

Obstruent voicing before sonorants. The case of West-Flemish.

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Abstract

This article reports on an acoustic study of voicing in obstruents followed by a sonorant across a word boundary in two dialects of Dutch: East- and West-Flemish. In both varieties only gradient phonetic voicing was typically found in word-final stops when a sonorant followed in the next word. In addition, West-Flemish showed optional categorical voicing in word-final pre-sonorant fricatives. The voicing of fricatives is argued to be phonological, as it extends beyond the scope of automated coarticulation, and as the data pattern to form a distinct phonetic voicing target. However, the phonetic results do not support the hypothesis that West-Flemish sonorants are laryngeally specified, and thus able to spread voicing to neighbouring fricatives. Instead, fricative voicing is proposed to be an optional positional realisation in West-Flemish. Although the process cannot be directly motivated by reference to the phonological specifications of the segments surrounding its target, it makes sense in terms of perceptual factors leading to diachronic reanalysis. The West-Flemish positional variation may arise when partially voiced fricatives are perceived and subsequently reanalysed as categorically voiced by listeners, as proposed by Jansen (2004). It is further argued that fricatives are more likely than stops to be reinterpreted as voiced, as additional acoustic cues prevent voiced percepts in passively voiced stops.

1 Introduction

For a number of languages it has been reported that a word-final obstruent assimilates in voicing to the initial sonorant segment in the next word. This process, which we shall call pre-sonorant voicing, appears in the descriptions of Quito Spanish (Robinson, 1979; Lipski, 1989), Catalan (Wheeler, 1986; Hualde, 1992), Poznań-Kraków Polish (Rubach, 1996), West-Flemish (De Schutter and Taeldeman, 1986; Weijnen, 1991), and Breton (Ternes, 1970) and Slovak (Blaho, 2008). Pre-sonorant voicing is phonologically problematic, partly owing to its recurrent properties: positional application, apparent activity of non-contrastively specified [(+)voice] in sonorants, and targeting only subclasses of obstruents. Identified for a number of languages, these properties have spawned a debate among the proponents of different grammatical architectures. This

paper studies the phonetics of pre-sonorant voicing in one of the attested cases, West-Flemish, and discusses the consequences of the phonetic findings for the interpretation of pre-sonorant voicing in phonology.

Pre-sonorant voicing tends to be positionally restricted to final (word-final, prefix-final, or syllable-final) obstruents¹. An example is Ecuadorian Spanish /s/-voicing, as reported by Robinson (1979), and confirmed by Lipski (1989). In Highland Ecuadorian Spanish, an underlying /s/ undergoes voicing when a vowel follows in the next word, as illustrated in (1-a). However, /s/ does not undergo prevocalic voicing within a word, as shown in (1-b).

- (1) Prevocalic /s/ in Ecuadorian Spanish (Robinson, 1979; Lipski, 1989)

- a. /as ido/ [a.zi.ðo] ‘has gone’
- /los otros/ [lo.zo.tros] ‘the others’
- b. /a sido/ [a.si.ðo] ‘has been’
- /kasa/ [ka.sa] ‘house’

The same positional restriction has been reported for Dutch. As illustrated in (2), word-final fricatives can be voiced preceding vowel-initial words and in compounds, but not word-medially (De Schutter and Taeldeman, 1986).

- (2) Pre-sonorant voicing in Dutch

- /dat mens is/ [dat.men.zis] ‘that person is’
- /ras+ɛχt/ [ra.zɛχt] ‘pure bred’
- /jasən/ [ja.sən] ‘coats’

The voicing of fricatives preceding a vowel has been reported to occur in all of the Southern Dutch dialects (De Schutter and Taeldeman, 1986). Additionally, the voicing of fricatives preceding sonorant consonants across word-boundaries has been reported for West-Flemish, as exemplified in (3).

- (3) Voicing of word-final fricatives preceding sonorant consonants in West-Flemish
(De Schutter and Taeldeman, 1986)

- /zes jaːr/ [zɛz.jaːr] ‘six years’

Word-medially, fricatives followed by sonorant consonants only occur in borrowed words such as *moslim* ‘muslim’, *islam*, and *kosmos*. The realisation of the fricative as voiced or voiceless in these words seems to be variable (cf. Simon (2010, 135)).

The special status of word-final segments has received multiple explanations, couched within competing theories on the structure of the phonological component. Colina (2009) proposes that codas in Ecuadorian Spanish cannot license laryngeal features.

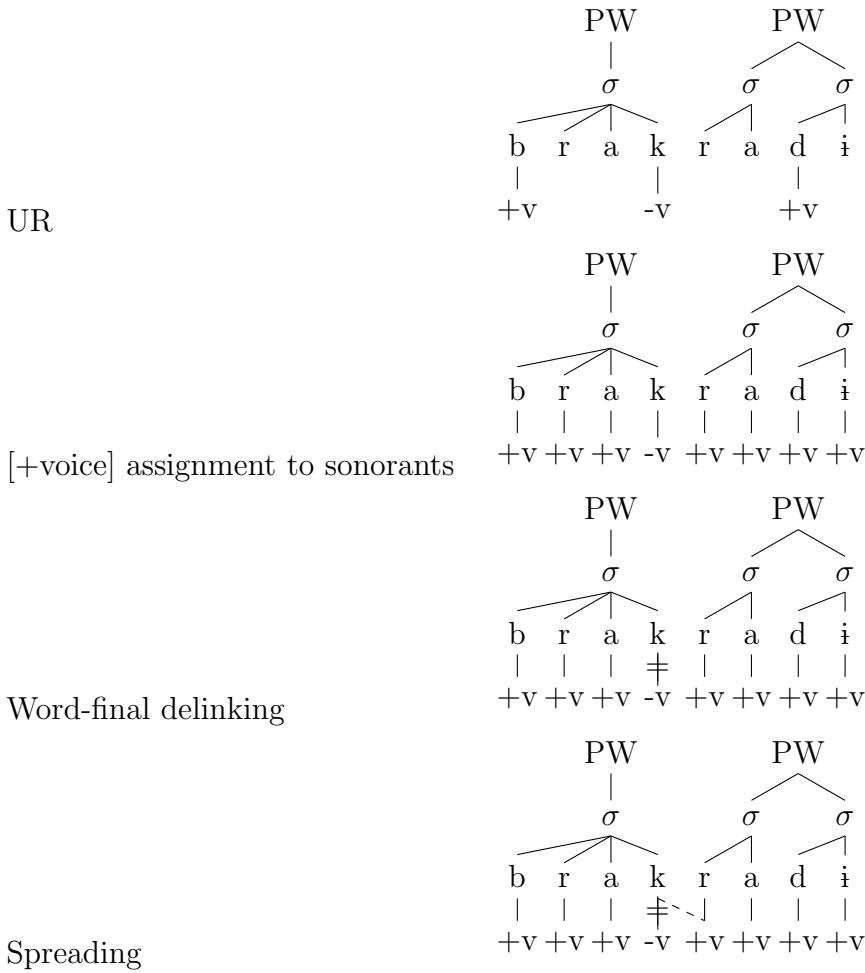
¹Bradley and Delforge (2006), citing Torreblanca (1978, 1986a,b), give the Spanish dialects spoken around Toledo, Ávila, and Cáceres as a counterexample since, according to Torreblanca, voicing applies in those dialects to prevocalic sibilants across the board.

This suggestion is linked to Itô's (1986) idea of prosodic licensing. In order to satisfy constraints against laryngeal features in the coda, an underlying /s/ becomes a laryngeally unspecified archiphoneme S in the output of phonology. S then receives its voicing by phonetic default, which involves phonetic voicing when a voiced sound follows.

The analysis proposed by Colina (2009), as pointed out by Bermúdez-Otero (2011), involves one crucial empirical prediction, i.e. that prevocalic voicing must be phonetic, i.e. variable and gradient. If the Ecuadorian Spanish /s/-voicing is found to be categorical, then it constitutes a case of phonological opacity, underapplying in the word-medial context, as shown in (1-b). Opaque processes like this cannot be easily accommodated within a single level model of phonology, such as parallel OT (Prince and Smolensky, 2004 [1993]), and have been argued to require multiple levels of derivation. Bermúdez-Otero (2011) provides just such a formalisation of Ecuadorian /s/-voicing, by proposing that word-final obstruents undergo delaryngealisation at the word level, followed by (phonological) voicing and resyllabification at the phrase level. Bermúdez-Otero concedes, however, that although phonological pre-sonorant voicing necessitates postulating a multilevel phonology, the existence of such a process is an empirical question, and one that has not, as yet, been settled.

Assuming, for the moment, that there is phonological pre-sonorant voicing, the source of voicing need also to be addressed. Sonorants (comprising nasals, laterals, rhotics, glides, and vowels) are rarely contrastively voiced, most certainly not in Flemish, Spanish, Catalan or Polish. Kiparsky (1985) argues that, in the absence of contrastive voicing, sonorants should not be lexically specified for [(+)voice]. A possible solution, adopted by Booij (1995) and Rubach (1996) is that the feature [+voice] is filled in for sonorants by a redundancy rule. Further to the rule's application, [+voice] spread may occur in the postlexical phonology, as shown in (4).

- (4) Spreading analysis of Poznań-Kraków voicing by Rubach (1996)



Redundant [(+)voice] specification of sonorants and spreading are also incorporated in the analyses by Jiménez and Lloret (2008) and Bermúdez-Otero (2001), who propose constraints and constraint interactions which condition [(+)voice] spreading from sonorants to a laryngeally unspedied obstruent after a redundancy rule specifying these sonorants for [voice] has applied.

However, it is not accepted by everyone that sonorants should be laryngeally active. Jansen (2004) states that only actively voiced sounds are able to trigger anticipatory voice assimilation, actively voiced sounds being the ones whose voicing is a result of a pre-planned gesture. Jansen argues that no such planning is present for sonorant voicing. Instead, sonorant voicing follows spontaneously from the low supraglottal pressure associated with the open articulation².

²Jansen (2004, 36) provides the following definition of spontaneous (passive) voicing: "Sounds or parts of sounds are said to be passively voiced if a closed equilibrium position of the vocal folds and normal subglottal pressure (according to Stevens (1998), 8000 dyne/cm² / 800 Pa is typical) are sufficient to initiate or maintain the physical conditions for vocal fold vibration. Sonorants are typical examples of passively voiced sounds: because their supralaryngeal articulations allow air to escape freely from the supraglottal vocal tract (either through the oral or nasal tract or both) the

Where does pre-sonorant voicing come from then? In the light of Jansen's proposal, the process is blocked unless a sonorant follows, but the actual source of voicing is the preceding vowel rather than the following sonorant. Sonorants, as previously explained, are inherently voiced. Once vocal folds have been set into motion, for instance during sonorant production, they naturally keep on vibrating for a certain amount of time (40 ms is the average estimate by Westbury and Keating (1986); cf. an illustration of a voicing tail in Figure 8) unless an actively voiceless target follows. If the following sound is *actively* devoiced, some devoicing gesture may be executed by the speaker that counteracts voicing, such as raising the larynx, tensing the vocal tract walls, glottalisation, or glottal abduction.

However, word-final obstruents in final-devoicing languages do not have their own voicing targets in Jansen's (2004) model. Thus, in these obstruents uncounteracted passive voicing can continue longer. Prolonged passive voicing can make obstruents be perceived as categorically voiced by listeners. Such perceptions, in turn, might give rise to reinterpretation as a categorical pattern, which eventually stabilises as a result of language change. In that way, pre-sonorant voicing is synchronically a reflection of a perceptually motivated diachronic change, but the synchronic grammar need not necessarily directly refer to the factors that motivate the change in question.

The final peculiarity of pre-sonorant voicing is that it tends to target only a subclass of obstruents, typically fricatives or sibilants. Reports of pre-sonorant voicing in West-Flemish single out fricatives as the undergoers of voicing, while similar reports of stops are absent³. Collins and Mees (1999, 214) note that voiced realisations are frequent in Dutch coda *fricatives* (emphasis added) followed by a vowel. Similarly, De Schutter and Taeldeman (1986) report that in West-Flemish word-final fricatives are usually realised as voiced when the next word begins in a sonorant. Finally, Simon (2010) found pre-sonorant voicing in fricatives, but not in stops in the production of West-Flemish speakers. A similar situation is found in Ecuadorian Spanish, where prevocalic voicing is restricted to sibilants. Word-final stops are also exempted from pre-sonorant voicing in most Catalan dialects⁴.

Stops pattern with fricatives with respect to final devoicing and voice assimilation to obstruents, which makes the pre-sonorant asymmetry puzzling. Most authors attribute the disparate behaviour of the obstruent subclasses to phonetics. Wheeler (2005) proposes an articulatory explanation implemented in a specific constraint (**LAZYSIBILANT**) which voices sibilants before a vowel. However, the generalisation that intervocalic voicing is natural holds for both stops and fricatives, and Westbury and Keating (1986) show how voicing may be favoured in intervocalic stops. This being the case, should not a constraint like **LAZYSTOP** also be posited? An analysis that draws constraints

supraglottal pressure during these sounds remains approximately equal to atmospheric pressure.”

³There are, however, reports of stop voicing word-finally before a vowel, e.g. /pɔ:t/ is/ → [pɔ:dɪs] in some Limburg dialects and in the northwest of East Flanders (De Schutter and Taeldeman, 1986)

⁴Jiménez and Lloret (2008) report a dialect continuum in Catalan, where all dialects except Central Valencian have sibilant voicing before vowels. In addition to sibilant voicing, Central Catalan has (variable) /f/ voicing, while Alicantino is reported to voice all obstruents.

from independently motivated observations concerning phonetic naturalness ought to admit LAZYSTOP alongside with LAZYSIBILANT. It might be that LAZYSTOP is implicitly assumed in Wheeler's (2005) analysis but is absent from the tableaux, as its low ranking suppresses its activity in the language. But what is the source of this putative low ranking? Is it a universal observation that fricatives are more prone to voicing than stops? Such generalisation does not square with the typological rarity of voiced fricatives, as reported by Ladefoged and Maddieson (1996)⁵. If, on the other hand, the ranking of LAZYSIBILANT and LAZYSTOP is free, and Catalan just happens to disfavour intervocalic stops, the question of where this sort of ranking may come from still remains.

Alternative proposals involve linking voicing to sonority (Jiménez and Lloret, 2008), or continuancy (Bermúdez-Otero, 2001). However, these accounts receive theoretical and typological, but not functional support, as the authors offer little discussion of why sonority or continuancy might affect voicing.

This article reports phonetic findings on pre-sonorant voicing from 6 West-Flemish speakers, and addresses the following research questions:

1. Does a phonetic analysis of new data confirm the existence of pre-sonorant voicing in West-Flemish fricatives, as opposed to stops?
2. If so, do we find categorical (phonological) or gradient (phonetic) voicing?
3. Is there any phonetic evidence for sonorants having active voicing targets, or do we need to look for an alternative explanation?

§2 presents the experiment used to study the properties of pre-sonorant voicing in Dutch, and introduces the method employed to analyse voicing. §3 presents the results, which show that there is a clear dialectal difference between West- and East-Flemish, as pre-sonorant fricatives undergo optional but categorical voicing in West-Flemish, but in East-Flemish they surface as either partially voiced or voiceless. Neither of the dialects shows a significant effect of pre-sonorant stop voicing. §4 proceeds to reconcile these findings in the diachronic perspective, by arguing that categorical voicing in pre-sonorant fricatives is a result of perceptual reinterpretation which did not affect stops, due to the presence of additional acoustic cues. §5 concludes the discussion.

2 Materials and method

A production experiment was carried out to study the phonetics of West-Flemish pre-sonorant voicing. The experiment consisted in recording the pronunciation of test stimuli which were presented in writing to the participants.

⁵Fur further discussion on the role of naturalness in stop vs. fricative voicing see Silverman (2006, 164–65) and Section 4 of this paper.

2.1 Speakers

12 native speakers of Dutch participated: 6 from West Flanders (WF) and 6 from East Flanders (EF). The participants were all female, aged 19-47. Participation was voluntary, and the subjects were not paid.

2.2 Stimuli

The test items including stops were monosyllabic words ending in /aut/, or /aud/, followed by a trochaic word beginning in a sonorant segment (/m/, /n/, /r/, /l/, /w/, /j/, /ɛ/), as exemplified in (5-a). The test items for fricatives were monosyllabic words ending in /i:s/, or /i:z/⁶ followed by a trochaic word beginning in sonorant (including vowels), as shown in (5-b).

(5) Sample test items

- a. Stops
koud muntje
'cold mint'
- b. Fricatives
Fries liefje
'Frisian boyfriend/girlfriend'

The test items were embedded in a standard carrier sentence, as shown in (6).

(6) The carrier sentence

- '*Was een koud muntje, we, geen koud nootje.*'
'It was a cold mint, not a cold nut.'

The dialectal marker *we* was used in the stimuli presented to the West-Flemish speakers. A corresponding marker *ze* was used in the version for the East-Flemish controls.

In order to establish the baseline for voicing measurements, tokens of word-final obstruents followed by obstruents in the next word were also included. Voiced obstruents are not expected to surface word-finally in Dutch, except when a voiced stop follows in the next word. Although external voice sandhi is inherently variable (Slis, 1985), the sandhi context is the only available baseline for voicing in word final position, since Dutch obstruents are devoiced before a pause. Thus, the previously included test items were also put in the context where a voiced labial stop followed in the next word. Similarly, the context of following voiceless labial stops was used as the baseline for voiceless. Examples of the control items are in (7).

(7) Sample control items
koud boontje

⁶While the vowel in the adjective of the target items was thus held constant before voiced and voiceless fricatives (/i:/), and before voiced and voiceless stops (/au/), no four adjectives could be found with the same vowel before underlying voiced and voiceless fricative and stops.

‘cold bean’
koud peertje
‘cold pear’

Tokens of word-final obstruents followed by fricatives (/f/, /v/) in the next word were also included, but fricatives were consistently found to be the undergoers, rather than triggers of voice assimilation, which is in line with the established generalisations for voicing in Dutch (Booij, 1995). Thus, the results from the fricative context will not be counted or discussed here.

2.3 Procedure

The stimuli were randomised for each speaker, and presented, one at a time, on a computer screen. The experiment was self-timed, and the speakers were encouraged to produce the utterances at a natural speed. The recordings were made in a quiet room, using a Marantz Professional solid state recorder (PMD620), with a Sony condenser microphone (ECM-MS907) placed on a stand. The recordings were sampled at 44 kHz.

Altogether 4 (obstruents: /t/, /d/, /s/, /z/)*9 (contexts: /m/, /n/, /r/, /l/, /w/, /j/, /ɛ/), /p/, /b/)*12 (speakers)*2 (repetitions)=864 utterances were recorded. 66 utterances were discarded due to reading errors, mispronunciations, or hesitations, leaving 798 utterances for analysis.

2.4 Acoustic analysis

Acoustic analysis was performed using Praat (Boersma and Weenink, 2010), on a 5 ms Gaussian window. The spectrograms were analysed visually and segmented manually. Based on the inserted boundaries, the following measurements were made.

(8) Acoustic measurements made for stops:

- 1.Duration of the preceding vowel.
- 2.Stop closure duration. The closure was taken to be the period of low acoustic energy between the preceding vowel and the following stop release.
- 3.Duration of voicing during stop closure, based on the presence of the voicing bar on the spectrogram.
- 4.Duration of the burst, based on the presence of high frequency noise following the closure phase of the stop. The absence of burst was coded as 0.
5. F_0 at 20 ms and 10 ms before the onset of the stop, using the autocorrelation algorithm in Praat.
6. F_1 at 20 ms and 10 ms before the onset of the stop, using the Burg algorithm in Praat.

(9) Acoustic measurements made for fricatives:

1. Duration of the preceding vowel.
2. Duration of the frication noise.
3. Duration of voicing during frication, based on the presence of the voicing bar on the spectrogram.
4. F_0 at 20 ms and 10 ms before the onset of frication, using the autocorrelation algorithm in Praat.
5. F_1 at 20 ms and 10 ms before the onset of frication, using the Burg algorithm in Praat.
6. Maximum intensity at high frequencies (bandpass filtered from 500 to 10000 Hz).
7. Minimum intensity at low frequencies (bandpass filtered from 0 to 500 Hz).

During the analysis of the recordings, it became apparent that some West-Flemish speakers have a split in their production of the *ou* vowel. While all East-Flemish speakers produced it as a monophthong, the pronunciation of the West-Flemish speakers varied between monophthongal [u:] and diphthongal [au]. The variation was not categorically lexically conditioned (both variants were found in the production of *koud*, *zout* and *fout*), but the majority of monophthongal realisations were found with *koud*, which skewed the vocalic measurements. To avoid this problem, all of the vocalic measurements (vowel duration, F_0 and F_1) in the context of a stop were discarded from the subsequent statistical analysis.

2.5 Statistical analysis

The statistical analysis had two aims. The first was to find an exponent of voicing based on all the different voicing-related measurements that had been taken. The second aim was to examine the effect of environment on voicing in the two dialects of Belgian Dutch.

The statistical analysis was performed using R (R Development Core Team, 2005), version 2.11.1. The exponent of voicing was obtained by using a classification analysis. Linear Discriminant Analysis (LDA) was chosen as the classification method, and it was run with the MASS package (Venables and Ripley, 2002). LDA is used to find a linear combination of multiple numeric variables that best expresses the given response categories. The linear reduction was obtained by running the analysis on a training set which consisted of the baseline tokens (stops/fricatives followed by voiced and voiceless stops which were treated as categorically voiced and voiceless). Two separate analyses were applied to stops and fricatives, since different acoustic measurements had been made for these two groups. For stops the submitted variables were: duration of voicing during closure, duration of closure and duration of burst, and the two response categories were: voiced and voiceless. The linear discriminant obtained from the analysis was a combination of the three vectors that best separates the two classes. A similar

procedure was applied for fricatives: an LDA was run on a training set consisting of fricatives followed by voiced and voiceless stops, which were treated as the ‘voiced’ and ‘voiceless’ response categories. Seven measurements were submitted to the analysis: duration of frication, duration of voicing during frication, duration of the preceding vowel, F_0 at 10 and 20 ms before the end onset of frication, and F_1 at 10 and 20 ms before the onset of frication.

The linear discriminants obtained from the two training sets were further employed as classifiers to predict the class membership of all the baseline and test tokens (again, the classification was performed separately for stops and fricatives using the linear discriminants obtained from the respective training sets). This was done to gauge the success of LDA in the case of baseline tokens, and to assess whether there was pre-sonorant voicing comparable to voicing before a voiced stop. The results of the classification are represented in Figure 1.

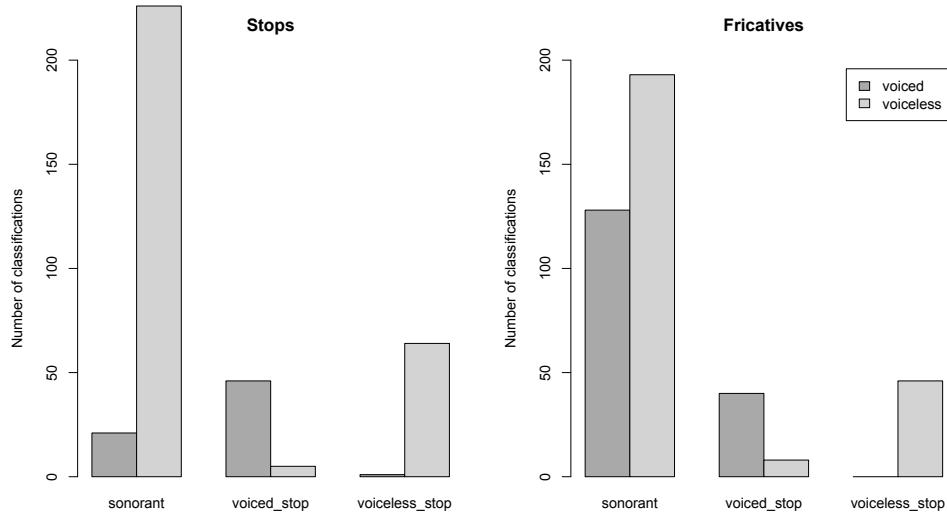


Figure 1: Bar charts representing the classification results by LDA for stops and fricatives by the right-hand environment pooled over all speakers.

As shown in the plot in Figure 1, all stops and fricatives followed by a voiceless stop were classified as voiceless, with the exception of one stop token (this token involved an extended portion of coarticulatory voicing). Most stops and fricatives in the context of a voiced stop were classified as voiced. The few exceptions (8 out of 48 fricative tokens and 5 out of 51 stop tokens) that were attested are not unexpected. This sort of variability in external sandhi has also been found by previous studies on voicing in Dutch (Slis, 1985; Menert, 1994; Jansen, 2004). Variability was also found in the voicing of pre-sonorant stops and fricatives. Trends in the variation were analysed in a series of generalised mixed effects models (Bates and Maechler, 2009), and are presented in section 3.

3 Results

3.1 Categorical voicing

A generalised mixed linear model was fitted to the data with categorical classification result ('voiced' vs. 'voiceless') as a dependent variable and speaker as a random effect. The fixed effects in the model included an interaction between dialect and the right-hand environment, and the underlying voicing of the stop. West-Flemish speakers were found less likely to voice stops followed by a voiced stop ($z=-2.1$, $p=0.04$), but the two dialects did not differ significantly in their voicing of stops followed by either sonorants or voiceless stops. For both dialects, sonorants and voiceless stops patterned together in how much voicing they trigger in a preceding stop. The interaction is plotted in Figure 2. No significant effect of the underlying voicing of the stop was found ($z=1.51$, $p=0.13$).

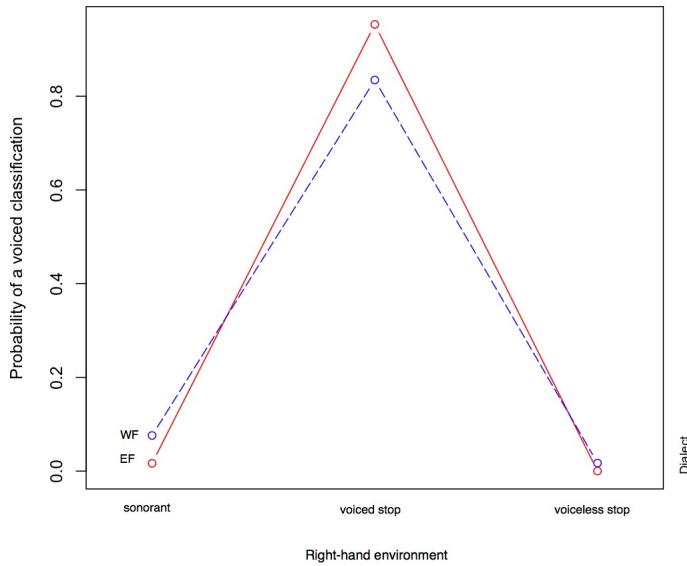


Figure 2: Interaction between dialect (East-Flemish vs. West-Flemish) and environment in conditioning stop voicing.

Further, the effect of manner of articulation on stop voicing was examined in another model with the same dependent variable (classification result), and speaker as a random effect. For this second model the overarching group of sonorants had been broken down into subclasses (nasals, laterals, rhotics, glides and vowels). No significant interaction between manner of articulation and dialect was found for stops followed by sonorant consonants. A borderline significant main effect of manner was found, whereby stops were slightly more likely to undergo voicing before a vowel ($z=1.94$, $p=0.053$). The

remaining obstruent subclasses were equally (un)likely to trigger voicing in a preceding stop.

While pre-sonorant voicing was uncommon in the case of stops, it was considerably more frequent in the case of fricatives, as evident already from the pooled classification results in Figure 1. A mixed effects model with classification as a dependent variable and speaker as a random effect showed that pre-sonorant voicing in fricatives is conditioned by dialect, as a significant interaction was found between dialect and the right-hand environment. The two dialects were similar with respect to voicing of fricatives followed by stops. However, there was a major difference between the two when it comes to fricative voicing before a sonorant (cf. Figure 3). In West-Flemish fricatives underwent voicing before a sonorant to a similar extent as before a voiced stop. In East-Flemish there was no pre-sonorant voicing, and the pre-sonorant fricatives patterned with the fricatives followed by voiceless stops. The difference between West-Flemish and East-Flemish pre-sonorant fricatives was significant at $z=6.95$, $p<.001$. There was no significant main effect of the underlying voicing of the fricative ($z=0.04$, $p=0.97$).

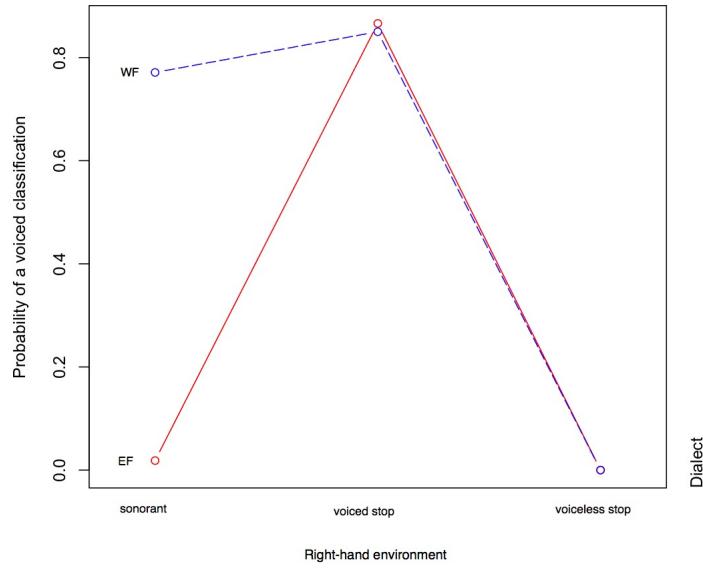


Figure 3: Interaction between dialect (East-Flemish vs. West-Flemish) with the right-hand environment in fricative voicing.

Another generalised mixed model was fitted to the data to investigate the effect of sonorant subclasses (nasals, laterals, rhotics, glides, and vowels) on pre-sonorant fricatives. The only significant effect was that of a vowel ($z=2.74$, $p=0.006$); voicing was more likely before vowels than before sonorant consonants. No significant differences were found between sonorant consonant subgroups in the degree to which they triggered pre-sonorant voicing in fricatives.

The regression models show that prevocalic obstruents seem more likely to undergo voicing than obstruents in the context of a sonorant consonant. The increased trend for intervocalic stop voicing in the current data ties in with the generalisations previously made for Limburg and some East-Flemish dialects, where intervocalic voicing of stops is possible (cf. Footnote 3). Increased prevocalic voicing in fricatives is in line with the descriptions of most Dutch dialects. However, one must be cautious about interpreting these data, as the vowel effect is possibly confounded by glottal insertion. The tokens of word-initial vowels produced by the participants in the current study commonly involved initial glottalisation, as exemplified by the spectrogram in Figure 4. Glottalisation was found in 44% of prevocalic contexts, all of which were discounted. The rationale for that was that tokens with initial glottalisation are sequences of word-final obstruents followed by an initial glottal stop, rather than an initial vowel. However, this affected the size of the population from which the vowel tokens were drawn in the regression model with consequences for the effect size. Voiced prevocalic tokens were not necessarily more numerous (in absolute terms) than voiced tokens before any sonorant consonant, but reducing the pool size elevated the percentage of voiced tokens. While this does not warrant the conclusion that prevocalic voicing does not enjoy a special status in Dutch (literature reports and native intuitions point to the contrary; cf. Section 1), the exact extent to which this is true is difficult to gauge based on our data.

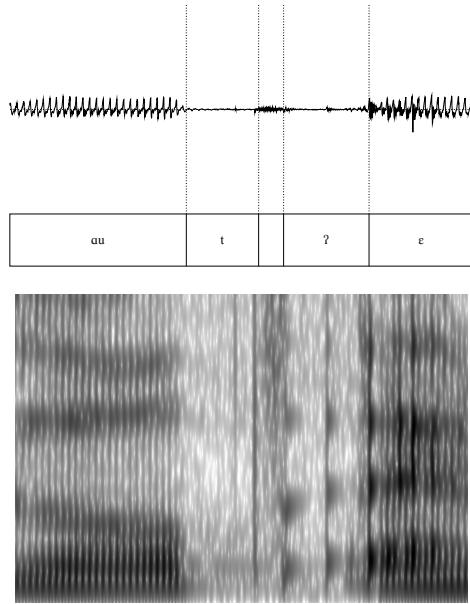


Figure 4: Initial glottalisation

Before we go on to discuss the remaining trends in the data, we must ask to what extent it is justified to treat the findings in categorical terms, and whether we are

not looking at a case of continuous gradient data being forced into two groups. As it turns out, there is independent support for categoricity in West-Flemish voicing, which comes from bimodality. Figure 5 presents a density plot, reflecting the distribution of obstruents with specific voicing durations during frication/closure. In the case of pre-sonorant fricatives there is a very clear bimodal distribution, which approximates the bimodality found before voiced and voiceless stops (represented by dashed lines)⁷. In comparison, a different situation is found in stops. While pre-sonorant stops are not entirely normally distributed (there are a few tokens with extended voicing during closure), a clear bimodality is missing.

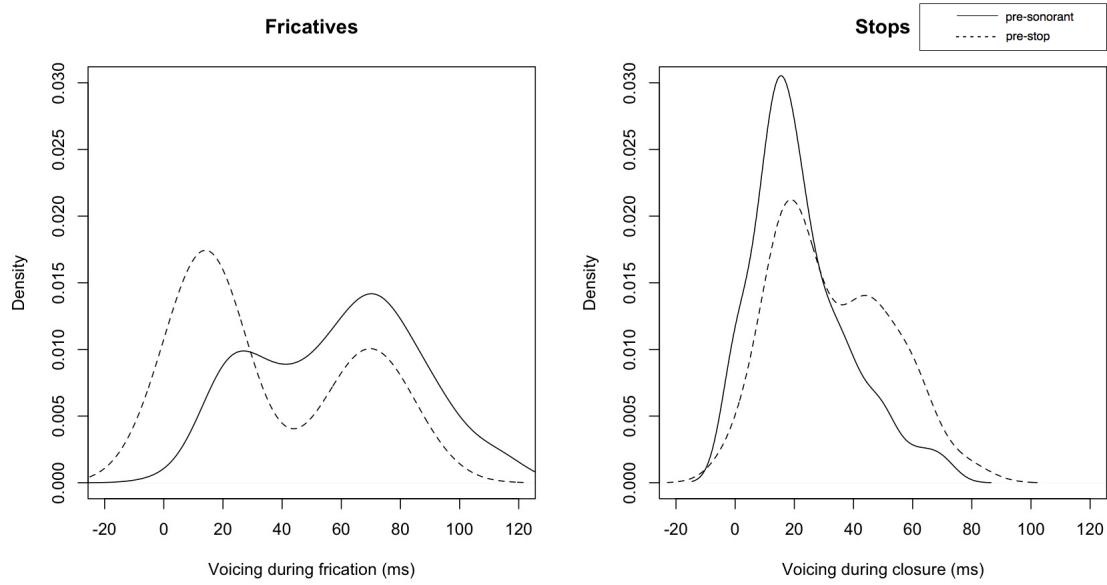


Figure 5: Density plots of voicing duration in West-Flemish obstruents. The continuous lines represent voicing of obstruents followed by a sonorant. The dashed lines represent voicing of obstruents in the baseline condition, i.e. obstruents followed by a voiceless or a voiced stop. The first mode in a distribution of the baseline tokens is associated with a following voiceless stop, the second mode is associated with a following voiced stop.

This asymmetry between stops and fricatives is reasonably well reflected in the categorical classification of pre-sonorant obstruents in West-Flemish (Figure 6), in that for pre-sonorant fricatives the relative number of voiced and voiceless tokens approximates the differences in the distribution peaks. From that we conclude that the use of binary categories in the discussion of the voicing case at hand, albeit a simplification,

⁷The first peak in the distribution is associated with somewhat shorter voicing in fricatives followed by voiceless stops than in fricatives followed by sonorants. A possible explanation lies in coarticulation which might be present when a voiceless stop follows, but is absent in the presence of a following sonorant.

is justified, since it captures the two categories that independently emerge from the continuous data.

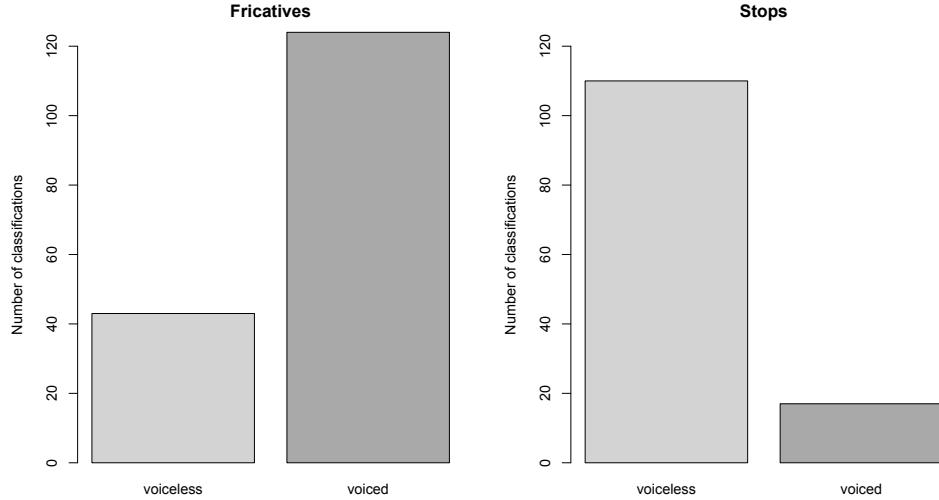


Figure 6: Classification results for West-Flemish pre-sonorant obstruents.

3.2 Gradient voicing

On top of the two voicing categories, as observed in WF pre-sonorant fricatives, evidence of gradient voicing was also found in the data. For instance, as shown in the right panel of Figure 5, some phonetic voicing was present in most pre-sonorant stops in West-Flemish, even though they were typically classified as voiceless (cf. Figure 1). The East-Flemish produced hardly any pre-sonorant obstruents with categorical voicing. Instead, as shown in Figure 7, EF speakers realised their pre-sonorant obstruents either as categorically devoiced (with no phonetic voicing whatsoever), or with gradient voicing up to 40 ms in duration⁸.

The remaining question is which part of the stop is affected by the gradient voicing. What transpired from the visual spectrographic analysis was that partial voicing was invariably found in the initial part of the closure. Figure 8 shows two typical tokens of a postvocalic voicing tail, as observed in the data.

⁸Figure 7 shows a dip in the distribution of voicing duration in voiceless obstruents produced by EF speakers. Interesting though it is, we do not attempt to provide a full account for this bimodality, and we refrain from discussing whether it should in any way be reflected in the feature inventory of East Flemish. For our purposes it is only crucial to observe that EF speakers did not typically produce categorical voicing before a sonorant.

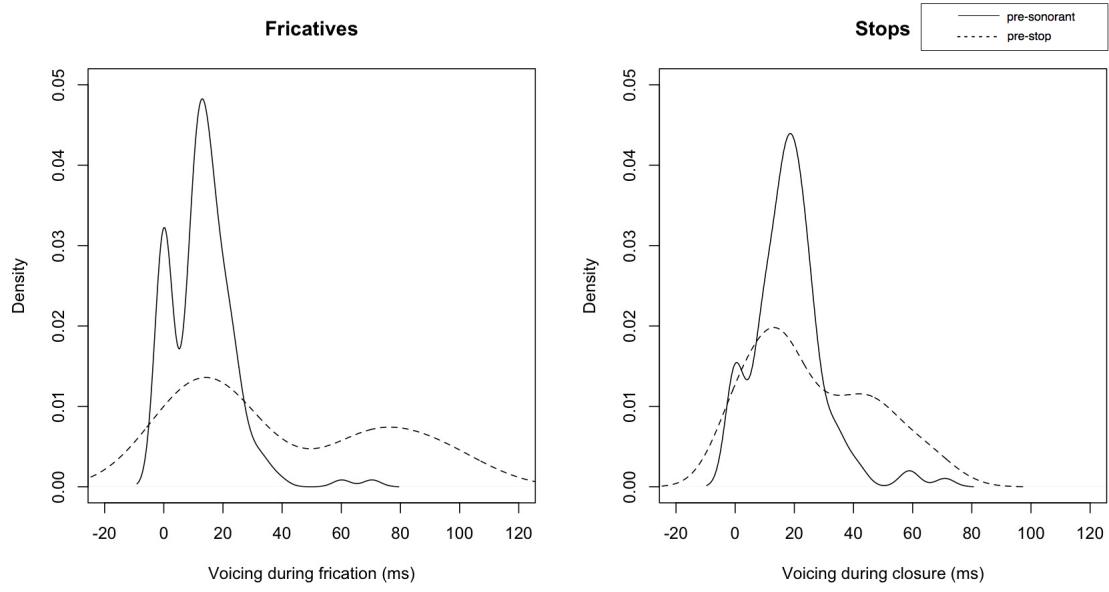


Figure 7: Density plot of voicing duration in East-Flemish pre-sonorant obstruents. The dashed line represents the density of obstruents in the baseline condition, i.e. obstruents followed by a voiceless or a voiced stop.

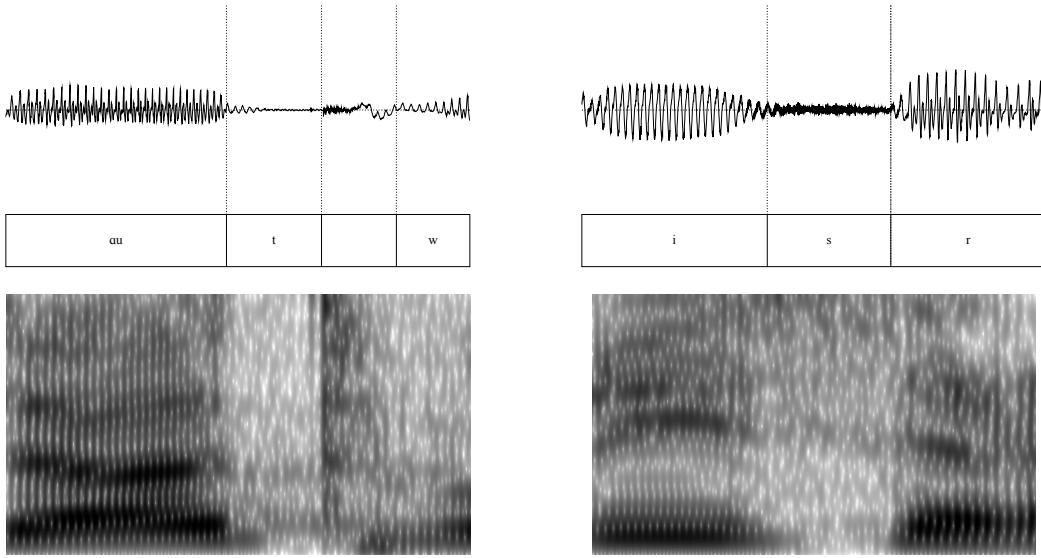


Figure 8: Pre-sonorant /t/ (left) and /s/ (right) with a short voicing tail

3.3 Summary

To sum up, a linear discriminant trained on baseline items (stops/fricatives followed by stops) classified all the tokens in the pool as either voiced or voiceless. A series of

regression models analysing trends in pre-sonorant voicing revealed a significant dialect difference with respect to fricatives, in that pre-sonorant fricatives tend to surface as voiced in West-Flemish, but not in East-Flemish. Pre-sonorant stops showed altogether less voicing than pre-sonorant fricatives. Even though some tokens of pre-sonorant stops were classified as voiced, this did not amount to any significant difference between stops followed by voiceless stops and stops followed by sonorants, and there was no significant difference between the two dialects. Finally, prevocalic fricatives and (to a lesser extent) prevocalic stops were found more likely to surface as voiced than those followed by sonorant consonants. This effect, however, might be largely due to the fact that a relatively large number of prevocalic voiceless items had been discarded from the pool due to glottalisation. Within sonorant consonants no significant effect of manner was found. All speakers had the option to realise their pre-sonorant obstruents with gradient voicing continuing from the preceding vowel. WF speakers tended to realise their pre-sonorant stops with gradient voicing, while their fricative realisation varied between gradient and categorical voicing. EF speakers varied between gradient voicing and categorical devoicing, although a handful of cases with categorical voicing were also attested.

4 Discussion

The phonetic results presented in the previous section furnish important information about the nature and the source of pre-sonorant voicing. Crucially, our results do not confirm that pre-sonorant voicing in West-Flemish word-final obstruents derives from the following sonorant, be it by means of gradient coarticulation, or categorical spreading.

The predictions made by the coarticulation analysis are inconsistent with our finding that voicing in the West-Flemish fricatives is optional, but categorical. The core idea behind the coarticulatory explanation is that word-final /s/ surfaces as a delaryngealised archiphoneme [S], which undergoes passive voicing in the phonetics (Colina (2009) for Ecuadorian Spanish). This analysis cannot be extended to West-Flemish: while some pre-sonorant fricative tokens surfaced as gradually voiced, in the majority of cases the fricative was fully voiced, with the duration of glottal pulsing exceeding the effect of passive voicing. This categorical application refutes the crucial prediction of a passive voicing analysis, and necessitates a phonological account of the West-Flemish pre-sonorant fricative voicing.

When it comes to categorical spreading analyses, these also make predictions which are not borne out by our results. Specifically, the outcome of the experiment does not confirm that West-Flemish sonorants are redundantly laryngeally specified⁹, as proposed by Rubach (1996) for Polish, and by Bermúdez-Otero (2001) and Jiménez and

⁹For our purposes it is irrelevant whether the feature is generic [(+)voice], or a more sonorant-specific feature, e.g. [Sonorant Voice] (cf. Rice (1993)). We also leave aside the issue of whether the feature in question is privative, binary or ternary at the phonological level.

Lloret (2008) for Catalan. Three sources of evidence converge on the lack of laryngeal targets in West-Flemish sonorants.

First, sonorants do not trigger increased phonetic voicing in West-Flemish pre-sonorant stops, which would be expected if they were indeed laryngeally specified, and thus had an actively voiced target. This type of coarticulatory effect is observed by Jansen (2004) for the voiced fricative [z] in English¹⁰. Jansen (2004) found significantly more voicing during closure in word-final stops followed by [z] than in stops followed by [r] (e.g. the [g] voicing was longer in *Limburg zombie* than in *Limburg relish*). In stops followed by the actively devoiced [s] (*Limburg satin*), the voicing was shorter still. These findings provide support to the hypothesis that sounds with a voicing target, are phonetically active with respect to voicing. Following this logic, if West-Flemish sonorants were indeed phonologically voiced, they should trigger more voicing in the preceding obstruent than voiceless stops. However, this prediction is not confirmed by the West-Flemish sonorants. A Wilcox test of the voicing duration in stops followed by sonorants and stops followed by voiceless stops returns the p-value of 0.73; sonorants trigger as little coarticulatory phonetic voicing as voiceless stops. This result suggests that the voicing in sonorants is not phonetically active.

Second, other than not triggering phonetic voice assimilation, sonorants pattern differently from phonologically voiced stops. Unlike stop voicing, sonorant voicing is not contrastive. Pre-sonorant voicing also has a different distribution from regressive voice assimilation before stops, as [(+)voice] can spread from voiced stops, but not from sonorants, to the preceding word-final stops.

Third, the coarticulatory voicing hypothesis is corroborated by the observation that partial obstruent voicing in pre-sonorant position is invariably perseverative, as illustrated in Figure 8. The presence of a voicing tail readily follows from the aerodynamics of voicing: once set into motion (as during the articulation of a sonorant segment), the vocal folds naturally continue to vibrate until their movement is ceased by a rise in the supraglottal pressure, unless an extra articulatory gesture is performed to counteract the voicing. This is a typical coarticulatory effect which does not necessitate positing phonological assimilation¹¹. This interpretation is also consistent with the observation made by Daniloff and Hammarberg (1973) that perseverative coarticulation is more typical of articulatory inertia, than of speech planning.

Challenging the proposal that pre-sonorant voicing is sourced by the following sonorant brings about the question of where the pre-sonorant voicing might come from. Following Jansen (2004), we propose that the actual source is the vowel preceding a word-final fricative. Further we argue that the categorical application of pre-sonorant voicing, as observed in West-Flemish fricatives, emerges through diachronic perceptual reinterpretation.

Following Jansen, we take it that vocal fold inertia gives rise to an automatic coar-

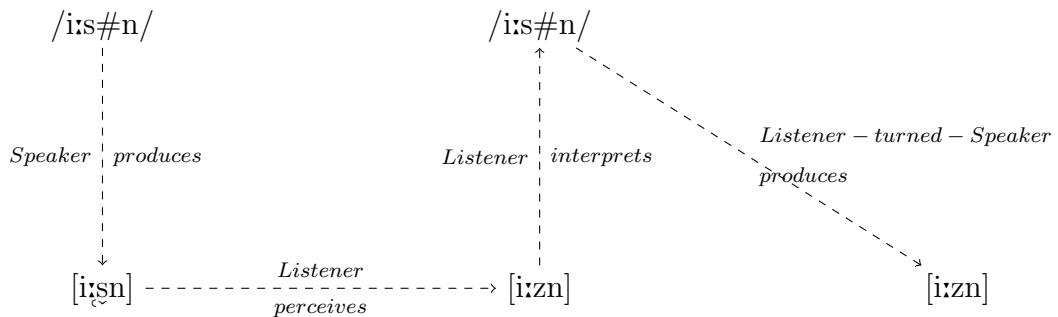
¹⁰In the absence of phonological voice assimilation English provides a good test case of for the effect of voicing targets on phonetic voice coarticulation.

¹¹In comparison, stops followed by a voiced stop typically had continuous voicing extending throughout the entire cluster

ticulatory effect of partial voicing in word-final obstruents. The vocal folds are set into vibration for the articulation of a preceding vowel, and some of the vibration continues into the word final obstruent. This voicing is not counteracted in any way, due to the final obstruents' lack of voicing targets¹². Jansen also notes that passively voiced obstruents, being able to sustain voicing for longer than actively devoiced ones, can be perceived as categorically voiced by listeners. In consequence, listeners may start to reinterpret these obstruents as categorically voiced, and realise voiced targets in their own production. In that way a categorical voicing pattern, such as the one we find in West-Flemish word-final fricatives, may arise.

An important aspect of the model outlined above is that it considers the roles of both speakers and listeners in the evolution of phonological patterns. Speakers initiate the change by producing coarticulation. However, the propagation of the change relies crucially on the listeners. The idea, going back to Ohala (1981), is that listeners participate in sound change by reproducing the linguistic input *as perceived*. If listeners perceive a coarticulatory process as a categorical change, they will produce the innovative pattern in their own production. The diagram in (10), modelled after Ohala (1981), illustrates the process with respect to West-Flemish fricatives. Speakers produce a word-final pre-sonorant /s/ with partial voicing which continues from the preceding vowel. A listener perceives the partial voicing as categorical, and maps the underlying /s/ onto the surface [z] in her own production.

(10) Reinterpretation of voicing in West-Flemish fricatives

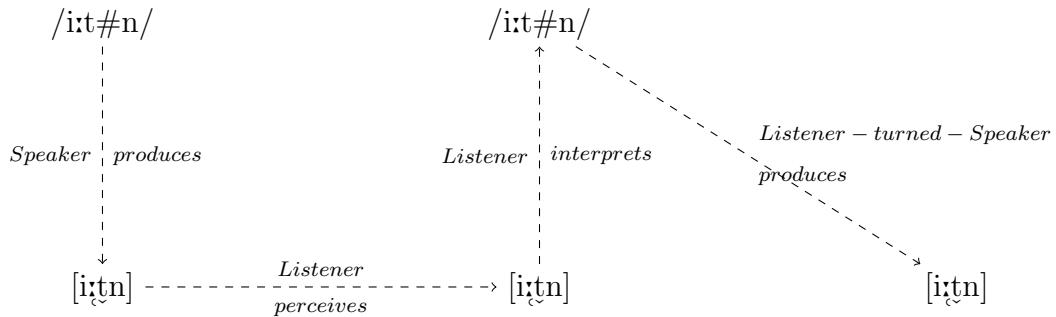


Although the diagram is meant to represent the change in time, its rightmost part also reflects what happens in the synchronic phonology and in acquisition. Children acquiring the West-Flemish system will perceive the variable voicing of pre-sonorant fricatives, and reproduce the same variation. However, they will also reconstruct the underlying voicing of the fricative (/s/ or /z/) through their knowledge of alternations involving suffixation when the underlying voicing surfaces phonetically. In this way the learners effectively arrive at mastering the pre-sonorant voicing process, without going through an intermediate step of assigning [(+)voice] to sonorants.

¹²The prediction that word-final obstruents in final-devoicing languages do not have their own voicing targets is confirmed by the current data, as we found no significant effect of the underlying voicing on the phonetic realisation of voicing in word-final stops or fricatives (see Section 3.1).

A perception-driven model has an additional advantage in allowing us to analyse the observed voicing asymmetry between stops and fricatives as resulting not from increased stop resistance to voicing, but from a voiceless perception of partially voiced stops. The diagram in (11) schematises the following scenario: even though coarticulatory voicing is present in stops, just like in fricatives, it does not result in a voiced perception by the listeners.

(11) No reinterpretation of voicing in West-Flemish stops



A motivation for why the perception of voicing might differ between subclasses of obstruents can be found in how voicing is cued in stops and fricatives. First, there are acoustic cues to stop voicing which are absent from fricatives. As noted by Slis and Cohen (1969), when it comes to obstruent voicing, it is more relevant to talk about the presence of voicing in the case of fricatives, and the onset of voicing in the case of stops. Onset of voicing is associated with the VOT parameter (Voice Onset Time), found by Lisker and Abramson (1964) to correlate significantly with the realisation of stop voicing in 11 languages, including Dutch. According to Lisker and Abramson (1964), voicing starts earlier relative to the release for voiced stops than for voiceless stops. The way this difference manifests itself in Dutch, especially in intervocalic position, is by means of the opposition between a negative and a positive VOT. In voiced sounds the VOT tends to be negative, i.e. the continuous voicing of the sound following the stop starts before the release. In the case of voiceless sounds, the VOT is positive, i.e. voicing only starts after the onset of the burst. A commutation test administered by Slis and Cohen (1969) confirms that the presence of a voice lag (a portion of voicelessness following the release of a plosive) leads to voiceless perceptions by listeners. Let us now consider the VOT values in West-Flemish pre-sonorant stops. According to the definition of VOT (distance between the onset of the release and the onset of *continuous* voicing of the following sound), stops with a short initial period of voicing have a positive VOT, because there is a lag between the initial closure voicing and the continuous voicing of the next segment. 119 out of 127 presonorant stops (93.7%) realised by the West-Flemish speakers in the experiment had a positive VOT. Thus, a cue for voicelessness was present in the vast majority of pre-sonorant stops.

Secondly, in addition to positive VOT, voicelessness was cued in most pre-sonorant stops by a long burst of 28 ms on average. In the absence of our own data on burst

duration in voiced and voiceless stops in a position of contrast¹³, we shall compare this figure to the findings of Ernestus (2000) on Dutch. Ernestus analysed the duration of closure and burst in single intervocalic stops in casual Dutch conversations, and evaluated the measurements against a categorical classification of the stop (voiced vs. voiceless) by 3 trained phoneticians who were also native speakers of Dutch. As illustrated by the scatterplots in the left panel of Figure 9, voiced percepts of coronal stops were found with shorter bursts, both absolute and relative to the closure. The right panel shows the ratio of burst to closure in our data¹⁴. It transpires that West-Flemish pre-sonorant stops tend to pattern like Standard Dutch intervocalic voiceless stops. What this means is that although some coarticulatory voicing is present in the closure, the voicing is not enhanced by a shorter burst. In consequence, the duration of the burst is longer in partially voiced pre-sonorant stops than in intervocalic voiced stops, potentially preventing voiced percepts.

In fricatives, unlike in stops, the presence of voicing is more salient than the onset of voicing, as noted by Slis and Cohen (1969). To support this view, they present the results of Forrez (1966), who found that adding voice to the frication noise leads to [z] perceptions. Stevens et al. (1992) report a similar result, having analysed the acoustic correlates of voicing in the production and perception of voiced fricatives in American English. They found increased duration of glottal pulsing during the frication noise in voiced fricatives. Further, they examined the effect of voicing during friction in a forced choice perception experiment. In the classification of voiced and voiceless intervocalic fricatives listeners were found to rely on the duration of the frication noise where no glottal pulsing was present. 60 ms (or more) of voiceless frication noise triggered voiceless fricative percepts. Importantly, this result considers the duration of voicing relative to the duration of the frication noise. Coarticulatory voicing is expected to either not affect the duration of a word-final fricative, or even to shorten the frication noise¹⁵. Either way, the presence of coarticulatory voicing both enhances the duration of a voiced part of the frication, and shortens the portion where the fricative is voiceless. Both these cues facilitate voiced percepts.

Voicing in fricatives is also cued by the relative intensity of high-frequency noise, as high energy at low frequencies masks the intensity of high-frequency frication (Ladefoged and Maddieson, 1996). In order to assess the scale of this effect in West-Flemish, we measured the maximum intensity at high frequency (band-pass filtered from 500 to 10000 Hz), which we further compared with the minimum intensity at low frequency (0 to 500 Hz)¹⁶. The maximum high-frequency intensity in fully voiced pre-sonorant frica-

¹³The participants in our experiment neutralised the underlying voicing contrast in the word-final position. Consequently, word-final stops studied in the current experiment do not provide information on how the voicing is cued.

¹⁴Some observations are missing as the scale has been adjusted to correspond to Ernestus (2000). Also the durations are noticeably longer in the current data, which might be an effect of the reading task.

¹⁵Jansen (2004) notes that friction noise is mechanically linked to voicing, and so it might shorten as an effect of passive voicing.

¹⁶A reviewer asks why we measured maximum intensity for high frequencies and minimum intensity

tives was on average 6.72 dB lower than the minimum low-frequency intensity. With such intensity differences, the masking effect is likely to occur, preventing voiceless percepts. Moreover, the intensity difference correlates significantly with the duration of voicing during frication. As illustrated in Figure 10, the longer the voicing tail, the lower the high-frequency intensity as compared with the low-frequency one. In that way, the capacity for masking high-frequency noise increases steadily with the duration of voicing.

In addition, the peak intensity at high frequencies is positively correlated with the duration of the voiceless portion of a fricative (Pearson's product-moment correlation: $r=0.66$, $p<0.01$). It appears that in the fricatives with a shorter voiceless portion, the high-frequency intensity does not reach quite as high values as when the voiceless frication continues for longer. From a perceptual point of view, the longer the voiceless frication, the more robust the intensity cue for voiceless fricatives. This observation squares with the finding by Stevens et al. (1992), who argue that what matters in the perception of voice in fricatives is the length of not only the duration of voicing, but also the duration of the voiceless portion of the frication.

The significance of that argument is crucial, when one considers what happens in West-Flemish pre-pausal fricatives. If a word-final fricative has a voicing tail from the preceding vowel, and if voicing can be reinterpreted as categorical, then in principle word-final fricatives could undergo voicing before a voiceless stop, or before a pause. Voicing before voiceless stops is unlikely to occur in a language like Dutch, where there is regressive voice assimilation, and where obstruent clusters with conflicting voicing are unattested. The final voicing prediction, however, is more troublesome, especially if one wants to avoid stipulating independent constraints against word-final voicing.

Yet the prediction no longer holds if the duration of coarticulatory voicing is considered relative to the duration of the fricative. In discourse pre-pausal fricatives typically occur at the end of an utterance, sometimes at the end of a phrase. These are also the positions of increased final lengthening (Klatt, 1975). Cooper and Danly (1981) studied the effect of final lengthening on obstruents and vowels in different positions within a word in American English. Within fricatives they found the greatest amount of lengthening in the word-final position at the end of an utterance. A similar result was replicated for word-final fricatives in Dutch by Hofhuis et al. (1995), who found that word-final fricatives are twice as long at the Utterance boundary, as at the end of a word within discourse. In the light of the results by Stevens et al. (1992) and Hofhuis et al. (1995) the following scenario seems plausible. Coarticulatory voicing from the preceding vowel affects pre-sonorant and prepausal fricatives alike. This type of voicing is more likely to be reinterpreted as categorical in shorter fricatives. In effect, listeners might perceive gradient voicing as categorical in pre-sonorant position, but not prepausally, where the fricative is longer. Once this kind of gap in perception occurs,

for low frequencies, rather than use the same intensity measure. Our rationale was to use the most conservative approach available, and since we find that the low intensity minimum is, on average, higher than the high frequency maximum, the effect can only increase if any other intensity measures (e.g. means) are considered.

it is reflected in the production, so that pre-sonorant voicing is found in a language alongside with final devoicing before a pause.

The lack of prepausal voicing is an additional argument against laryngeal specifications in West-Flemish sonorants. As we have previously seen, partial obstruent voicing from sonorants is perseverative, rather than anticipatory. Thus, a parsimonious and phonetically accurate account should assume the same direction of categorical voicing. However, if voicing did indeed consist in rightward feature spreading, it would be expected that fricatives should surface as voiced following vowels in word-final position. Feature spreading, being a categorical process, is not sensitive to the relative duration of the target, and cannot differentiate between word-final fricatives before sonorants and fricatives followed by a pause. The most straightforward way to employ durational conditioning, and reconcile pre-sonorant voicing, final devoicing and the left-to-right directionality is through the perceptual filter of a language user in a diachronic perspective. Listeners perceive voicing in the (relatively shorter) pre-sonorant fricatives, and reanalyse it as categorical voicing in pre-sonorant position. Pre-pausal fricatives, being longer, are perceived as voiceless, and the reanalysis yields devoicing before a pause.

To sum up, the main idea of the perceptual re-interpretation model is that pre-sonorant voicing is a direct reflection of how listeners and learners perceive coarticulatory voicing in word-final obstruents. Initial coarticulatory voicing in stops does not affect VOT, or burst duration, both of which provide cues to voicelessness. While this observation does not warrant an immediate conclusion that partial closure voicing is not perceived by listeners, the cues to voicing are most likely offset by the co-occurring cues to voicelessness. A similar effect is absent from fricatives. Instead, there is the opposite trend, where adding voiced portions to the frication noise is likely to bring about voiced percepts. Even coarticulatory voicing is associated with high intensity at low frequencies which might mask higher frequency energy similarly as in voiced fricatives. The acoustic differences provide phonetic grounds for the different perception of voicing in stops and fricatives. Those perceptions, in the diachronic model, give rise to the different patterns observed in obstruent subclasses. Perceptual factors also prevent fricatives from voicing before a pause, as the longer prepausal fricatives favour voiceless perceptions, which lead to voiceless (or more accurately: gradually voiced), and not categorically voiced productions.

One might wonder whether the occurrence of pre-sonorant voicing, and the stop-fricative asymmetry could not be explained by aerodynamic factors. The issue of positional application aside, intersonorant voicing is cross-linguistically a fairly common pattern. Westbury and Keating (1986) offer some explanation for this typological tendency, based on their aerodynamic model of voicing. Westbury and Keating show that voicing may be harder to terminate than to maintain in the intervocalic position¹⁷. In a phonological model where phonetic naturalness can trigger phonological change, the

¹⁷Westbury and Keating (1986) focus on the intervocalic position in their discussion, but their conclusions seem readily extendable to the broader intersonorant context, since the aerodynamics of voicing is similar in sonorant consonants and in vowels.

naturalness of intersonorant voicing could perhaps play a role in the initiation of the change we hypothesise to have occurred in West-Flemish.

However, whereas aerodynamic facts may explain why intersonorant obstruents are voiced, they cannot account for another trend present in the data, i.e. the asymmetry in the voicing of West-Flemish stops and fricatives. From a certain point of view, voicing could be seen as more natural in fricatives than in stops, as voicing is most difficult to maintain with the full closure in the vocal tract. However, this phonetic reasoning has been considered in Ohala (1983)¹⁸, and rejected on typological grounds. Ohala notices that languages are far more likely to have a voicing contrast in stops but not in fricatives than vice versa. As a potential functional explanation for this asymmetry, he considers the inherent aerodynamic conflict between voicing (low intraoral pressure) and frication (high intraoral pressure). This results in voiced fricatives being aerodynamically more demanding than voiced stops, which could explain why they are typologically dispreferred. Silverman (2006, 165) offers some further typological discussion on the naturalness of stop vs. fricative voicing. He comments on the uncommonness of a diachronic change where a stop which has undergone intervocalic voicing is further spirantised. This observation could possibly be taken as tangential evidence for the unnaturalness of intervocalic fricative voicing *vis-à-vis* intervocalic stop voicing.

The upshot of Silverman's (2006) discussion of the relative naturalness of stop and of fricative voicing, which we fully endorse, is that we simply do not know whether it is easier to voice an intervocalic stop or an intervocalic fricative. In the absence of a quantifiable measure of effort involved in the production of stop and fricative voicing, and in the face of conflicting typological evidence, the hypothesis that fricative voicing evolves due to relative ease is unfalsifiable.

5 Conclusion

In this paper we have shown that pre-sonorant voicing can be phonological. Phonetic evidence reveals that the voicing of West-Flemish fricatives in pre-sonorant position is optional, but categorical, and must therefore take place in the phonology. However, both phonetic and phonological evidence speak against positing laryngeal specifications for sonorants. Based on this evidence, we have proposed that the categorical voicing in word-final fricatives in West-Flemish does not come from the neighbouring sonorant via feature spreading. Instead, we have argued that the West-Flemish pattern can evolve through language change based on categorical re-analysis of postvocalic coarticulatory voicing. We have also argued that acoustically voicing is more amenable to reinterpretation in fricatives than in stops. This proposal finds support in what we know about the perception of voicing (e.g. Stevens et al. 1992), and it makes predictions

¹⁸“If the problem with stops and voicing is that the accumulation of air in the oral cavity eventually quenches voicing, then this constraint should be less evident with fricatives since they have continuous venting of oral air pressure. So much for a priori prediction, since this turns out not to be true.”(Ohala, 1983, 201)

which are borne out closely by the production data obtained in our study. In addition, the perceptual hypothesis also has the advantage of employing explicit and falsifiable empirical premises which can be tested by future research.

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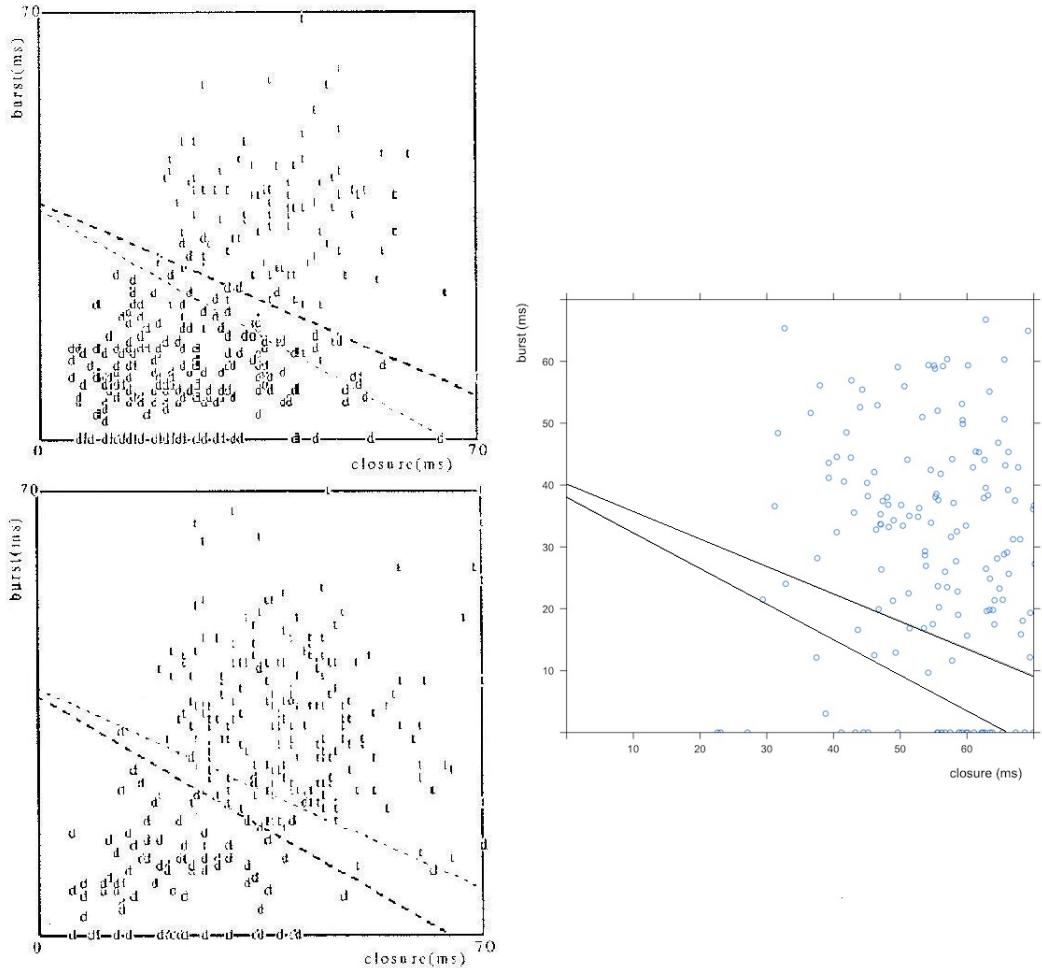


Figure 9: Left panel: closure and burst durations of intervocalic coronal stops classified as either voiced or voiceless, when preceded by a high (top), or low (bottom) vowel. Data from Ernestus (2000, 219). Right panel: closure and burst duration of pre-sonorant stops in the current data

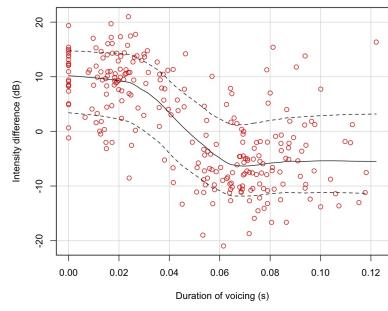


Figure 10: Left: Intensity difference (difference between intensity peak at high frequencies and intensity dip at low frequencies) as a function of voicing duration in pre-sonorant fricatives. Negative intensity difference means that the minimum low-frequency intensity is higher than the high-frequency maximum intensity; Pearson's product-moment correlation: $r=-0.65$, $p<0.001$