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

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Abstract

This paper proposes that closed-syllable laxing and open-syllable tensing of nonlow vowels before the major places of articulation (e.g. /p t k/) are motivated by conflicting strategies of contrast enhancement in vowel-consonant sequences. Laxing enhances the distinctiveness of consonant contrasts by allowing for more distinct VC formant transitions. Tensing enhances the distinctiveness of vowel contrasts by providing more distinct formant realisations for vowels. Linguistic variation results from different ways of resolving the tension between maximising vowel dispersion and maximising consonant dispersion. Laxing typically applies before coda consonants as a way to compensate for the absence of good perceptual cues to consonant place of articulation in this context. The hypothesis that laxing enhances the distinctiveness of postvocalic consonant-place contrasts is supported by a study on mid-vowel laxing in French. If correct, this analysis corroborates the general claim that perceptual contrast plays a role in shaping phonotactic restrictions.

1 Introduction

Crosslinguistically, vowel systems commonly distinguish between two sets of vowels: tense vowels (e.g. /i e a o u/) and lax vowels (e.g. /ɪ ɛ ʌ ɔ ʊ/). Lax vowels are more central than tense vowels in the acoustic space defined by the first and second vowel formants (F1, F2), as schematically represented in Figure 1. Tense and lax vowels may also differ along other dimensions: for instance, tense vowels are often longer than lax vowels (Stevens 1998: 294-299).

Although tense and lax vowels may be used contrastively, tense-lax contrasts are often neutralised contextually, giving rise to tense-lax alternations, as represented with the arrows in Figure 1. This paper focuses on two phonotactic restrictions involving the POSTVOCALIC
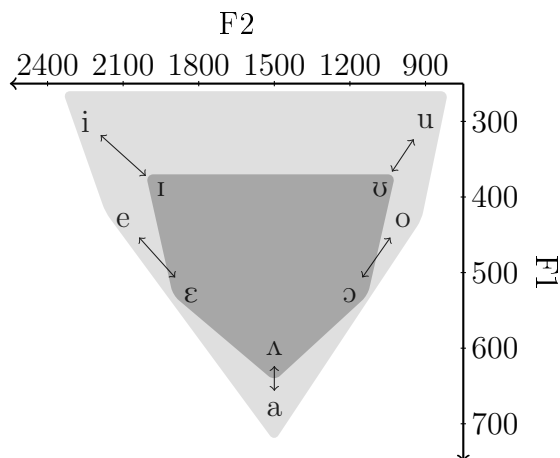

Figure 1: Tense and lax vowels in the F1×F2 space and tense-lax alternations

CONSONANTAL CONTEXT: a restriction against tense vowels before word-final and/or pre-obstruent consonants (as a shorthand, in closed syllables), and a restriction against lax vowels in word-final position and/or before prevocalic consonants (as a shorthand, in open syllables). Common strategies to avoid these configurations are closed-syllable laxing (CSL) and open-syllable tensing (OST), respectively. Both processes apply in Southern French, as shown in (1a) and (1b) (Coquillon & Turcsan 2012: 110-112).

(1)   Southern French
       a.   Closed-syllable laxing
            _CV   *Sébastien*   [sebastjɛ̃]   (base)
            _C#   *Seb*   [sɛb]/*[seb]   (diminutive)
       b.   Open-syllable tensing
            _C#   *fête*   [fɛt]   'party'   (base)
            _CV   *fêtard* [fetaʁ]/*[fɛtaʁ] 'partier' (derivative)

What is the nature of the constraints that drive CSL and OST? Several authors (e.g. Botma & Van Oostendorp 2012) have suggested that these processes are driven by CONTEXTUAL VOWEL DURATION ADJUSTMENTS: CSL is due to closed-syllable shortening and OST to open-syllable lengthening. The idea that the tense-lax distinction is derived from a more basic long-short distinction was also proposed by Lindau (1978: 557). However, this proposal is problematic because it is not compatible with acoustic theories of vowel reduction (e.g. Lindblom 1963). For instance, closed-syllable shortening should not generally result in vowel laxing, in particular in the consonantal contexts illustrated in (1), i.e. before the major places of articulation (labial, dental/coronal, velar). Vowel reduction is generally characterised by RAISING in these contexts (i.e. decrease of F1), due to stronger coarticulation with adjacent consonants. But vowel laxing is generally characterised by LOWERING (i.e. increase of F1), at least for nonlow vowels /i-ɪ e-ɛ o-ɔ u-ʊ/.

This paper proposes an alternative analysis according to which CSL and OST are motivated by CONTRAST ENHANCEMENT (Stevens et al. 1986), for nonlow vowels specifically. This analysis relies on three main hypotheses. First, nonlow 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 (=H1). Concretely, a sequence [ɛk] may be preferred over a sequence [ek] because [ɛ] provides better perceptual cues than [e] to [k]'s velar place of articulation.

Second, vowel laxing is argued to typically apply before coda consonants as a way to compensate for the absence of good perceptual cues to consonant place in these contexts (=H2). In general, consonant-place contrasts are signaled by two types of acoustic cues: internal cues (e.g. information contained in the burst for oral stops) and external cues provided by adjacent segments, in particular formant transitions into and from adjacent sonorous segments (e.g. vowels). But coda consonants systematically lack RELEASE TRANSITIONS, a major acoustic cue to place provided by a following sonorous segment (e.g. Fujimura et al. 1978; Wright 2004). As a consequence, place contrasts are typically less distinct in coda than in onset (Ohala 1990, 1992; Redford & Diehl 1999). Concretely, laxing may happen in [ɛk] before word-final [k] but not in [eka] before prevocalic [k] because the velar place of articulation of [k] is in need of perceptual enhancement word-finally but not prevocalically.

Third, vowel tensing is argued to correspond to a default preference for more distinct vowel contrasts. Tense vowels are more peripheral than lax vowels in the F1×F2 space and therefore should be more distinct (=H3). Indeed, the first two vowel formants correspond to the main auditory dimensions for the perception of vowels (e.g. Shepard 1972: 78-82). Concretely, [eka] may be preferred over [ɛka] because tense [e] can be more readily distinguished from other vowels than lax [ɛ], due to its greater peripherality.

(H1) *Vowel laxing increases consonant-place distinctiveness in VC:*
   Consonant-place contrasts are more distinct after nonlow lax than after nonlow tense vowels.

(H2) *Vowel laxing as enhancement of poorly cued consonant-place contrasts in VC:*
   Nonlow-vowel laxing applies in contexts where the postvocalic consonant lacks good place cues (in particular, release transitions).

(H3) *Vowel tensing as enhancement of vowel contrasts:*
   Tense vowels are more distinct from each other than lax vowels.

The two enhancement strategies conflict to determine vowel quality in vowel-consonant sequences: the requirement to have distinct enough consonant contrasts favors laxing whereas the requirement to have distinct enough vowel contrasts favors tensing. Language variation results from different ways of resolving this conflict.

The main goal of this paper is to motivate (H1), the most innovative hypothesis of this account. Indeed, (H2) and (H3) should already be familiar to the reader. (H2) plays a central role in typological accounts of contextual place neutralisation/assimilation: it explains why place contrasts are more likely to be neutralised or targeted by assimilation in coda than in onset (Ohala 1990; Jun 2004, 2011). As for (H3), it was formulated at least as early as 1952 by Jakobson et al. (1952: 36-39) and is supported by a range of studies showing that tense vowels are more peripheral than lax vowels (e.g. English: Stevens 1998: 296; Javanese: van Zanten 1989: 72; Québec French: Martin 2002; Southern French: Storme 2017b).

Section 2 presents a survey of languages with CSL and/or OST and shows why these processes cannot generally be derived from contextual adjustments of vowel duration. Section 3 provides preliminary evidence for (H1), using earlier phonetic results on English and other languages. Section 4 further tests (H1) through an acoustic and perceptual study of the effect of mid-vowel laxing in French. Section 5 discusses how (H2) can account for the split between contexts favoring tensing vs. laxing in the languages surveyed in section 2. Section 6 sketches an analysis of the typology of vowel tensing and laxing in the framework of Dispersion Theory (Liljencrants & Lindblom 1972; Flemming 2002). Section 7 concludes with a discussion of the role of duration in the tense-lax distinction.

The enhancement-based 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. If correct, this analysis provides further support for the role of perceptual contrast in driving phonotactic restrictions (Ohala 1990; Steriade 1997; Flemming 2002; Jun 2004; Stanton 2017), and more specifically, for the role of contrast enhancement in phonology (Stevens et al. 1986).

2 Language survey

CSL and OST are widespread phonological processes crosslinguistically. This section builds on a survey of 15 languages with CSL and/or OST plus a few other languages without these patterns. Section 2.1 describes the basic patterns attested in the sample. Section 2.2 shows that OST cannot follow from open-syllable lengthening but may follow from a default preference for better vowel dispersion (=H3). Section 2.3 shows that coarticulatory analyses of CSL do not extend to nonlow vowels before oral stops and fricatives corresponding to the major places of articulation.

2.1 Patterns

The 15 languages included in the survey are shown in Table 1, together with their broad genetic affiliation, phonological inventory of oral vowels, tense-lax (T-L) pairs, and the main source of information. The inventory represents the vowel phonemes in the language (as opposed to the surface vowels). For instance, in Southern French, the phonological inventory only includes one series of mid vowels /e ø o/ because surface tense and lax mid vowels never contrast in the language. The column with tense-lax pairs only reports pairs including vowels subject to OST or CSL in some contexts. For instance, Paluai [u]-[ʊ] is not listed in this column because both vowels occur in V and VC (Schokkin 2014: 38).

		Inventory	T-L pairs	Source
Austronesian	Bario Kelabit	iɛəaɔu	i-ɪ, u-ʊ	Blust 2013, 2016
	Chamorro	ieæaou	i-ɪ, u-ʊ, e-ɛ, o-ɔ	Topping 1973
	Hiligaynon	ieaou	i-ɪ, u-ʊ, a-ɐ	Wolfenden 1971
	Javanese	ieəaou	i-ɪ, e-ɛ, o-ɔ, u-ʊ	Dudas 1976
	Kairiru	ieaou	i-ɪ, u-ʊ	Wivell 1981
	Keley-I	iɛaou	i-ɪ, u-ʊ	Hohulin & Kenstowicz 1979
	Paluai	iieɐouu	i-ɪ, e-ɛ, o-ɔ	Schokkin 2014
	Thao	iau	i-ɪ, u-ʊ	Blust 2003, 2013
Indo-European	Dutch	iieɛəaɑɔoyøœ	i-ɪ, e-ɛ, ø-œ, o-ɔ, a-ɑ	Trommelen 1983: 65
	Southern French	ieəaouyø	e-ɛ, ø-œ, o-ɔ	Coquillon & Turcsan 2012
	Standard French	ieɛəaoɔuyøœ	e-ɛ, ø-œ, o-ɔ	Tranel 1987
	Québec French	ieɛəaɑɔouyøœ	i-ɪ, y-ʏ, u-ʊ	Côté 2012
Niger-Congo	Kuteb	iɨeæaou	i-ɪ, u-ʊ, e-ɛ, o-ɔ, a-ʌ	Koops 2009
	Nchufie	ieɛaɐɔoɯɨu	i-ɪ	Byrd 1994
Penutian	Klamath	ieau	i-ɪ, u-ʊ, a-ə	Blevins 1993

Table 1: Language sample with vowel inventory, tense-lax pairs, and sources.

Table 2 represents the basic patterns that were found in the language sample. Many languages are reported to have both CSL and OST, with tense and lax vowels in complementary distribution. These languages are represented as pattern (a) in Table 2. Pattern (a) is particularly well represented among Austronesian languages (Blust 2013: 263-265): all Austronesian languages in the survey (except for Paluai) belong to pattern (a). Kuteb, Nchufie, Klamath, Québec French, and Southern French are also reported to belong to pattern (a).

	Pattern	Distribution	V and VC	Language
(a)	CSL-OST	complementary distribution	e ɛC	Austronesian languages
(b)	CSL-only	contextual neutralisation	e ɛ ɛC	Standard French ([e]-[ɛ], word-final syllables)
(c)	OST-only	contextual neutralisation	e eC ɛC	Dutch (word-final syllables)
(d)	ATB-contrast	contrast	e ɛ eC ɛC	Paluai ([u]-[ʊ])
(e)	No T-L	no alternation/contrast	e̞ e̞C	Modern Greek

Table 2: Patterns of tense-lax alternations/contrasts and patterns without tense or lax vowels.

But CSL and OST are also attested as independent processes. Patterns with CSL only and with OST only are represented as (b) and (c), respectively. Pattern (b) is attested in Standard French, where only CSL applies to front mid vowels in word-final syllables: [e] and [ɛ] contrast word-finally but only [ɛ] occurs before word-final consonants (Tranel 1987: 51-53). Pattern (c) is attested in Dutch, where only OST applies in word-final syllables: tense and lax vowels contrast before word-final consonants but only tense vowels occur word-finally (Kager 1990). Two patterns involve neither CSL nor OST: pattern (d) and pattern (e). In pattern (d), tense-lax contrasts are allowed across open and closed syllables. For instance, in Paluai, high back vowels [u]-[ʊ] contrast in both contexts (Schokkin 2014: 38). In pattern (e), a single vowel is available across the board (i.e. across open and closed syllables). For instance, in Modern Greek, there is no tense-lax contrast and vowels 'do not exhibit much

variation in terms of quality' (Arvaniti 1999): in particular, they are not reported as having distinct allophones in open and closed syllables.

In languages following pattern (e) and for which phonetic studies are available, vowels are reported to have an intermediary quality (noted /i̞ e̞ a̝ o̞ u̞/) between the corresponding tense and lax vowels in languages where they contrast. For instance, Becker-Kristal's typological study of vowel inventories shows that the average F1 targets for nonlow vowels in five-vowel inventories /i e a o u/ is comprised between the F1 targets of the corresponding tense and lax vowels in nine-vowel inventories /i ɪ e ɛ a ɔ o ʊ u/ (Becker-Kristal 2010: 191, 195). See also Recasens & Espinosa (2006) on Catalan dialects with and without tense-lax contrasts.

A single language may display several of the patterns in Table 2 depending on the context. For instance, in Standard French, [e] and [ɛ] contrast in word-final open syllables but not in nonfinal open syllables (Tranel 1987: 58-62), where the distribution of tense and lax mid vowels tends to conform to pattern (a) (Nguyen & Fagyal 2008: 22-23). In Chamorro, high vowels follow pattern (a) in stressed syllables but pattern (e) in unstressed syllables (Topping 1973: 20). Although the paper will not attempt to provide a systematic explanation for these subtle contextual effects and instead mainly focus on the general, crosslinguistically robust asymmetry between word-final V# and VC#, the existence of contextual variability in the distribution of tense and lax vowels is not surprising. For instance, the fact that tense-lax contrasts are only allowed word-finally in Standard French can be understood as an effect of vowel reduction: there is less target undershoot in word-final syllables due to the presence of stress (see Storme 2017b and citations therein) and therefore more vowel contrasts can be accomodated in this position, in accordance with Flemming's (2005) model of vowel reduction. Similarly, vowel undershoot in unstressed syllables in Chamorro might make the vowel space too compressed to maintain distinct allophones in this position.

2.2 Perceptual motivations for vowel tensing

Because vowels are often longer in open syllables than in closed syllables (Maddieson 1985) and tense vowels are often longer than lax vowels (Lindau 1978), it is tempting to attribute OST and CSL to open-syllable lengthening and closed-syllable shortening, respectively. However, this approach is problematic because tensing and laxing are not expected to result mechanically from lengthening and shortening. This section focuses on OST.

Acoustic theory predicts that vowel lengthening should result in less coarticulation with adjacent consonants (e.g. Lindblom 1963): as a vowel becomes longer, its formant realisations should get more faithful to its formant targets but not necessarily more peripheral. For instance, when lengthened, an underlying /ɛ/ becomes lower and not higher (see Gendrot & Adda-Decker 2005 for evidence in French and German). Therefore, lengthening cannot explain why /ɛ/ is realised as [e] in open syllables in languages with OST.

By contrast, if the location of acoustic targets for vowels is driven by a preference for more distinct contrasts (=H3), vowels are expected to be peripheral in the acoustic space. In a simulation of vowel-inventory selection based on the principle of maximal perceptual contrast, Liljencrants & Lindblom (1972) indeed show that vowels tend to occupy the periphery of the acoustic space.

The hypothesis that vowel tensing corresponds to a default preference for better vowel contrasts (rather than a preference specific to open syllables) accounts straightforwardly

for the distribution of tensing in allophonic patterns (i.e. pattern (a) in Table 2): tensing happens everywhere where CSL does not, i.e. in open syllables. However, the hypothesis seems problematic to account for OST-only patterns (pattern (c)). Indeed, these patterns seem to point to a context-specific preference for tense vowels in open syllables and are therefore potentially problematic for the view of tensing as a default.

This section proposes that OST-only patterns do not actually reflect a direct preference for tensing in open syllables but follow indirectly from a loss of duration contrasts in open syllables. Indeed, in the two OST-only languages in the sample (Dutch and Standard French[1]), the tense-lax contrasts neutralised by OST (all tense-lax contrasts in Dutch, only [o]-[ɔ] and [ø]-[œ] in Standard French) involve both quality and duration, with tense vowels being both longer and more peripheral than lax vowels (e.g. Trommelen 1983 on Dutch, Gottfried & Beddor 1988 on French). Also, the specific open-syllable contexts targeted by OST in these languages (word-finally in the two languages and also before a vowel in Dutch; van der Hulst 1985; Kager 1990; Tranel 1987)[2] are typical contexts for neutralisation of duration contrasts (see Myers & Hansen 2007 on final positions and Sihler 1995: 80 on neutralisation in hiatus, specifically in Latin). Neutralisation of duration contrasts in open syllables ultimately results in neutralisation of quality distinctions and tensing by the following mechanism. Once the long-short distinction has been neutralised, the relevant tense-lax pairs only differ in quality. Assuming this difference alone is not sufficient to support a vowel contrast, quality distinctions are also neutralised. The choice of a tense quality for the resulting neutralised vowel then corresponds to the same default preference for better vowel dispersion as in allophonic patterns.

This duration-based analysis is corroborated by two facts in Dutch and Standard French. In Dutch, tensing does not target all open syllables: it happens in _# and _V but not in _CV (e.g. *auto* [oto] vs. *Otto* [ɔto]; van der Hulst 1985; Kager 1990). This asymmetry is compatible with the current proposal because vowel-duration contrasts are typically neutralised in _# and _V but not in _CV. In Standard French, OST targets [ø]-[œ] and [o]-[ɔ] but not [e]-[ɛ]. And [e]-[ɛ] happens to be the only tense-lax pair that does not involve a durational difference in the language (see section 4). Hence, the distinctiveness of [e]-[ɛ] should not be affected by the loss of duration contrasts word-finally, explaining why this contrast is not targeted by OST in this context.

2.3 Limits of coarticulatory analyses of CSL

Acoustic theory predicts that shorter vowels should be more coarticulated with adjacent consonants. Therefore, if CSL were a coarticulatory consequence of shortening, the resulting lax vowel quality should be explained as a compromise between the acoustic targets for the corresponding tense vowel and the consonantal context in which it occurs (Lindblom 1963).

To get a better sense of the vowels and consonants involved in patterns of laxing in the language sample, the list of tense-lax pairs in Table 1 was supplemented with the information in Table 3 and Table 4. Table 3 lists the consonants occurring in word-final positions for each

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[1]In Standard French, [ø]-[œ] and [o]-[ɔ] may contrast in word-final closed syllables but only [ø] and [o] occur in word-final open syllables. The pair [e]-[ɛ] has a different distribution, as seen in section 2.1.

[2]Only final syllables are relevant in Standard French for OST-only. Nonfinal syllables are targeted both by OST and CSL (see section 2.1).

	Labial	Lab-Dent	Dental	Postalv	Pal.	Velar	Uvul.	Glott.	Source
B. Kelabit	p b m w		t d n l r		j	k g ŋ		ʔ h	Blust 2016: 255-258
Chamorro	p m	f	t n s			k ŋ		ʔ	Topping 1973: 27, 36
Hiligaynon	p b m w		t d n s l r		j	k g ŋ		ʔ	Wolfenden 1971: 17-24
Javanese	p m		t n s l r			k ŋ		h (ʔ)[1]	Dudas 1976: 118-143
Kairiru	p ɸ β m		t n s r/ɾ l	ʃ/tʃ	ɲ	k ŋ			Wivell 1981: 12-23
Keley-i	p m w[2]		t d n l[2]		j	k g ŋ		ʔ h	Hohulin & Kenstowicz 1979
Paluai	p m w		t n l		j	k ŋ			Schokkin 2014: 30-35, 41-43
Thao	p m w	f	t n s r	ʃ	j	k	q		Blust 2003
Dutch	p m	ʋ	t n s l r		j	k ŋ x			Linke 2018
French	p b m	f v	t d n s z l	ʃ ʒ	ɲ j	k g	ʁ		Tranel 1987
Kuteb	p m		t n			k ŋ			Koops 2009: 37
Nchufie						ŋ			Byrd 1994
Klamath	p m[3]		t n s l	tʃ	j	k	q	h	O'Hara 2014

[1] [k] and [ʔ] are in complementary distribution word-finally: [k] occurs after [ə] and [ʔ] after other vowels. [ʔ] comes from [k] historically according to Dudas (1976).

[2] Hohulin & Kenstowicz (1979) do not cite any word ending in [b] or [s] but it could be an accidental gap.

[3] Only plain consonants are shown for Klamath. There is also a series of glottalized consonants [p' m' w' t' n' l' tʃ' j' k' q'], a series of aspirated consonants [pʰ tʰ tʃʰ kʰ qʰ], and a series of voiceless sonorants [m̥ w̥ n̥ l̥ j̥].

Table 3: Consonants available in word-final position in the survey (for Dutch, the table reports consonants available as C_1 in C_1C_2 clusters).

language in the sample, according to the sources listed in the rightmost column. Word-final syllables were chosen to represent vowel-laxing contexts because this is is the most typically documented context for vowel laxing in the sample.[3] For each language and each place of articulation, Table 4 shows whether tense and lax vowels contrast before the coda consonants in Table 3 or not (the presence of contrasts is signaled by C). In case of absence of contrasts, the table indicates whether tense or lax vowels are preferred (T vs. L).[4]

Nonlow vowels. Plausible coarticulatory analyses of nonlow-vowel laxing in VC have been proposed for specific classes of consonants and can account for some of the patterns in the language sample. In some languages, nonlow-vowel laxing is observed specifically before coda liquids (laterals or rhotics; Gick & Wilson 2006). For instance, in Utah English, nonlow vowels have been reported to lax before coda [l] (see Di Paolo & Faber 1990 for references). These patterns have been analysed as coarticulatory, based on the observation that the relevant liquids involve a postvelar (i.e. uvular or pharyngeal) constriction and a retracted tongue root (Gick & Wilson 2006). Indeed, acoustic theory predicts that an increase in back constriction narrowing causes F1 to raise (Stevens 1998: 268) and that therefore greater coarticulation with posterior consonants could result in laxing. Brunner & Żygis (2011) also provide crosslinguistic evidence for nonlow-vowel laxing/lowering in the context of glottal consonants and attribute this effect to tongue retraction.

Laxing of high vowels is also observed specifically before coda nasals. In Paluai, tense

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[3]Laxing is also often reported before clusters but the information on consonants available in clusters is usually hard to find. One exception is Dutch, where tense and lax vowels contrast in VC# and obligatory laxing is only observed before clusters, i.e. in VC_1C_2 (Trommelen 1983: 67-69, Botma & Van Oostendorp 2012). In the case of Dutch, Table 3 therefore lists the consonants available as C_1 in consonant clusters.

[4]When a source reports a general pattern of CSL in a language without further qualification, laxing was assumed to potentially happen before all word-final consonants.

	Labial	Lab-Dent	Dental	Postalveolar	Palatal	Velar	Uvular	Glottal
B. Kelabit	L		L/T[1]			L		T
Chamorro	L/T[2]	L/T[2]	L/T[2]			L		L[3]
Hiligaynon	L		L		L	L		L
Javanese	L		L		L	L		L
Kairiru	L		L	L		L		
Keley-I	T		T		T	L		T
Paluai	L/C[4]		L/C[4]		L	L/C[4]		
Thao	L	L	L	L	L	L	L	
Dutch	L	L	C		L	L		
S. French	L	L	L	L	L	L	L	
Q. French	L	L/T[5]	L/T[5]	L/T[5]	L	L	L	
Kuteb	L		L			L		
Nchufie						L		
Klamath	L		L		L	L	L	L

[1] /i u/ lax to [ɪ ʊ] before all dentals except the rhotic [r].

[2] /i u e/ lax to [ɪ ʊ ɛ] before three major places of articulation; /o/ laxes to [ɔ] only before velars.

[3] Laxing also occurs before prevocalic /ʔ/.

[4] [i ɪ] contrast everywhere except before word-final nasals [m n ŋ], where [ɪ] occurs.

[5] High vowels are always lax except before fricatives [v z ʒ].

Table 4: Distribution of tense and lax vowels before the consonants listed in Table 3 (L: lax vowels only; T: tense vowels only; C: tense-lax contrasts; blank: place of articulation missing in the language or unavailable in this position).

and lax front high vowels [i] and [ɪ] generally contrast word-finally, except before word-final nasals where only [ɪ] is allowed (Schokkin 2014: 36-37). These effects can also be analysed as coarticulatory since nasalisation results in a higher frequency of the first formant for nonlow vowels (Beddor 1993: 180).

These analyses of nonlow-vowel laxing rely on specific articulatory properties of the relevant coda consonants and therefore do not generalise to coda oral stops like /p t k b d g/ or coda fricatives like /s f z v/. Yet many languages lax nonlow vowels before these consonants (see Table 4). One case where the coarticulatory analysis might actually generalise is for coda velars, assuming a slightly more posterior articulation for velars in languages with CSL than for typical velars (Gick & Wilson 2006: footnote 1). For instance, in Keley-I, high vowels lax only before coda velars and this could be explained as coarticulation if /k g ŋ/ are actually postvelar phonetically (e.g. uvular). However, this approach cannot generalise to CSL languages where velars are clearly distinct from uvulars phonetically. For instance, French (where CSL is attested before velars) has both velar and uvular consonants. But velars and uvulars have opposite coarticulatory influences on adjacent vowels: vowels do lower in the context of uvular /ʁ/ (Delattre 1959) but they raise in the context of velars /k g/ (see section 4). Laxing before coda velars can therefore not be attributed to increased coarticulation in French.

An alternative, noncoarticulatory analysis therefore seems to be required for laxing of nonlow vowels before coda consonants like /p t k b d g s f z v/. This conclusion is strengthened by the observation that coarticulation with posterior consonants and laxing before oral stops/fricatives do not necessarily have the same phonetic effects and distribution when they

are both attested in a language. In Thao, high vowels are reported to be subject both to coarticulation with the rhotic [ɾ] (an alveolar flap) and to closed-syllable laxing (Blust 2013: 265). But the two processes are described as having different phonetic effects (lowering vs. laxing, respectively) and different distributions. The coarticulatory effect of the rhotic is both progressive and regressive and not limited to coda contexts (e.g. *turu* [toɾo] 'three'). However, the process of laxing before other consonants is limited to precoda contexts (e.g. *duruk-ik* [ʔdoɾokɪk] 'I stabbed it').

Low vowels. The only vowel for which a coarticulatory analysis is plausible is the low vowel. Indeed, shortening of low vowels is characterised by raising before the major places of articulation (see Lindblom 1963) and so is laxing. The conclusion that low-vowel laxing and nonlow-vowel laxing may be motivated by different mechanisms (despite being usually described as a single process) is not necessarily problematic. First, the two processes have different phonetic effects (decrease of F1 vs. increase of F1, respectively). Second, they do not always cooccur in languages. For instance, many languages in the survey (see Table 1) lax nonlow vowels in closed syllables but not low vowels. The survey does not include any language laxing only low vowels in closed syllables but this could be because these languages are not described as laxing languages. For instance, patterns where a low vowel raises to [ʌ] or [ə] in unstressed syllables are generally described as vowel reduction but not as vowel laxing.

3   The effect of vowel laxing on postvocalic place contrasts

This section proposes that nonlow-vowel laxing before the major places of articulation is motivated by contrast enhancement. Sections 3.1-3.3 focus on the acoustic and perceptual effects of laxing on place contrasts. Section 3.4 provides evidence for two phonological predictions following from the enhancement-based analysis.

3.1   Acoustics

In what follows, the formant value measured right before consonant's closure or after relese is referred to as the consonant's formant realisation. Consonants have different formant realisations depending on the vowel context: through coarticulation, consonants' formant realisations track the formant realisations of adjacent vowels (e.g. Delattre et al. 1955). 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 distinctiveness of place contrasts after lax than after tense vowels.

F1 realisations

Acoustic theory predicts that a consonant's F1 realisation should vary as a function of the speed of the articulator movement involved in producing that consonant: in CV, the F1
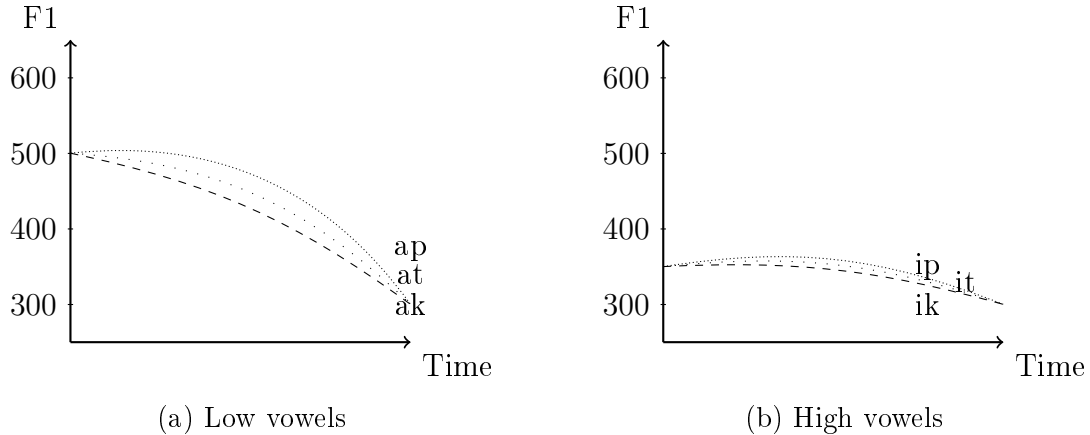
Figure 2: Schematized F1 VC transitions into [p t k] after low and high vowels.

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. The movement is the fastest for labials and therefore labials' F1 onset frequency should be the highest. These predictions were confirmed in a study on F1 realisations of prevocalic /b d g/ in English, where F1([b]) > F1([d]) > F1([g]) (Stevens et al. 1999).

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 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. In this context, 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, F1 transitions should be less distinct in this context than after a low vowel (compare Figures 2a and 2b).

In accordance with this hypothesis, there is evidence that F1 realisations of labials and alveolars are more distinct acoustically before low than before high vowels in English. Looking at the F1 realisations of /p t b d f s v z/ at release before /a i u/, 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 before [a] than before [i] or [u].
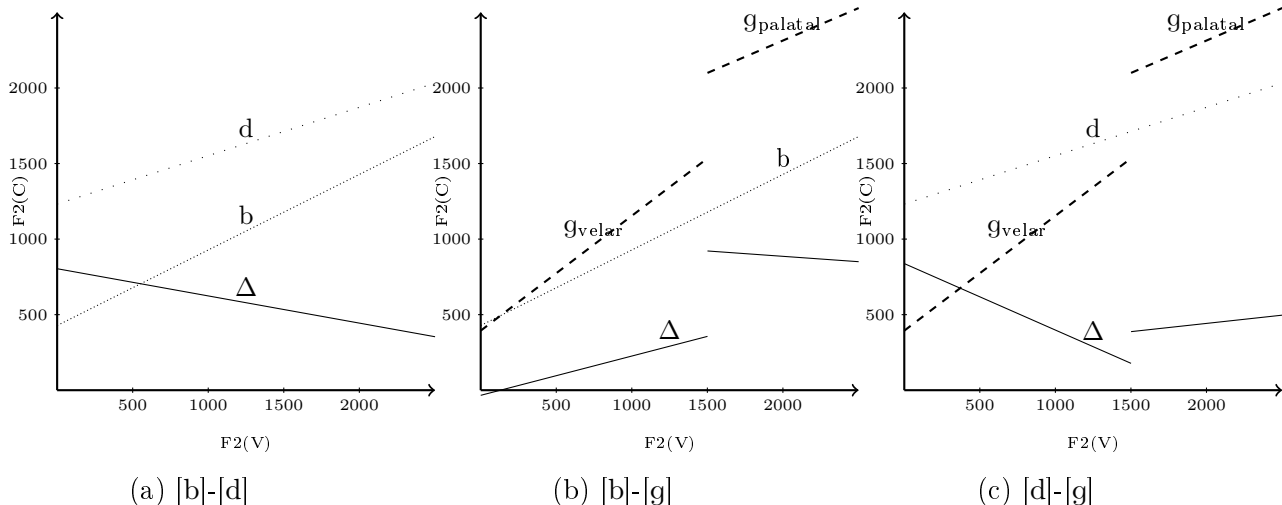
11

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).

Nonlow lax vowels have higher F1 targets than the corresponding tense vowels. Therefore, according to the reasoning above, they should allow for more distinct F1 realisations of postvocalic consonants. However, because the distance between the F1 targets of tense and lax vowels (e.g. /e-ɛ/) is much smaller than that between high and low vowels (e.g. /i-a/), it is important to test whether the increase in distinctiveness is significant. This prediction will be tested in section 4.

F2 realisations

A consonant's F2 realisation also varies as a function of the vowel context and this variation can be characterised by locus equations (e.g. Sussman et al. 1993). 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 English [b d g] in VC sequences (Sussman et al. 1997) can be used to reason about place distinctiveness as a function of the preceding vowel context.

For each pair among /b d 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. The velar is associated with two different locus equations after front and back vowels, each one corresponding to a different allophone (palatal and velar).

Based on these results, two contrasts should be clearly improved by 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). These contrasts happen to be particularly confusable perceptually in these contexts (e.g. Halle et al. 1957; Delattre 1958; Winitz et al. 1972; Ohala & Ohala 2001; Alwan et al. 2011; Marty 2012). For instance, Ohala & Ohala (2001) found that, among the three contrasts involving /p t k/ after /i a u/ in Hindi, [p]-[t] after [i] and [p]-[k] after [u] are the most confusable.

However, in two cases, vowel centralising should actually result in less distinct F2 offsets,

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

namely the dental-velar and dental-labial contrasts after back vowels (see Figures 3c and 3a). However, centralising of back vowels before dentals is unlikely to result in very bad dental-velar and dental-labial contrasts. For instance, 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].

3.2   Perception

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 5. 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 whereas it is never lower than 95% after lax vowels. Contrasts involving [k] are particularly less distinct after tense than lax vowels. Less than 80% of [k] and [t] stimuli are identified correctly after tense front vowels. These results are slightly different from other studies which found that the contrast between [p] and [t] was the most affected in this context (e.g. Ohala & Ohala 2001). 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] stimuli are identified correctly less than 80% of the time. [k]-[p] confusability is likely to drive this result, based on other studies (e.g. Ohala & Ohala 2001).[5]

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[5]The fact that the percentage of correct identification for labial stimuli is not as low as expected should probably be attributed to a response bias towards [p] (see Marty 2012 for a possible explanation of this effect).

3.3 Interim summary

Acoustic theory predicts that lowering should improve the F1 distinctiveness of major place contrasts in VC. Centralising should improve specifically the F2 distinctiveness of contrasts that are particularly confusable after peripheral vowels. As a combination of lowering and centralising, laxing should generally increase the distinctiveness of place contrasts in VC. In accordance with these acoustic results, Lisker's study suggests that the major place contrasts are generally less confusable after lax than after tense vowels in English.

However, Lisker's results on English do not necessarily generalize to languages where tense mid vowels lack offglides (i.e. all languages in the language sample except Dutch; Botma et al. 2012). Indeed, the presence of high offglides in English (e.g. [ej]) could explain part of the results. To avoid this confound, the phonetic study in section 4 will focus on French, a language where mid vowels lack offglides.

Sections 3.1 and 3.2 focused on the three major places of articulation. However, laxing might also increase the distinctiveness of other places of articulation or even other consonantal features. For instance, laxing could also improve contrasts between liquids [l]/[ɫ] and glides [j]/[w]: the lower F1 target for liquids and the higher F1 target for glides (Stevens 1998: 532) should have more distinct realisations in a lower than in a higher vowel. However, a comprehensive exploration of the effect of laxing on postvocalic consonant contrasts is left for future research. The study in section 4 will also focus on the major places of articulation.

3.4 Further phonological predictions

Before moving on to the phonetic study in section 4, this section provides evidence for two phonological predictions following from the hypothesis that lowering/centralising enhances postvocalic place contrasts.

Height and ATR alternations

Lower vowels typically have higher F1 targets and more central F2 targets than the corresponding higher vowels (e.g. [e]-[i] and [o]-[u]). Therefore, one expects to find patterns of open-syllable raising and closed-syllable lowering parallel to OST and CSL. This prediction is borne out. In Dupaningan Agta (Austronesian), mid vowels /e/ and /o/ raise to high vowels [i] and [u] in unstressed open syllables (2a), but raising is blocked in unstressed closed syllables (2b), resulting in high-mid alternations (Robinson 2008: 68-70). The blocking of vowel reduction cannot be attributed to stress: both vowels in (2a) and (2b) are unstressed and Robinson (2008) does not report any secondary stress falling on closed syllables. Similar patterns of high-mid or high-low alternations that cannot be attributed to stress are documented in Latin (Niedermann 1985: 18-31) and in Bedouin Hijazi Arabic (Al Mozainy 1981: 194-195).

(2)   Dupaningan Agta vowel reduction
   a.   /o/ raises to [u] in unstressed open syllables.
         /pot-pot-an/   ['potp**u**tan]   'pluck out'
   b.   /o/ does not raise in unstressed closed syllables.
         /mag-pot-p**o**t/   [mag'potp**o**t]   'harvest by plucking'

[-ATR] vowels are generally characterised by higher F1 targets than corresponding [+ATR] vowels (Lindau 1978). [-ATR] vowels are therefore expected to provide more distinct F1 transitions in VC sequences than [+ATR] vowels. As a consequence, one should observe syllable-based [+ATR]-[-ATR] alternations. This prediction is also borne out. Paulian (1986) documents a pattern of alternation involving ATR in Kàlɔ̀ŋ (Bantu), where some lexemes have [+ATR] vowels /i u/ occurring in open syllables (e.g. [kù-lì̀ᵐb-à] 'bewitch') but [-ATR] vowels /ɛ ɔ/ occuring in closed syllables (e.g. [à-lɛ̀ᵐb] 'witchcraft'). The connection with CSL is due to Hyman (2003).

Neutralisation of place contrasts conditioned on vowel quality

Poor distinctiveness of contrast is known to correlate with phonological neutralisation crosslinguistically (Steriade 1997; Jun 2004). The hypothesis that place contrasts are less distinct after tense/high vowels than after lax/low vowels predicts that one should find languages where place contrasts are neutralised after tense/high vowels but not after lax/low vowels. A preliminary investigation of languages with vowel-specific patterns of consonant-place neutralisation suggests that this prediction is borne out. For instance, in Cantonese, all three places of articulation (labial [p m], coronal [t n], velar [k ŋ]) are available in VC after low vowels [a] and [ɐ] but only subsets of those are available after higher vowels (Hashimoto 1972). 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] (all [m n ŋ] are attested after [ɛ ə a], [m ŋ] are attested after [o ɔ]) but not after high vowels [i u] and [e], after which a single consonant is available ([n] after [i e] and [ŋ] after [u]).

4 Acoustic and perceptual study

Section 3 has motivated the central hypothesis underlying the analysis of CSL as a strategy of contrast enhancement. This section provides a further test of this hypothesis by focusing on Standard French, a language with the three tense-lax pairs /e-ɛ ø-œ o-ɔ/ and where tense vowels lack offglides. Sections 4.1-4.3 describe an acoustic study comparing the formant realisations of /p t k/ after the ten French oral vowels. Sections 4.4-4.5 describe a perceptual study using a subset of the stimuli collected in the acoustic study. Section 4.6 summarises and discusses the results.

4.1 Acoustic study: methods

Two Standard French native speakers (a female and a male) were recorded uttering C_1VC_2 syllables, with V in /i y u e ø o ɛ œ ɔ a/ and C_1 and C_2 in /p t k/. Stimuli were presented graphically to the two speakers. The vowels were represented graphically as <i u ou é eû au è eu o a>, following general orthographic trends in French, and the consonants as <p t k>. French words were provided to illustrate how graphemes should be pronounced (e.g. *eû-eu*: *jeûne* [ʒøn] - *jeune* [ʒœn], *au-o*: *glauque* [glok] - *cloque* [klɔk], etc.).

All syllables were phonotactically licit syllables for those speakers, except for the C_1eC_2 syllables. In Standard French, tense rounded mid vowels [ø] and [o] are licit in word-final

closed syllables (e.g. *côte* [kot] and *meute* [møt]) but the tense unrounded mid vowel [e] is not (Tranel 1987). The two speakers were explicitly told to pronounce the <é> in <CéC> syllables as close-mid [e]. The Belgian pronunciation of the municipality of *Molenbeek* [molœnbek] was used to illustrate the [e] pronunciation in a closed syllable. Acoustic measurements were made to verify that [e]'s formant values and duration in C_1eC_2 syllables were sensible (see section 4.2).

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. The recordings were made using the Audacity software, with 44 kHz/16 bit sampling. Vowels were manually segmented and 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 place distinctiveness, measurements of F1 and F2 were made at the vowel offset, defined as the point located five milliseconds before the end of the vowel. All acoustic analyses were performed using the Praat software (Boersma & Weenink 2017).

The formant frequencies were Bark-transformed and normalized by speaker (using the R function `scale`). R (R Core Team 2017) and lme4 (Bates et al. 2014) were used to perform linear mixed effects analyses of the relationship between the response variables (F1, F2) and the categorical predictors (Height, Backness, C_2) and their interactions. The details of the models will be provided in the next section with the results.

4.2   Acoustic study: results

Acoustic realisation of vowels

Figure 4 summarises the distribution of the ten oral vowels over the F1×F2 space across speakers and consonantal contexts. The results are generally compatible with previous studies 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). The average vowel durations are reported in Table 6 (with standard deviations). /o ø/ are longer than their lax counterparts /ɔ œ/, as found in other studies (e.g. Gottfried & Beddor 1988). Leaving /o ø/ aside, lower vowels are generally longer than higher vowels, in accordance with Lehiste's (1970) crosslinguistic findings.
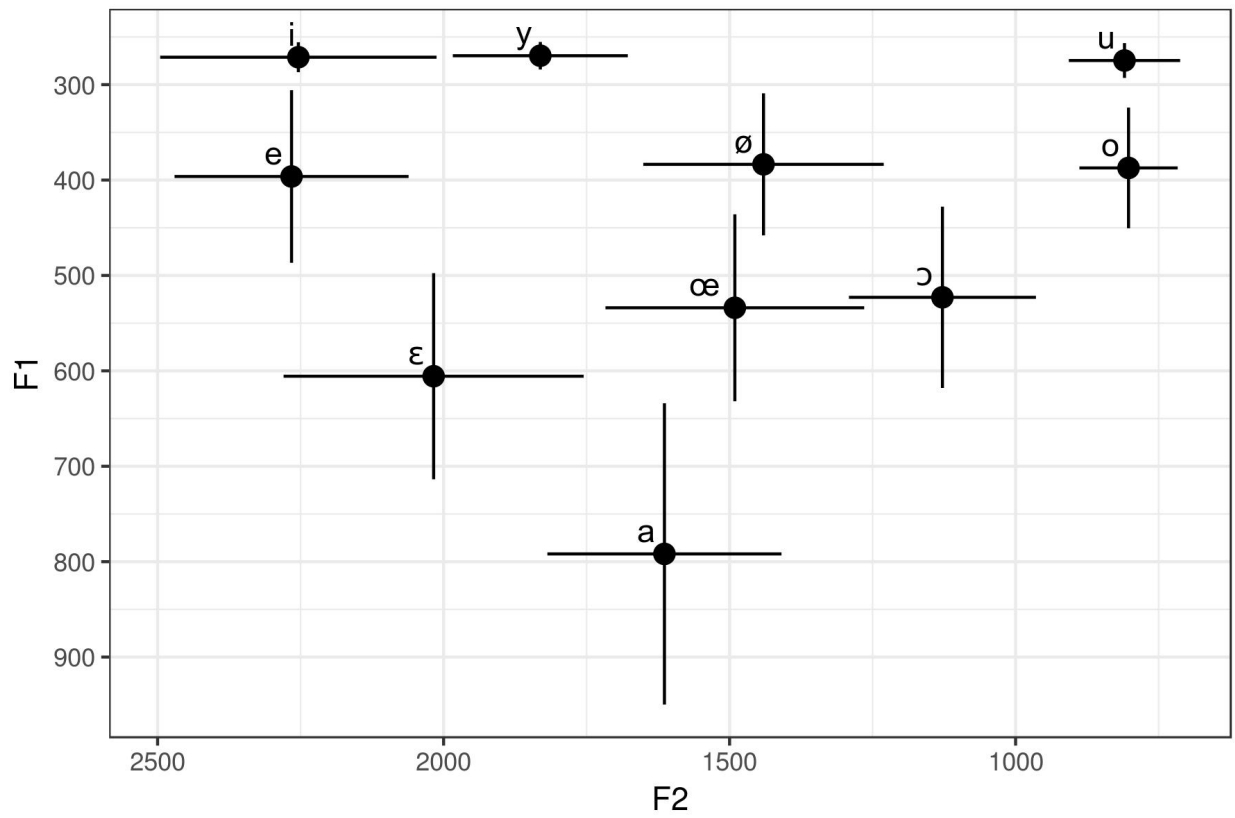
Figure 4: Mean vowel F1 and F2 (in Hz) with standard deviations (measured at vowel midpoint).

Vowel	Mean duration (ms)	Standard deviation
i	88	21
y	96	19
u	98	20
e	113	16
ø	126	21
o	127	21
ɛ	112	14
œ	115	21
ɔ	116	13
a	118	14

Table 6: Average vowel duration (in ms) with standard deviations.

As previewed in section 4.1, [e] is the only French oral vowel that is phonotactically illicit in the context elicited in this study. It is important to check that the realisation of [e] in this context is coherent with typical realisations in contexts where [e] is available in French (e.g. in absolute word-final position). The formant and duration data reported in Figure 4 and Table 6 suggest that it is. As found in other studies (e.g. Ménard et al. 2008), the F1 realisation of [e] is aligned with the F1 realisations of the other tense mid vowels [ø o]. The F2 realisation of [e] in the present study is also consistent with the results in Ménard et al. (2008). The fact that [e] was not found to be longer than its lax counterpart [ɛ] is also in accordance with descriptions of Standard French, which report tense-lax durational differences only for rounded mid vowels.

F1 realisations of consonants

Figure 5 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 (front unrounded, front rounded, back rounded), and C_2 (/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 C_2. This model was compared to more complex models that were able to converge, using likelihood ratio tests. But the increase in model complexity was not justified by an improvement in fit. In particular, including C_1 in the model (along with interactions involving C_1 and all other variables) was not found to significantly improve model fit ($\chi^2(54)$=42.571, p=.8693). The P-values reported below were obtained using the lmerTest package (Kuznetsova et al. 2015).

After high vowels, the F1 realisations of /p t k/ were not found to be significantly different. After tense mid vowels, the F1 realisation of [k] was found to be slightly lower than that of [t] but this effect did not reach significance (β=-.11, se=.07, p=.10). After lax mid vowels, the
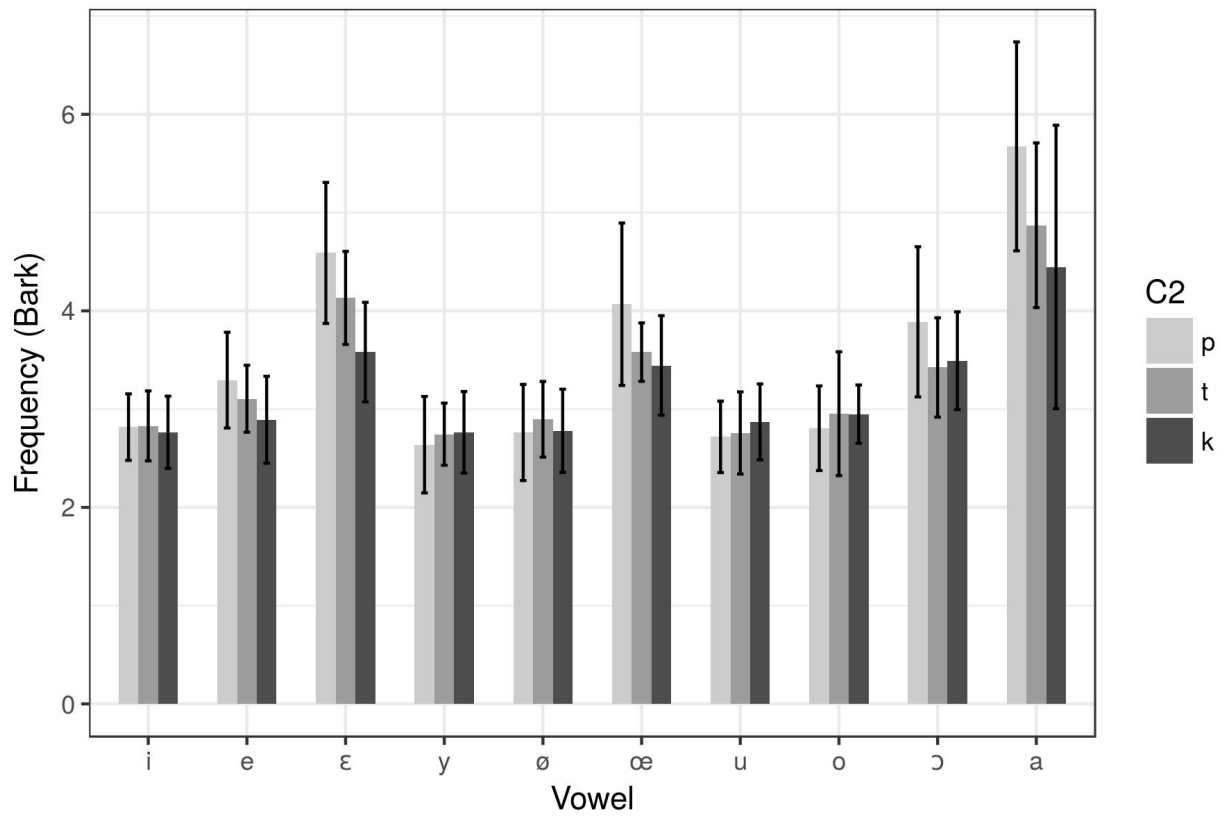
Figure 5: Vowel F1 before /p t k/ five milliseconds before the end of the vowel (mean and standard deviation).

F1 realisation of [k] was found to be lower than that of [t] (β=-.20, se=.07, p=.003) and the F1 realisation of [p] was found to be higher than that of [t] (β=.41, se=.07, p=2.91e-09), i.e. F1([k]) < F1([t]) < F1([p]; see Stevens et al. 1999 for similar results on English). However, the effect of laxing on the [k]-[t] F1 distance is probably entirely driven by [ɛ], as indicated by the significant three-way interaction of Height, Backness, and Consonant (β=-.213179, se=.09, p=.025032). These findings are summarised in Table 7.

F2 realisations of consonants

Figure 6 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). As for F1, the low vowel was excluded from the analyses.

The three models differed in the way Backness and C_2 were coded: in the first model, the baseline for comparison was front unrounded vowels before [t]; in the second model, it was back rounded vowels before [p]; in the third model, it was front rounded vowels before [k]. Analysing the effect of Height on consonant's F2 realisations within a single level of Backness was easier because Backness had a large effect on consonant's F2 realisations (as expected) and three-way interactions of Height, Backness, and C_2 were difficult to interpret in a single model.

As fixed effects, the three models included Height, Backness, C_1 and C_2, all two-way and three-way interactions involving Height, Backness and C_2, and all two-way and three-way interactions involving Backness, C_1 and C_2. The random effect structure included a by-speaker random intercept, a by-speaker random slope for Height, and a by-speaker random slope for C_2.

These models were compared to more complex models that were able to converge, using likelihood ratio tests. The increase in model complexity was not justified by an increase in model fit. In particular, the model including all interactions of the four variables Height, Backness, C_1 and C_2 as fixed effects did not provide a significantly better fit to the data ($\chi^2(36)$=33.437, p=.5911). Concretely, this means that the effect of Height on the F2 realization of C_2 can be analyzed independently from C_1 in this dataset. Indeed, the final model does not include any interaction involving both C_1 and Height and yet does not provide a worse fit than the full model including these interactions. The effect of Height on the F2 realisation of C_2 reported below is averaged across the three different values for C_1.

The results are summarised in Table 7 and described in more details in the following paragraphs.

Front unrounded vowels. After [e], [t] and [k] were found to have significantly different F2 realisations (β=.585181, se=.113657, p=.01090) but not [t] and [p] (β=-.048941, se=.146368, p=.77159). After [i], the [t]-[k] distance is significantly decreased compared to after [e] (β=-.323961, se=.114374, p=.00483) but the [t]-[p] distance is not (β=-.039210, se=.114374, p=.73190). Concretely, this means that /p t k/ are generally more similar along F2 after [i] than after [e]. After [ɛ], the distance between the F2 realisations of [t] and [p] (and as a consequence of [p] and [k]) is significantly increased compared to after [e] (β=-.238779, se=.114374, p=.03740) but the [t]-[k] distance is not (β=.034635, se=.114374, p=.76217).

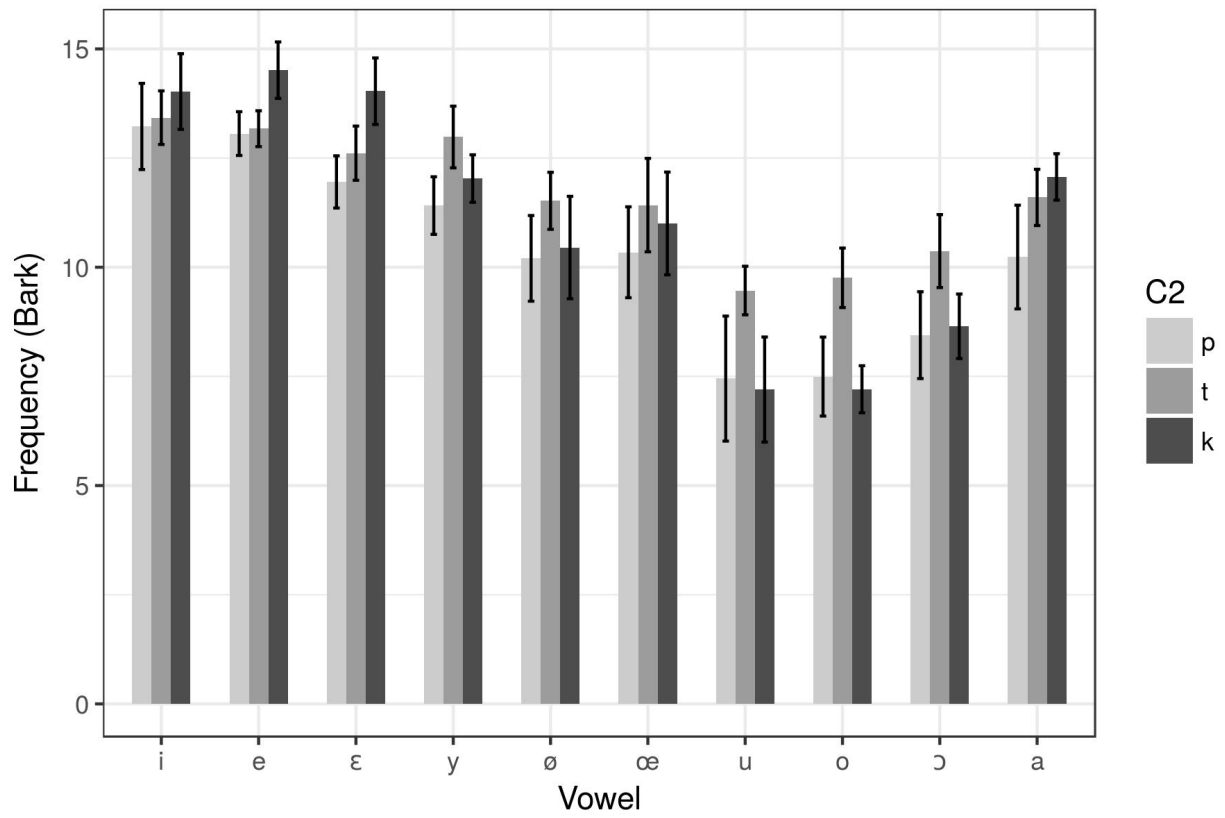Figure 6: Vowel F2 before /p t k/ five milliseconds before the end of the vowel (mean and standard deviation).

	F1						F2					
	i-e	e-ε	y-ø	ø-œ	u-o	o-ɔ	i-e	e-ε	y-ø	ø-œ	u-o	o-ɔ
Δ_{pt}	=	✓	=	✓	=	✓	=	✓	=	✗	=	=
Δ_{pk}	=	✓	=	✓	=	✓	✓	✓	=	=	=	=
Δ_{kt}	=	✓	=	=	=	=	✓	=	=	✗	=	=

Table 7: Summary of the acoustic study.

Concretely, this means that /p t k/ are generally more distinct along F2 after [ε] than after [i] and [e].

Back vowels. After [o], [p] and [t] have significantly different F2 realisations (β=.98955, se=.14637, p=.024593) but [p] and [k] do not (β=-.12689, se=.09119, p=.189658). There is no significant effect of Height on the F2 distances between /p t k/ after back vowels. This means that raising F2 (i.e. centralising) from [o] to [ɔ] does not affect the F2 distinctiveness of /p t k/.

Front rounded vowels. After [ø], the F2 realisation of [k] is significantly different from both [p] (β=-.27426, se=.11259, p=.021798) and [t] (β=.32589, se=.13145, p=.048227). The distances between /p t k/'s F2 realisations are not significantly different after [ø] and after [y]. However, the F2 distance between [k] and [t] (and therefore between [t] and [p]) decreases significantly after [œ] as compared to after [ø] (β=-.28426, se=.11437, p=.013313). The distance between [k] and [p] does not vary significantly after [ø] and after [œ]. Concretely, this means that /p t k/ are generally more distinct along F2 after [y] and [ø] than after [œ].

4.3   Acoustic study: summary

For each pair of vowels differing in Height, Table 7 summarises whether the F1 or F2 acoustic distance between the two consonants in the correponding row is (i) larger after the lower vowel than after the higher one (indicated by ✓), (ii) larger after the higher one than after the lower one (indicated by ✗) or (iii) not significantly different after the two vowels (indicated by =).

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/, in accordance with the predictions of acoustic theory laid out in section 3.1. The increase was observed for all pairs after [ε] but only for the pairs involving [p] after rounded vowels [ɔ œ]. This difference could be due to the fact that [ε] had a higher F1 value than [œ ɔ] in this study (see Figure 4).

The results for F2 do not straightforwardly support the predictions laid out in section 3.1. For front unrounded vowels [e]-[ε], mid-vowel laxing was found to increase the distance between the F2 realisations of [p t], as expected. But it was also found to increase the F2 distinctiveness of [p k], a result that was not particularly expected (the F2 distance between /p/ and /k/ appeared roughly constant across front vowels in Figure 3b). For back rounded vowels [o]-[ɔ], mid-vowel laxing (i.e. centralising) was not found to have any effect on F2 distinctiveness, contrary to what was predicted in section 3.1. For front rounded mid vowels

[ø]-[œ], vowel laxing was actually found to decrease the F2 distance between consonant pairs involving [t]. This is a bit surprising since the two vowels do not have very different F2 targets. However, the English stimuli used to establish the locus equations that served as a basis for the predictions in section 3.1 did not include central vowels like /ø/ and /œ/ (see Sussman et al. 1997: 2828). Therefore, these locus equations are probably not fully appropriate to estimate how small vowel-F2 variations in the center of the F2 range could affect place distinctiveness.

4.4   Perceptual study: methods

A third of the stimuli recorded in the acoustic study (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.

Both English and French speakers were recruited to participate in the study. There were two main reasons for this choice. First, perception is known to be language-dependent (e.g. Iverson et al. 2003) and therefore it is important to test whether the effects hypothesised here are robust across different languages. Second, as previewed in section 4.1, the tense front mid vowel [e] is phonotactically illicit before word-final consonants in French and, because phonotactics may influence perception (e.g. Dupoux et al. 1999), this could affect French listeners' performance on place discrimination after this vowel. By contrast, English phonotactics are not expected to confound the results in the same way because the tense front vowel is available before word-final consonants in English.

85 participants took part in an online experiment. 43 English speakers were recruited through Mechanical Turk and were paid 3.5 dollars for their participation. 42 French speakers participants were recruited through the CNRS RISC mailing list 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. Participants were instructed to identify the final consonant among /p t k/. They all indicated that they wore headphones while taking the test.

Confusion matrices were built for the two groups of listeners (French listeners vs. English listeners), collapsing across speakers, listeners, and C_1 within each group. These confusion matrices indicate how many times each of the three stimuli (/p t k/) was identified as each of the three possible responses (/p t k/) in the 10 vowel contexts. The confusion matrices were analyzed using Luce's (1963) Biased Choice Model (BCM). This model infers measures of stimulus similarity and response bias from a confusion matrix and may be used as a model of identification tasks. The reader is referred to Luce (1963) for more details.

BCM was implemented as log-linear model in R and fit to the confusion matrices. Two contextual parameters (vowel and listeners' native language) were added in the model in order to obtain estimates of consonant similarity after different vowels for each of the two groups of listeners. Only the estimates of the perceptual distances between the stimuli are reported.[6]

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[6]The perceptual distance d between two sounds corresponds to the negation of the logarithm of their
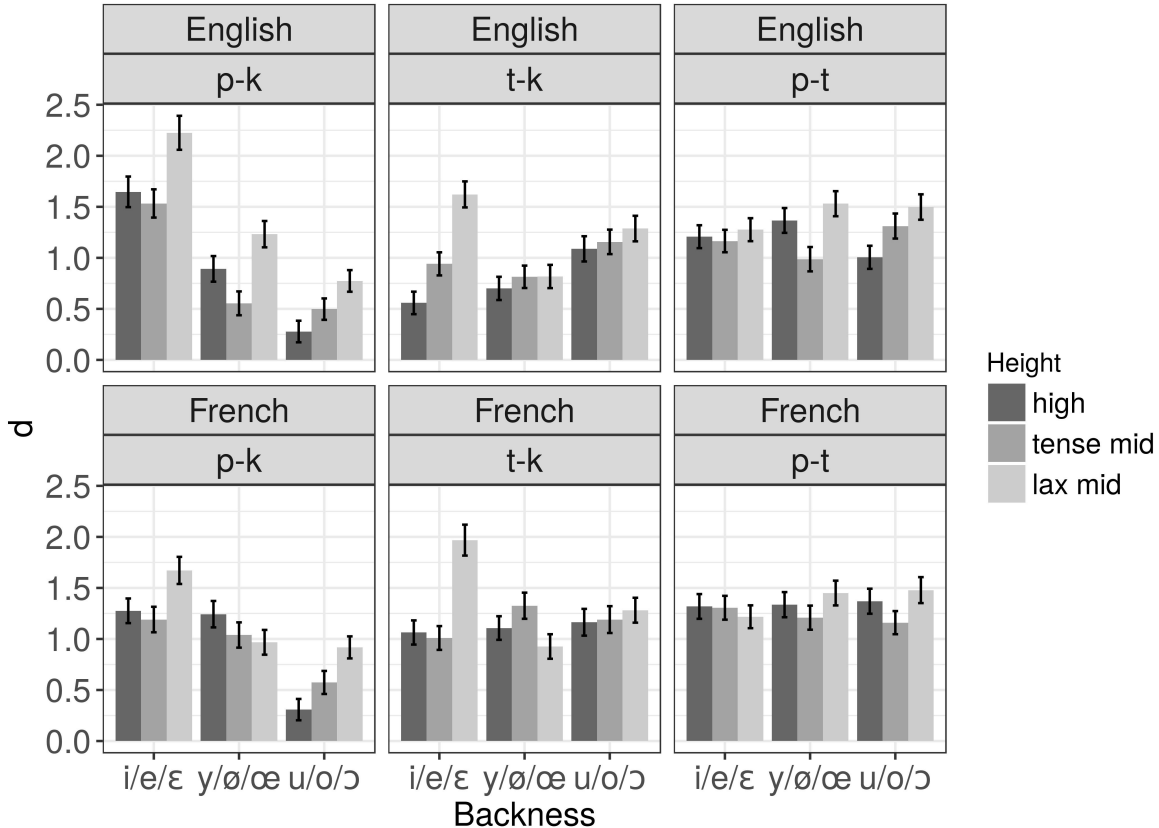
23

Figure 7: Perceptual distances between [p], [t], and [k] after French high, tense mid, and lax mid vowels. Error bars represent standard errors.

4.5 Perceptual study: results

Figure 7 shows, for each pair of consonants and each vowel, the estimated perceptual distance between the two consonants after this vowel. Overall, the distance between [k] and [p] varies greatly as a function of the identity of the preceding vowel whereas the distance between [p] and [t] much less. This is consistent with the finding that the identification of [k] is the most dependent on vowel transitions and the identification of [t] the least (Cooper et al. 1952; Winitz et al. 1972).

Front unrounded vowels [i e ɛ]. [p]-[k] and [t]-[k] were found to be significantly more distinct after [ɛ] than after [e] (β=-.5868262, se=.1415571, p=3.39e-05; β=-.8196235, se=.1280375, p=1.54e-10). The perceptual improvement due to laxing before [p] and [k] was found to be slightly smaller for the French listeners but this effect did not reach significance (β=.1712542, se=.0932194 , p=0.066194). However, laxing was not found to increase (or decrease) the distinctiveness of [p]-[t]. Place contrasts were not found to be less distinct after [i] than after [e], except for [t]-[k] for English listeners (β=-0.2182685, se=0.1145982, p=0.056827).

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similarity η (with $0 < \eta < 1$), i.e. $-\log \eta$. This ensures that complete identity, i.e. $\eta = 1$, corresponds to a perceptual distance of zero, and complete dissimilarity, i.e. $\eta = 0$, corresponds to an infinite perceptual distance.

	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
Δ_{pt}	=	✓	=	✓	=	✓	=	✓	=	✗	=	=
Δ_{pk}	=	✓	=	✓	=	✓	✓	✓	=	=	=	=
Δ_{kt}	=	✓	=	=	=	=	✓	=	=	✗	=	=

(a) Acoustic distances.

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

(b) Perceptual distances.

Table 8: Summary of the results.

Back vowels [u o ɔ]. [p]-[k] and [p]-[t] were found to be significantly more distinct after [ɔ] than after [o] (β=-.3100310, se=.1079595, p=.004082; β=-.2525653, se=.1220524, p=.038516), and this independently of the listeners' language background. However, laxing was not found to increase (or decrease) the distinctiveness of [t]-[k] in either group. Raising from [o] to [u] was found to significantly decrease the distinctiveness of [p]-[k] (β=.2426410, se=.1070332, p=.023392), and this independently of native language. Raising had opposite effects on the distinctiveness of [p]-[t] in the two groups of listeners: it improved the contrast for French listeners but made it worse for English listeners (β=-.2581656, se=.1180126, p=.028698).

Front rounded vowels [y ø œ]. The results for front rounded tense vs. lax mid vowels are less consistent across the two groups of speakers. Only [p]-[t] was found to be consistently more distinct after [œ] than after [ø] for both groups (β=-.392479, se=.120324, p=.001107). For [t]-[k], the results suggest a slight decrease in distinctiveness after [œ] as compared to after [ø] across the two groups (β=.198065, se=.118170, p=.093718), but this effect is most likely entirely driven by the French listeners (β=.201387, se=.118170, p=.088340). For [p]-[k], the results suggest an increase in distinctiveness after [œ] as compared to after [ø] across the two groups (β=-.303190, se=.122834, p=.013576), but this effect is probably entirely driven by the English listeners (β=.0.374572, se=0.122834, p=.002293). The effects of raising from [ø] to [y] on place distinctiveness are more consistent across the two groups. Raising actually improves place distinctiveness for [p]-[k] (β=-.270954, se=.123954, p=.028821) and [p]-[t] (β=-0.253392, se=.120546, p=.035550), and this independently of language background. Raising was not found to have any significant effect on the distinctiveness of [t]-[k] in either group.

4.6 Summary and discussion

The results of the acoustic and perceptual studies are summarised in Table 8. In Table 8b, the symbol on the left side of the slash corresponds to the results for English listeners, the one on the right to French listeners. There is a single symbol when the results were the same for both groups of listeners.

For each tense-lax mid-vowel pair [e]-[ɛ] and [o]-[ɔ], two place contrasts are perceptually improved after the lax vowel as compared to after the tense vowel, and these are the same contrasts for both groups of listeners. In other words, each consonant among /p t k/ is involved in a contrast that is improved by vowel laxing, and the effect is robust across the two languages. Note that, for [e], the results are the same for English and French listeners regardless of phonotactic acceptability in each language.

The acoustic study shows that the perceptual improvement after lax [ɛ] and [ɔ] 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. However, an increase in the F1 distance is not sufficient to guarantee a perceptual improvement after these vowels (see [p]-[t] after [e] vs. after [ɛ]). Further work is needed to better establish what drives the perceptual improvement after lax vowels and what is the contribution of F1.

For the tense-lax pair [ø]-[œ], the results are as expected for the English listeners (two place contrasts are improved by laxing and this improvement correlates with an increase in the distance between the F1 realisations of the relevant consonants) but not for the French listeners (one contrast is improved by laxing, another one is actually made less distinct). The contrast that is made perceptually less distinct by laxing ([p]-[k]) is actually less distinct along F2. The French listeners might have relied on a complex combination of F1 and F2 as perceptual cues for place after front rounded vowels whereas the English listeners relied more on F1.

Anyhow, laxing does not robustly improve place contrasts in the case of front rounded mid vowels. This raises the question why closed-syllable laxing should ever affect these vowels in languages like Southern French. Two answers can be considered. Listeners in these languages might rely on the same acoustic cues as the English listeners. Alternatively, laxing of the front round mid vowel in closed syllables could be driven by a pressure to align this vowel with the other vowels of the same height ([ɛ] and [ɔ]). Alignments of vowels along F1 beyond what is predicted by perceptual dispersion have been observed, in Catalan (Recasens & Espinosa 2006) and in French (Ménard et al. 2008) for instance.

Lowering high vowels to tense mid vowels does not result in greater consonant distinctiveness for the French listeners. This fact may explain why high vowels are not lowered/laxed before word-final and preobstruent consonants in European French: the loss in vowel distinctiveness is not compensated by a gain in place distinctiveness for these listeners. For the English listeners, lowering was actually found to improve three out of six place contrasts. This suggests that English listeners might be sensitive to acoustic cues that are ignored by the French listeners. However, the acoustic study does not provide any clear explanation for the perceptual results for high vs. tense mid vowels. The reason for this might be due to the fact that only formant trajectories' endpoints were considered. Whole trajectories are conceivably important to identify consonant place in vowels with high F1 targets, since endpoints are very close to each other.

5 Laxing as enhancement of poorly cued consonant-place contrasts

The preceding sections have motivated the hypothesis that nonlow-vowel laxing increases the distinctiveness of postvocalic consonant-place contrasts. This section now briefly addresses the hypothesis that laxing is used to compensate for the absence of strong perceptual cues to the consonant's identity in VC. This section focuses specifically on how the enhancement-based analysis can account for conditionings that go beyond the basic split between word-final/preobstruent and prevocalic consonants. The patterns discussed are taken from the languages surveyed in section 2.

5.1 Preliquid and preglide consonants

In several languages, preliquid and preglide consonants are reported to be syllabified as onset consonants and therefore to favor tensing, like prevocalic consonants. For instance, in Chamorro, stressed nonlow vowels are obligatorily tense before _C{l, r}V and _CwV (Topping 1973: 38-40). This pattern is also found in the different varieties of French, in Javanese (Yallop 1982: 300), and in Kairiru (Wivell 1981: 34-35). According to the cue-based hypothesis, liquids and glides typically pattern with vowels because they have formant structure and therefore can provide sufficiently informative release transitions to a preceding consonant (Flemming 2007).

5.2 Preobstruent vs. word-final consonants

In some languages, word-final consonants and preobstruent consonants pattern differently with respect to laxing. In Dutch, tense and lax vowels contrast before word-final single consonants but not before clusters, unless all consonants in the cluster are dental (in this case, tense-lax contrasts are allowed, e.g. *b*[e]*ld* 'idea' vs. *g*[ɛ]*ld* 'money'). Before nondental clusters, all vowels are systematically lax (Trommelen 1983: 67-69). In Javanese, all nonlow lax vowels /ɪ ɛ ɔ ʊ/ are available before word-final consonants but only [a] and [ə] are available before preobstruent consonants in the native vocabulary (Dudas 1976: 10).

These asymmetries are expected in the current approach if consonant-place contrasts are more distinct word-finally than within a cluster. Coarticulation with the following consonant in a C_1C_2 cluster is likely to weaken C_1's internal place cues and make C_1 less perceptible than word-finally.[7] The hypothesis that laxing happens preferentially in contexts where C_1 has worse place cues then explains why laxing may occur in VC_1C_2 but not in $VC_1\#$ in Dutch.[8] The Javanese pattern may receive a similar explanation: nonlow vowels are required to lower all the way to /ə/ or /a/ before clusters but not before word-final consonants because

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[7]This hypothesis is also needed to explain why place neutralisation is more likely in C_1C_2 than in $C_1\#$. For instance, in casual speech in Kiowa, place contrasts are neutralised in C_1C_2 but not word-finally (De Lacy 2002: 357-358).

[8]The reason why dental clusters in Dutch behave differently is not entirely clear. One possibility is that dentals benefit less from the information provided by formant transitions than labials and velars (see Winitz et al. 1972: 1313 and section 4 in this paper).

place contrasts are less distinct and therefore more in need of enhancement in clusters than word-finally.

5.3   Consonants preceding schwa and high vowels

Two languages in the survey present exceptions to the generalisation that prevocalic consonants favor tensing. In Javanese, preschwa syllables (_Cə) and syllables followed by word-final high vowels (_C{i, u}#) pattern with closed syllables with respect to laxing: they must be preceded by a lax mid vowel /ɛ ɔ/ (Yallop 1982: 302). Similarly, in Southern French, mid vowels are lax in preschwa syllables (Coquillon & Turcsan 2012).

The fact that high vowels or schwa may favor laxing as compared to other vowels can be derived in the present analysis if these vowels provide less informative place cues to a preceding consonant. The reason could be that these vowels are short (and typically subject to syncope across languages) and therefore do not provide sufficiently distinct release transitions (or do not provide any release transitions in case of syncope). The hypothesis that laxing in these contexts is related to the duration of the vowel in the following syllable is supported by Storme's (2017a) experimental results according to which French speakers who lax mid vowels in preschwa syllables (i.e. Southern speakers) have shorter schwas on average than speakers who do not (i.e. Northern speakers).

5.4   Geminate vs. singleton consonants

In some languages, laxing is observed not only before clusters but also before geminates (e.g. Chamorro; Topping 1973). The fact that geminates might pattern differently from singletons receives an explanation under the cue-based approach if clusters (e.g. [ikta]) are more confusable with geminates (e.g. [itːa]) than with singletons (e.g. [ita]), due to geminates' longer closure duration. Vowel laxing before geminates is then used to enhance the contrast between the closure transitions going into the geminate and the closure transitions going into the first consonant of the competing cluster (e.g. [ɪtːa]-[ɪkta]). In the case of singletons (e.g. [ita]), the consonant closure is too short for the consonant to be confused with a cluster and laxing is superfluous.

6   Dispersion-theoretic analysis

The preceding sections have motivated the main hypotheses underlying the enhancement-based analysis of CSL and OST. This section sketches a preliminary dispersion-theoretic analysis of the typology of tense-lax vowels based on these hypotheses. The analysis is simplified in several respects. In particular, vowel duration will not be included although it was argued to be crucial to explain OST-only patterns like Dutch (see section 2.2) and patterns of low-vowel raising in closed syllables (see section 2.3). The main goal of this section is to pave the way for a more comprehensive analysis that would include both formant and temporal information.

6.1 Model

A key hypothesis in Dispersion Theory (DT; Liljencrants & Lindblom 1972; Flemming 2002) is that sounds used in languages should be sufficiently distinct in order to allow for an efficient communication between language users. For this reason, this theory is well suited to model patterns of contrast enhancement. This paper follows the implementation of DT in Optimality Theory proposed by Flemming (2008) and elaborated upon by Stanton (2017: chapter 1). Contrast preservation is ensured by a constraint which favors large phonological inventories over smaller ones. Contrast neutralisation or enhancement is made possible by a set of constraints which favor more distinct contrasts over less distinct ones.

The specific grammatical architecture used by these authors is modular, with the selection of sound inventories and the selection of sound sequences belonging to two distinct modules: the sounds of a language are selected in a first module (the inventory module), these sounds are then concatenated and coarticulated according to a language-specific phonetic grammar (the phonetic-realisation module), and the resulting sound sequences are evaluated as to their phonotactic well-formedness (in the phonotactic module). This modular architecture is convenient because it makes it possible to treat inventory selection and phonotactics as distinct optimisation problems and therefore to keep the analysis simple by focusing on a single problem at a time. This section focuses on the phonotactic problem.

6.2 Analysis

To simplify, only two tense-lax pairs will be considered in the analysis, [i]-[ɪ] and [u]-[ʊ]. Vowel inventories are selected in an auditory space with two dimensions, corresponding to the auditory correlates of F1 and F2. According to Liljencrants & Lindblom's (1972) model, the best dispersed five-vowel inventory in this space is /i e a o u/, with the three cardinal vowels and two mid vowels. In general, lax high vowels have similar F1 and F2 targets as the corresponding mid vowels (see Figure 1). Therefore, the five-vowel inventory can be transcribed as /i ɪ a ʊ u/. This latter notation will be used in order to make the tense-lax pairs [i]-[ɪ] and [u]-[ʊ] appear more clearly.

Because tense-lax alternations and contrasts are the main focus in the paper, the inventory without any tense or lax vowels (i.e. /i̠ a̠ u̠/; see Table 2e, section 2.1) is not considered in this analysis. This pattern could arguably be derived in a more comprehensive model including not only perceptual but also articulatory factors, as will be discussed in section 6.3. Similarly, the lax low vowel is not included in the inventory because low-vowel laxing in closed syllable was analysed as vowel reduction in section 2.3 and not as enhancement.

The following minimal consonant inventory is assumed: $/C_1\ C_2/$, where C_1 and C_2 stand for two consonants with different places of articulation among labial, dental, and velar (see Schwartz et al. 2012 for a discussion of consonant-place features in the context of DT). In addition, it is assumed that, for all possible phonetic grammars for VC coarticulation, (i) the contextual realisations of /i a u/ are always more distinct than the contextual realisations of /ɪ a ʊ/ and (ii) contextual realisations of C_1 and C_2 are always more distinct after lax vowels /ɪ ʊ/ than after tense vowels /i u/.

The phonotactic module evaluates the well-formedness of concatenations over the set of sounds. There is a total of $5 + 5 \times 2 = 15$ V and VC syllables that can be formed by con-

	Pattern	Distribution	V and VC	Attested/Predicted
(a)	OST-CSL	allophony	i a u ɪC$_{1,2}$ aC$_{1,2}$ ʊC$_{1,2}$	✓/✓
(b)	CST-OSL	allophony	ɪ a ʊ iC$_{1,2}$ aC$_{1,2}$ uC$_{1,2}$	✗/✗
(c)	OST-only	contextual neutralisation	i a u iC$_{1,2}$ ɪC$_{1,2}$ aC$_{1,2}$ ʊC$_{1,2}$ uC$_{1,2}$	✓/✗
(d)	CSL-only	contextual neutralisation	i ɪ a ʊ u ɪC$_{1,2}$ aC$_{1,2}$ ʊC$_{1,2}$	✓/✓
(e)	CST-only	contextual neutralisation	i ɪ a ʊ u iC$_{1,2}$ aC$_{1,2}$ uC$_{1,2}$	✗/✗
(f)	OSL-only	contextual neutralisation	ɪ a ʊiC$_{1,2}$ ɪC$_{1,2}$ aC$_{1,2}$ ʊC$_{1,2}$ uC$_{1,2}$	✗/✗
(g)	ATB-contrast	contrast	i ɪ a ʊ u iC$_{1,2}$ ɪC$_{1,2}$ aC$_{1,2}$ ʊC$_{1,2}$ uC$_{1,2}$	✓/✓
(h)	ATB-tensing	no alternation/contrast	i a u iC$_{1,2}$ aC$_{1,2}$ uC$_{1,2}$	✗/✓
(i)	ATB-laxing	no alternation/contrast	ɪ a ʊ ɪC$_{1,2}$ aC$_{1,2}$ ʊC$_{1,2}$	✗/✗

Table 9: Patterns attested vs. patterns predicted by the duration-free DT model.

catenating the five vowels and two consonants considered here. There are as many candidate syllable inventories as there are nonempty subsets of the set of V and VC concatenations (i.e. $2^{15} - 1$). However, this analysis only considers a small subset of candidates, i.e. the nine patterns in Table 9 (/VC$_{1,2}$/ is used as a shorthand for /VC$_1$ VC$_2$/). These patterns correspond to the nine possible ways of distributing the three tense-lax patterns (tensing, laxing, and tense-lax contrasts) in two contexts (V and VC). The rightmost column indicates which among those patterns are attested in the language survey in section 2.

Pattern (b) is an unattested pattern of allophonic distribution with open-syllable laxing (OSL) and closed-syllable tensing (CST). Patterns (e) and (f) have only OSL and CST, respectively. In patterns (h) and (i), there are no tense-lax alternations or contrasts and vowels are tense and lax across the board, respectively. These patterns are considered unattested because, in inventories without tense-lax alternations or contrasts, vowels are reported to have an intermediary quality between the corresponding tense and lax vowels (see section 2.1).

The patterns in Table 9 are evaluated by a constraint-based phonotactic grammar. The text file with the candidates and their violation profiles is available in the supplementary material (under the name `typology.txt`). A constraint assigns a violation for each syllable among the 15 basic V and VC syllables that is missing in the relevant candidate inventory. This constraint has the effect of favoring large syllable inventories over small ones (see Flemming's MAXCONTRAST constraint).

A family of constraints assigns violations to syllable pairs according to the perceptual distinctiveness of their internal segments (see Flemming's MINDIST constraints). For instance, the pair [ɪC$_1$]-[ʊC$_1$] violates a constraint requiring the distance between two vowels to be strictly larger than the [ɪ]-[ʊ] distance. This constraint is not violated by the more distinct pair [iC$_1$]-[uC$_1$] and therefore will favor more distinct vowel contrasts, as desired. In `typology.txt`, vowel-dispersion constraints penalise vowel contrasts in the following order, from the least to the most distinct one: [i]-[ɪ], [ɪ]-[a], [u]-[ʊ], [ʊ]-[a] > [ɪ]-[ʊ] > [ɪ]-[u], [ʊ]-[i]. Contrasts among cardinal vowels are not penalised by any constraint. This ordering enforces a preference for /i u/ over /ɪ ʊ/.

Similarly, the pair [uC$_1$]-[uC$_2$] violates a constraint requiring the distance between [C$_1$] and [C$_2$] to be strictly larger than allowed after [u]. This constraint is not violated by [ʊC$_1$]-[ʊC$_2$], because a lax vowel allows for more distinct VC transitions into [C$_1$] and [C$_2$], and therefore will favor more distinct place contrasts, as desired. In `typology.txt`, a place-

dispersion constraint penalises [iC$_1$]-[iC$_2$] and [uC$_1$]-[uC$_2$] but no constraint penalises the more distinct [ɪC$_1$]-[ɪC$_2$] and [ʊC$_1$]-[ʊC$_2$].[9]

6.3   Results

The software OT-Help 2.0 (Staubs et al. 2010) was used to run a factorial typology using `typology.txt` as input. The analysis' predictions are indicated in the rightmost column in Table 9.

The analysis correctly predicts that CSL and OST should be attested as phonological processes (patterns (a) and (d)) but not CST and OSL (patterns (b), (e), (f)). It also correctly predicts that tense-lax contrasts may be maintained across the board (pattern (g)) and that there should be no default preference for lax vowels (pattern (i)).

One potentially problematic prediction concerns OST. OST is not predicted to be attested as an independent process. Indeed, it cannot occur alone (pattern (c) is ruled out). This result is not surprising because the model does not include any context-specific preference for tense vowels: if tensing is observed in open syllables, then it should be observed in closed syllables as well. It was argued in section 2.2 that OST-only patterns are best analysed as driven by a neutralisation of duration contrasts. Therefore modeling this type of patterns would require a richer notion of vowel distinctiveness, involving both formants and duration.

Among patterns without tense-lax alternations or contrasts, the analysis derives the apparently unattested pattern with across-the-board tensing (Table 9h). This candidate is the best candidate in terms of vowel dispersion among all candidates (a) to (g). It can be derived when maximal vowel dispersion is required (e.g. when the vowel-distinctiveness constraints are top-ranked). This problematic prediction could arguably be avoided in a more comprehensive model where the preference for maximal dispersion is counterbalanced by a preference for less articulatory effort in small vowel inventories. Indeed, in such a model, the three-vowel inventory /i̩ a̩ u̩/ could be preferrable over the better dispersed three-vowel inventory /i a u/ because /i̩ a̩ u̩/ have less extreme formant targets than /i a u/ and are therefore less difficult to produce (see Becker-Kristal 2010: 15).

7   Conclusion

This paper gave a primary role to vowel quality in explaining the crosslinguistic preference for lax vowels in closed syllables and tense vowels in open syllables. Vowel laxing enhances poorly cued postvocalic consonant-place contrasts by providing more distinct formant (in particular F1) transitions into a following consonant. In contexts where postvocalic consonant-place contrasts need not be enhanced, vowel tensing enhances vowel contrasts by providing more distinct formant realisations for vowels. The hypotheses that underly this account were supported by phonetic and typological evidence.

But duration was also attributed a primary role to explain the distribution of vowel tensing in languages where the tense-lax distinction involves both quality and duration and to explain patterns of low-vowel laxing. Section 6 briefly discussed how these patterns could

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[9]No place distinctiveness constraint refers to /a/ because all candidate inventories include /aC$_1$/ and /aC$_2$/ and therefore would all violate this constraint identically.

be derived in a more comprehensive model where contextual effects on vowel dispersion along both formant and temporal dimensions are integrated.

This section briefly concludes by discussing the relationship between vowel quality and vowel duration in tense-lax patterns. On purely articulatory grounds, lax vowels should be longer than tense vowels since lower vowels require a greater articulatory movement and are generally longer than high vowels (Lehiste 1970). This raises the question why lax vowels are often shorter than tense vowels (Lindau 1978).

In languages where tense and lax vowels are in allophonic distribution, laxness and shorter duration might go together because contexts where the postvocalic consonant lacks good cues to place generally happen to be contexts that trigger vowel shortening, i.e. consonant clusters and word-final consonants (see Maddieson 1985 on closed-syllable shortening and Katz 2012 on vowel compression before clusters in English). However, if laxing and shortening are caused by different mechanisms, they should not always have the same distribution. And indeed, in Southern French, mid-vowel laxing applies before coda [s], but mid-vowel shortening does not (Storme 2017b).

In languages where tense-lax contrasts are signaled both by vowel-quality and vowel-duration differences, covariation of duration and quality is probably best understood in terms of enhancement, as originally proposed by Stevens (1998: 294-299): differences along the two acoustic dimensions enhance each other to signal phonemic distinctions. This conclusion is strengthened by the fact that tense vowels are not always longer than lax vowels in systems with tense-lax contrasts. For instance, in Standard French, no durational difference is reported for contrasting tense [e] vs. lax [ɛ]. In Italian, lax mid vowels /ɛ ɔ/ are actually reported to be longer than their tense counterparts /e o/ (Kenstowicz 2010), in accordance with Lehiste's (1970) results on inherent vowel duration.

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