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History in the making: Voicing alternation as stop lenition via an automatic analysis of large-scale corpora in French and Spanish

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ABSTRACT: This study focuses on voicing alternation in French and Spanish stops, i.e. canonically voiceless /ptk/ realized as voiced [bdg] or canonically voiced /bdg/ realized as voiceless [ptk]. Forced alignment with voicing variants was used to annotate large speech corpora in French and in Spanish. The following factors of variation were examined: position in the word, preceding and following context, duration of the stop and that of surrounding phones, speech rate, part of speech, and the weight of these factors on voicing alternation. The voicing nature of the stops (whether the stop is phonologically voiceless /ptk/ or voiced /bdg/) turns out to be the factor that contributes the most to the prediction of voicing alternations among all investigated factors for Spanish, according to the random forest model. Whereas for French, the same factor comes after contextual and acoustic factors in the ranking. These results suggest that stop

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voicing patterns differently in these two Romance languages, although they both have a similar voiced-voiceless phonological contrast.

KEYWORDS: stop voicing alternation; large-scale speech corpora; forced alignment; continuous speech.

1. Introduction

Continuous, spontaneous speech provides a privileged context for observing variation. Experimental studies of speech variability typically rely on data elicited in controlled laboratory settings, using specially designed methods such as Diapix (Van Engen *et al.* 2010), but the naturally-occurring variation encountered in everyday communication situations remains hard to replicate in a laboratory setting. While it is essential to test specific factors hypothesized to engender variation, it is an added privilege to be able to observe, in parallel, what forms of variation emerge naturally, with minimal interference from the experimenter. The two methods complement each other.

The last decade has seen a rapid development of tools for automatic data extraction and analysis, and a rich literature consisting of studies of variability in large-scale speech corpora. A major research interest since Ohala (1989) has been understanding whether and how synchronic phonetic variation may be related to diachronic sound change. If diachronic change can be predicted from synchronic variation, as Ohala proposes, then it is essential to describe variation, to understand under what conditions it emerges, and to identify factors that facilitate or constrain it. Studying variability in large-scale corpora allows us to test phonetic motivations for sound change by identifying patterns of variable production. Following Adda-Decker & Lamel (1999), we rely on automatic classification methods to locate patterns of variability in the signal, and the contextual regularity surrounding that variability. Previous work has explored the connection with sound change (Chitoran *et al.* 2016; Chitoran *et al.* 2018). The current study follows the same approach, but is primarily interested in comparing the contribution of the relevant factors in two languages.

As part of a larger project currently underway, we focus here on variability in obstruent voicing in corpora from two Romance languages — Spanish and French. While the overall goal of the project is to establish a typology of phonetic variation (see Popescu *et al.* 2023), based on the comparison of several languages, here we restrict our comparison to only two languages, specifically selected for the following criteria: French and Spanish are both Western Romance languages that have been extensively studied in terms of their phonetic and phonological structure, and with respect to their evolution from Latin. Both are high-resource languages in terms of the size and structure of the speech corpora available. Speech technologies are well developed for French and Spanish, which are widely spoken languages. We propose that by minimizing the structural differences between the two test languages and the availability of data from speech corpora we should be able to observe language-specific patterns, more likely to reflect phonological differences.

The choice to study consonant voicing alternations is motivated by their relevance for the widely studied phenomena of lenition and fortition in their synchronic

and diachronic manifestations. We are adopting here a simplistic view of lenition/fortition, without making any assumptions about its sources (see instead the studies by Broś *et al.* 2021; Cohen Priva & Gleason 2020; Katz 2016). We simply observe that, from a diachronic perspective, when a canonically (i.e., contrastively) voiceless segment is realized as voiced, the segment is considered to undergo lenition. Lenition is thus understood as a process of segmental reduction and is often manifested by consonantal 'weakening' under the influence of a neighboring segment. Similarly, when a canonically (contrastively) voiced segment is realized without voicing, the segment is considered to undergo fortition, understood as a process of consonantal reinforcement, manifested as an increase in oral constriction, which may involve devoicing. Fortition is not the exact opposite of lenition (Lavoie 2001). While lenition can concern all obstruents, fortition often concerns the articulatory strengthening of glides that can become fricatives, affricates, or obstruents diachronically (Bybee & Easterday 2019). Nevertheless, lenition and fortition share similar variation factors such as neighboring context, word length, word position, prosodic position (de Carvalho *et al.* 2008; Gurevich 2013; Bybee & Easterday 2019).

2. The approach

Research on voicing alternation is particularly rich for the Romance languages. Voicing alternation constitutes one of the major criteria for dividing the Romance area into Western and Eastern Romance, with lenition of Latin intervocalic consonants only in the West (von Wartburg 1950; Posner 1996; Honeybone 2008). Individual Romance languages in particular have been studied in-depth: Hualde & Nadeu (2011) for Italian, Hualde & Prieto (2014) for Spanish and Catalan, Vasilescu *et al.* (2018) for dialectal Spanish, Niebuhr & Meunier (2011) for French, Broś *et al.* (2021) for the Spanish of Gran Canaria. Vasilescu *et al.* (2020) compared five Romance languages in terms of the factors affecting voicing alternations.

However, few studies so far have addressed the relative weight of each variation factor, in each language. Wu *et al.* (2022) used decision trees to investigate several variation factors of voicing alternation in stops in five Romance languages. The current study pursues this line of investigation. By comparing the weight of contributing variation factors for each language, we can have a better understanding of the distance between each pair of languages.

In this study, we are restricting our comparison to voicing alternation of French and Spanish stops, i.e. voicing and devoicing. That is to say, canonically voiceless /ptk/ realized as voiced [bdg] or canonically voiced /bdg/ realized as voiceless [ptk]. As mentioned earlier, different variation factors are found to impact stop voicing alternation in Romance languages. In this study, we consider the following factors, based on previous results in the literature:

1. *Canonical vs. non-canonical voicing.* Voicing patterns are observed to be different for canonically (phonologically) voiced (/bdg/) stops and canonically voiceless (/ptk/) realized as voiced (Vasilescu *et al.* 2020; Hutin *et al.* 2021; Wu *et al.* 2022).

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2. *Position in the word.* The position of the stop in the word is found to affect stop voicing alternation in Romance languages (Vasilescu *et al.* 2020; Ségéral & Scheer 2008; Popescu *et al.* 2023). In our study, the stops are therefore grouped into word initial (wInitial), medial (wMedial) or final (wFinal) positions for both languages accordingly.
3. *Preceding context.* The nature of the previous phone can also influence stop voicing alternation (Niebuhr & Meunier 2011; Meunier & Espesser 2011; Vasilescu *et al.* 2020). We categorized the preceding segment/context as: (a) pause (hesitation, breath or silence); (b) vowel (V); (c) sonorant (Son); (d) voiced obstruent (Ob+); (e) voiceless obstruent (Ob-).
4. *Following context.* Similarly, stop voicing alternation was also found to be related to the nature of the following phone (Jatteau *et al.* 2019). As for the nature of the previous phone, we categorized the nature of the following segment/context in the same way as the preceding one.
5. *Duration.* The duration of the stop and that of the surrounding phones tends to have an impact on voicing alternation as well (Snoeren *et al.* 2006; Vasilescu *et al.* 2014; Ryant & Liberman 2016; Wu *et al.* 2022). Shorter duration usually correlates with higher speech rate. Segments of shorter duration may be more prone to voicing alternations due to increased coarticulation.

In addition to these factors, we also included speech rate (number of words produced per second), local speech rate (corresponding to the speech rate locally observed for each word), and part of speech. Finally, part of speech was included mainly as an exploratory study, but we predicted that voicing alternation would be more likely to occur in function words, which are typically reduced in duration, than in lexical words. Our goal is to determine the relative contribution of each factor to the prediction of voicing alternation, and especially to observe any language-specific differences in the relative weight of the same factors.

3. Corpora

Approximately 400 hours of continuous French and Spanish speech data were used in this study. The corpora were either obtained from the Linguistic Data Consortium or ELRA, or developed in the framework of international research projects: IST ALERT for part of the data in French, and OSEO Quaero (Lamel *et al.* 2011) for both languages.

The French dataset covers mainly the standard variety of French. For Spanish, besides European broadcast sources, a small amount of broadcast speech in Latin American Spanish varieties was included as well. The data were manually transcribed for both languages.

4. Methodology

We use two approaches to studying voicing alternation of stops in French and in Spanish: (i) automatic decision of the voicing feature using forced alignment with

pronunciation variants, and (ii) feature ranking using a random forest paradigm. Our goal is to understand the relative strength of the different factors that contribute to voicing alternations in the two Romance languages.

4.1. Forced alignment

We used forced alignment with pronunciation variants —possible pronunciations of a word with systematic pronunciation variants (Adda-Decker & Lamel 2018)— to study voicing alternations of /ptkbdg/ in the two Romance languages (see also Hallé & Adda-Decker 2007; Popescu *et al.* 2023; Jatteau *et al.* 2019).

An acoustic model was used to identify the optimal association of speech segments based on the phonemic transcription of the word level transcription of the segment. The phonemic transcription was obtained through a pronunciation lexicon. The orthographic transcriptions were provided to the transcription system used in alignment mode. Thus, the word and phone boundaries were located automatically, along with pause, hesitation or breath. In this study, both the canonical and the non-canonical form of /ptk/ and /bdg/ were included in the pronunciation dictionary. Thus, for /ptk/, the system was allowed to choose between the canonical voiceless forms [ptk] and the non-canonical voiced form [bdg]. Similarly, for /bdg/, the system could select either the canonical voiced form [bdg] or the non-canonical voiceless form [ptk]. The baseline pronunciation dictionaries from the speech transcription systems were used for this study (Gauvain *et al.* 2002). The speech recognition system is thus allowed to choose during forced alignment the pronunciation variants included in pronunciation dictionaries that best match the production. The system selects the most probable variant given the actual acoustic realization (Gauvain *et al.* 2005). For instance, the French word *quel* /kɛl/ 'which' could be transcribed either as [kɛl] or as [gɛl], based on whether the system finds that the surface pronunciation best matches the voiceless or the voiced realization.

4.2. Part of speech (POS)

For both languages, the part-of-speech (POS) of each word-token in the corpora was automatically annotated using Stanza (Qi *et al.* 2020). As the basis structure, the system adopts a bidirectional long short-term memory network (Bi-LSTM). Stanza returns the universal part-of-speech (UPOS) tags and allows us to investigate the relationship between POS and voicing alternation of stops in French and Spanish. We excluded one Spanish word from our analysis —*donde*— since its occurrences in the corpus are extremely frequent and include different parts of speech, both as a lexical word (adverb) and as a grammatical word (conjunction). The automatically annotated parts of speech were grouped into the categories listed in Table 1.

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Table 1

Part of speech categories annotated in the corpora

ADJ	adjective
ADV	adverb
CONJ	conjunction
DET	determiner
INTJ	interjection
NOUN	noun
NUM	numeral
PRON	pronoun
PRP	preposition

4.3. Statistical analyses and random forest models

Generalized linear models (GLM) were used for the statistical analyses of this study (McCullagh 2019). The effects of different factors were analyzed in R. Two separate models were carried out, one for French and one for Spanish. In each model, the following were included as independent factors: voicing of the segments in the canonical, reference form (/ptk/ or /bdg/), position of the segment in the word, left-hand context, right-hand context, phone duration, previous phone duration, next phone duration, speech rate and local speech rate.

We implemented a random forest classifier to predict voicing alternation of stops in French and in Spanish as a function of different variation factors. In addition, we ranked the importance of factors that contributed to the model. The data were divided into two parts: 70% of the data were used for training and the remaining 30% were reserved as test data. The 10-fold cross-validation method was used to obtain the best combination of hyperparameters.

5. Results

The voicing alternation rates are similar in French and in Spanish for both voiceless and voiced stops (cf. Vasilescu *et al.* 2020, 8~10% voicing alternation is observed for canonically voiceless and voiced stops in both languages). However, the variation factors could contribute differently to voicing alternation in the two languages. The results of the random forest classification presented in this section help tease out the contribution of individual factors.

We first present results on analyses of factors that have not yet been much explored in previous literature on this subject, namely part-of-speech, speech rate, phone duration and position in the word (see Vasilescu *et al.* 2020 for investigations of other factors listed in Section 2). We will finally explore results based on random forest classifiers. In the random forest models, we included the voicing nature of the stops ("canonicallyNVorV": voiceless stops *vs* voiced stops) as a predictor. By adding this predictor, we will be able to examine how important the phonological voicing nature of the stops is for the prediction of voicing alternation for each language.

5.1. Part of speech

Figure 1 shows the voicing alternation rate (%) as a function of the part-of-speech (POS) of the word to which the segment belongs for canonically voiceless (/ptk/) and voiced (/bdg/) stops in French (above) and in Spanish (below). Interjections were not included in the analyses. In both languages, the highest alternation rate (close to 20%) is observed for /bdg/ stops realized as voiceless. In French this rate is found for stops in conjunctions, and in Spanish, in numbers. Relatively stable patterns are found for /ptk/ as a function of POS in the two languages. However, different patterns are found for the voicing alternation of /bdg/ between the two languages in the case of conjunctions (CONJ), numbers (NUM) and pronouns (PRON). Frequent examples for each relevant category in French are shown in Table 4. These results suggest a potential influence of word frequency on voicing alternation, given that conjunctions, numbers and pronouns often concern frequently observed words in speech. Nine levels were included in the POS factor. Pairwise comparisons show significant results for most levels, and non-significant for others.

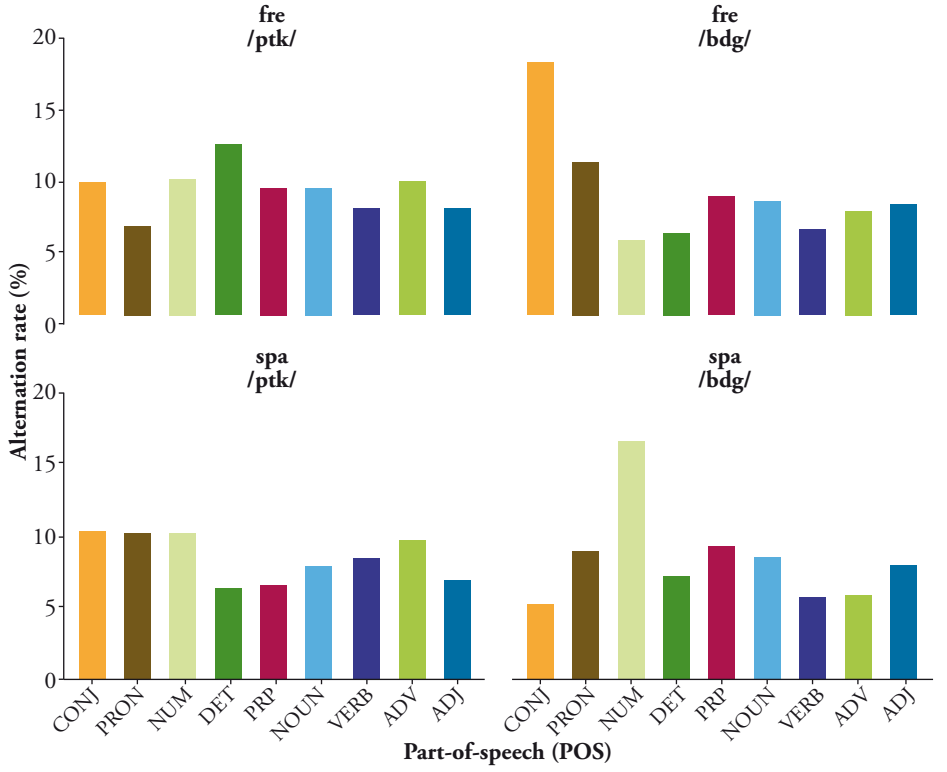

Figure 1

Voicing alternation rates of canonically voiceless (/ptk/, left panel) and voiced (/bdg/, right panel) stops as a function of part-of-speech in French (top panel) and in Spanish (bottom panel)

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Interestingly, results are different for French and for Spanish. Detailed results of *emmeans* analyses based on the main model for French and for Spanish are shown in Table 2 and Table 3, respectively.

Table 2

Pairwise comparisons for French

ADJ - ADV **p <.001**	ADJ - CONJ NS	ADJ - DET **p <.05**	ADJ - NOUN **p <.001**	ADJ - NUM NS	ADJ - PRON **p <.01**	ADJ - PRP NS	ADJ - VERB NS
	ADV - CONJ **p <.001**	ADV - DET **p <.001**	ADV - NOUN **p <.001**	ADV - NUM **p <.001**	ADV - PRON **p <.001**	ADV - PRP **p <.001**	ADV - VERB **p <.001**
		CONJ - DET **p <.001**	CONJ - NOUN NS	CONJ - NUM NS	CONJ - PRON **p <.001**	CONJ - PRP **p <.05**	CONJ - VERB NS
			DET - NOUN **p <.001**	DET - NUM NS	DET - PRON **p <.05**	DET - PRP **p <.001**	DET - VERB **p <.001**
				NOUN - NUM NS	NOUN - PRON **p <.001**	NOUN - PRP **p <.001**	NOUN - VERB **p <.05**
					NUM - PRON **p <.001**	NUM - PRP NS	NUM - VERB NS
						PRON - PRP **p <.05**	PRON - VERB **p <.001**
							PRP - VERB NS

Table 3

Pairwise comparisons for Spanish

ADJ - ADV NS	ADJ - CONJ **p <.01**	ADJ - DET **p <.001**	ADJ - NOUN **p <.05**	ADJ - NUM **p <.001**	ADJ - PRON NS	ADJ - PRP **p <.001**	ADJ - VERB **p <.001**
	ADV - CONJ **p <.001**	ADV - DET **p <.001**	ADV - NOUN **p <.001**	ADV - NUM **p <.001**	ADV - PRON NS	ADV - PRP **p <.001**	ADV - VERB **p <.001**
		CONJ - DET **p <.001**	CONJ - NOUN NS	CONJ - NUM **p <.001**	CONJ - PRON **p <.01**	CONJ - PRP **p <.001**	CONJ - VERB NS
			DET - NOUN **p <.001**	DET - NUM **p <.001**	DET - PRON **p <.05**	DET - PRP **p <.01**	DET - VERB **p <.001**
				NOUN - NUM **p <.001**	NOUN - PRON **p <.05**	NOUN - PRP **p <.001**	NOUN - VERB **p <.001**
					NUM - PRON **p <.001**	NUM - PRP **p <.001**	NUM - VERB **p <.001**
						PRON - PRP **p <.001**	PRON - VERB **p <.001**
							PRP - VERB **p <.001**

The following table provides words in French and in Spanish that frequently undergo voicing alternation, as observed in the automatic transcription. As we can see, words with voicing alternation often concern frequent words in the language. This is the case for both grammatical and lexical words.

Table 4

Representative examples of French and Spanish words most often undergoing voicing alternation

POS	Part of speech	Examples in French	Examples in Spanish
ADJ	adjective	e.g. *bon*	e.g. *bueno, buenas, buenos*
ADV	adverb	e.g. *dessus*	e.g. *después, bien*
CONJ	conjunction	e.g. *dont*	e.g. *cuando*
DET	determiner	e.g. *de*	e.g. *del*
NOUN	noun	e.g. *monde*	e.g. *gracias, días*
NUM	numeral	e.g. *deux*	e.g. *doce, dos*
PRON	pronoun	e.g. *dont*	e.g. *algo*
PRP	preposition	e.g. *de, dans*	e.g. *de*
VERB	verb	e.g. *dis*	e.g. *dice, dicen*

5.2. Speech rate

Speech rate is calculated between pauses/breaths as the number of words produced per second. Voicing alternation tends to be related to speech rate for canonically voiceless stops (/ptk/) for both French and Spanish: the voicing of /ptk/ (i.e. /ptk/ realized as [bdg]) corresponds to faster speech rate than /ptk/ realized canonically as [ptk]. No clear patterns are found for canonically voiced stops (/bdg/). GLM results suggest that higher speech rate favors voicing alternation in both French [log odds ratio = 0.106776, $|Z| = 20.458$, $p < 0.001$], and Spanish [log odds ratio = 0.0741147, $|Z| = 22.624$, $p < 0.001$].

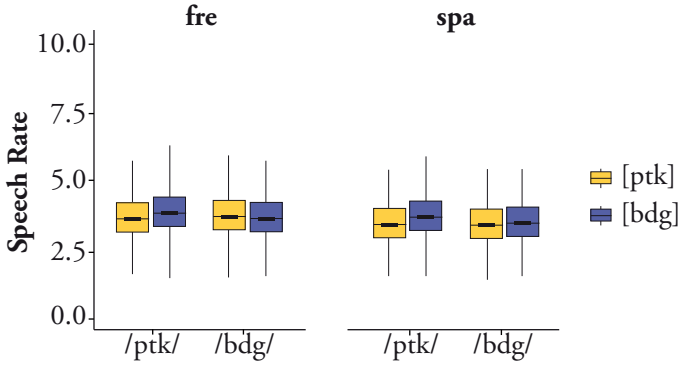

Figure 2

Speech rate (words/sec) of canonically voiceless (/ptk/) and voiced (/bdg/) realized as [ptk] (in grey) or [bdg] (in dark grey) in French (on the left) and in Spanish (on the right)

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5.3. Phone duration

Figure 3 shows voicing alternation (x-axis) as a function of the duration of the segment for canonically voiceless (/ptk/) and voiced (/bdg/) consonants in French (left) and in Spanish (right). Results show that for both languages, more voiced realizations of /ptk/ are observed when /ptk/ has shorter duration. A similar trend is found for canonical /bdg/ in French. GLM results confirm that shorter phone duration tends to favor voicing alternation both in French [log odds ratio = –7.963115, |Z| = 35.066, p < 0.001] and in Spanish [log odds ratio = –13.1896668, |Z| = 85.241, p < 0.001].

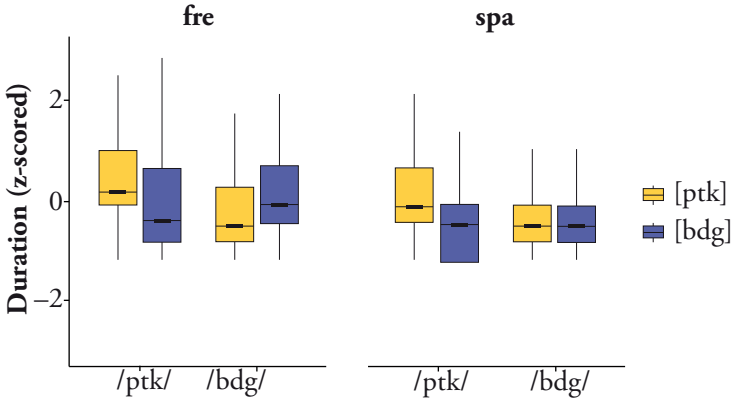

Figure 3

Phone duration of canonically voiceless (/ptk/) and voiced (/bdg/) realized as [ptk] (in grey) or [bdg] (in dark grey) in French (left) and in Spanish (right)

5.4. Position in the word

Voicing alternation rate (%) is shown in Figure 4 for both languages as a function of the position of the segment in the word. For both languages, voicing alternation occurs more in word-final than in initial or medial positions. GLM results for French confirm that voicing alternation tends to occur less word-initially [log odds ratio = –0.405476, |Z| = 22.436, p < 0.001] or word-medially [log odds ratio = –0.512482, |Z| = 30.703, p < 0.001] compared to the word-final position. A similar tendency is observed in GLM results for Spanish. Voicing alternation tends to happen less word-initially [log odds ratio = –1.0264385, |Z| = 50.384, p < 0.001] or word-medially [log odds ratio = –1.3888030, |Z| = 69.767, p < 0.001] than in word-final position.

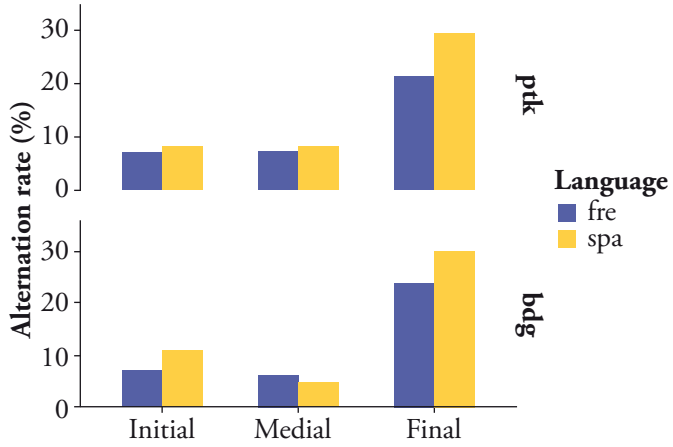

Figure 4

Voicing alternation rates of canonically voiceless (/ptk/, top panel) and voiced (/bdg/, bottom panel) stops as a function of position of the phoneme in the word in French (grey) and in Spanish (dark grey)

5.5. Ranking of the factors (results from Random Forest models)

Results of the random forest models are shown in this section. We first present the obtained accuracy rate, then the factors that contribute the most to each model via the figures illustrating the permutation importances.

5.5.1. Voicing alternation in French

The accuracy of the prediction on voicing alternation of stops in French is ~68%. The variables examined are ranked by importance in Figure 5, according to the random forest model. The decrease in accuracy score is shown on the x-axis and the relevant factors are listed on the y-axis according to their contribution in the model. If a factor is dropped, the relevant impact on the accuracy score will decrease by the number indicated on the x-axis.

For French, Figure 5 indicates that the right-hand (following) context is shown to be the factor that contributes the most to the prediction of voicing alternation, followed by phone duration, the canonical voicing of the stop (/ptk/ vs /bdg/), the duration of the previous phone, and the left-hand context.

POS is the factor that contributes the least. By dropping POS, the accuracy of the model is minimally impacted.

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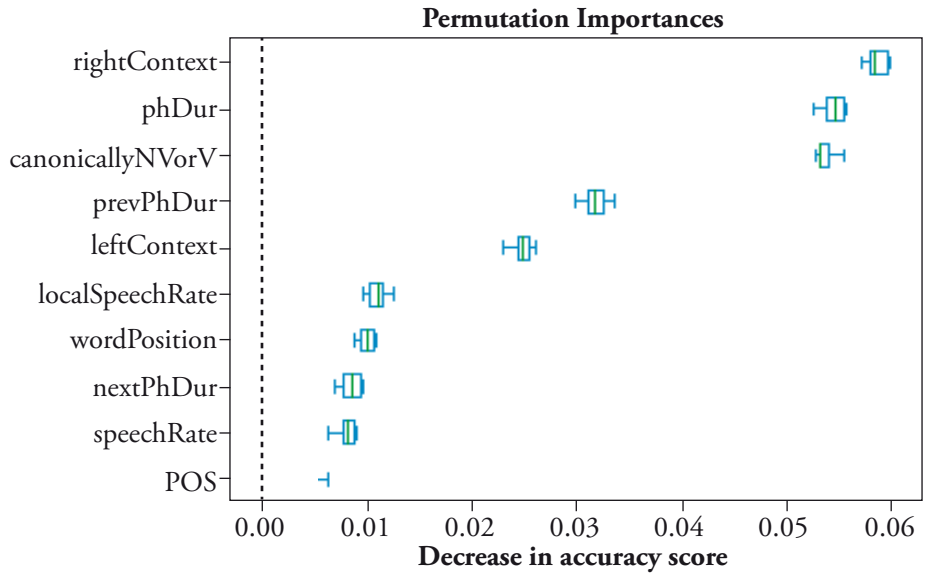

Figure 5

Results of the random forest model for French

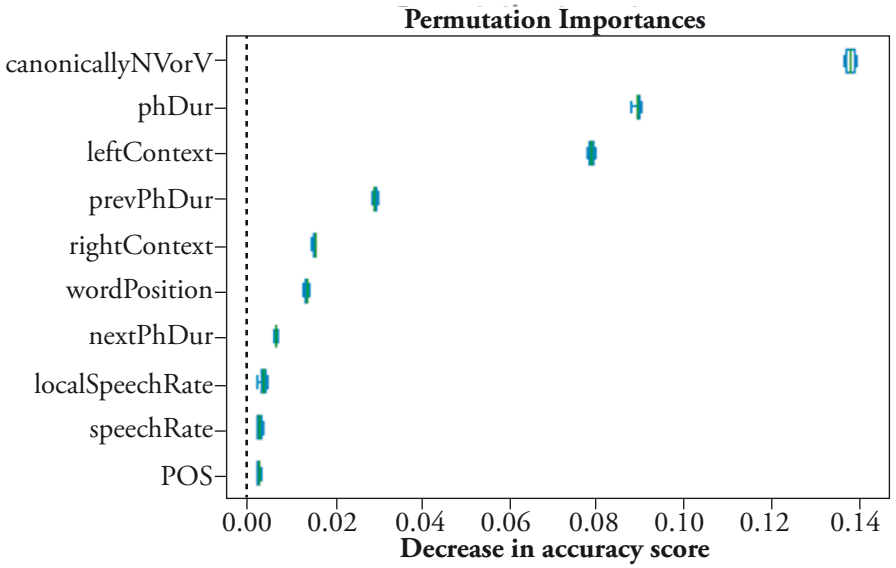

Figure 6

Results of the random forest model for Spanish

5.5.2. Voicing alternation in Spanish

The accuracy of the prediction on voicing alternation of stops in Spanish is over 70% (≈71%). The ranking of the contributing factors is illustrated in Figure 6 according to the random forest model. Contrary to what is observed for French stops, the canonical voicing nature of the stop (/ptk/ vs /bdg/) is shown to be the factor that contributes the most to the prediction of voicing alternation in Spanish, followed by phone duration, left-hand (preceding) context, the duration of the previous phone and the right-hand (following) context.

As for French, part-of-speech again plays a minor role in this analysis.

6. Conclusion

This study investigated voicing alternation in two Romance languages – French and Spanish. We focused our analyses on canonically voiceless stops /ptk/ and canonically voiced stops /bdg/. Different variation factors were investigated to examine the link between these factors and patterns of stop voicing alternation in French and Spanish. About 400 hours of continuous speech in each of French and Spanish were used. The data was automatically annotated using forced alignment with systematic voicing variants (i.e. canonically voiceless /ptk/ can either be aligned as voiceless [ptk] or voiced [bdg]; canonically voiced /bdg/ can either be aligned as voiced [bdg] or voiceless [ptk]). The approach using forced alignment with voicing variants allows us to investigate the voicing of canonically voiceless segments (lenition) and the devoicing of canonically voiced segments (fortition). In addition to variation factors attested in the literature on Romance languages (position in the word, nature of the surrounding segments, duration of the segment and its neighboring contexts), we also considered speech rate, local speech rate, and part of speech.

We ranked the contribution of these factors to stop voicing alternation in each language by applying random forest paradigms to the dataset. Random forest models were implemented for the two languages separately. Results show that, although French and Spanish have similar rates of stop voicing alternation, the two languages pattern differently with regards to the contribution of the individual factors. Based on the ranking proposed by random forest models, the contribution of the voicing nature of the stops appears to be very different in Spanish and in French. The Random Forest model predicts the voicing alternation in French first according to contextual and acoustic factors; the voicing nature of the stops (voiceless stops *vs* voiced stops) comes third only. Whereas for Spanish, the factor that contributes the most to the model is the voicing nature of the stops. Other than the voicing nature of the stops, immediate context, as well as duration of the stops were ranked as most relevant for both languages, but do not tend to contribute equally to the models. Interestingly, even though both Romance languages have a voiced-voiceless phonological contrast in stops, the results suggest different patterns of stop voicing alternations.

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