

## Article

# The Role of (Re)Syllabification on Coarticulatory Nasalization: Aerodynamic Evidence from Spanish

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**Abstract:** Tautosyllabic segment sequences exhibit greater gestural overlap than heterosyllabic ones. In Spanish, it is presumed that word-final consonants followed by a word-initial vowel undergo resyllabification, and generative phonology assumes that canonical CV.CV# and derived CV.C#V onsets are structurally identical. However, recent studies have not found evidence of this structural similarity in the acoustics. The current goal is to investigate anticipatory and carryover vowel nasalization patterns in tautosyllabic, heterosyllabic, and resyllabified segment sequences in Spanish. Nine native speakers of Peninsular Spanish participated in a read-aloud task. Nasal airflow data were extracted using pressure transducers connected to a vented mask. Each participant produced forty target tokens with CV.CV# (control), CVN# (tautosyllabic), CV.NV# (heterosyllabic), and CV.N#V (resyllabification) structures. Forty timepoints were obtained from each vowel to observe airflow dynamics, resulting in a total of 25,200 datapoints analyzed. Regarding anticipatory vowel nasalization, the CVN# sequence shows an earlier onset of nasalization, while CV.NV# and CV.N#V sequences illustrate parallel patterns among them. Carryover vowel nasalization exhibited greater nasal spreading than anticipatory nasalization, and vowels in CV.NV# and CV.N#V structures showed symmetrical nasalization patterns. These results imply that syllable structure affects nasal gestural overlap and that aerodynamic characteristics of vowels are unaffected across word boundaries.

**Keywords:** coarticulatory nasalization; resyllabification; aerodynamics; Spanish



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## 1. Introduction

Traditionally, generative phonology assumes that, in connected speech in Spanish, word-final consonants undergo resyllabification before a word that starts with a vowel, e.g., *un amigo* [u.n#a.mi.ɣo] ‘a friend’ (Harris and Kaisse 1999) (henceforth, ‘C’: consonant, ‘V’: vowel, ‘N’: nasal consonant, ‘.’: syllable boundary, ‘#’: word boundary). The process is understood as complete and a part of the phonology of Spanish. Nevertheless, recent laboratory studies have questioned the status of ‘obligatory’ or ‘complete’ resyllabification of C#V sequences in Spanish by providing evidence for acoustic and phonetic differences between ‘canonical’ onsets, e.g., CV.CV#, and ‘derived’ (resyllabified) onsets, e.g., CV.C#V (Bradley et al. 2022; Hualde and Prieto 2014; Jiménez-Bravo and Lahoz-Bengoechea 2023; Strycharczuk and Kohlberger 2016).

To date, most of the studies investigating resyllabification have focused on the consonantal segments, which were, in most cases, oral fricative sounds, disregarding how neighboring vowels or other types of segments such as nasal structures might be affected by (re)syllabification rules. Furthermore, research has shown that syllabic structure plays a role in nasalization degree (Byrd et al. 2009; Cohn 1993); thus, tautosyllabic VN segments will show greater gestural overlap than heterosyllabic V.N segments (see Krakow 1989, 1993, 1999).

Remarkably, the effect of (re)syllabification of nasal consonants on neighboring vowels in Spanish has not been thoroughly investigated, especially via articulatory methods. The present study seeks to understand the aerodynamics (Beristain 2022, 2023a, 2023b; Cohn 1993; Huffman and Krakow 1993; Shosted 2009; Shosted et al. 2012; Solé 1992;

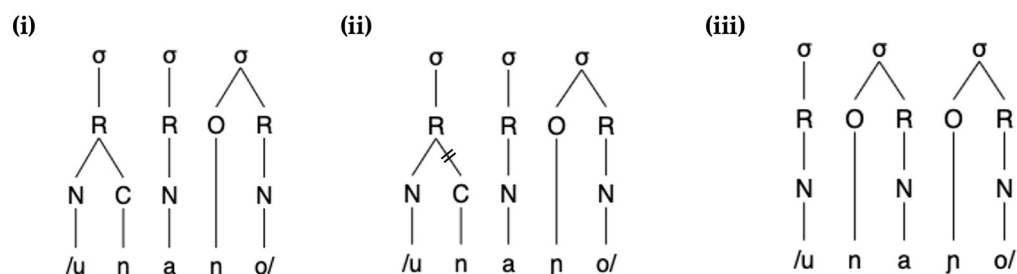
Stoakes et al. 2020) of the spread of anticipatory and carryover coarticulatory nasalization across various syllabic contexts within word boundaries and across word junctures. The study determines that tautosyllabic segments show greater articulatory overlap and that carryover nasalization is unaffected by resyllabification, which provides evidence for complete resyllabification.

The structure in the current article is as follows: first, the relevant literature on syllable structure, resyllabification, and nasalization is provided; second, research questions and hypotheses are presented; third, the methods are included; fourth, the results pertaining to anticipatory and carryover nasalization are summarized, followed by the discussion and conclusions.

## 2. Literature Review

### 2.1. Resyllabification Revisited

Resyllabification is a process by which a word-final coda delinks from its original syllable structure and attaches to the following vowel-initial word as an onset. It should be noted that this process is not universal across languages and/or dialects. For instance, English has ambisyllabicity (Kahn 1976) or glottal stop insertion (Bissiri et al. 2011), German has glottal stop insertion (Kohler 1994), and eastern Abruzzese dialects opt for voiced glottal fricative [ɦ] or velar fricative [ɣ] as an empty onset repair mechanism (Passino et al. 2022, p. 93). On the other hand, resyllabification is found in Spanish (Harris 1983), French (Durand et al. 2011), and dialects of Occitan (Sauzet 2012), among others. Harris and Kaisse (1999) explain that for a segment to be resyllabified, three stages need to happen: (i) initial syllabification (no change); (ii) delinking (change initiates); and (iii) attach onset (resyllabification occurs, change is complete). Below is Figure 1, which illustrates the derivation of resyllabification for the word sequence *un año* ‘a year’ in Spanish (adapted from Harris and Kaisse 1999, p. 137).



**Figure 1.** Derivation showing (re)syllabification in word sequence *un año* ‘a year’ in Spanish [where (i) initial syllabification; (ii) delinking; (iii) attach onset (resyllabification)].

In this view, resyllabified codas should behave like onsets. Remarkably, weakening phenomena that affect word-internal coda consonants may also affect word-final consonants, even if they are resyllabified as onsets preceding a vowel in the following word. These cases have been modeled using either rule ordering (Harris 1983) or constraint ranking within optimality theory (Colina 1995, 1997, 2009) approaches. In Spanish varieties where /s/ reduces to [h] in the coda (but not in word-internal position), word-final /s/ is aspirated before resyllabification occurs in Vs#V structures, suggesting that a sequence such as *los amigos* /los amigos/ ‘the friends’ would undergo [loh. a.mi.ɣoh → lo.ha.mi.ɣoh] versus VsV structures, e.g., *losa* /losa/ ‘slab’ → \*[lo.ha] (Colina 2002; Harris 1983; Kaisse 1999). Nevertheless, as pointed out and illustrated by a reviewer, in more conservative varieties, the sibilant [s] is retained. Brown (2008) states that lower levels of word-final [s] retention correlate with high-frequency words, unless word-strings are taken into consideration and the following word starts with a stressed vowel, in which case the relation is inversed. For instance, Brown (2008, pp. 200–1) indicates that, because of the higher frequency of the word combination *dos años* ‘two years’, this word-string is stored as a single unit in memory, i.e., /dosajnos/. This results in word-final /s/ being reanalyzed as

word-medial, and being less likely to undergo reduction. On the other hand, the author points out that a low-frequency word-string such as *dos asnos* ‘two donkeys’ is stored as two separate words, i.e., /dos asnos/. As such, the word-final /s/ is being processed as word-final, and it is more likely to be reduced (Brown 2008, pp. 201–2). As far as nasal segments are concerned, in velarizing dialects, word-final /n/ is velarized to [ŋ] in Vn#V structures, e.g., *van a casa* /ban a kasa/ ‘they go home’ we find [baŋ. a. ka.sa → ba.ŋa.ka.sa] versus in VnV structures, e.g., *vana* /bana/ ‘vain’ → \*[ba.ŋa] (Harris 1983; Robinson 2012).

The generative literature assumes that the syllabic structure of the resyllabified C#V segments (also termed ‘derived onsets’) and ‘canonical’ CV onsets are identical. From the perspective of connected speech, such an assumption could be well received. However, the postulate of structure similarity has been questioned, as will be shown in the next paragraph. It should be noted that the number of studies that have explored word-internal and across-word syllabic structure implementing articulatory approaches is scarce (see Byrd et al. 2009; Krakow 1999, and references therein), even though those approaches provide a more reliable and less ambiguous description of linguistic patterns and speech gestures than acoustic studies.

In recent years, there has been an effort by phoneticians to identify the acoustic correlates of resyllabified onsets. The language under study in this paper is Spanish, which shows phonotactic restrictions as to which consonants can appear in the coda position, those being /n, l, r, d, s, θ/ (Hualde 2014, p. 62). Most recent studies on the acoustic correlates of resyllabified consonantal segments have focused on the sibilant fricative /s/. As will be explained, word-final /s/ is shorter and more voiced in the coda position; as such, it is expected that resyllabified onsets will have longer durations. Hualde and Prieto (2014) analyzed spontaneous acoustic data of /s/ in Madrid Spanish and investigated uninterrupted voicing, voicing frames, and duration of that segment in word-initial, medial, and final positions. Their results showed that intervocalic word-final position (i.e., resyllabification) led to higher rates of fully voiced /s/ and shorter durations, indicating differences from ‘canonical’ conditions (see Torreira and Ernestus 2012 for similar results). Furthermore, Strycharczuk and Kohlberger (2016) analyzed the fricative /s/ in northern and central Peninsular Spanish and compared the effects of the position within the syllable and word on the acoustic properties of the segment. They found that word-final, derived onset consonants were shorter than canonical ones. Strycharczuk and Kohlberger (2016) is among the few studies that also provided an acoustic description of neighboring vowels. Unlike for the duration of /s/, the researchers found evidence for complete resyllabification in terms of vowel durations. Strycharczuk and Kohlberger (2016, p. 11) encountered that the duration of vowels was not significantly different between word-initial onsets and derived onsets (the latter were 0.09 ms longer) but it was significantly greater compared to word-medial codas (the latter were 17.28 ms shorter) and word-medial onsets (the latter were 11.43 ms shorter). Moreover, Jiménez-Bravo and Lahoz-Bengoechea (2023) conducted an acoustic study where they compared canonical /s, n, l/ onsets, e.g., *vende naves* ‘(s/he) sells ships’ and derived ones *venden aves* ‘(they) sell birds’. Similar to previous studies, their results illustrate that derived (resyllabified) onsets were shorter than canonical ones in duration, respectively; /s/: 97.6 vs. 90.6 ms, /n/: 53.1 vs. 50.2 ms, and /l/: 63.5 vs. 58.7 ms, which provides additional evidence for incomplete resyllabification patterns in Spanish.

In the case of word-final /n/ in Spanish, an allophonic variation in certain varieties is its velarization, i.e., [ŋ] (see Bongiovanni 2021). The velarization of word final /n/ has been attested in the north-west and south of Spain, the Canary Islands, Caribbean varieties, and certain Spanish varieties in South America (Hualde 2014, p. 174). Robinson (2012) provided impressionistic data from Ecuadorian Spanish, specifically from Quito and Cuenca, where participants were asked to resyllabify words that contained a final /n/ in a velarizing context across word junctures, and all participants exhibited a significant pause between words. This would indicate that resyllabification rules might not be applicable

universally in Spanish, as the ‘expected’ syllabic production of the word was misaligned in connected speech.

## 2.2. Syllable Structure and Vocalic Nasalization

Coarticulatory vowel nasalization is the gestural coordination between a vowel (V) next to a nasal consonant (N). The effects of coarticulation can spread from left to right (carryover), e.g., *no* /no/ [nō] ‘no’ in Spanish, or right to left (anticipatory), e.g., *en* [ēn] ‘in’ in Spanish. The outcome in both conditions is gestural overlap with partial phonetic nasalization of the vowel. Cross-linguistic differences have been found with regard to the degree of gestural overlap across carryover and anticipatory, and within each type of process (see [Beristain 2023a, 2023b](#); [Clumeck 1976](#); [Goodin-Mayedá 2016](#); [Martínez 2021](#)).

Previous studies have analyzed the effect of syllable structure on the nasalization of the vowel ([Beristain 2022](#); [Byrd et al. 2009](#)), and the general resolution that they have found is that nasalization develops earlier in vowels in tautosyllabic VN sequences than in heterosyllabic V.N ones because of gestural timing differences ([Krakow 1989, 1999](#)). For instance, [Diakoumakou \(2005\)](#) analyzed coarticulatory vowel nasalization in Modern Greek and compared it to Spanish, Chinese, Japanese, Thai, Ikalanga, French, Italian, American English, Hindi, and Bengali. As far as Greek is concerned, she provides acoustic evidence to point out that the differences found in the nasalization patterns of vowels in tautosyllabic or heterosyllabic environments is due to different articulatory patterns found in syllable-initial and syllable-final contexts, with the latter having a lower velum position than the former. [Diakoumakou \(2009\)](#) shows that only the final 17% of the vowel was nasalized in heterosyllabic V.N sequences, whereas 33% of the vowel was nasalized in tautosyllabic VN ones. Similarly, [Cohn \(1990\)](#) finds that the onset of nasalization in tautosyllabic VN sequences is earlier than in those of heterosyllabic V.N ones in French. Moreover, [Krakow \(1999, p. 27\)](#) analyzed the effect of syllable structure on nasalization patterns in English, comparing word sets such as *see more* vs. *seam ore* and *pa made* vs. *palm aid* (i.e., CV#NV vs. CVN#V). She used the Velotrace ([Horiguchi and Bell-Berti 1987](#)), which collected velum raising and lowering movements with an LED attached to the lower lip with the Selspot System to capture labial aperture and closure during the bilabial nasal /m/ and contiguous vowels. Similarly to [Cohn \(1990\)](#), Krakow found that, in carefully read speech, tautosyllabic VN sequences show an earlier onset of nasalization than heterosyllabic V.N ones. Under similar contexts, [Lahoz-Bengoechea and Jiménez-Bravo \(forthcoming\)](#) compared the degree of nasalization in VN#V and V#NV sequences using Nasalization from Acoustic Features (NAF) measurements (see [Carignan 2021](#) for a methodological overview). Their acoustic data came from 19 individuals from Spain whose first language was Spanish. The authors found no significant differences in the degree of nasal coarticulation between the two contexts: VN#V: 0.714; V#NV: 0.713. These results provide evidence in support of complete resyllabification in connected speech.

We may surmise that an earlier onset of nasalization in tautosyllabic segments is correlated with the development of nasal vowels in Romance languages. As [Sampson \(1999, p. 35\)](#) points out, “the process of vowel nasalization has often been significantly affected by whether the conditioning nasal is tautosyllabic or heterosyllabic, reflecting the importance of the syllable as a structural unit in the diachronic and synchronic phonological patterning of Romance.” Notice how vowels in VN tautosyllabic sequences developed and eventually became nasal vowels in some languages, e.g., BONU ‘good, masc.’ > [bon] > [bōn] > [bõ] (in Modern French), whereas vowels in heterosyllabic sequences showed more coarticulatory resistance, in some cases even leading to denasalization, e.g., BONA ‘good, fem.’ > [bona] in Northern Italian ([Hajek 1997, p. 10](#)).

[Diakoumakou \(2005\)](#) points out that languages with a tendency for open syllables show greater carryover nasalization, while languages with a preference for close syllables have more extensive anticipatory nasalization. She conducted an acoustic study investigating the temporal extent of vowel nasalization in Modern Greek. She obtained data from six native speakers and found that the temporal extent of nasalization was 27 ms long in the

heterosyllabic anticipatory condition, 48 ms long for the tautosyllabic anticipatory condition, and 70 ms for the carryover condition. Diakoumakou discusses these results, comparing them to what has been found in other languages, and explains that the tendency for open syllables, such as in Greek, Spanish, or Italian, seems to be conducive for greater carryover nasalization. On the other hand, she mentions that languages that show a preference for closed syllables show greater anticipatory nasalization (see results for English in Krakow (1999)).

When comparing anticipatory versus carryover nasalization patterns, Cohn (1990) provides airflow contours for various contexts that include tautosyllabic VN and heterosyllabic V.NV and V#NV sequences within a word and across word junctures in French. Her results indicate that there is greater carryover nasalization (e.g., *nez* ‘nose’, p. 123) than anticipatory nasalization (e.g., *bonne* ‘good’, p. 97). Similar aerodynamic results were found by Delvaux et al. (2009). In Cohn (1990), airflow contours in derived onsets, e.g., *bonne ode* ‘good ode’ (p. 123) vs. canonical onsets, e.g., *beau nez* ‘beautiful nose’ (p. 101) do not exhibit significant differences in French. Both conditions show a cline-like rise that appears late in the vocalic segment and then a rapid drop after the offset of the nasal consonant, which is followed by a constant and smooth transition throughout the nasalized segment. This indicates that articulatory correlates are similar across heterosyllabic V#NV and resyllabification V.N#V structures.

### 3. Research Questions

A vast amount of research about resyllabification has focused on the properties of the consonant that changes its syllabic linking. The features associated with such consonants were usually [+oral][−nasal]. Evidence has been provided for sub-phonemic differences between canonical and derived onsets (see Bradley et al. 2022). The role that resyllabification may have on the vowels surrounding the resyllabified consonant has been less investigated, especially in the context of coarticulatory nasalization. Studies on gestural timing and nasalization point out that the syllable structure of contiguous segments plays a significant role, as tautosyllabic segments will show greater gestural overlap than heterosyllabic ones (Krakow 1989; Byrd et al. 2009). Moreover, Diakoumakou (2009) and Delvaux et al. (2009) state that languages that show a tendency towards open syllables usually exhibit greater carryover coarticulatory nasalization than anticipatory nasalization.

Based on the previous findings, the specific research questions (RQs) and hypotheses that the present study will investigate are as follows:

- RQ 1: Are there differences between nasal airflow contours in the degree of phonetic implementation of carryover and anticipatory coarticulatory nasalization in Spanish?

**Hypothesis 1:** Yes. Considering that Spanish shows a tendency for open syllables (Hualde 2014, p. 59), according to Cohn (1990), Diakoumakou (2009), and Delvaux et al. (2009), it is expected that carryover vocalic nasalization should show greater nasal spreading than anticipatory nasalization.

- RQ 2: Does syllable structure play a role in the degree of anticipatory coarticulatory nasality in Spanish?

**Hypothesis 2:** Yes. Based on Krakow (1989, 1999) and Cohn (1990), it is expected that vowels in tautosyllabic CVN# segment sequences will show an earlier onset of nasalization than vowels in canonical CV.NV# and derived CV.N#V heterosyllabic segment sequences. Furthermore, vowels in heterosyllabic (canonical and derived) contexts should exhibit similar anticipatory nasalization patterns.

- RQ 3: Do vowels across word junctures (resyllabification) show parallel carryover nasalization patterns as those within word boundaries?

**Hypothesis 3:** Yes. According to derivational rules of Spanish phonology and studies such as Cohn (1990) and Lahoz-Bengoechea and Jiménez-Bravo (forthcoming), it is expected that vocalic nasalization patterns in resyllabification CV.N#V contexts should present symmetrical patterns to those in heterosyllabic CV.NV# sequences.



## 4. Methodology

### 4.1. Participants

Nine native speakers of Northern Peninsular Spanish (7F, 2M) participated in this experiment. Their average age was 26 (age range = 23–29). All the participants were graduate students at a US university when the experiment took place. They were originally from the Basque Country, spoke Spanish as a native language, and had different levels of proficiency in Basque. There is no reason to believe that the internal structure of Basque could interfere with Spanish nasalization patterns, because, firstly, both Basque and Spanish show resyllabification (Hualde and Ortiz de Urbina 2003; Hualde 2014, respectively); secondly, there are no phonologically nasal vowels in the Basque varieties spoken by the participants (Central and Western), nor is there direct contact with the French language (Zuazo 2014); and, thirdly, none of the participants were proficient in any language that included phonologically nasal vowels. On the other hand, strictly speaking, the evidence presented here describes the Spanish variety of the Basque Country. In principle, there could be dialectal differences in this respect.

### 4.2. Stimuli

The target tokens were adapted from Beristain (2022, p. 50) and fell under the following four different conditions: (1) CV.CV, tautosyllabic oral C and oral V sequences (as oral control tokens); (2) CVN#, tautosyllabic nasalized V and contiguous coda N; (3) CV.NV#, heterosyllabic nasalized V and canonical onset N, as well as a proceeding nasalized V; and (4) CV.N#V, derived onset N, with preceding and proceeding nasalized Vs (resyllabification context). The first vowel of each word was each of the vowels in Spanish, /i, e, a, o, u/, and the second vowel in the nasal structures was always /a/. The wordlist can be found in Table 1.

**Table 1.** Target tokens.

|     | CV.CV<br>(Oral Control)         | CVN#<br>(Tautosyllabic)        | CV.NV#<br>(Heterosyllabic)           | CVN#V<br>(Resyllabification)             |
|-----|---------------------------------|--------------------------------|--------------------------------------|------------------------------------------|
| /i/ | <i>tita</i><br>'aunt'           | <i>patín</i><br>'rollerblade'  | <i>patina</i><br>'s/he rollerblades' | <i>patín atado</i><br>'tied rollerblade' |
| /e/ | <i>cateto</i><br>'ignorant'     | <i>ten</i><br>'you have, IMP.' | <i>tena</i><br>'timber'              | <i>ten atado</i><br>'have (it) tied'     |
| /a/ | <i>tato</i><br>'little brother' | <i>tan</i><br>'so'             | <i>gitana</i><br>'gypsy'             | <i>tan atado</i><br>'so tied'            |
| /o/ | <i>pitote</i><br>'fuss'         | <i>botón</i><br>'button'       | <i>botona</i><br>'s/he buttons'      | <i>botón atado</i><br>'tied button'      |
| /u/ | <i>batuta</i><br>'baton'        | <i>atún</i><br>'tuna'          | <i>gatuna</i><br>'cat-like'          | <i>atún atado</i><br>'tied tuna'         |

As can be noted, the stress patterns across words were uniform: the first vowel (V1) was always stressed, and the second vowel (V2), in the CV.NV# and CV.N#V contexts, was an unstressed /a/. This was undertaken to normalize the data because research has shown that differences in stress may lead to varying degrees of nasalization (Byrd et al. 2009; Cohn 1990; Krakow 1989, 1999).

The list was presented to participants before the experiment started, and the meaning of the words was explained in case they were not familiar with it, which did not happen in the current experiment. Target words were included in the carrier phrase Digo TARGET ligeramente 'I say TARGET softly'.

### 4.3. Equipment

The aerodynamic data were collected via a vented Scicon OM-2 oral mask (Scicon R&D, Inc., Beverly Hills, CA, USA) that was connected to two TSD160A pressure transducers (operational pressure 72.5 cm H<sub>2</sub>O; Biopac Systems, Goleta, CA, USA). Simultaneous

acoustic data were obtained to facilitate the segmentation process. For that, the signal was preamplified using a Grace M101 microphone preamplifier (Grace Designs, Boulder, CO, USA) and digitized at 2 kHz, the highest allowed in the Biopac System (BIOPAC 2020). Participants wore an AKG C-520 head-mounted microphone (Harman International, Stamford, CT, USA) that was located approximately 3 cm (1 inch) away from their mouths. For a more detailed report about the equipment, see Beristain (2022, 2023a).

#### 4.4. Data Collection and Procedure

The author of the current study calibrated the equipment manually before every session by utilizing an AFTA6A Calibration syringe of 600 mL (Beristain 2023a, 2023b) and annotating the correction value of the signal for every word uttered and the surface area of the air volume expelled by the syringe. Those numbers were inserted in a calibration formula that was applied to the raw data of each participant. The conversion equation used is presented in (1) (Beristain 2023a, 2023b; Shosted 2009), as follows:

$$s' = \text{filtfilt} \left( s \times \frac{v}{\int s} + c \right) \quad (1)$$

As cited in Beristain (2023b, p. 9): “ $s'$  is the new, resulting signal; *filtfilt* is the MATLAB function;  $s$  is the original, unaltered signal;  $\int$  means integration in order to calculate the area under the signal curve;  $v$  is the total volume of the syringe (= 600 mL), and  $c$  is the correction number (specific to every word)”.

Data were collected in a sound-attenuating booth inside a phonetics laboratory of a university in the USA. In order to avoid as much linguistic co-activation as possible, the author of the current study (who is a native speaker of Northern Peninsular Spanish) communicated with the participants in Spanish at all times. Participants signed a written consent before starting the experiment.<sup>1</sup>

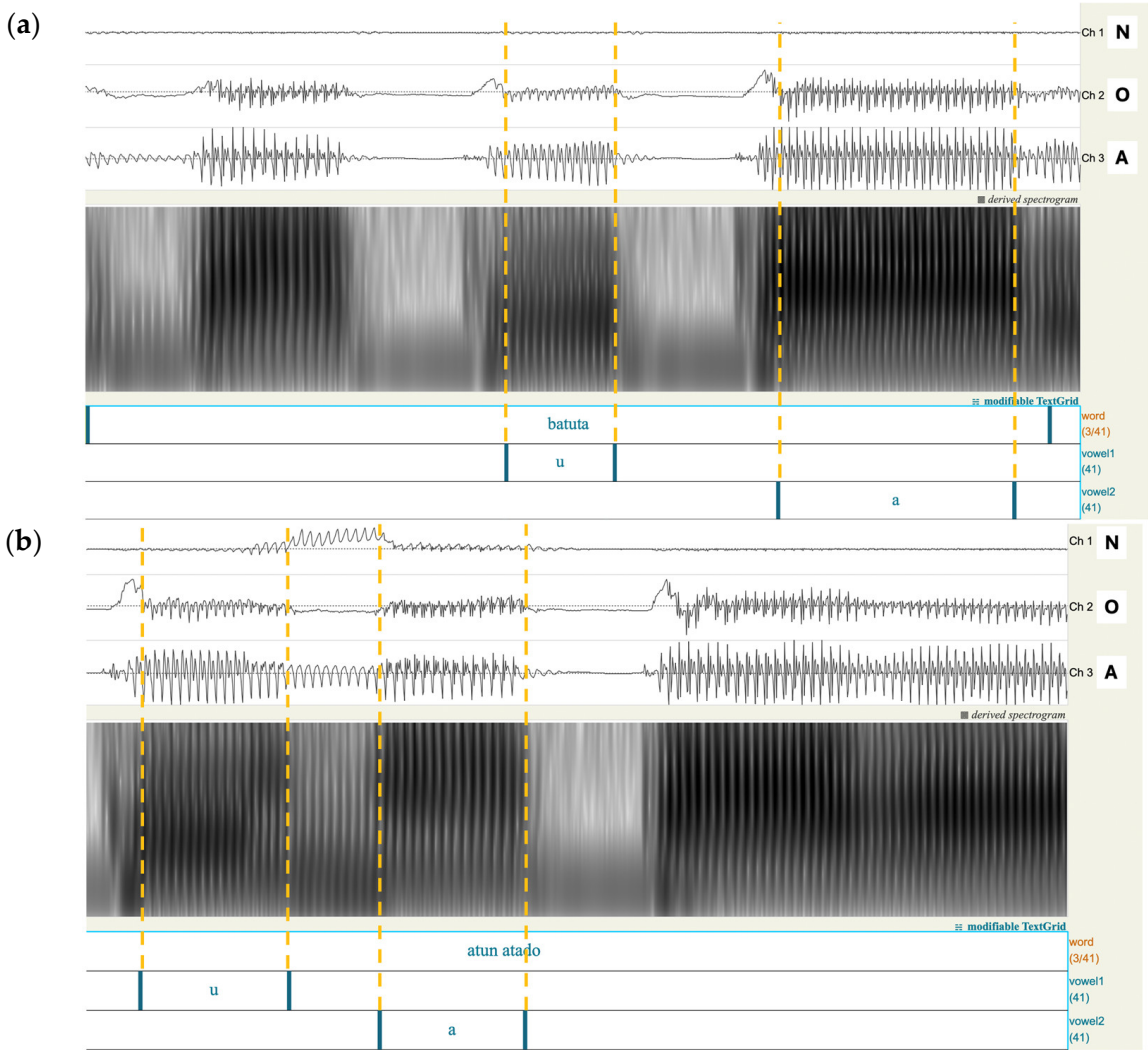
Participants were then informed about the experiment and shown how to operate the equipment. Before every experimental procedure, a trial session took place to ensure no air leakage was present. None of the current participants showed anomalous results in their Spanish trial productions. Once the experiment began, participants held the mask holding the handle attached to it. Recordings were stopped after every minute, in order to alleviate any possible discomfort.

The software that was utilized to obtain the data was AcqKnowledge (version 3.9.1). Three different and simultaneous signals were collected: (1) nasal airflow, (2) oral airflow, and (3) audio (acoustics). The current study will only present nasal airflow data. Future studies will provide a multidimensional analysis presenting a combination of several signal types. MATLAB (version 2020a; MATLAB 2020) was used to convert the AcqKnowledge files into .wav files that were readable in Praat (Boersma and Weenink 2020).

#### 4.5. Data Annotation

In Praat, data were segmented and annotated by inspecting the nasal airflow, oral airflow, and audio signals. The onset of the first vowel (V1) was located after the visible burst of air of /t/ decreased and a more periodic signal was present both in the oral airflow and audio signals, indicating vowel periodicity (see Beristain 2023a, 2023b; Delvaux et al. 2009). The amplitude of the spectrogram was also a clear cue for distinguishing the vowel from contiguous consonants, both oral and nasal. The cues used to segment oral second vowels (V2) were: the oral air burst of /t/, the more periodic signal apparent in oral and audio channels, and the greater amplitude. The cues for nasalized V2s were as follows: the onset of oral airflow following the decrease in nasal airflow (indicating the N-V transition) and the greater amplitude present in the vowel. The offset of nasalized V2s was located when the amplitude decreased significantly from the V-/C/ transition. Figure 2 presents two examples with segmentations that include a fully oral CVCV token, *batuta* ‘baton’, and a CV.N#V (resyllabification) one, *atún atado* ‘tied tuna’. Notice how the signal in Channel 1

(nasal airflow) is virtually flat, showing essentially zero nasal airflow in *batuta* (N: nasal; O: oral; A: audio/acoustic).



**Figure 2.** Sample segmentation of CVCV and CV.N#V sequences: (a) *batuta* ‘baton’; (b) *atún atado* ‘tied tuna’; (Speaker #21, Rep. #1).

4.6. Data Analysis

Taking into consideration the goal of this experiment, the time dynamics of nasal airflow in V1 and V2 were analyzed. Each segment was further divided into 40 equidistant timepoints. The total number of datapoints gathered and submitted for the statistical analysis is presented in Table 2.

**Table 2.** Number of tokens analyzed.

|                                | Number                                                                                                                                           |
|--------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------|
| Anticipatory nasalization (V1) | 9 speakers × 5 vowel conditions [i, e, a, o, u] × 40 time-points × 4 syllable conditions [CVCV; CVN#; CV.NV#; CV.N#V] × 2 repetitions × = 14,400 |
| Carryover nasalization (V2)    | 9 speakers × 5 vowel conditions [i, e, a, o, u] × 40 time-points × 3 syllable conditions [CVCV; CV.NV#; CV.N#V] × 2 repetitions = 10,800         |
|                                | Total: 25,200 datapoints                                                                                                                         |



To statistically analyze the time dynamics of nasal airflow, generalized additive mixed models (GAMMs) were run in R (R Core Team 2020) and RStudio (R Studio Team 2020) using the *mgcv*, v. 1.8.31 package (Wood 2011). Data visualization was conducted using the *itsadug* package, v. 2.3 (Van Rij et al. 2017). The optimal statistical models for V1 and V2 were chosen by inspecting Akaike Information Criterion (AIC) scores (Akaike 1974). Such models are listed below (see Appendix A for further details).

- Optimal model for V1: `Context * Vowel + Sex + s(NormTime, by = interaction(Context, Vowel)) + s(NormTime, by = Sex) + s(NormTime, Speaker, by = interaction(Context, Vowel), bs = "fs", m = 1) + s(Word, bs = "re")`
- Optimal model for V2: `Context + Sex + s(NormTime, by = Context) + s(NormTime, by = Sex) + s(NormTime, Speaker, by = Context, bs = "fs", m = 1) + s(Word, bs = "re")`

As shown, the statistical model to analyze anticipatory vowel nasalization (V1) included an interaction between CONTEXT (CVCV; CVN#; CV.NV#; CV.N#V) and VOWEL (i; e; a; o; u) as well as the fixed factor of SEX (male; female). A smooth function was included through NORMTIME (from 0 to 1 with 0.025 increments). The statistical model to analyze carryover nasalization (V2) was similar to that of V1 without VOWEL in it. This is because V2 was always /a/ in CV.NV# and CV.N#V tokens.

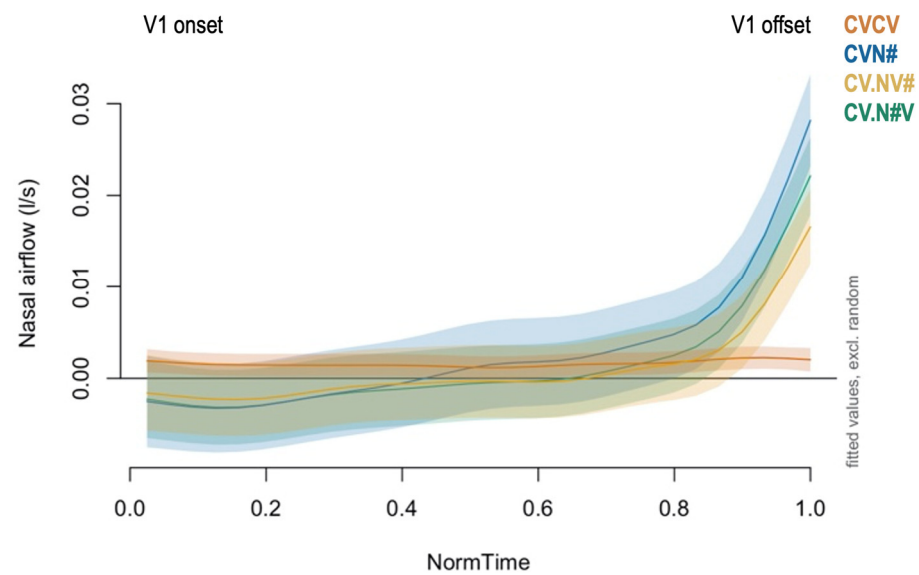
## 5. Results

This section is divided into two parts: (1) V1 (anticipatory vowel nasalization) and (2) V2 (carryover vowel nasalization). As is customary with GAMM reports, figures will present contours and difference curves. The *x*-axis of each figure indicates normalized time (NormTime), which analyzes nasal airflow (in L/s) across 40 equidistant timepoints from the onset to the offset of the vocalic segment. The darker line within the contour indicates the mean values, while the lighter color indicates confidence intervals, i.e., variability in the data. The nasalized target and oral control contexts are presented. Note that even the oral control context shows a certain degree of nasal airflow, as air will inevitably be exhaled through both oral and nasal apertures when producing speech. Most importantly, the quantity and shape of nasal airflow in the oral control context is significantly lesser and stable, as opposed to rising contours in sequences that contain nasal structures.

The way in which statistical significances are provided and onset and offset of nasalization are calculated is by means of statistical pair-wise comparisons, retrieved via the `plot_diff()` function under the *itsadug* package<sup>2</sup>. Oral control segments and nasalized target segments are compared, and the difference curves of their nasal airflow are analyzed, thus pointing out and locating the onset and offset of the nasal gesture in the time window of the whole segment (Beristain 2023a). The area in which the two airflow curves are significantly different is the “time region of significance”, and that will be delimited by red dotted lines in the difference curve figures. Those areas are what will be reported in the results section. The full statistical model output for V1 can be found in Appendix B, while that for V2 can be found in Appendix C.

### 5.1. Anticipatory Vowel Nasalization

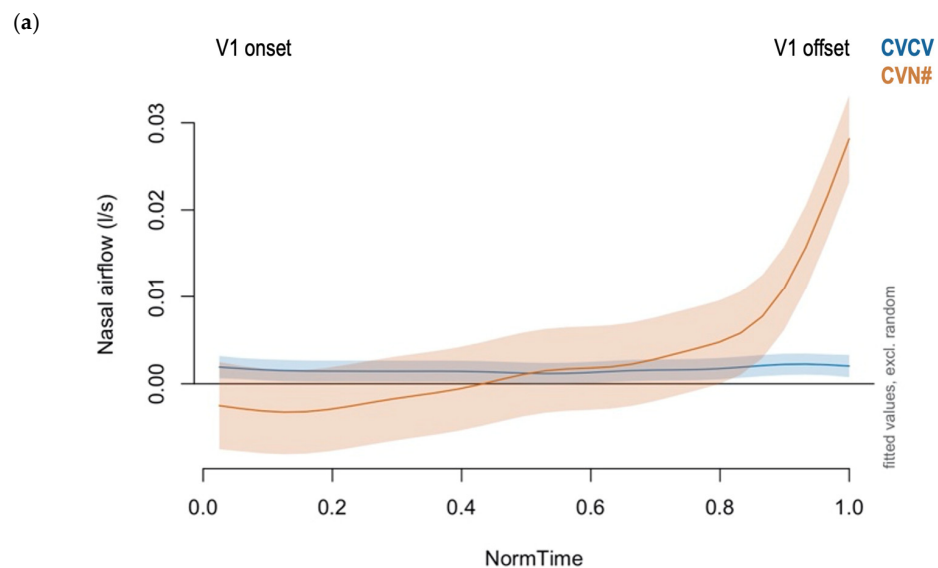
The results for V1 nasal airflow curves are illustrated in Figure 3.



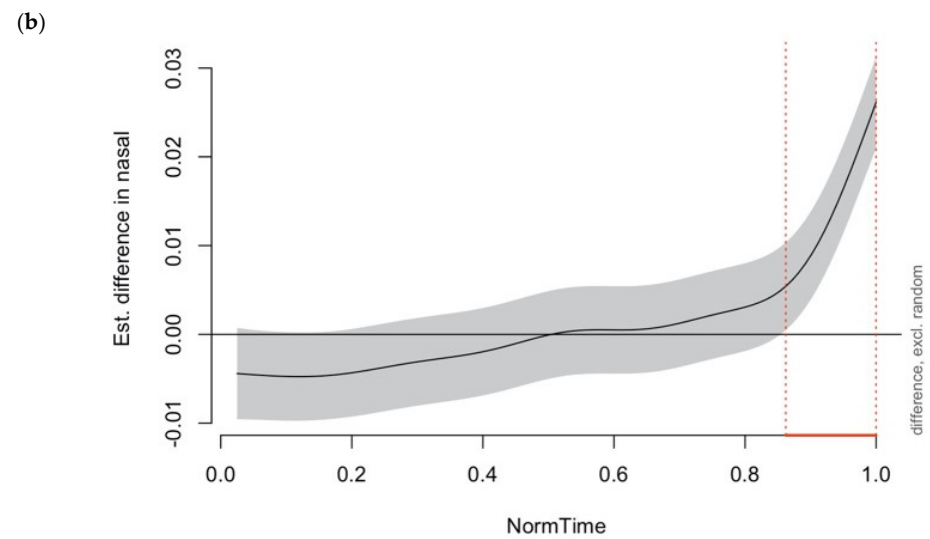
**Figure 3.** Nasal airflow GAMM curves of V1 in CVCV (oral control), CVN# (tautosyllabic), CV.NV# (heterosyllabic), and CV.N#V (resyllabification)<sup>3</sup>.

As can be seen, the nasal airflow contour in the oral control (CVCV) context is stable and virtually non-existent. The tautosyllabic (CVN#) sequence shows the greatest amount of nasal airflow for V1, followed by resyllabification (CV.N#V), and then the heterosyllabic (CV.NV#) one. The pair-wise comparisons between each nasalized context and the oral control exhibit differences. Such differences are shown and described in Figures 4a,b, 5a,b and 6a,b.<sup>4</sup>

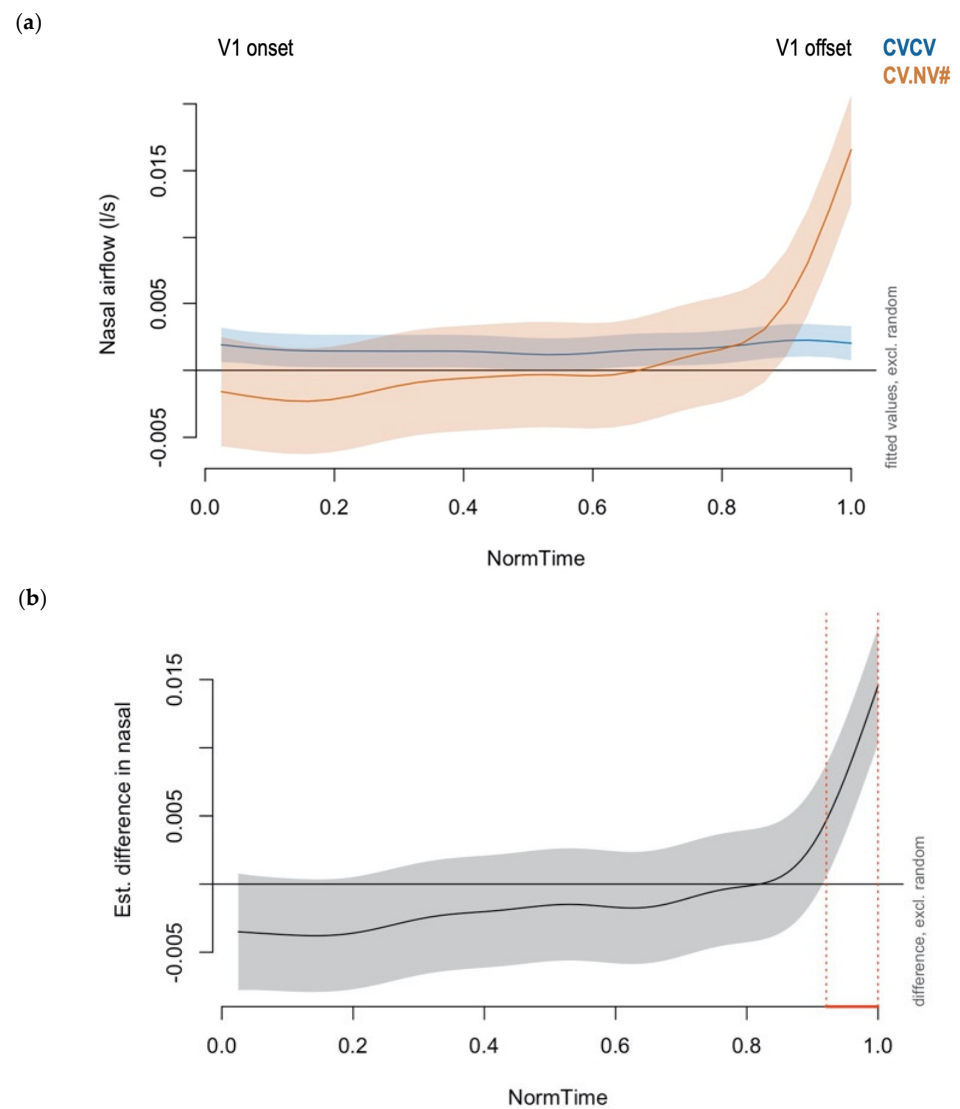
Figure 4a compares anticipatory nasalization contours in the oral control CVCV structure and the tautosyllabic CVN# one and illustrates a minimal and stable development of nasal airflow contour for CVCV, while a rise is seen towards to end of the segment for CVN#. This is to be expected, as the segment to follow V1 in CVN# is a nasal consonant, and as such, due to anticipatory coarticulatory nasalization, the onset of the nasal gesture that applies to the nasal consonant will begin before the offset of the previous vowel, i.e., V1. As shown in Figure 4b, the time region of significance starts at 0.86. Aerodynamic data for Spanish has shown delayed onsets of nasalization, as opposed to other languages like English (Beristain 2023a).



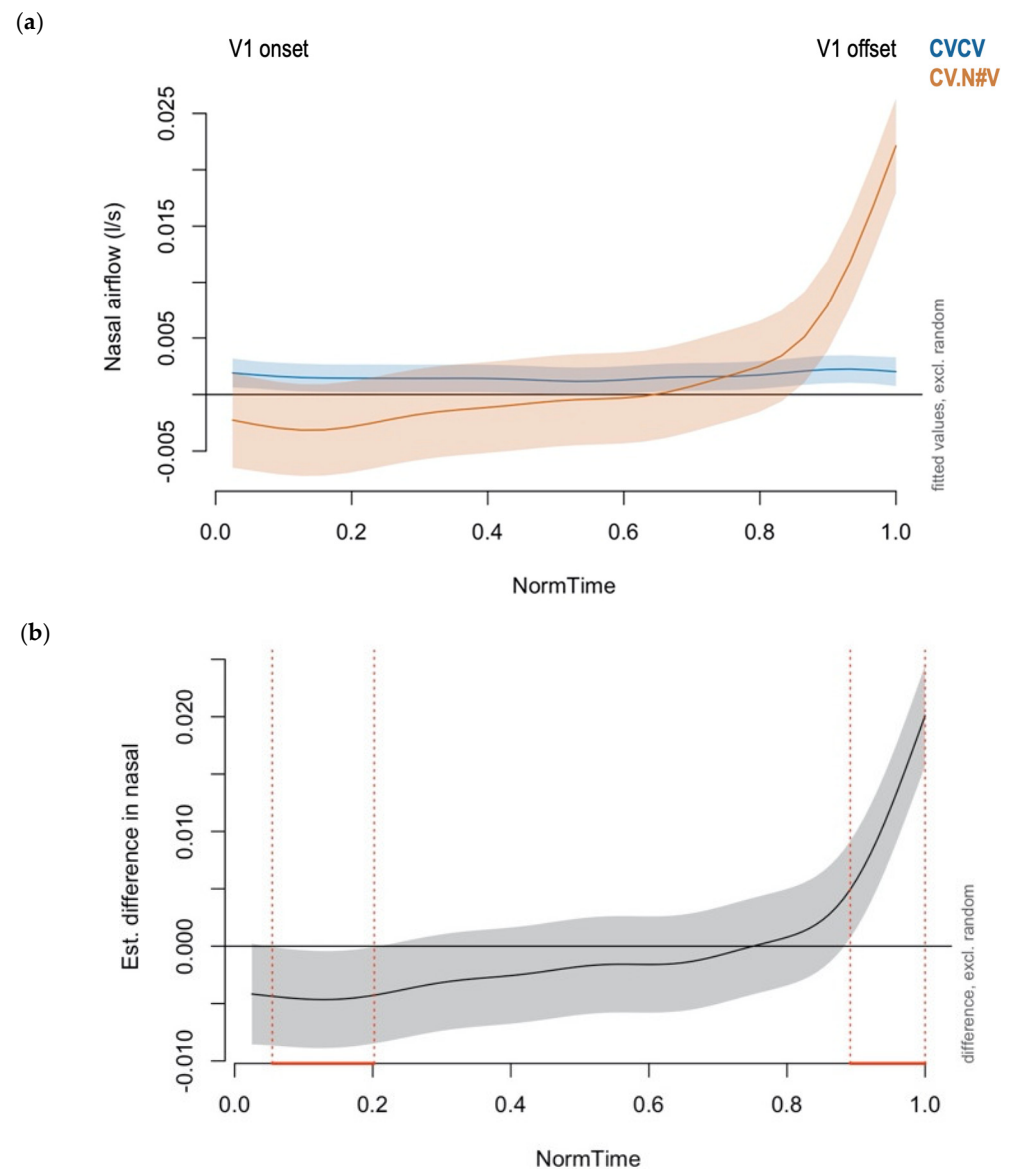
**Figure 4.** Cont.



**Figure 4.** (a) Nasal airflow GAMM curves of V1 in CVCV and CVN# syllable structures; (b) difference curve of CVN# and CVCV (in V1).



**Figure 5.** (a) Nasal airflow GAMM curves of V1 in CVCV and CV.NV# syllable structures; (b) difference curve of CV.NV# and CVCV (in V1).



**Figure 6.** (a) Nasal airflow GAMM curves of V1 in CVCV and CV.N#V syllable structures; (b) difference curve of CV.N#V and CVCV (in V1).

Figure 5a compares anticipatory nasalization contours in CVCV and the heterosyllabic CV.NV# sequences, and it shows similar patterns to those in Figure 4a. The main difference is that the nasal airflow contour for CV.NV# exhibits lower amplitude, and confidence intervals are wider. Figure 5b reveals that the time region of significance starts at 0.92, which is later than for CVN#.

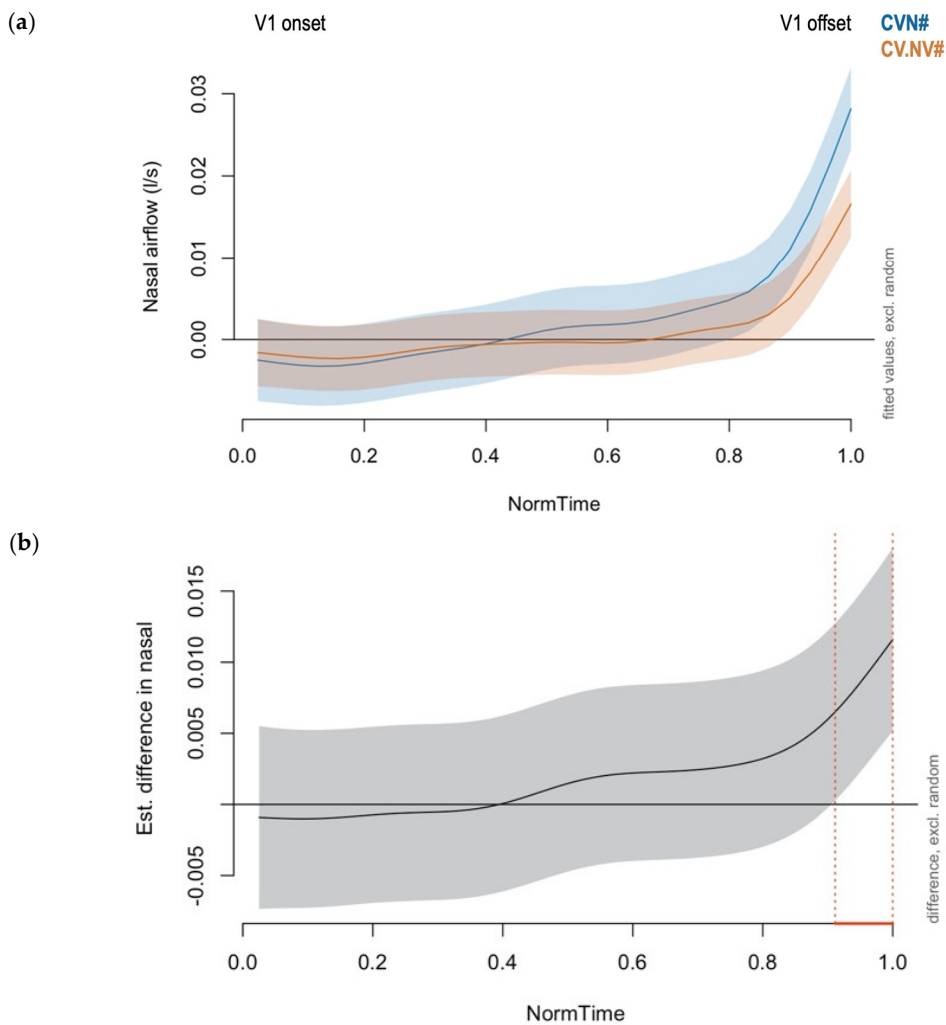
In Figure 6a, the CVCV sequence is compared to the CV.N#V resyllabification context. The patterns found are more similar to those in CVN#. The first time region of significance in Figure 6b (0.05 to 0.20) should not be considered an indicator of onset of nasalization because the downward directionality of the nasal airflow could pertain to air inhalation and not velum lowering. The second time region of significance starts at 0.89.

Below is Table 3, which summarizes the onset of significant differences between nasalized and oral V1s, which we consider a cue for onset of nasalization.

**Table 3.** Onset of nasalization (0–1) of V1.

|                            | Onset of Nasalization |
|----------------------------|-----------------------|
| CVN# (tautosyllabic)       | 0.86                  |
| CV.NV# (heterosyllabic)    | 0.92                  |
| CV.N#V (resyllabification) | 0.89                  |

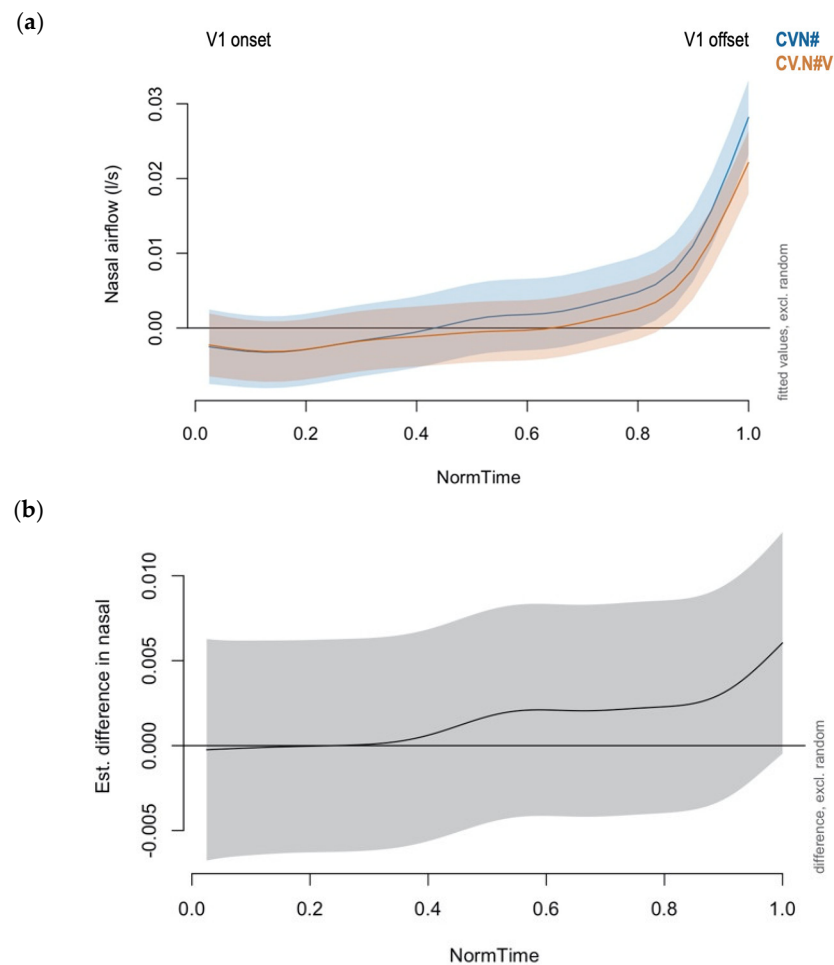
Regarding inferential statistics, the only significant difference between the nasal airflow contours in nasalized vowels (CVN#, CV.NV#, and CV.N#V) was retrieved between CVN# and CV.NV#, as illustrated in Figure 7a,b. The tautosyllabic CVN# sequence exhibited a greater amount of nasal airflow than the resyllabification CV.N#V context. The time region of significance started at 0.91.



**Figure 7.** (a) Nasal airflow GAMM curves of V1 in CVN# and CV.NV# syllable structures; (b) difference curve of CVN# and CV.NV# (in V1).

Regarding the contour differences between CVN# and CV.N#V, the former showed a higher degree of nasal airflow starting relatively close to the midpoint of the vowel (see Figure 8a). However, no significant differences were found between the two contexts, as shown in Figure 8b.



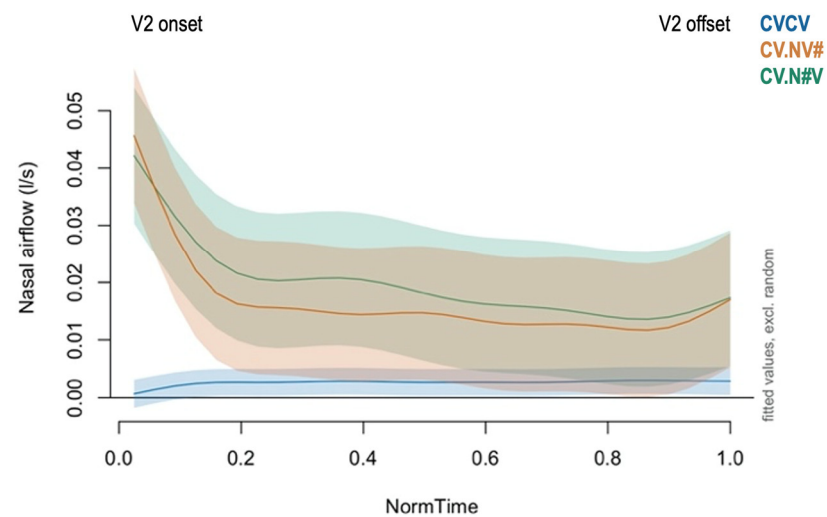


**Figure 8.** (a) Nasal airflow GAMM curves of V1 in CVN# and CV.N#V syllable structures; (b) difference curve of CVN# and CV.N#V (in V1).

### 5.2. Carryover Vowel Nasalization

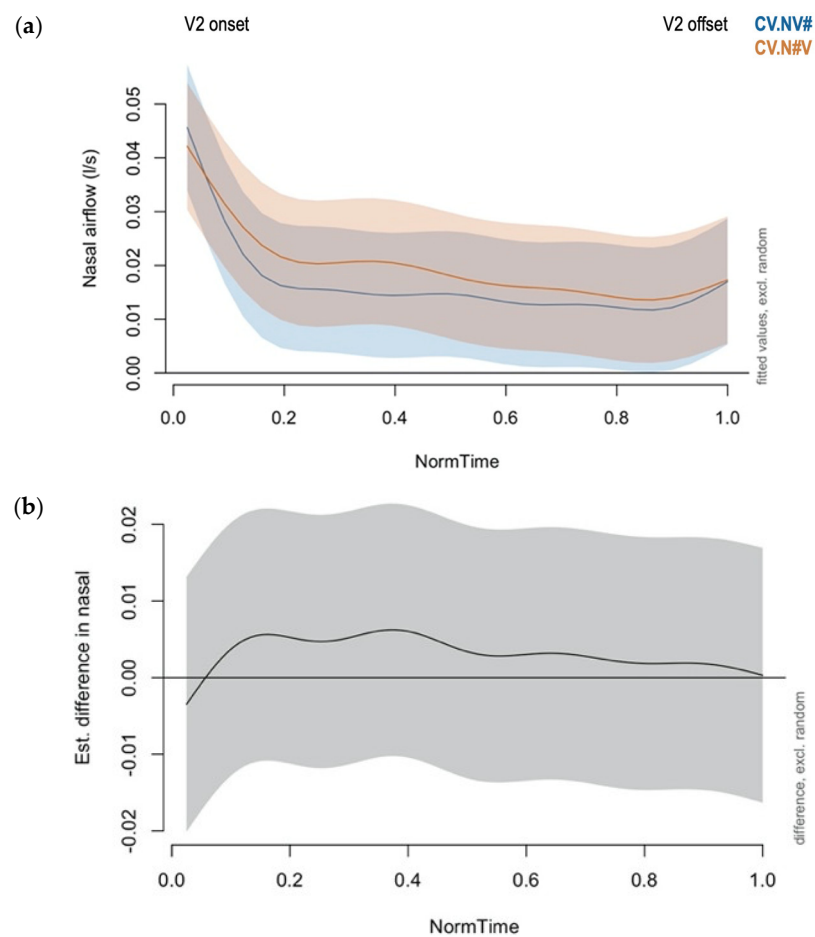
The results in this section pertain to nasal airflow in the second vowel (V2), i.e., CVCV (oral control), CV.NV# (heterosyllabic), and CV.N#V (resyllabification). Figure styles are similar to those in Section 5.1. The  $x$ -axis represents normalized time (NormTime) of 40 equidistant points, and  $y$ -axis indicates the amount of nasal airflow produced (in L/s). The left side of figures are the onset of the vowel, while the right side are its offset. Notice that the CVN# (tautosyllabic) syllable structure will not be included in this section because there is no V2. The offset of carryover nasalization was calculated by contrasting the V2 nasal airflow contours in CVCV (oral control) versus CV.NV# and CV.N#V (nasalized).

Figure 9 illustrates nasal airflow in CVCV, CV.NV#, and CV.N#V. As can be seen, CVCV shows a stable and virtually non-existent nasal airflow, which is to be expected as no nasal segment is present in that sequence. With regard to the nasalized contexts and carryover nasalization patterns, CV.NV# and CV.N#V show parallel patterns: a sharp decline is present at the beginning of V2, induced by the presence of the preceding nasal segment /n/. After this, nasal airflow stabilizes throughout the remainder of the vowel, always showing higher nasal airflow values than the oral control context CVCV.

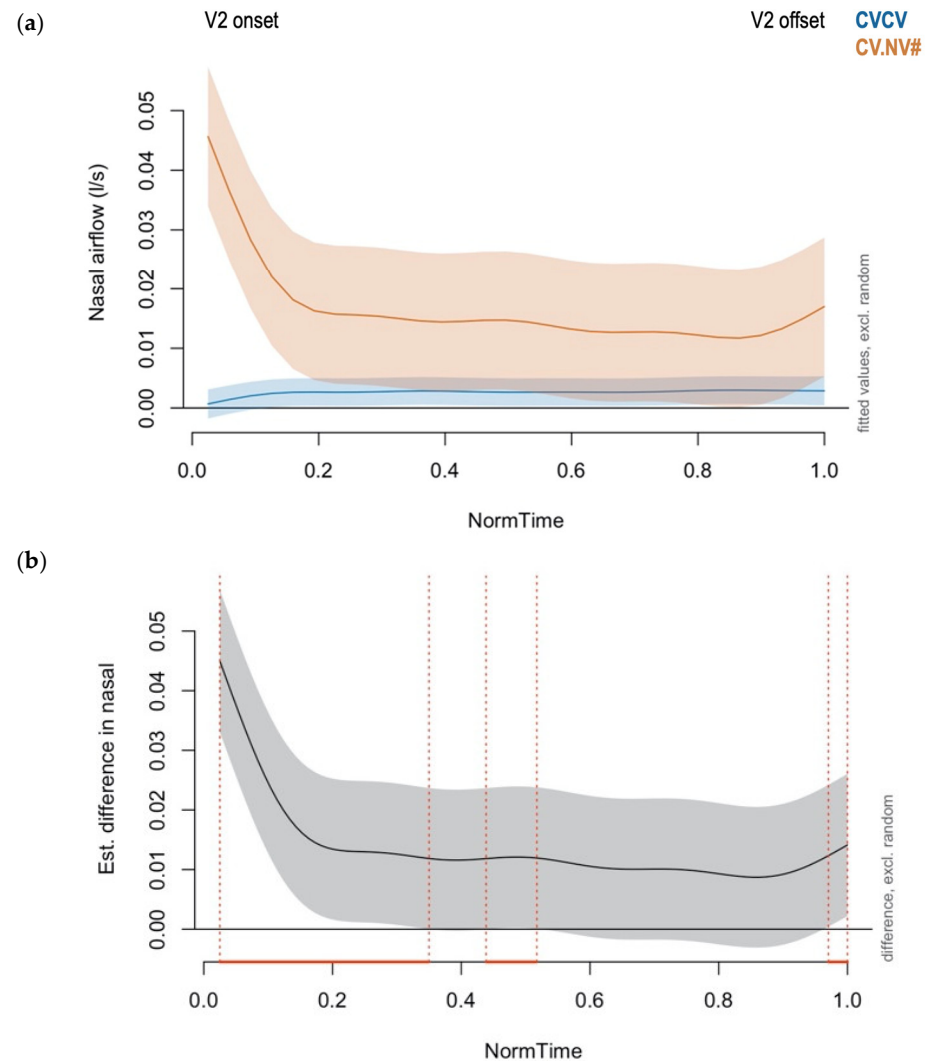


**Figure 9.** Nasal airflow GAMM curves of V2 in CVCV, CV.NV#, and CV.N#V.

Pair-wise comparisons are presented in Figures 10a,b, 11a,b, and 12a,b.



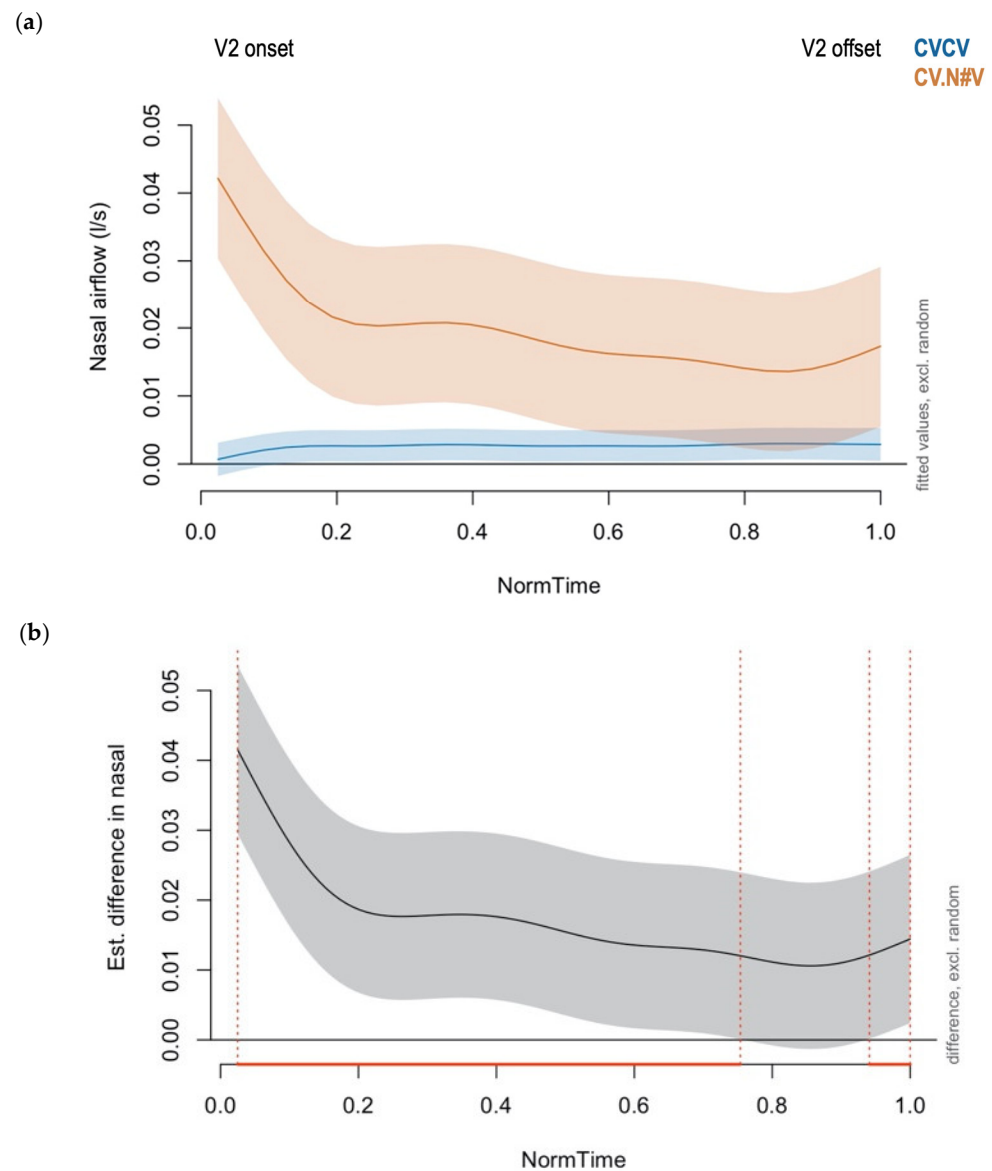
**Figure 10.** (a) Nasal airflow GAMM curves of V2 in CV.NV# and CV.N#V syllable structures; (b) difference curve of CV.NV# and CV.N#V (in V2).



**Figure 11.** (a) Nasal airflow GAMM curves of V2 in CV.NV# and CVCV syllable structures; (b) difference curve of CV.NV# and CVCV (in V2).

As shown in Figure 10a, the V2 nasal airflow contours in nasalized contexts show similar patterns between CV.NV# and CV.N#V. As explained in Figure 9, a rapid decline during the initial portion of the vowel is followed by a more stable nasal airflow contour that does not decrease to zero. When contrasting both nasal airflow contours, no significant differences are found (see Figure 10b).

Figure 11a compares the nasal airflow contours of CVCV and CV.NV#. The oral context shows a stable and low degree of nasalization, to be expected from its structure, and the heterosyllabic CV.NV# sequence shows a rapid decline, with some overlap between the 0.2–1 time region. The time regions of significance between contours arise in 0–0.35, 0.43–0.51, and 0.97–1 (Figure 11b). One could argue the offset may be when the first time region of significance culminates, but we should be cautious considering the various time regions of significance and the physiological nature of the data. If we observe the data, we will see that the reason for the lack of statistical difference between the two time regions of significance is due to the downward directionality of the nasal airflow in CV.NV#. Since the nasal airflow remains relatively stable in that portion of the vowel, there is no reason to believe that the offset of carryover vocalic nasalization is that first instance, and we should thus set it at the second one at 0.51. The third time region of significance is not an indicator or cue of onset of nasalization, as the following consonant is a /l/.



**Figure 12.** (a) Nasal airflow GAMM curves of V2 in CV.N#V and CVCV syllable structures; (b) difference curve of CV.N#V and CVCV (in V2).

In Figure 12a, the CV.N#V nasal airflow contour is compared to that of CVCV. As can be seen, the distance between the two curves is greater and the overlap is more delayed than in Figure 11a, which applies to CV.NV#. Approximately, the overlap in Figure 12a begins close to 0.6, and extends until the end of V2. By contrasting both contours, time regions of significance arise at 0–0.75 and 0.94–1 (see Figure 12b). Notice that the second significance window frame arises in the nasal airflow due to the rise of the CV.N#V curve in the final portion of V2.

Table 4 provides a summary of the offsets of nasalization for V2.

**Table 4.** Offset of nasalization (0–1) of V2.

|                            | Offset of Nasalization |
|----------------------------|------------------------|
| CV.NV# (heterosyllabic)    | 0.51                   |
| CV.N#V (resyllabification) | 0.75                   |

## 6. Discussion

Let us revisit the goals and hypotheses of the current study: first, to document the differences between anticipatory and carryover coarticulatory nasalization in Spanish. Based on previous studies such as [Diakoumakou \(2009\)](#) and [Delvaux et al. \(2009\)](#), we hypothesized that carryover nasalization would present to a greater extent than anticipatory nasalization. Second, to elucidate whether the extent of coarticulatory anticipatory and carryover nasalization in Spanish is affected by tautosyllabicity and heterosyllabicity of VN sequences. We hypothesized that segments within the same syllable would show greater gestural overlap ([Byrd et al. 2009](#)) and an earlier onset of nasalization than those in canonical and derived (resyllabification) heterosyllabic sequences. Third, to test the role of resyllabification on anticipatory and carryover coarticulatory nasalization. Previous literature ([Bradley et al. 2022](#); [Hualde and Prieto 2014](#); [Jiménez-Bravo and Lahoz-Bengoechea 2023](#); [Strycharczuk and Kohlberger 2016](#)) has shown differences between canonical and derived onset consonants. However, articulatory data show that the characteristics of neighboring vowels in those contexts are similar ([Cohn 1990](#); [Krakow 1989, 1999](#)). Moreover, [Lahoz-Bengoechea and Jiménez-Bravo \(forthcoming\)](#) find the degree of anticipatory nasalization in V#NV and VN#V sequences to be identical.

This study showed that the degree of coarticulatory carryover nasalization is greater than that of anticipatory nasalization in Spanish (RQ1, Hypothesis 1). Anticipatory nasalization was implemented in the final 15% of the segment, while carryover nasalization extended from the beginning to 51–75% of the vocalic segment. Previous literature had diverging proposals as to which one of the two shows greater nasal spreading. An argument that is generally used in favor of this view is how current phonologically nasal vowels in Romance languages are a development of contiguous VN segments and not NV ([Sampson 1999](#)). [Henderson \(1984\)](#), by means of data obtained with a fiberoptic endoscope, argues that it is anticipatory nasalization which shows greater extent, and provides evidence for the velum reaching lower positions in CVN# sequences than in NVC#. However, it should be noted that, in Henderson's study, the coda consonant in the NVC# sequence is a /t/, which could induce an earlier rise of the velum in the gestural timing and transition. Other studies such as [Diakoumakou \(2009\)](#) have pointed out that the extent of coarticulatory nasalization is language-specific. Her investigation focuses on Modern Greek, but also considers other languages, and proposes that languages that favor open syllables show a tendency for greater carryover nasalization, while those languages that favor closed syllables show greater extent of anticipatory vowel nasalization. Spanish is an example of a language that favors the CVCV type of open syllables, and greater carryover nasalization is indeed the pattern that is encountered. In recent studies comparing coarticulatory nasalization in CVN sequences in English and Spanish, [Beristain \(2023a, 2023b\)](#) found that the onset of nasalization was significantly earlier in English, and that the ratio of nasal airflow proportion (to total airflow produced) was significantly higher in English, too. Whether this can simply be explained by the preference of English for closed syllables or linguistically internal reasons goes beyond the scope of the current study.

Furthermore, evidence for an earlier onset of vocalic nasalization in tautosyllabic CVN# sequences as opposed to heterosyllabic canonical CV.NV# and derived CV.N#V sequences (RQ2, Hypothesis 2) was found. This finding is in alignment with previous literature that considers (a) articulatory gestures to be an important part of the physiological part of the syllable ([Byrd et al. 2009](#); [Krakow 1999](#)), and (b) that the timing among gestures of segments within the same syllable possess greater articulatory overlap and coordination than those in different syllables. In the CVN# sequence, the velum will have started to reach a spatially lower position during the vocalic segment by the time we have the onset of N. On the other hand, for a vowel that is contiguous to a nasal consonant in a heterosyllabic condition, the gestural coordination will be different. As a word-medial onset, the articulatory effort is not equal to a word-initial onset. [Krakow \(1999\)](#) points out that syllable-initial consonants are 'stronger' because "it is generally associated with tighter articulatory constrictions and with greater stability" (p. 25). The significant difference

found in anticipatory nasalization between CVN# and CV.NV# could be induced because of syllable structure. However, the lack of significant differences between CVN# and CV.N#V complicates that argument. As far as structural similarities are concerned in the generative literature, one would have expected differences to arise between CVN# vs. CV.NV#, and CVN# vs. CV.N#V, not solely in the former<sup>5</sup>. Lahoz-Bengoechea and Jiménez-Bravo (forthcoming) found similar results when comparing VN sequences in VN# and V#N structures. The authors point out that as coarticulatory nasalization is a purely phonetic and a mechanical byproduct in Spanish, “[its effect arises in close contact to the nasal consonant, independently from its phonological structure]” (p. 3, translated by the author of this manuscript). Previous literature on the resyllabification of non-nasal segments has deduced that derived onsets exhibit distinct sub-phonemic characteristics from canonical onsets (Hualde and Prieto 2014; Strycharczuk and Kohlberger 2016). Although those studies have focused on oral fricatives mostly, it could be hypothesized that some additional cues might be affected in nasal consonants in resyllabification contexts as well. A future study will provide a multidimensional view of aerodynamic and acoustic characteristics of the nasal segments that were examined in the current study.

Third, in alignment with results presented in Cohn (1990), the current data demonstrated that carryover nasalization patterns were parallel between: (i) within word, heterosyllabic CV.NV#, and (ii) across word boundaries, resyllabification CV.N#V sequences (RQ3, Hypothesis 3). Most of the previous literature had focused on the way in which resyllabification affected the consonant, and those studies found differences in terms of the acoustic cues such as duration and voicing frames of oral fricatives. Little had been mentioned about how coarticulatory nasalization could spread across word junctures and across syllabic reorganization processes. This study showed that no significant differences were found regarding anticipatory or carryover nasalization among CV.NV# and CV.N#V sequences, which correlates with what Strycharczuk and Kohlberger (2016) found; that is, that vowels are less malleable in their phonetic production as opposed to the consonant for which the syllabic linking changes. As pointed out in the previous paragraph, one of the reasons for this may be that coarticulatory nasalization is a mechanical byproduct in Spanish, and the generative literature considers CV.NV# and CV.N#V sequences structurally identical. An important difference between previous studies and the current one is the nature of the data. While most of the previous studies investigating the effect of resyllabification explore acoustic correlates, the current one delves into the physiological characteristics of speech; in other words, it analyzes the way in which air is exhaled during speech production. This avenue had not been explored in the context of syllable structure realignment. As far as resyllabification is concerned, generative phonology considers its structure identical to any other heterosyllabic structure, yet previously mentioned laboratory studies provided evidence for acoustic differences between canonical and derived onsets. The results obtained in this study may elucidate a novel perspective on connected speech and its articulatory features. Here, the extent of phonetic characteristics such as coarticulation can be studied more accurately and without the need to conclude differences from fine-grained details in the acoustic signal.

Lastly, the limitations of the current study cannot go unnoticed. A sample of nine participants and a database of 630 vocalic tokens were used to draw conclusions. Furthermore, Spanish data were collected in an English-speaking environment. As such, we need to consider that participants’ English could have influenced their Spanish productions. The researcher, a native Spanish speaker, tried to induce participants into a “monolingual”-mode to the best of his abilities where only Spanish was used during the experimental setting. Moreover, while none of the target tokens were uncommon words, their lexical frequency was not meticulously controlled (cf. Brown 2008). Doing so could have contributed to a more thorough understanding and analysis of the topic under study. Considering that aerodynamic experiments have reported small(er) sample sizes (Kochetov 2020), the current study is a significant contribution to the literature on syllable structure, Spanish phonology, and articulatory phonetics.



## 7. Conclusions

The two aims of the current study were to investigate aerodynamic differences between anticipatory and carryover coarticulatory nasalization in Spanish and to observe whether nasalization can be used as a cue to resyllabification.

The contours of aerodynamic nasal airflow data illustrate that carryover nasalization exhibited greater nasal spreading than the anticipatory context. This was in alignment with previous literature, which points out that such a pattern can be found in languages that favor open syllables. In that regard, the degree of anticipatory nasalization was greater in CVN# tautosyllabic structures compared to in heterosyllabic CV.NV# and resyllabification CV.N#V ones. Regarding carryover nasalization, vowels in the heterosyllabic CV.NV# and resyllabification CV.N#V contexts showed parallel patterns.

These findings indicate that the position and structure of the syllable are crucial elements to take into consideration and that they affect inter-articulatory gestural overlap. Furthermore, the current study demonstrates that vowels in heterosyllabic CV.NV# and resyllabification CV.N#V structures are similar in terms of their aerodynamic properties, thus providing evidence in favor of derivational rules in Spanish phonology as an exemplar of complete resyllabification in connected speech.

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**Institutional Review Board Statement:** The study was conducted in accordance with the Declaration of Helsinki, and approved by the Institutional Review Board of the University of Illinois Urbana-Champaign (protocol code #20071 and 16 August 2019) for studies involving humans.

**Informed Consent Statement:** Informed consent was obtained from all subjects involved in the study.

**Data Availability Statement:** Not applicable due to the IRB protocol does not allow the author to share the data openly for privacy and confidentiality restrictions.

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**Conflicts of Interest:** The authors declare no conflicts of interest.

## Appendix A

### Model selection and AIC scores

| Model                                                                                                                                                                                         | AIC Score  | Deviance Explained |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------|--------------------|
| <b>Coarticulatory anticipatory nasalization (V1):</b>                                                                                                                                         |            |                    |
| Context * Vowel + Sex + s(NormTime, by = interaction(Context, Vowel)) + s(NormTime, by = Sex) + s(NormTime, Speaker, by = interaction(Context, Vowel), bs = “fs”, m = 1) + s(Word, bs = “re”) | −127,117.7 | 72.9%              |
| Context * Vowel + s(NormTime, by = interaction(Context, Vowel)) + s(NormTime, Speaker, by = interaction(Context, Vowel), bs = “fs”, m = 1) + s(Word, bs = “re”)                               | −114,413.8 | 67%                |
| <b>Coarticulatory carryover nasalization (V2):</b>                                                                                                                                            |            |                    |
| Context + Sex + s(NormTime, by = Context) + s(NormTime, by = Sex) + s(NormTime, Speaker, by = Context, bs = “fs”, m = 1) + s(Word, bs = “re”)                                                 | −86,151.6  | 80.7%              |
| Context + s(NormTime, by = Context) + s(NormTime, Speaker, by = Context, bs = “fs”, m = 1) + s(Word, bs = “re”)                                                                               | −77,586.6  | 78.5%              |

## Appendix B

Model output for anticipatory vowel nasalization (V1)

Formula: `nasal ~ Context * Vowel + Sex + s(NormTime, by = interaction(Context, Vowel)) + s(NormTime, by = Sex) + s(NormTime, Speaker, by = interaction(Context, Vowel), bs = "fs", m = 1) + s(Word, bs = "re")`

| Parametric Coefficients: | Estimate | SE    | t-Value | p-Value |
|--------------------------|----------|-------|---------|---------|
| (Intercept)              | 0.0009   | 0.002 | 0.502   | 0.61580 |
| Context CVN#             | 0.002    | 0.003 | 0.735   | 0.46240 |
| Context CV.N#V           | 0.0004   | 0.002 | 0.174   | 0.86202 |
| Context CVCV             | 0.0007   | 0.002 | 0.378   | 0.70522 |
| Vowel e                  | 0.00006  | 0.002 | 0.027   | 0.97817 |
| Vowel i                  | 0.0008   | 0.002 | 0.321   | 0.74846 |
| Vowel o                  | 0.00000  | 0.003 | 0.000   | 0.99962 |
| Vowel u                  | 0.002    | 0.003 | 0.494   | 0.62124 |
| Sex Male                 | −0.002   | 0.001 | −3.128  | <0.01   |
| Context CVN# x Vowel e   | −0.002   | 0.003 | −0.667  | 0.50486 |
| Context CV.N#V x Vowel e | 0.0031   | 0.004 | 0.843   | 0.39919 |
| Context CVCV x Vowel e   | 0.0003   | 0.002 | 0.121   | 0.90404 |
| Context CVN# x Vowel i   | 0.0003   | 0.004 | 0.073   | 0.94213 |
| Context CV.N#V x Vowel i | 0.0001   | 0.003 | 0.034   | 0.97307 |
| Context CVCV x Vowel i   | −0.00008 | 0.002 | −0.036  | 0.97096 |
| Context CVN# x Vowel o   | −0.0024  | 0.004 | −0.564  | 0.57271 |
| Context CV.N#V x Vowel o | −0.0003  | 0.004 | −0.075  | 0.93988 |
| Context CVCV x Vowel o   | 0.0007   | 0.003 | 0.227   | 0.82066 |
| Context CVN# x Vowel u   | −0.0009  | 0.005 | −0.183  | 0.85497 |
| Context CV.N#V x Vowel u | 0.0008   | 0.004 | 0.191   | 0.84872 |
| Context CVCV x Vowel u   | −0.0005  | 0.003 | −0.170  | 0.86534 |

Deviance explained = 72.9%.

## Appendix C

Model output for carryover vowel nasalization (V2)

Formula: `nasal ~ Context + Sex + s(NormTime, by = Context) + s(NormTime, by = Sex) + s(NormTime, Speaker, by = Context, bs = "fs", m = 1) + s(Word, bs = "re")`

| Parametric Coefficients: | Estimate | SE    | t-Value | p-Value |
|--------------------------|----------|-------|---------|---------|
| (Intercept)              | 0.017    | 0.005 | 3.148   | <0.01   |
| Context CVCV             | −0.0149  | 0.005 | −2.781  | <0.01   |
| Context CVN#V            | 0.0018   | 0.007 | 0.239   | 0.81    |
| Sex Male                 | −0.0008  | 0.001 | −0.563  | 0.57    |

Deviance explained = 80.7%.

## Notes

- 1 IRB Protocol Number: 20071, University of Illinois Urbana-Champaign.
- 2 It is worth mentioning that `plot_diff()` curve differences can only conduct pair-wise comparisons.
- 3 The colors in this palette are color vision deficiency-friendly in the original version in color.
- 4 A remark should be made about the visible “negative” airflow results. As Beristain (2023a) pointed out, the equipment’s built-in electric voltage and DC offset could explain such results, or there might be some phonetic cue involving negative airflow and vocalic nasalization in Spanish, as such results only appeared in Spanish but not in other languages that were originally analyzed by Beristain (2022). Considering that the negative values are generally a part of the confidence intervals, it should not pose any significant alterations in the current results.
- 5 Using vowels with different height and a relatively small corpus may have contributed to a somewhat large standard error.

## References

- Akaike, Hirotugu. 1974. A new look at the statistical model identification. *IEEE Transactions on Automatic Control* 19: 716–23. [CrossRef]
- Beristain, Ander. 2022. The Acquisition of Acoustic and Aerodynamic Patterns of Coarticulation in Second and Heritage Languages. Ph.D. thesis, University of Illinois Urbana-Champaign, Champaign, IL, USA.
- Beristain, Ander. 2023a. Gestural timing patterns of nasality in highly proficient Spanish learners of English: Aerodynamic evidence. *Language and Speech*. [CrossRef] [PubMed]
- Beristain, Ander. 2023b. An airflow analysis of Spanish and English anticipatory vowel nasalization among heritage bilinguals. *Languages* 8: 205. [CrossRef]
- BIOPAC Hardware Systems, Inc. 2020. *AcqKnowledge Data Acquisition and Analysis Software*. version 3.9.1. Goleta: BIOPAC Hardware Systems, Inc.
- Bissiri, Maria P., Maria-Luisa García-Lecumberri, Martin Cooke, and Jan Volín. 2011. The role of word-initial glottal stops in recognizing English words. Paper presented at Interspeech 2011, Florence, Italy, August 27–31.
- Boersma, Paul, and David Weenink. 2020. Praat: Doing Phonetics by Computer [Computer Program], Version 6.1.10. Available online: <http://www.praat.org/> (accessed on 25 March 2020).
- Bongiovanni, Silvina. 2021. Acoustic investigation of anticipatory vowel nasalization in a Caribbean and a non-Caribbean dialect of Spanish. *Linguistics Vanguard* 7: 1–11. [CrossRef]
- Bradley, Travis G., Kimberly Morris, and Lillian Jones. 2022. Incomplete resyllabification and ambisyllabic gestural coupling in Spanish. *Loquens* 9: e094. [CrossRef]
- Brown, Earl K. 2008. A Usage-Based Account of Syllable- and Word-Final /s/ Reduction in Four Dialects of Spanish. Ph.D. thesis, The University of New Mexico, Albuquerque, NM, USA.
- Byrd, Dani, Stephen Tobin, Erik Bresch, and Shrikanth Narayanan. 2009. Timing effects of syllable structure and stress on nasals: A real-time MRI examination. *Journal of Phonetics* 37: 97–110. [CrossRef]
- Carignan, Christopher. 2021. A practical method of estimating the time-varying degree of vowel nasalization from acoustic features. *Journal of the Acoustical Society of America* 149: 911–22. [CrossRef] [PubMed]
- Clumeck, Harold. 1976. Patterns of soft palate movements in six languages. *Journal of Phonetics* 4: 337–51. [CrossRef]
- Cohn, Abigail C. 1990. Phonetic and phonological rules of nasalization. *UCLA Working Papers* 76. Available online: <https://escholarship.org/uc/item/1xq3d5hr> (accessed on 20 December 2023).
- Cohn, Abigail C. 1993. Nasalisation in English: Phonology or phonetics. *Phonology* 10: 43–81. [CrossRef]
- Colina, Sonia. 1995. A Constraint-Based Analysis of Syllabification in Spanish, Catalan, and Galician. Ph.D. dissertation, University of Illinois at Urbana-Champaign, Champaign, IL, USA.
- Colina, Sonia. 1997. Identity constraints and Spanish resyllabification. *Lingua* 103: 1–23. [CrossRef]
- Colina, Sonia. 2002. Interdialectal variation in Spanish /s/ aspiration: The role of prosodic structure and output-to-output constraints. In *Structure, Meaning, and Acquisition in Spanish: Papers from the 4th Hispanic Linguistics Symposium*. Edited by James F. Lee, Kimberly L. Geeslin and J. Clancy Clements. Somerville: Cascadia Press, pp. 230–43.
- Colina, Sonia. 2009. *Spanish Phonology: A Syllabic Perspective*. Washington, DC: Georgetown University Press.
- Delvaux, Véronique, Didier Demolin, Bernard Harmegnies, and Alain Soquet. 2009. The aerodynamics of nasalization in French. *Journal of Phonetics* 36: 578–606. [CrossRef]
- Diakoumakou, Evanthia. 2005. Coarticulatory nasalization in modern Greek: Evidence for a link between coarticulation and syllable structure. *Journal of the Acoustical Society of America* 117: 2459. [CrossRef]
- Diakoumakou, Evanthia. 2009. *Coarticulatory Vowel Nasalization: Evidence from Modern Greek*. Riga: VDM Verlag.
- Durand, Jacques, Bernard Laks, Basilio Calderone, and Atanas Tchobanov. 2011. Que savons-nous de la liaison aujourd'hui? [What do we know today about liaison]? *Langue Française* 169: 103–35. [CrossRef]
- Goodin-Mayeda, C. Elizabeth. 2016. *Nasals and Nasalization in Spanish and Portuguese: Perception, Phonetics, and Phonology*. Amsterdam: John Benjamins. [CrossRef]
- Hajek, John. 1997. *Universals of Sound Change in Nasalization*. Hoboken: Wiley-Blackwell.
- Harris, James. 1983. *Syllable Structure and Stress in Spanish: A Nonlinear Analysis*. Cambridge, MA: MIT Press.
- Harris, James, and Ellen M. Kaisse. 1999. Palatal vowels, glides and obstruents in Argentinian Spanish. *Phonology* 19: 117–90. [CrossRef]
- Henderson, Janette B. 1984. Velopharyngeal Function in Oral and Nasal Vowels. Ph.D. thesis, University of Connecticut, Storrs, CT, USA.
- Horiguchi, Satoshi, and Fredericka Bell-Berti. 1987. The Velotrace: A device for monitoring velar position. *Cleft Palate Journal* 24: 104–11. [PubMed]
- Hualde, José I. 2014. *Los Sonidos del Español [The Sounds of Spanish]*. Cambridge: Cambridge University Press. [CrossRef]
- Hualde, José I., and Jon Ortiz de Urbina. 2003. *A Grammar of Basque*. Berlin: De Gruyter Mouton. [CrossRef]
- Hualde, José I., and Pilar Prieto. 2014. Lenition of sibilants in Catalan and Spanish. *Phonetica* 71: 109–27. [CrossRef] [PubMed]
- Huffman, Marie K., and Rena A. Krakow, eds. 1993. *Nasals, Nasalization, and the Velum (Phonetics and Phonology V)*. San Diego: Academic Press. [CrossRef]
- Jiménez-Bravo, Miguel, and José María Lahoz-Bengoechea. 2023. Durational cues to resyllabification in Spanish. *Loquens* 10: e099. [CrossRef]

- Kahn, Daniel. 1976. Syllable-Based Generalizations in English Phonology. Ph.D. thesis, Massachusetts Institute of Technology, Cambridge, MA, USA.
- Kaisse, Ellen M. 1999. Resyllabification precedes all segmental rules. In *Formal Perspectives on Romance Linguistics: Selected Papers from the 28th Linguistic Symposium on Romance Languages*. Edited by Jean-Marc Authier, Barbara E. Bullock and Lisa A. Reed. Amsterdam: John Benjamins, pp. 197–210.
- Kochetov, Alexei. 2020. Research methods in articulatory phonetics II: Studying other gestures and recent trends. *Language and Linguistics Compass* 14: e12371. [CrossRef]
- Kohler, Klaus J. 1994. Glottal stops and glottalization in German. *Phonetica* 51: 38–51. [CrossRef]
- Krakow, Rena A. 1989. The Articulatory Organization of Syllables: A Kinematic Analysis of Labial and Velar Gestures. Ph.D. thesis, Yale University, New Haven, CT, USA.
- Krakow, Rena A. 1993. Nonsegmental influences on velum movement patterns: Syllables, sentences, stress, and speaking rate. In *Nasals, Nasalization, and the Velum*. Edited by Marie K. Huffman and Rena A. Krakow. San Diego: Academic Press, pp. 87–116.
- Krakow, Rena A. 1999. Articulatory organization of syllables: A review. *Journal of Phonetics* 27: 23–54. [CrossRef]
- Lahoz-Bengoechea, José María, and Miguel Jiménez-Bravo. Forthcoming. Mismo grado de nasalización en VN# y V#N en español [Same degree of nasalization in VN# and V#N in Spanish]. In *Proceedings from the 9th International Conference on Experimental Phonetics (CIFE)*. Vigo: Universidad de Vigo, in press.
- Martínez, Ruth M. 2021. The Bidirectional Acquisition of Oral and Nasal Gestural Timing in L2 Brazilian Portuguese and Rioplatense Spanish Nasal Structures. Ph.D. thesis, University of Toronto, Toronto, ON, USA.
- MATLAB. 2020. 9.8.0.1323502. R2020a. Natick: The MathWorks Inc.
- Passino, Diana, Joaquim Brandão de Carvalho, and Tobias Scheer. 2022. Syllable structure and (re)syllabification. In *Manual of Romance Phonetics and Phonology*. Edited by Christoph Gabriel, Randall Gess and Trudel Meisenburg. Berlin and Boston: De Gruyter, pp. 89–126. [CrossRef]
- R Core Team. 2020. R: A Language for Statistical Computing. Available online: <https://www.R-project.org/> (accessed on 15 January 2024).
- R Studio Team. 2020. RStudio: Integrated Development for R. Available online: <http://www.rstudio.com/> (accessed on 15 January 2024).
- Robinson, Kimball. 2012. The dialectology of syllabification: A review of variation in the Ecuadorian Highlands. *Romance Philology* 66: 115–45. [CrossRef]
- Sampson, Rodney. 1999. *Nasal Vowel Evolution in Romance*. Oxford: Oxford University Press.
- Sauzet, Patrick. 2012. Occitan plurals. A case for a morpheme-based morphology. In *Inflection and Word Formation in Romance Languages*. Edited by Sascha Gaglia and Marc-Olivier Hinzelin. Amsterdam and Philadelphia: Benjamins, pp. 179–200.
- Shosted, Ryan K. 2009. *The Aeroacoustics of Nasalized Fricatives: An Instrumental Study in Phonetic Typology*. Saarbrücken: VDM Verlag.
- Shosted, Ryan K., Christopher Carignan, and Panyong Rong. 2012. Managing the distinctiveness of phonemic nasal vowels: Articulatory evidence from Hindi. *The Journal of Acoustical Society of America* 131: 455–65. [CrossRef] [PubMed]
- Solé, Maria-Josep. 1992. Phonetic and phonological processes: The case of nasalization. *Language and Speech* 35: 29–43. [CrossRef]
- Stoakes, Hywel M., Janet M. Fletcher, and Andrew R. Butcher. 2020. Nasal coarticulation in Bininj Kunwok: An aerodynamic analysis. *Journal of the International Phonetic Association* 50: 305–32. [CrossRef]
- Strycharczuk, Patricia, and Martin Kohlberger. 2016. Resyllabification reconsidered: On the durational properties of word-final /s/ in Spanish. *Journal of the Association for Laboratory Phonology* 7: 3. [CrossRef]
- Torreira, Francisco, and Mirjam Ernestus. 2012. Weakening of intervocalic /s/ in the Nijmegen Corpus of Casual Spanish. *Phonetica* 69: 124–48. [CrossRef]
- Van Rij, Jacolien, Martijn Wieling, R. Harald Baayen, and Hedderik Van Rij. 2017. Itsadug: Interpreting Time Series and Autocorrelated Data Using GAMMs (R Package Version 2.3). Available online: <https://cran.r-project.org/web/packages/itsadug/index.html> (accessed on 15 January 2024).
- Wood, Simon N. 2011. Fast stable restricted maximum likelihood and marginal likelihood estimation of semiparametric generalized linear models. *Journal of the Royal Statistical Society (B)* 73: 3–36. [CrossRef]
- Zuazo, Koldo. 2014. *Euskalkiak [The Basque Dialects]*. Donostia: Elkar.

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