftɛk] > *bíp tế́k* [ɓip̚tek̚] ‘beef steak’

CLV vs. COV. There is evidence that glides and liquids provide release transitions that can cue the place of articulation of a preceding consonant whereas obstruents do not. Glides are acoustically similar to vowels and it is therefore unsurprising that they pattern together with vowels. The lateral [l] also has formant structure that can carry information about place of articulation (Flemming 2007). Bakst & Katz (2014) provide evidence that the French uvular fricative [ʁ] (treated as a liquid phonologically) has formant structure whereas the fricative [f] does not and that listeners show more sensitivity to the presence of bursts before [f] than before [ʁ]. They interpret these results as showing that, in the absence of bursts, listeners may be able to recover cues to a preceding stop when the following fricative is [ʁ] better than when it is [f], implying that [ʁ] carries stronger perceptual cues to the place of a preceding consonant than [f]

Interestingly, prevocalic [tl] clusters are an exception to the generalization that CLV triggers tensing of a preceding mid vowel (see (29-a) and (29-b)). These clusters are known to be perceptually confusable with [kl] in French (Hallé & Best 2007). Laxing before [tl] may therefore be way to enhance the contrast between [tl] and [kl].

(29) a. Mid-vowel tensing before prevocalic [kl] and [pl]
   _klV, _plV *éclat* [**e**kla]/*[**ɛ**kla] ‘radiance’
   écran [**e**kʁɑ̃]/*[**ɛ**kʁɑ̃] ‘screen’
   b. Mid-vowel laxing before prevocalic [tl]
   _tlV *Bethléem* [b**ɛ**tleɛm]/*[b**e**tleɛm]
   potelé [p**ɔ**tle]/*[p**o**tle]

CL# vs. CLV. Liquids are subject to deletion in word-final OL clusters but not in word-internal, prevocalic OL clusters (Dell 1985; Tranel 1987). When the word-final liquid deletes, the preceding obstruent ends up in word-final position, a position where it lacks good place cues. The fact that liquids in word-final OL clusters do not provide consistent cues due to their propensity to delete may explain why mid vowels are lax in this context.

Cə vs. CV. Storme (2017a) proposes 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 syllables before schwa have shorter schwas than speakers who do not. As a short vowel, schwa might provide shorter and therefore less informative release transitions than longer vowels. The fact that French schwa is subject to deletion (Dell 1985; Tranel 1987) might be an additional factor. However it cannot be the only factor because undeletable schwas also trigger laxing of preceding mid vowels in Southern French (Storme 2017a).

6 Acoustic and perceptual study

To test whether mid-vowel laxing improves postvocalic place contrasts in French, a perception experiment was conducted. Section 6 describes the results of an acoustic study comparing the F1 and F2 realisations of [p t k] in coda position after the ten French oral vowels. Section 6.2 describes the results of a perceptual study using a subset of the stimuli collected in the acoustic study to investigate the effect of vowel quality on the perceptual distinctiveness of place contrasts.

6.1 Acoustic study

6.1.1 Methods

Two Standard French native speakers (a female and a male) were recorded uttering C_1VC_2 nonsense syllables, with V in [i y u e ø o ɛ œ ɔ a] and C_1 and C_2 in [p t k]. Each of the 90 syllables was repeated three times by each speaker, yielding a total of 540 syllables. 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. All acoustic analyses were performed using the Praat software (Boersma & Weenink 2017). The ceiling of the formant search range was set to 5500 Hz for the the female speaker and to 5000 Hz for the male speaker.

The formant frequencies were Bark-transformed and normalized by speaker (using the R function `scale`). R and lme4 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.

6.1.2 Results

Figure 5 summarises the distribution of the ten oral vowels over the F1xF2 space across speakers and consonantal contexts. The results are generally compatible with previous stud-

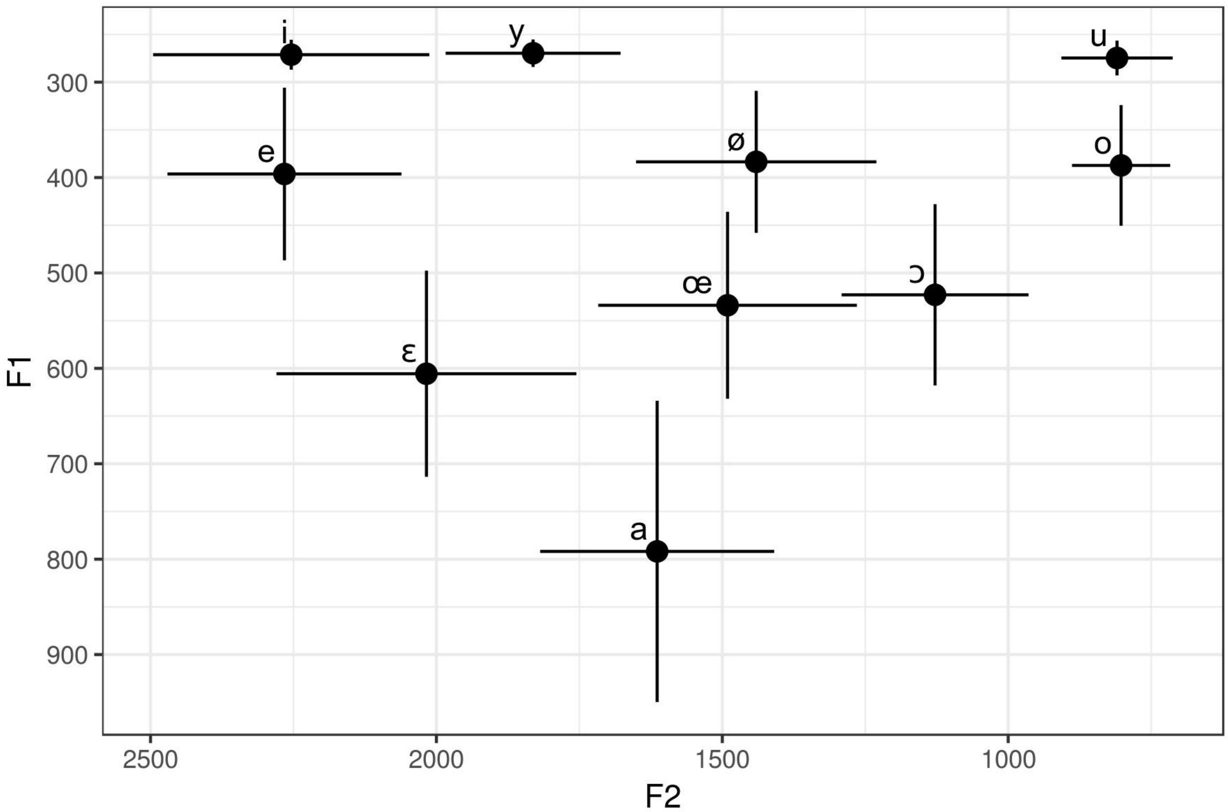


Figure 5: Mean vowel F1 and F2 (in Hz) with standard deviations across speakers and consonantal contexts (measured at vowel midpoint).

ies on the realisation of oral vowels in final syllables. One difference is that [ɛ] appears to have a slightly higher F1 value than [œ] and [ɔ], whereas these vowels have been found to have roughly the same F1 values in other studies (Ménard et al. 2008).

F1

Figure 6 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 realisations, a linear mixed effects model was fit to the 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 e ø o ɛ œ ɔ]. Because there is only a single low vowel in French, it is not possible to define a full model including this vowel 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.

Before high vowels, the F1 realisations of [p t k] were not found to be significantly

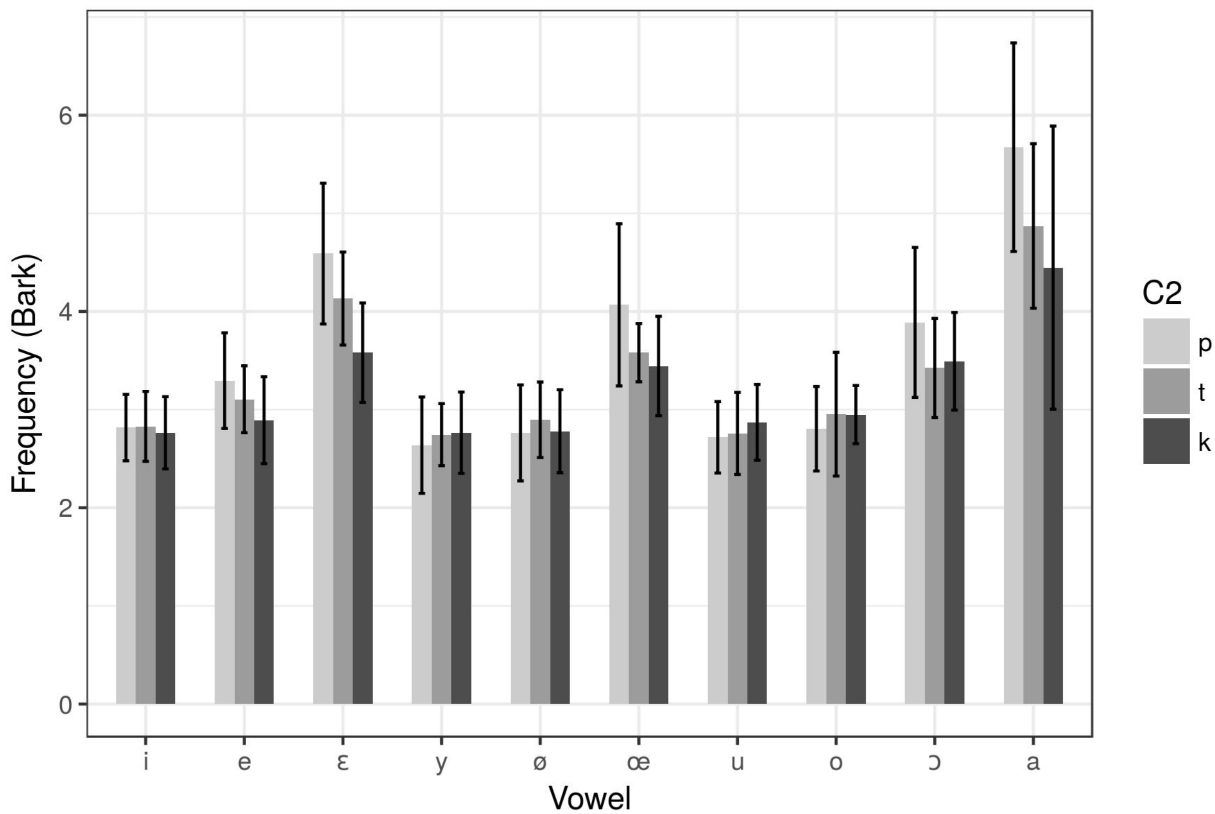


Figure 6: Vowel F1 before [p t k] five milliseconds before the end of the vowel (mean and standard deviation).

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 (beta=-.11, se=.07, p=.01). Before lax mid vowels, the F1 locus of [k] is lower (beta=-0.20, se=.07, p=0.003) and the F1 locus of [p] is higher (beta=0.41, se=.07, p=2.91e -09) than the F1 locus of [t]. However, the effect of laxing on the [k]-[t] distance is probably entirely driven by [ɛ], as indicated by the significant three-way interaction of Height, Backness, and Consonant (beta=-0.213179, se=0.09, p=0.025032). These findings are summarised in Table 4.

F2

Figure 7 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 realisations, linear mixed effects models were fit to the 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-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. The results are summarised in Table 4 and described in more details in the following paragraphs.

Front unrounded vowels. After [e], the F2 realisations of [t] and [k] were found to be significantly different (beta=.58518, se=.11481, p=0.01030) but not the F2 realisations of [t] and [p] (beta=-0.04894, se=.14724, p=0.7722). After [i], the distance between the F2 realisations of [t] and [k] is significantly decreased compared to after [e] (beta=-.32396, se=.11671, p=.00573). This means that the F2 realisations of [p t k] are generally more similar after [i] than after [e]. After [ɛ], the distance between the F2 realisations of [p] and [t] (and as a consequence of [p] and [k]) is significantly increased compared to after [e] (beta=-0.23878, se=.11671, p=0.04134). This means that the F2 realisations of [p t k] are generally more distinct after [ɛ] than after [i] and [e].

Back vowels. After [o], the F2 realisations of [p] and [t] are significantly different (beta=.98955, se=.14724, p=0.023534) but not the F2 realisations of [p] and [k] (beta=-0.12689, se=0.09265, p=0.195114). There is no significant effect of height on the distances between the F2 realisations of [p t k] after back vowels. This means that the F2 centralisation observed in [ɔ] does not affect the distinctiveness of F2 transitions into [p t k].

Front rounded vowels. After [ø], the F2 realisations of [k] and [t] are significantly different (beta=0.46825, se=0.11481, p=0.020298) but not the F2 realisations of [p] and [k] (beta=-0.10844, se=0.09265, p=0.263804). The distances between [p t k]'s F2 realisations are not significantly different after [ø] and after [y]. However, the distance between the F2 realisations of [t] and [k] (and therefore of [t] and [p]) decreases significantly after [œ] as compared to after [ø] (beta=-0.28426, se=0.11671, p=0.015250).

6.1.3 Summary

For each pair of vowels differing in height, Table 4 summarises whether the F1 or F2 acoustic distance between the two consonants in the correponding row is larger after the lower vowel

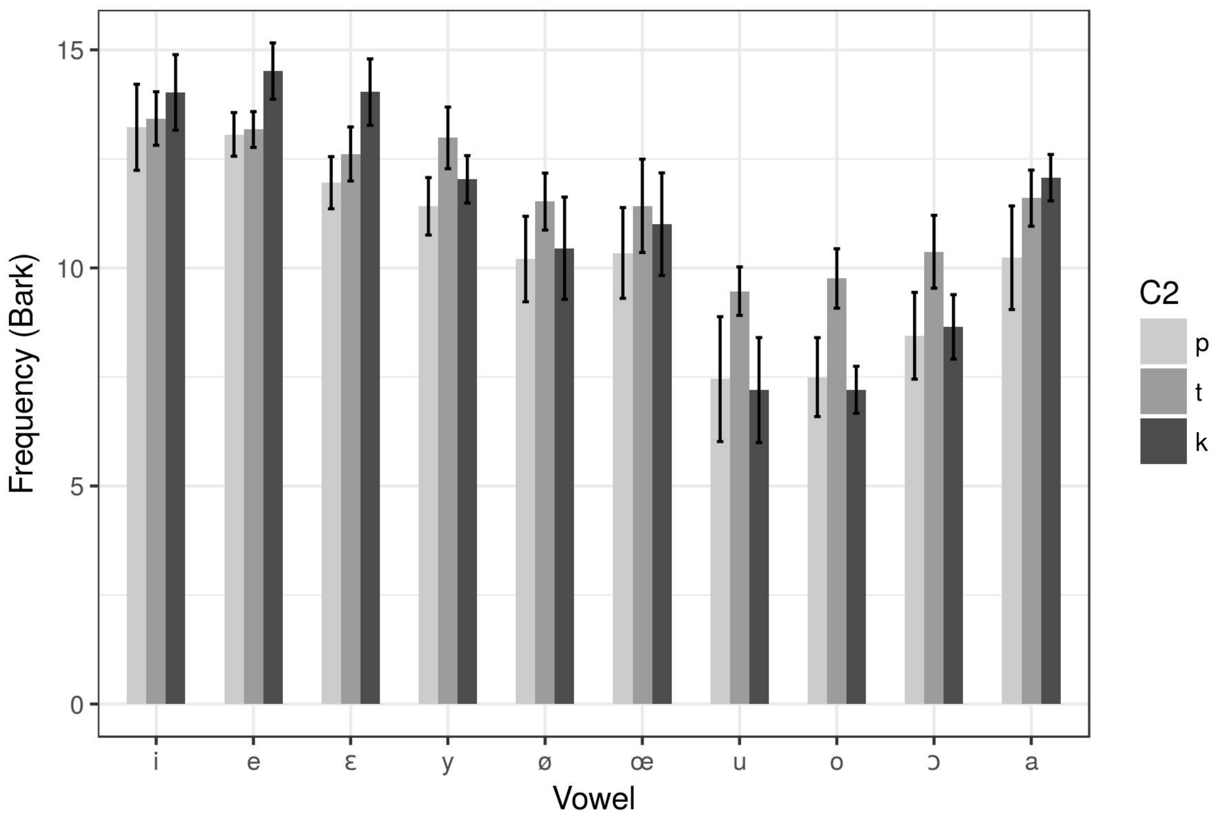


Figure 7: Vowel F2 before [p t k] five milliseconds before the end of the vowel (mean and standard deviation).

	F1						F2					
	i-e	e-ɛ	y-ø	ø-œ	u-o	o-ɔ	i-e	e-ɛ	y-ø	ø-œ	u-o	o-ɔ
pt	=	✓	=	✓	=	✓	=	✓	=	✖	=	=
pk	=	✓	=	✓	=	✓	✓	✓	=	=	=	=
kt	=	✓	=	=	=	=	✓	=	=	✖	=	=

Table 4: The effect of height on the distances between the F1 and F2 realisations of [p t k]. 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.

than after the higher one or does not differ significantly after the two vowels. The distances between the formant realisations 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].

Mid-vowel laxing was found to generally increase the distance between the F1 realisations of [p t k]. The increase was observed for all pairs after [ɛ] but only for the pairs involving [p] after rounded vowels [ɔ œ]. This difference could be due to the fact that [ɛ] had a higher F1 value than [œ ɔ] in this study (see Figure 5). However, mid-vowel laxing was not found to generally increase the distance between the F2 realisations of [p t k]. This was the case only for [ɛ], after which the distances between [p] and [t] and between [p] and [k] were found to increase as compared to after [e].

6.2 Perceptual study

6.2.1 Methods

One third of the stimuli recorded in section 6 (from the first repetition) were used in a perceptual study evaluating the effect of vowel quality on place distinctiveness. The final burst was edited out in order to directly test the effect of vowel transitions on place discriminability. 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 an online experiment. 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. 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 C_1. These confusion matrices indicate how many times [p], [t] or [k] was identified as [p], [t] or [k] in each of the 10 vowel contexts [i y u e ø o ɛ œ ɔ a]. The confusion matrices were analyzed using Luce's (1963) Biased Choice Model (BCM). This model may be used as 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.

$$p(r_j|s_i) = \frac{\eta_{ij} b_j}{\sum_{r_k} \eta_{ik} b_k}$$

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.

BCM was implemented as log-linear model in R and fit to the confusion matrices. 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 are reported (the perceptual distance d between two sounds corresponds to the negation of the logarithm of their similarity η).

6.2.2 Results

Figure 8 shows, for each pair of consonants and each vowel, the estimated perceptual distance between the two consonants after this vowel. Figure 9 zooms in on the comparison between tense and lax mid vowels. The overall results are consistent with what is known about the role of transitions in signaling place. The distance between [k] and [p] varies greatly as a function of the identity of the preceding vowel and the distance between [p] and [t] varies much less as a function of the vowel context. 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 et al. 1972).

[k]-[p] and [k]-[t] were found to be significantly more distinct after [ɛ] than after [e] (beta=-0.749436, se=0.168364, p=8.54e-06; beta=-0.959854, se=0.147299, p=7.20e-11), but lowering to [ɛ] was not found to increase the distinctiveness of [p]-[t]. Raising from [e] to [i] was not found to decrease consonants' distinctiveness significantly.

[k]-[p] and [p]-[t] were found to be significantly more distinct after [œ] than after [ø] (beta=-.355155, se=.135109, p=.008572) and after [ɔ] than after [o] (beta=-.359958, se=.115225, p=.001784), but neither lowering to [œ] nor lowering to [ɔ] was found to increase the distinctiveness of [k]-[t]. Raising from [ø] to [y] was found to improve the distinctiveness of [k]-[p] (beta=-0.309830, se= 0.134646, p=.021388). Raising from [o] to [u] was found to decrease the distinctiveness of [k]-[p] (beta=.251675, se=.113749, p=.026929).

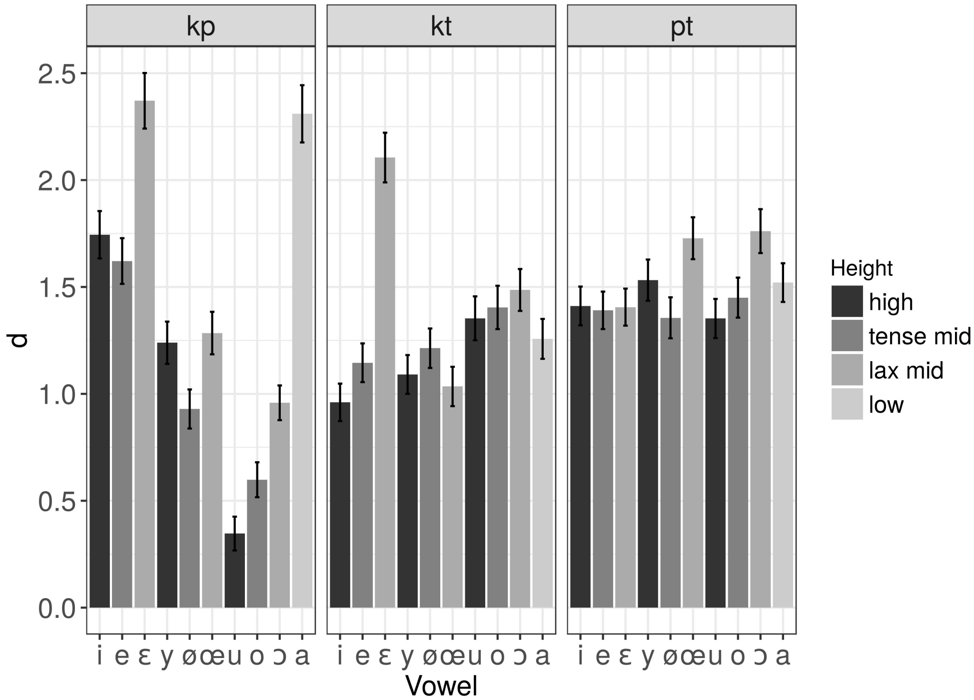


Figure 8: Perceptual distances between [p], [t], and [k] after the ten French oral vowels.

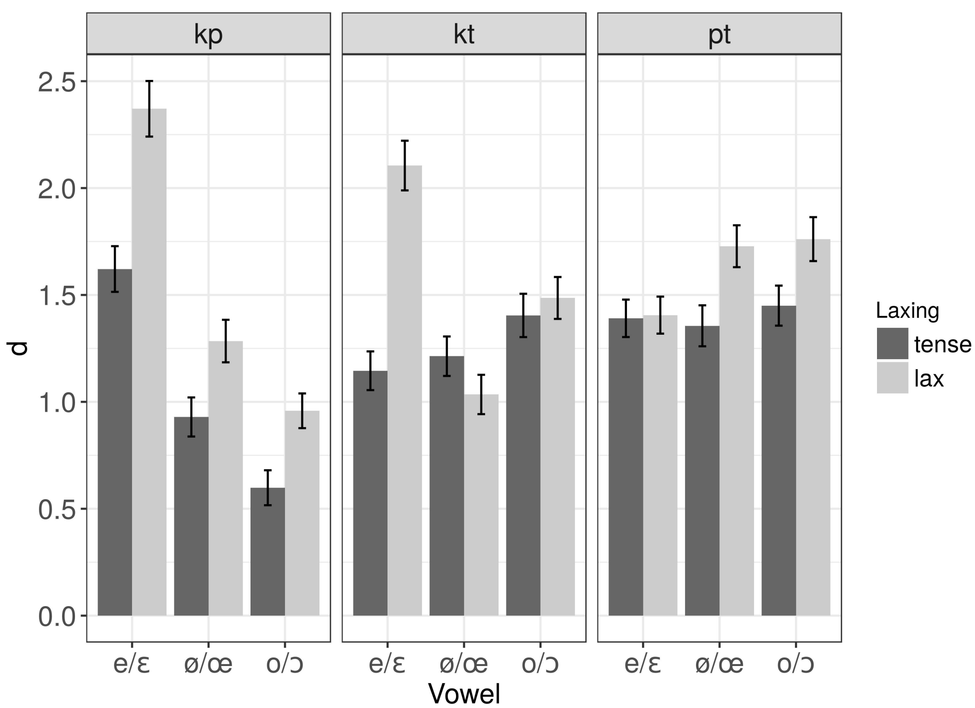


Figure 9: Perceptual distances (d) between [p], [t], and [k] after tense and lax mid vowels.

6.2.3 Summary and discussion

The results are summarised in Table 5, where ✓ indicates that the perceptual distance between the consonants in the corresponding row is significantly larger after the lower vowel than after the higher vowel in the corresponding column, ✖ indicates that the perceptual distance is larger after the higher vowel than after the lower vowel, and = indicates that no significant difference was found. For each tense-lax mid-vowel pair, at least two place contrasts are improved after the lax vowel as compared to after the tense vowel. Lowering high vowels to tense mid vowels does not generally result in greater consonant distinctiveness.

	i-e	e-ɛ	y-ø	ø-œ	u-o	o-ɔ
d_{pt}	=	=	=	✓	=	✓
d_{pk}	=	✓	✖	✓	✓	✓
d_{kt}	=	✓	=	=	=	=

Table 5: Summary of the results.

These results support the hypothesis that mid-vowel laxing improves postvocalic place contrasts in French. The fact that lowering high vowels to tense mid vowels does not improve place discriminability may explain why high vowels are not lowered before word-final and preobstruent consonants in French: the loss in vowel distinctiveness is not compensated by a gain in place distinctiveness.

The acoustic study shows that the perceptual improvement after lax vowels correlates with an increase in the distance between the F1 realisations 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 realisations of the two relevant consonants was also found to be increased but not necessarily the acoustic distance between their F2 realisations. This suggests that vowel lowering rather than vowel centralising 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 place perception: 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 in French, why does CSL also involve centralising in this language? One possibility is that centralising is a by-product of lowering in this variety of French, due to the shape of the vowel space (see section 2.3 on the relationship between lowering and centralising).

7 Discussion and conclusion

The results in section 6 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 section 7.1. Section 7.2 discusses the predictions that the present analysis makes for the typology of place neutralization.

7.1 Across-the-board vs. consonant-specific CSL

In the analysis presented in section 4, inventories where CSL applies only before specific consonants were not considered in the analysis (e.g. /up ut ʊk/, with laxing of back vowels before velars). However, such inventories must be considered in a complete analysis because there are languages where CSL targets specific consonants (see section 2.2).

However, when inventories with consonant-specific CSL are considered, inventories with across-the-board CSL (e.g. /ʊp ʊt ʊk/) should no longer win. There are two reasons for that. First, covarying vowel quality and place in VC should result in inventories with more distinct components: for instance, the two syllables /up ʊk/ (where vowel quality and place covary) should be more distinct than the two syllables /ʊp ʊk/ (where vowel quality and place do not covary). Second, consonant-specific CSL makes it possible to eliminate the problematic place contrast while minimizing the cost in terms of vowel dispersion. For instance, the inventory /up ʊk ap ak/ both avoids the perceptually weak [p]-[k] contrast after [u] and maintains [ap] and [up] as distinct as possible. However, the inventory /ʊp ʊk ap ak/ eliminates the [p]-[k] contrast after [u] at a higher price: it also reduces the distinctiveness of low and high vowels across contexts. Why should across-the-board CSL ever be attested then?

This section proposes that consonant-specific CSL and across-the-board CSL are due to two types of distinctiveness constraints. Constraints evaluating pairs of diphones (e.g. *up-uk, as defined in (30-a)) derive consonant-specific CSL whereas dispersion constraints evaluating pairs of sounds in a given context (e.g. *p-k/u_, as defined in (30-b)) derive across-the-board CSL.

(30) Two conceptions of contextual distinctiveness constraints

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

b. *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])

The difference between the two constraints is illustrated in (31). The constraint *up-uk in (30-a) only penalizes inventories where the two diphones [up] and [uk] are attested: satisfying *up-uk will not necessarily result in across-the-board laxing. The constraint *p-k/u_ in (30-b) penalizes inventories where any of the two diphones [up] or [uk] is attested: satisfying this constraint will result in across-the-board CSL (assuming no other option is available).

(31) How the two distinctiveness constraints penalize candidates.

	*p-k/u_	*up-uk
up uk	*	*
up ʊk	*	
ʊp uk	*	
ʊp ʊk		

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). For instance, 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.

Nearey & 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. 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's formant realisation, Fn(V), and language-specific locus equations (with language-specific slope and intercept). 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 realisation of the adjacent vowel, Fn(V), to make its decision. The identity of that vowel, Tn(V) (where Tn(V) denotes the target formant value of V), does not matter.

The constraint *p-k/u_ in (30-b) 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 (Flemming 2002; see section 7.2). 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 (32). 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).

(32) *p-k/u_ (final version)
Penalize any occurence of [p] or [k] after [u] if both [p] and [k] may occur postvocalically in the inventory.

The tableau in (33) 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 postvocalically. 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 (33)).

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

	*p-k/u_	*up ∨ uk
up uk	*	*
up ʊk	*	*
ʊp uk	*	*
ʊp ʊk		
up		*
uk		*

Generally, the approach based on contextual distinctiveness constraints like (32) 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. Because for all French mid vowels, all consonants among [p t k] were involved in a contrast that was worse after the tense allophone than after the lax allophone, mid-vowel laxing can be derived before all three consonants.

7.2 Enhancement and neutralization

Are there alternative repairs available to avoid sequences containing a tense vowel followed by a nonprevocalic consonant? Another way to satisfy a distinctiveness constraint is to neutralize the relevant contrast. In Flemming's (2002) framework, the decision to neutralize or not a contrast depends on the interaction of distinctiveness constraints and MaxContrast, a constraint that favors large inventories. Because the present analysis selects inventories of VC syllables, this constraint is stated in terms of maximizing the number of syllables in an inventory (34). 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).

(34) MaxContrast
Assign one check mark ✓ for each distinct syllable in an inventory of syllables.

Tableaux in (35) show how different rankings of MaxContrast yield the two different repairs, enhancement (35-a) and neutralization (35-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 outrank MaxContrast, the inventory that eliminates the contrast in this position is selected as the winner. (The constraint that penalizes the [p]-[k] contrast after [a] is not shown in the analysis: it is low ranked, due to the high distinctiveness of this contrast in this context; see section 6.2).

(35) a. Enhancement of place contrasts

	MaxContrast	*p-k/u_	*p-k/ʊ_	*a-ʊ	*a-u
ap ak up uk	✓✓✓✓	*!			**
☞ ap ak ʊp ʊk	✓✓✓✓		*	**	
ap ak uk	✓✓✓!				*
		Place contrasts		Vowel contrasts	

b. Neutralization of place contrasts

	*p-k/u_	*p-k/ʊ_	MaxContrast	*a-ʊ	*a-u
ap ak up uk	∗!		✓✓✓✓		∗∗
ap ak ʊp ʊk		∗!	✓✓✓✓	∗∗	
☞ ap ak uk			✓✓✓		∗
	Place contrasts			Vowel contrasts	

Because place contrasts are generally less distinct after higher and more peripheral vowels than after lower and more central vowels, the current approach predicts that neutralization of place contrasts after lower vowels entails neutralization of place contrasts after higher vowels. In accordance with this prediction, there are languages where neutralization of place contrasts is attested after high vowels only but seemingly no language where neutralization of place contrasts is attested after low vowels only. In Munken (Niger-Congo), in a corpus of about 250 verbs, Lovegren (2013: 95) found evidence for place contrasts word-finally after nonhigh vowels [ɛ o ɔ ə a] but not after high vowels [i u] and [e]. In Cantonese, all three place contrasts [p t k] and [m n ŋ] are available in VC after low vowels [a] and [ɐ] but only subsets of those contrasts are available after higher vowels (Hashimoto 1972).

7.3 Conclusion

This paper is the first one to provide a fully motivated account of CSL and OST. CSL and OST were proposed to be driven by the conflicting perceptual requirements of vowels and consonants in vowel-consonant sequences. The characterisation of the vowel-laxing contexts as contexts where the postvocalic consonant lacks good place cues captures well the distribution of tense and lax vowels cross-linguistically, and specifically in Southern French. It captures not only the broad asymmetry between prevocalic vs. nonprevocalic consonants, but also more specific conditionings on CSL involving the postvocalic consonant's manner of articulation (e.g. nasal vs. stop vs. fricative), its place of articulation (e.g. velar vs. nonvelar), the quality of the preceding vowel (e.g. back vs. front), the nature of the post-consonantal consonant (e.g. liquid and glide vs. obstruent), etc. The key prediction that vowel laxing enhances the distinctiveness of postvocalic consonant contrasts was borne out.

If correct, this analysis supports the more general hypothesis that perceptual contrast, and more specifically contrast enhancement, plays a role in shaping phonological patterns (e.g. Flemming 2002).

Appendix

This appendix lists the languages which provide the empirical basis for this paper. Most of these languages have CSL or OST or both. Bedouin Hijazi Arabic, Latin, and Dupaninga Agta show vowel alternations that are not tense-lax alternations in the strict sense, but that also manifest a preference for lower and more central vowels before preobstruent consonants. Munken and Cantonese are listed because they provide evidence for neutralization of place contrasts after high vowels (see section 7.2).

Language family	Language	Source
Arabic	Bedouin Hijazi Arabic	Al Mozainy 1981
Austronesian	Bario Kelabit	Blust 2013, 2016
	Chamorro	Topping 1973
	Dupaninga Agta	Robinson 2008
	Hiligaynon	Wolfenden 1971
	Indonesian (Javanese variety)	van Zanten 1989
	Kairiru	Wivell 1981
	Long Semado	Blust 2013
	Paluai	Schokkin 2014
	Sri Lanka Malay	Nordhoff 2009
	Thao	Blust 2003
	Uma Juman Kayan	Blust 1977
Germanic	Dutch	Trommelen 1983; Kager 1990; Pols et al. 1973; Botma et al. 2012
Penutian	Klamath	Barker 1964; Blevins 1993
Niger-Congo	Agagwune	Lindau-Webb 1987
	Kuteb	Koops 2009
	Munken	Lovegren 2013
Romance	French (Québec)	Martin 2002; Côté 2012
	French (Southern)	Coquillon & Turcsan 2012; Eychenne 2014; Storme 2017b
	French (Standard)	Tranel 1987; Féry 2003
	Latin	Niedermann 1985
Sino-Tibetan	Cantonese	Hashimoto 1972

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