Nasals Unplugged: The Aerodynamics of Nasal De-occlusivization in Spanish

Ryan Shosted and Beatriz Willgohs
University of California, Berkeley

1. Introduction

The specification of "canonical" nasal consonants (excluding, e.g., the phonemically breathy nasals of Tsonga and the creaky nasals of Kwakw'ala) with respect to the feature VOICE presents phonologists with a problem. Certain assimilatory behaviors of nasals suggest they may be voiced, others that they are voiceless or at least unspecified for the feature. In Japanese, for example, sonorants (including nasals) do not behave like other voiced obstruents when it comes to Lyman's Law for Rendaku voicing (Itô et al. 1995). Nonetheless, voiceless obstruents in Japanese become voiced after nasals. The voicing of nasals and other sonorants has thus been viewed as an instance of featural underspecification (Steriade 1994). Is there a way to instrumentally verify formal claims about the featural specification of nasals?

From the perspective of laboratory phonology, it is reasonable to assess the validity of any claim about the featural specification of a sound by instrumentally evaluating its behavior in a given language. One celebrated phonological behavior in Spanish is spirantization, lenition, or "de-occlusivization." This is the process by which the voiced stops /b d g/ become voiced fricatives [β ð ɣ] in intervocalic position (Harris 1969, Quilis 1981, Martínez-Celdrán 1991). The same change occurs when the stop is adjacent to sonorant consonants as well (Widdison 1997). Spirantization of the voiceless stops /p t k/ only occurs if the voiceless stops first become voiced /b d g/. The results are voiced fricatives, as in Canary Island, Peninsular (Bilbao), and Central Colombian Spanish (Oftedal 1985, Lewis 2001). In short, the intervocalic output of /p t k/ in Spanish is never [ɸ θ x]. The phonetic output of spirantization applied to nasal obstruents, however, is still unclear. Will nasal obstruents de-occlusivize in a manner comparable to voiced stops[1]?

1.1. Spirantization in Spanish

In the transition from Vulgar Latin to Spanish, intervocalic voiced stops were "aspirated," "softened," "lenited", or "spirantized." Regardless of one's terminological choice, the process transformed voiced stops into voiced approximants or fricatives, depending on a number of aerodynamic and articulatory factors. The development of an approximant in this case would require continuous laminar airflow accompanied by articulatory undershoot or gestural reduction, i.e., the lack of full contact between articulators. A voiceless fricative would require a tighter constriction (i.e., less articulatory undershoot) and transglottal flow high enough to increase oral pressure behind the constriction, yielding increased particle velocity and audible frication. Voiced fricatives are not known for being particularly noisy or achieving high particle velocity, while voiceless fricatives are characterized by precisely these qualities. Further, in terms of constriction, approximants occupy a

[1] Another interesting question concerns whether the nasal obstruent, once de-occlusivized, would best be described as a fricative or a glide. A number of scholars have persuasively argued that nasal venting severely reduces the audibility of frication (Ohala & Ohala 1993, Solé 1999). Nevertheless, others regard nasalized fricatives as plausible segments (Gerfen 1999, Ternes 1989, Schadeberg 1982, Stringer & Hotz 1973). Due to the controversy surrounding nasalized fricatives, and since we are not prepared to account for the acoustic properties of the nasals in this study, we will refer to the objects of our investigation simply as "spirantized" or "de-occlusivized" nasals rather than fricatives or glides.

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position somewhere between a vowel and a fricative. That the outcome of Spanish spirantization may be termed a fricative or an approximant is therefore not surprising, though unfortunately not very precise (see Martínez-Celdrán 2004 for a comprehensive discussion). To avoid confusion, we will refer to the outcome as a fricative, since the IPA symbols traditionally used to transcribe the spirantized stops of Spanish are indeed fricatives. We note, however, that audible frication during these segments may be quite low.

Widdison (1997) suggests that spirantization originates in post-vocalic position in Spanish and is currently spreading to other contexts based on the sonority of adjacent segments. Further, he posits five physical parameters of spirantization and describes their influence on the process: (1) Lengthy stop closure endangers physiological voicing; (2) Venting oral pressure accommodates stop voicing; (3) Coincident oral closure imposes a stop element on obstruents; (4) Articulatory elasticity regulates duration of constriction; and (5) Gradiency of phonetic conditions accounts for variable weakening. The "gradiency" cited in (5) presumably accounts for the continuum of realizations extending from voiced approximant to voiced fricative just discussed.

It is clear that intervocalic voiced stops undergo spirantization in Spanish[2]. The following changes are thus amply attested: /b/ →[β]; /d/ → [ð]; /g/ → [ɣ] / V_V. Unattested are examples of voiceless stop spirantization, e.g., /p/ → *[ɸ]; /t/ → *[θ]; /k/ → [x] / V_V (though, as noted in the introduction, voiceless stops may become voiced fricatives in certain dialects). A third class of obstruent—nasal—has traditionally been ignored in the discussion of Spanish spirantization. It is unclear whether nasal consonants behave like voiceless or voiced stops with regard to this phenomenon. For example, do speakers undershoot in the articulation of intervocalic /m/, minimizing labial contact, just as they do during /b/?

1.2. Nasal de-occlusivization

Honorof (2003) was the first to address this matter. He analyzed magnetometer data from three speakers of Castilian Spanish to demonstrate that the tongue apex does not come into full contact with the hard palate during voiced singleton nasal stops. Honorof (2003) concludes that gestural reduction (undershoot) does in fact occur during the production of nasal obstruents, resulting in "de-occlusivization." Nasal de-occlusivization (NDO), he observes, is simply another manifestation of spirantization. In the study, the tokens were non-contrastive coronal nasal consonants used in four intervocalic positions (within word; before word boundary; after word boundary; and within a juncture geminate). It is unfortunately unclear from his report which vowels flanked the nasal obstruents in the experiment. He notes additionally, "It may be that [NDO] is strong only at faster speaking rates" (Honorof 2003:1761).

Hock (1991:82) mentions nasal obstruents in his discussion of lenition. He states that "[nasals] tend to undergo the same kind of changes [fricativization and flapping] as the [lenited] stops" and presents the following evidence of nasal "fricativization." The original Sanskrit [m] has lenited to a nasalized bilabial fricative in a dialect of New Indo-Aryan in (1):

(1) k[am]ala > k[ãβ]al > k[ãβ*]al 'lotus' (where [β*] represents a nasalized bilabial fricative)

[2] One anonymous reviewer points out that there are at least two alternative analyses to be mentioned: (1) Underlying approximants undergo fortition in the surface environments where stops are found; and (2) Underlying voiced obstruents are unspecified for the feature CONTINUANT and the surface values are determined entirely by the grammar. In our view, admitting either of these explanations for the phenomenon would merely constitute a change in nomenclature, at least for present purposes. Our interest lies in determining the aerodynamic properties of given consonants under variable conditions. Hence, the formal ontology of lenition and/or fortition lies beyond the scope of the present study. The view of lenition adopted here is in line with the opinion expressed by Ladefoged (1999:605), who regards the phenomenon as simple assimilation, "in which the intervocalic stops become more and more like the surrounding approximants."

2. Experimental design

2.1. Premise

Studies of nasalization are well-suited to experiments involving aerodynamic data, since it is precisely the varying ratio of oral to nasal flow that characterizes the difference between nasal obstruents, nasal vowels, and oral segments. Studies of spirantization are similarly well-suited to aerodynamic instrumentation since the magnitude of the effect can be detected by monitoring peak oral airflow. Thus, it seems plausible that the NDO reported by Honorof (2003) and cited by Hock (1991) as an example of nasal lenition can be captured and analyzed using an airflow-measuring device. In the current study, we used a circumferentially-vented pneumotach air mask manufactured by Glottal Enterprises (see Rothenberg 1977 for a technical description of the apparatus).

There are various advantages in using aerodynamic data. First, oral and nasal signals may be recorded simultaneously. Second, calibration of the aerodynamic signals is relatively straightforward. Third, the split-flow mask method is non-invasive. As with all experimental methodologies, however, there are a number of disadvantages in using the split-flow mask. Cohn (1990) cites several of these, viz., the possibility that the mask may slip or that the seal between oral and nasal chambers does not adequately form or is not maintained. We believe these problems were minimized by careful review of each recorded token during the recording session. Mask slippage results in dramatic discontinuities in the time-varying electrical signals produced by the mask's transducers. Whenever such discontinuities were detected by the researcher, the token was recorded again.

2.2. Goals

Our goal was to confirm through aerodynamic instrumentation Honorof's (2003) hypothesis that intervocalic [n] de-occlusivizes. In so doing, we aimed to determine the extent to which nasals pattern with voiced or voiceless consonants when it comes to the effects of spirantization (e.g., is intervocalic /n/ more like /t/ or /d/ in terms of oral occlusion?). We also widened Honorof's original analysis to consider the labial nasal [m]. We decided to forego an analysis of the velar nasal due to possible complications in the aerodynamics of this articulation[3].

2.3. Methods

Once the signals were recorded, the minimum oral flow (OF_{min}) value for each intervocalic consonant under investigation was tabulated. Our foundational assumption was that a greater OF_{min} means a greater degree of de-occlusivization or spirantization, i.e., less oral closure at the moment of greatest constriction.

2.3.1. Tokens

Token consonants were embedded in disyllabic nonsense words (e.g., *tabu, tadu, tanu*). In a pilot study, we discovered that the differences in OF_{min} between nonsense and real words were statistically insignificant. Furthermore, the use of nonsense words allowed us to exert tighter control over the experimental variables. To facilitate logging of the OF_{min} values, each word began with a voiceless coronal stop /t/, providing a useful visual anchor (a period of zero oral airflow followed by a dramatic spike of aspiration) for the researcher. The words were presented to each speaker in a randomized list that was repeated twice. We used six experimental variables: (1) Venting (oral/nasal); (2) Voicing (voiced/voiceless/nasal); (3) Stress pattern (initial/final); (4) V1 (a/i/u); (5) V2 (a/i/u); and (6) Place of articulation (labial/coronal). This amounted to 252 tokens of each consonant for each talker.

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[3] Preliminary results from a pilot version of this study and previous aerodynamic research involving velar nasals (Shosted 2003) suggest that indeterminate negative oral airflow may be a confounding factor in studying velar articulations.

2.3.2. Talkers

The seven talkers who participated were: one female from Badajoz; two females from Burgos; two females from Madrid; one female from Barcelona; and one male from Madrid. The talkers were all between the ages of 20 and 30.

2.3.3. Analysis

Before each recording session, the electrical output of the transducers in the air mask was calibrated at five flow rates (-1000, -500, 0, 500, 1000 ml/s) for both the oral and nasal components using least-squares linear regression. The average correlation coefficient of the calibrations was > 0.999. OF_{min} values were detected for each consonant under investigation by reference to a "known zero" in the aerodynamic signal. We believe this technique is necessary to avoid a shifting oral flow baseline across speakers. The known zero was easily established for each token since all the words began with a /t/ and were embedded in a carrier phrase where the consonant preceding /t/ was a coronal nasal: *digan t* ahora*. We felt confident that the prenasalized /nt/ could be characterized physiologically as a complete oral occlusion, thus allowing us to infer that oral flow fell to zero. To calculate the relative amount of airflow during the consonant under investigation, we logged the oral transducer output during the prenasalized stop /nt/ (the known zero) and at the lowest point of the oral signal during the consonant under investigation. The difference between the two values became the OF_{min}.

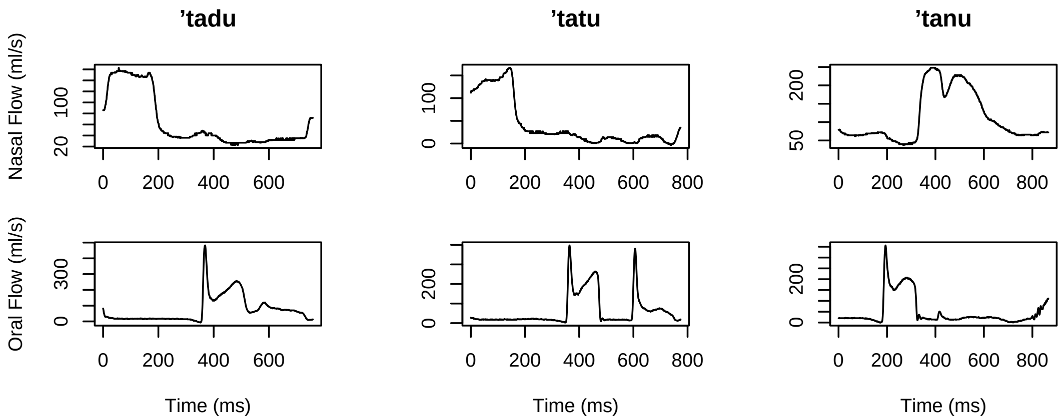

FIGURE 1. Aerodynamic traces for three stress-initial coronal tokens uttered by Talker 8. Time-aligned nasal and oral signals are shown in the upper window and lower windows for each token.

In FIGURE 1, observe the long, relatively flat line at the left side of each oral signal (accompanied by increased nasalization shown in the upper windows). This is the prenasalized stop /nt/. We postulate that the oral flow value here is effectively zero because in order to create sufficient back pressure for the consonantal burst there should be no oral leakage during the articulation. The first spike in oral flow indicates aspiration[4] on /t/, a feature of every token in the corpus.

OF_{min} is found at the lowest point after this initial oral spike and sometime before the initiation of the second vowel (found at the right side of each window in FIGURE 1). OF_{min} is easily discernible in the oral record of the voiceless token /ˈtatu/ (center bottom window). Here the horizontal line (from 475-600 ms) between the peaks (aspiration of C1 at 375 ms, highest oral flow for /a/ at 450 ms, and aspiration of C2 at 615 ms) indicates the moment when the tongue tip is producing oral occlusion. From 475-600 ms, oral flow is close to 0 ml/s for the voiceless token, indicating firm oral occlusion. In

[4] Here, "aspiration" refers to the increase in oral flow that appears to occur at the release of voiceless stops preceding the initiation of voicing in Spanish. We have made no attempt to compare our aerodynamic data with data from languages (like English) where voiceless stops presumably have higher levels of aspiration (and hence significantly longer VOT). By using the term we do not suggest that Spanish voiceless stops are comparable to English voiceless stops in terms of aspiration or VOT. This regular peak in oral airflow simply served as a useful landmark in segmenting the signals.

the voiced token (left bottom) de-occlusivization is visible in the rounded trough at 550 ms, after the aspiration of C1 (390 ms) and the vowel peak at approximately 490 ms. Oral flow during the articulation of /d/ is reduced to only about 50 ml/s at its minimum (550 ms). With oral flow this high (cf. the voiceless token) it is indeed appropriate to characterize the sound as the continuant [ð].

Finally, observe the contrast between oral flow during the nasal token (lower right of FIGURE 1) and the voiced token (lower left). During the nasal token, we should consider both the upper (nasal) and lower (oral) windows. Note the dramatic rise in nasal flow at 375 ms, corresponding to the terminus of the vowel /a/. During the nasal consonant, OF_{min} is more comparable to the minimum observed for the voiceless, rather than the voiced consonant. As will be shown, these observations exemplify some of the numerical and statistical tendencies among the tokens.

3. Results

3.1. Descriptive results

3.1.1. "Voicing"

A de-occlusivization hierarchy emerged with respect to the "voicing" variable (for convenience, we treat nasal as a third voicing option). The firmest oral occlusion occurred in the nasal, then voiceless, then voiced obstruents. In other words, the lowest average OF_{min} values were calculated for nasals and the highest for voiced obstruents. This suggests that nasal consonants probably do not achieve de-occlusivization on the scale that voiced consonants do. FIGURE 2 illustrates the histograms, density functions, and normal quantile-quantile plots of OF_{min} for the three classes of obstruent.

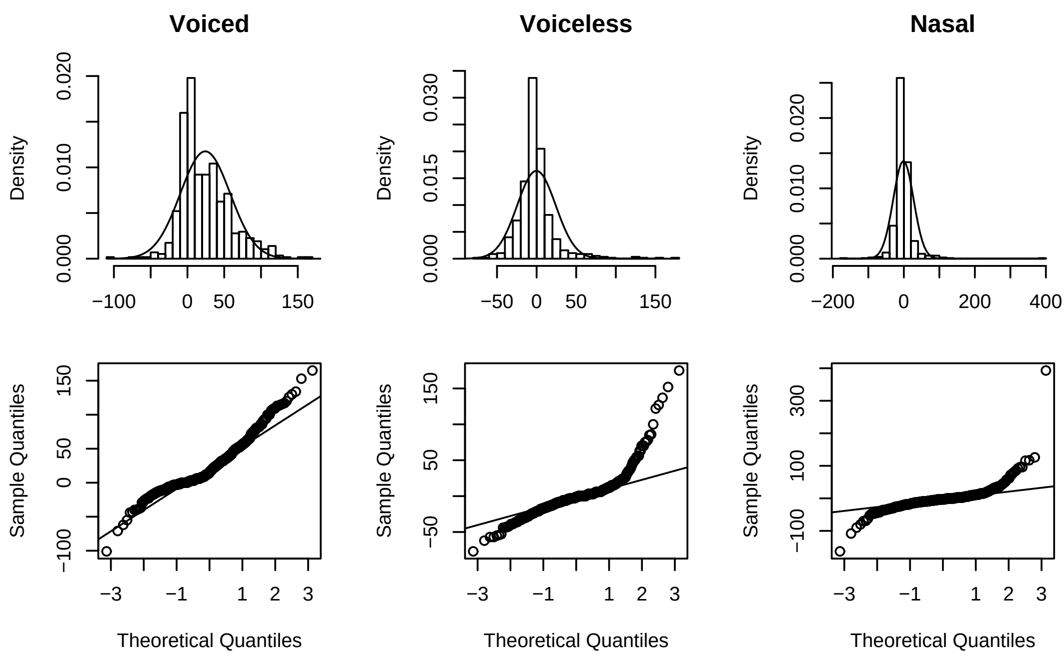

FIGURE 2. Top row: Histograms and normal density functions of OF_{min} for voiced (M=24.2; SD=33.9), voiceless (M=-0.2; SD=24.4), and nasal (M=-1.2; SD=28.7) consonants. Bottom row: corresponding normal quantile-quantile plots. The correlations (r) between expected and observed quantiles for the three data sets are: voiced (0.970), voiceless (0.900), and nasal (0.812).

3.1.2 Stress pattern

For voiced, voiceless, and nasal obstruents, it was found that oral occlusion is weaker (i.e. higher OF_{min}) when C is in the onset of an unstressed syllable (initial stress). Also, oral occlusion is firmer (i.e. lower OF_{min}) when C is in the onset of a stressed syllable (final stress). For example, in the minimal pair [ˈta.du] versus [ta.ˈdu], there is firmer occlusion in the second word, where the emphasis is placed on the onset of the second syllable. FIGURE 3 contains boxplots for stress conditions among nasal, voiced, and voiceless obstruents. Note in particular the difference between stress patterns for the voiced condition (the only difference that proves statistically significant, as we shall see below).

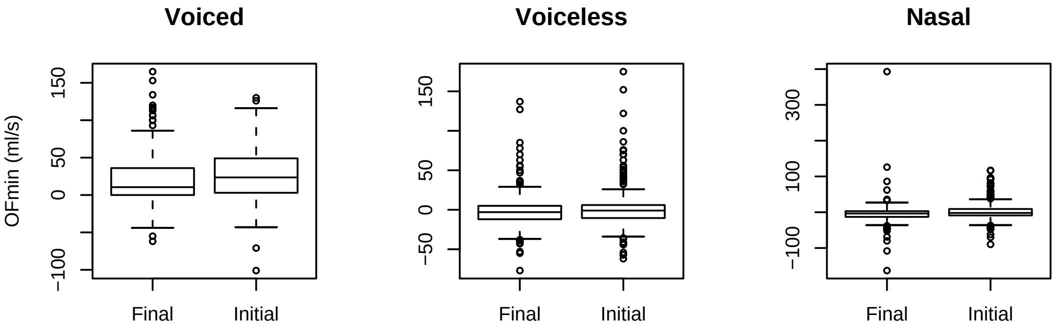

FIGURE 3. OF_{min} by stress pattern for voiced, voiceless, and nasal obstruents.

3.1.3. V1 and V2

For voiced, voiceless, and nasal obstruents, it was found that oral occlusion is weakest when V1 is the open vowel [a]. Conversely—and predictably, based on jaw opening—oral occlusion is firmer when V1 is a close vowel, [i] or [u]. Note how in FIGURE 4, OF_{min} for [a] is consistently greater than the other two vowels, though the effect is most dramatic (a difference in means of about 16 ml/s between [a] and [u]) for the voiced class. No coherent pattern emerged for V2.

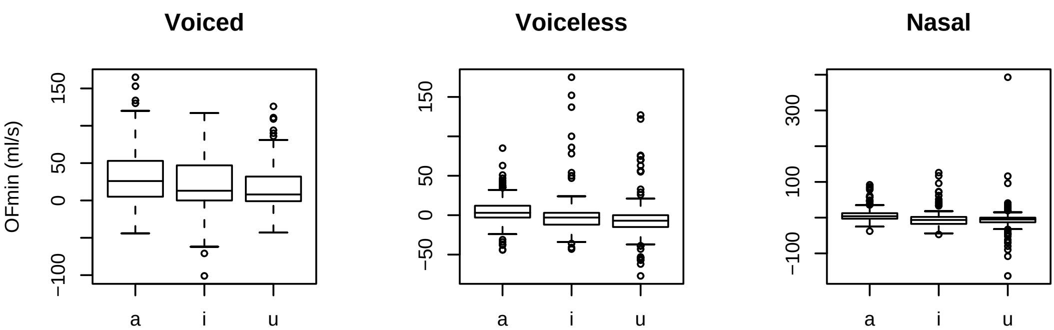

FIGURE 4. OF_{min} by V1 for voiced, voiceless, and nasal obstruents.

3.1.4. Place of articulation

No coherent pattern emerged for this variable, but mean values of OF_{min} confirmed that the consonant with the greatest degree of oral occlusion was /n/ (M=-3.3 ml/s) and the one with least degree of oral occlusion was /d/ (M=24.4 ml/s). There is little reason to believe that the labial place of articulation favors or disfavors de-occlusivization among voiced, voiceless, and/or nasal obstruents. As the boxplots in FIGURE 5 demonstrate, there is nothing to suggest a differential effect for NDO based on place of articulation. Both labial and coronal nasal consonants seem unlikely to de-occlusivize.

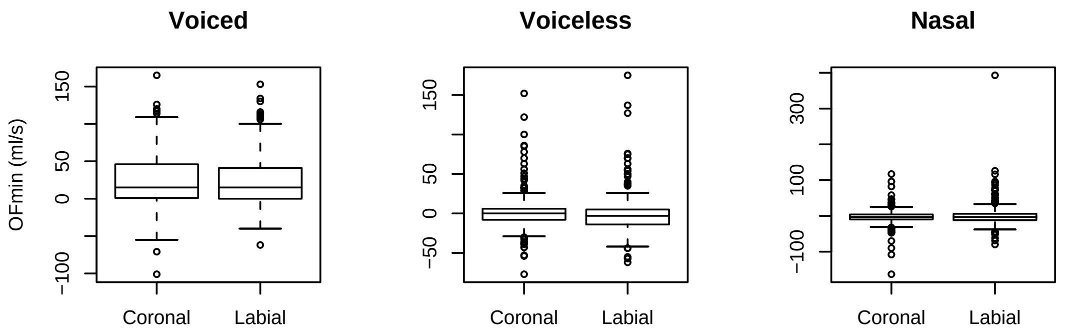

FIGURE 5. OF_{min} by POA for voiced, voiceless, and nasal obstruents.

3.2. Statistical analysis

A series of one-way ANOVAs tested the significance of differences in OF_{min} under various conditions. Differences in OF_{min} based solely on the "voicing" variable were significant. Specifically, for the voiceless versus voiced consonants, $F = 0.915$, $p < 0.0001$. For nasal versus voiced consonants, the difference in OF_{min} was also significant, $F = 3.01$, $p < 0.0001$. For nasal versus voiceless consonants, however, the differences were not significant.

There were also significant differences in OF_{min} based on V1. Specifically, for [a] versus [i], $F = 1.87$, $p < 0.0001$. For [a] vs. [u], $F = 1.95$, $p < 0.0001$. For [i] vs. [u], however, the differences in OF_{min} were not significant.

Differences in OF_{min} based on stress pattern were significant in the case of voiced consonants only. For these, $F = 8.929$, $p = 0.003$. For voiceless and nasal consonants, the differences based on stress pattern were insignificant. Moreover, there were no significant differences in OF_{min} based on V2 nor were there any significant differences based on place of articulation.

4. Discussion

From the data presented in the previous section, we observe that airflow measures clearly capture the robust distinction between spirantization of voiced stops and the non-spirantization of voiceless stops in Iberian Spanish. There are significant differences in oral flow minima between voiced and voiceless stops, with the predictable result that the voiced stops have higher minimum oral airflow than the voiceless stops. Further, we find confirmation of gestural reduction (resulting in higher oral airflow) accompanying the production of low vowels before the obstruents under investigation. Conversely, after high vowels, gestural reduction is less likely to occur and complete oral occlusion is the predicted result. In other words, the close vowels [i] and [u] pattern together in inhibiting spirantization, while [a] differs significantly from [i] and [u] in fostering it. Furthermore, we find that a stressed syllable onset is statistically less likely to spirantize than an unstressed one (but only for voiced consonants). So far, these are all indications that the aerodynamic methodology has produced reliable, predictable results.

With regard to the research hypothesis, our results confirm Honorof's (2003) observation that nasal consonants indeed evidence trace phonetic tendencies towards de-occlusivization. However, we find no statistical basis for concluding that this de-occlusivization is any different than the trace de-occlusivization that may occur among voiceless stops, where there is no indication that spirantization is on its way to becoming phonologized. Furthermore, we found that stress pattern significantly affects voiced obstruents, not voiceless or nasal obstruents. Thus, a significant phonological pattern (spirantization of an unstressed onset) is observed for only one class of obstruent—voiced. Crucially, however, stress is *not* a significant factor in determining oral flow during intervocalic voiceless and nasal obstruents. This is precisely because voiceless and nasal obstruents lack spirantized counterparts in Spanish.

5. Conclusion

We have shown that nasal consonants behave, for all intents and purposes, as do voiceless consonants under the effects of Spanish spirantization. Thus, it seems a tenable proposition, based on present evidence, that Spanish nasal consonants are underspecified for the feature VOICE. While gestural reduction is possible even in the production of nasal consonants, it is not unlike the reduction that occurs among voiceless stops. It is significantly different from the gestural reduction that occurs among voiced stops. On average, the oral flow for nasal obstruents is quite low and moreover, statistically indistinguishable from that of voiceless obstruents. Accordingly, we conclude that nasals are certainly not poised to undergo a phonological change similar to that which took place among Vulgar Latin voiced stops. We find it unlikely that nasal de-occlusivization is approaching phonological status in Spanish.

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