EXPERIMENTAL AND TYPOLOGICAL APPROACHES TO NASAL VOWEL SONORITY*

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1. Introduction

Despite their importance in the world's languages, nasal vowels appear to be absent from the generic sonority hierarchy and discussions thereof. This omission leaves open the question of whether a given nasal vowel's sonority is the same as or different than that of an oral vowel of similar quality, and though not explicitly stated, the absence of nasal vowels from the hierarchy may even suggest an implicit denial of their admissibility into the hierarchy. That is, this discussion taps into the larger debate about whether nasal vowels should be treated phonologically as [(+)nasal] variants of more primordial vowels or as discrete entities (e.g., Shosted 2015).

This gap in our knowledge has consequences both for phonological theory and for the phonetic-phonological interface. First, sonority relations (among consonants as well as among vowels) play a crucial role in the explanation of multiple phenomena. In the eventuality that sonority predetermines the phonological behaviour of nasal vowels (whether among themselves or between them and their oral counterparts), it would be important to discover what those relations are, and to what degree they are universal. Additionally, whereas intensity has been shown to correlate strongly with sonority, vowel nasalization not only has the general effect of diminishing intensity but also has quality-specific consequences which may not mirror the scale and precedence categorizing oral vowels.

This paper takes initial steps in filling in this gap from both an experimental and a typological point of view, with an emphasis on the former. In particular, I consider several scenarios for the inclusion of nasal vowels in the sonority hierarchy (within certain idealized criteria), examine intensity values according to quality and nasality in a pilot nasometric study, and speculate on the type of phonological evidence which may be investigated in the future. The remainder of this paper is structured as follows: Section 2 summarizes the notion of sonority and its link with phonetic factors such as intensity; the previously mentioned hypothetical scenarios are also presented here. Section 3 presents the methodology of the experimental study, and §4 provides its results. A general discussion follows in §5, and §6 concludes.

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2. Background

2.1 Sonority

Sonority can basically be described as a relationship of relative prominence among all segment classes. Dating back to origins of modern linguistics (e.g., Whitney 1865), one of the most common contemporary uses of sonority is syllabification. For instance, the relative sonority of a segment type along a generic scale such as in Fig. 1 is often used to explain its ability (or inability) to form a branching margin with another segment. In practice, various subcategories of those in Fig. 1 may be proposed (e.g., voiceless stops vs. voiced stops), according to language-specific phenomena, but the distinctions and/or the precedence between them may not be universal.

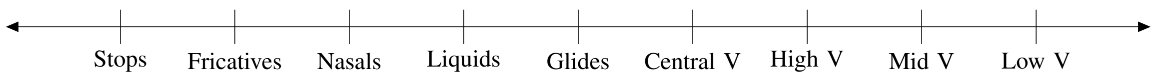

Figure 1. General sonority hierarchy (e.g., De Lacy 2006, after Kenstowicz 1997; Walker 1998)

The vowel categories and the relationship among them in this hierarchy are evidenced by, or can be used to explain numerous types of phonological phenomena, most of which, in essence, conspire towards preserving higher-sonority vowels, especially in prosodically strong positions. For instance, in certain circumstances, Kobon stress prefers more sonorous vowel of two candidates (Kenstowicz 1997, citing Davies 1981), and sonority reduction is blocked for vowels that are heads in every prosodic category (De Lacy 2006: 306-328). Higher-sonority vowels also behave as having greater amounts of structure. For instance, they are less likely to be transparent in harmony systems (Nevins 2010), as well as less likely to be epenthetic (De Lacy 2006). Conversely, a dispreference for low-sonority vowels may manifest itself, as in Blackfoot hiatus resolution (Elfner 2005) and Tahitian diphthong creation (Gordon 2016, citing Bickmore 1995).

Evidence for vowel sonority, or sonority more generally, is not strictly phonological in nature. While any given phonological category or feature is likely to have some degree of diversity, variation and language specificity in its phonetic correlates (e.g., Hamann 2011), most definitions of sonority incorporate a phonetic dimension. Parker (2002: 44-48) identifies nearly 100 such correlates in the literature, including aperture, impedance and susceptibility to spontaneous voicing in spoken languages, and visual salience in signed languages. However, using experimental evidence, he finds intensity to correlate most significantly with expected sonority categories and their hierarchization. While his results do not neatly match the vowel categories of the general hierarchy, in a later study, he obtains a more expected continuum with a slightly different measurement of intensity (Parker 2008). Whereas the former study measured intensity relative to a reference consonant, the latter study employs a reference low vowel.

The definition of sonority has recently been critiqued in the literature as vague (e.g., Clements 1990), some scholars maintaining that evidence for sonority is circular and/or problematic in its language specificity (e.g., Ohala and Kawasaki-Fukumori 1997, Harris 2006). Nevertheless, sonority remains commonplace in generative phonology, and its existence will be assumed in this paper, as it is not within its scope to prove or disprove this point.

2.2 Nasal coupling and intensity

Similar to intensity, susceptibility to spontaneous nasalization also covaries with height in peripheral vowels. In aerodynamic and acoustic terms, high vowels are the most susceptible, while low vowels are the least (House and Stevens 1956, Hajek 1997). These effects are also borne out in certain perceptual studies (e.g., Maeda 1982). This parameter may, however, be reversed from an articulatory perspective (e.g., Al Bamerni 1983), as well as from the perspective of the link between vowel length and nasality (Hajek and Maeda 2000). Ultimately, the resolution of this clash of hierarchies, and moreover whether one is more influential than the other in determining the inventory of nasal and/or nasalized vowels, may be at the discretion of the language in question.

When nasal coupling does occur, formant bandwidth is generally increased and amplitude is generally reduced (House and Stevens,1956), though the degree of that effect as well as its locus depends on the vowel in question. The acoustic contribution of the nasal cavities is theoretically constant, comprised of pairs of poles and zeroes situated in specific frequency ranges (Maeda 1993). The prominence of these nasal pole-zero pairs in a resulting nasal vowel's acoustic output may be determined in part by the degree of nasal coupling up to a certain point, as well as (and arguably more importantly) by the acoustic structure of the oral cavity.

In particular, the location of the first two formants with respect to the location of a nasal zero is highly influential on the acoustic structure of the combined vowel. For instance, the low F1 of high vowels such as [i] is largely unaffected by nasal coupling, the primary effect being the apparition of a nasal pole between F1 and F2. Meanwhile, the higher F1 of mid-low and low vowels in particular are likely to be diminished or entirely subsumed by the first nasal pole-zero pair (Feng and Castelli 1996). Note that while height is an important factor in these transfer functions, backness and rounding also play a role, and the consequences of nasal coupling on F3 should not be understated (Delvaux 2009). Furthermore, the set of vowels explored in most if not all of these modelling studies are limited to primary cardinal vowels, leading to an incomplete understanding of the effects of nasalization on central vowels.

All in all, it is entirely possible that nasal coupling, in its characteristic reduction of amplitude and widening of bandwidth, obscures the relationship between vowel quality and intensity, at least at the level of the combined signal (that is, the sound resulting from the bifurcated resonator system). Even in the absence of such an obfuscation, while height does play a role in determining the acoustic effects of nasal coupling, it is unclear whether this translates to a similar gradation of intensity values, or whether additional factors transform it. For instance, the spectral envelope of the oral contribution of [i] is largely intact when nasalized, its nasal contribution being an additional pole, while the oral first formant of vowels such as [a] disappears as a result of nasalization. This leads us to speculate on the consequences of this disparity for these vowels' overall intensity.

2.3 Predictions

In this section, I lay out three scenarios for nasal vowel sonority within a given set of strict conditions, in order to anticipate how the phonetic and phonological phenomena may be interpreted. Here, predictions will be made to generic "phonetic correlates," whether this is intensity, some other correlate or a combination thereof. These predictions assume a necessarily neat correspondence between a given ranking of categories and the values of the phonetic correlate, as well as convergence between the phonetic and the phonological evidence. It is entirely possible that the data in the real world will be less "well-behaved." In addition, though examples are provided for each scenario, phonological conflation of categories is quite possible within a given language (e.g., nasality aside, all central vowels may be treated the same in the phonology, regardless of height). These scenarios are simply offered as an illustration of potential analyses under ideal circumstances.

First, nasal vowels may be functionally no different from their oral counterparts in terms of sonority. This is the most likely scenario if nasal vowels are to be viewed as structurally different from a base vowel only by the specification of the feature [nasal]. In this scenario, as illustrated in Figure 2, we would expect the same relationship in relevant phonetic correlates among nasal vowel categories as among oral vowel categories, and furthermore, we would likely expect any given category to be the same within those correlates, regardless of nasality.

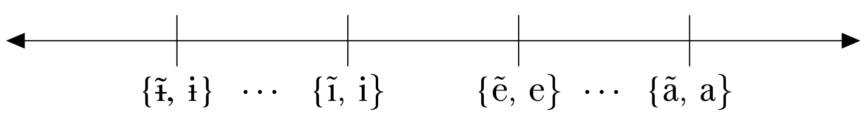

Figure 2. Scenario 1, no difference between oral and nasal vowel categories

For example, [ɨ̃] would differ from both [ə, ə̃] but not from [ɨ] in terms of our phonetic correlate. In addition, phonological evidence should reference categories in the same way. For example, in a given language, if sonority restricts [i] from a certain position, or drives a change from /i/ to [ə], we should expect these to apply to its nasal counterpart as well, in the absence of other complicating factors.

Second, nasal vowels may form a distinct, coherent class which could theoretically be inserted anywhere along the sonority hierarchy, as illustrated in Figure 3. Given the overall tendency for nasal coupling to decrease vowel amplitude, the scenario illustrated here places nasal vowels between glides and all oral vowels. Other placements are theoretically possible though less likely. Additionally, the organization among nasal vowels may not be the same as that of oral vowels, though the scale in Figure 3 reflects similar hierarchies within vowel types.

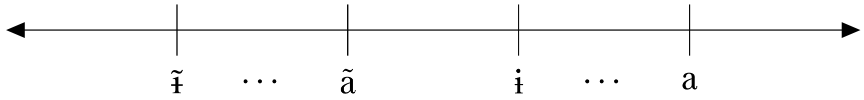

Figure 3. Scenario 2, contiguous categories

Within such a scenario, phonetic correlates such as intensity would be expected to fall along a continuum delineating nasal vowels from other categories as well as from each other. The phonological predictions made by such a hierarchy are less clear, but for instance, with the hierarchy above, a language could allow all nasal vowels in unstressed position but only lower-sonority oral vowels. The scenario as illustrated in Figure 3 could at worst result in some bizarre predictions (e.g., unstressed nasalization, avoidance of stress on nasal vowels, etc.) if only sonority is at play. However, faithfulness to nasality would likely prevent and/or obscure some of these more unexpected hypothesized sonority-driven phenomena.

Finally, oral and nasal vowels may be interspersed, as illustrated in Figure 4. There are many possibilities within this scenario, as the order of nasal vowels relative to each other again remains to be discovered. In addition, while we can imagine a hierarchy perfectly alternating between oral and nasal vowels, this is not necessarily the case. Figure 4 illustrates, for example, a hierarchy in which central nasal vowels are lowest in sonority, rather than alternating between high central nasal and high central oral vowels, and so on.

Figure 4. Scenario 3, interleaved hierarchy

In this scenario, the phonetic correlate of a given nasal vowel or natural class of nasal vowels would fall between that of 2 contiguous oral vowel (classes), and so on. We can predict similar phonological behaviour as the first scenario, i.e., restrictions and alternations applying to one category may reference those of a contiguous category. Oral-nasal sets may not be necessarily complete, however. For instance, as per Figure 4, a language could allow [ə̃, ə, ĩ] in unstressed positions but not [i].

Ultimately, the third scenario is the most versatile of the three while still making certain predictions. Again, however, these scenarios are founded upon some strong assumptions made for the sake of argument, which require further investigation.

3. Methodology

In order to investigate intensity values according to vowel nasality and quality, without the constraints of any given language's inventory, a metalinguistic task was designed. A linguistics graduate student with extensive training in phonetics was recruited. This participant, a French-English bilingual whose first language is French, was instructed to produce various nonce syllables which were displayed in IPA on a computer screen. The experiment was conducted in a quiet lab room.

The structure of these stimuli are as follows: First, target vowels consisted of /ɨ, ə, i, y, u, e, ø, o, ɛ, œ, ɔ, æ, a, ɑ/ and their nasal counterparts. The participant was instructed to attempt to maintain the same positioning of intraoral articulators within a given pair of oral and nasal vowels. For example, the only articulatory difference between [a] and [ã] should have been the position of the velum. These vowels were targeted in isolation and in s_ and s_s syllables (e.g., [a, sa, sas]), and this set of three syllables for a given vowel is referred to as a *series*. After pronouncing a given series of the stimuli in a self-directed, casual speaking rate, the participant was also asked to produce each syllable series at a slower pace than usual. Once the oral short and long series for a given quality was produced, the corresponding nasal counterpart was targeted. All stimuli were recorded twice; first in the order of vowel qualities presented above and second in the inverse order. In total, this design produced 560 stimuli.

For the sake of analysis, vowels were categorized into the typical groups on the sonority hierarchy, that is, high central, mid central, high peripheral, mid-high peripheral, mid-low peripheral and low peripheral. Vowels were classified as oral or nasal depending on the nasality of their target.

These stimuli were recorded using a hand-held nasometer (Glottal Enterprises NAS-1 SEP Clinic) in stereo, wherein each of the two microphones, one in front of the mouth and the other in front of the nose, corresponded to a channel. As the two microphones are separated by a sound-attenuating plate, this effectively allowed for simultaneous but separate recording of the oral and nasal signals. Recording was performed in Praat with a sampling rate of 44.1 kHz.

Each vowel was manually isolated in a Praat textgrid, and intensity in dB was extracted first from the combined channel (stereo) file, and then separately from each channel. All measurements were extracted at five millisecond intervals. Intensity from the channel of the microphone situated directly in front of the nose is hereafter referred to as *nasal intensity*, and that from the oral microphone as *oral intensity*.

Two caveats about the intensity values from this experiment are in order. First, while the participant was instructed to avoid moving (himself or the nasometer) during recording, no additional, special precautions were taken to ensure complete stability of the microphone. However, the hand-held nature of the nasometer, in addition to the necessary contact between its plate and the participant's philtrum (that is, the bridge between the nose and the mouth) mitigates in part this concern. It is possible, though, that the angle of the nasometer may have changed over the course of recording. Second, a carrier phrase was not used due to time constraints. While reference segments were used (see below), the temporal proximity of a given measurement and its relative reference was not controlled. The intensity results should thus be met with a healthy degree of scepticism, until a more principled measurement can be performed.

Low vowels were chosen as reference segments, following (Parker 2008). This was performed at the level of nasality, syllabic context (isolated, open or closed) and targeted length (short or long), within each channel and at the level of the combined signal. The maximal intensity reading among low vowels provided reference intensity, and the value was subtracted from each intensity value within a given set of conditions. This procedure was performed within each channel (nasal, oral and the combined stereo signal).

To provide an example, the maximal intensity values for long oral vowels in oral, open syllables were 72.6 dB in the nasal channel and 81.9 dB in the oral channel, and 79.1 dB in the combined signal. Thus, 72.6 was subtracted from the raw nasal-channel intensity readings of any vowel matching these conditions, and so on.

Means of these processed intensity values were calculated for nasal and oral channels and in the combined signals within unique targets as well as within vowels (e.g., the mean oral-channel intensity was calculated for each token of the vowel [ɑ̃] as well as for all tokens of the same target vowel).

Finally, energy values were additionally extracted for each vowel at each timestamp, once from the oral channel and once from the nasal channel, in order to perform a rapid verification of target nasality. The Differential Energy Ratio (DER; Dow 2020) was applied on each token. This formula models the proportion of the vowel during which nasal energy exceeds the sum of both channels' energy, ranging from 0 (completely oral) to 100 (completely nasal, applying to both nasal vowels and nasal consonants).

4. Results

The mean intensity values for oral vowels are presented in Table 1. Here and in the next table, negative values should be interpreted as having lower intensity than that of a particular reference low vowel within a given setting (channel or combined signal). Somewhat surprisingly, low vowels have some of the lowest intensity values among non-high vowels. This was confirmed in the mean raw values (e.g., low: 77.95 dB vs. mid-low: 79.92 dB).

Figure 5 plots the mean oral- versus nasal-channel amplitude for each token of oral vowels. The DER values (with a mean of 0 for oral vowels) confirmed that the greater mean nasal-channel intensity of certain vowels (mid-low in particular) is not indicative of spontaneous nasalization or instrument failure. Rather, the linear trend of nasal-channel intensity increasing proportionately with oral-channel intensity is indicative of an increase in overall intensity. Oral high vowels stand apart, however, in that their oral-channel intensity values are much lower than the rest while still having comparable values in nasal-channel intensity. Taken with their floor-rate DER values, this is suggestive not only of generally lower intensity values but also more lower values in the oral channel specifically.

The mean intensity values for nasal vowels are presented in Table 2. The average DER for this set of vowels was 98.3, indicating target-appropriate nasal coupling by the participant. Low nasal vowels stand out in their low nasal-channel intensity values. Rounding and backness appear to have an effect within height categories on oral-channel intensity, such that back vowels have the highest value in each category (or comparatively back, in the case of central vowels), and front rounded vowels have slightly higher values than their unrounded counterparts. With the exception of [u], high nasal vowels have the highest in-

Table 1. Mean intensity (dB) of oral vowels relative to reference low vowel, by oral & nasal channels and combined signal

Class	Vowel	Oral	Nasal	Combined
low	æ	-2.02	-2.96	-1.98
low	a	-3.91	-4.83	-3.87
low	ɑ	-2.62	-4.61	-2.63
mid-low	ɛ	-1.31	2.13	-0.96
mid-low	œ	-0.75	0.98	-0.55
mid-low	ɔ	0.14	1.73	0.33
mid-high	e	-3.23	-1.63	-3.03
mid-high	ø	-2.78	-1.13	-2.59
mid-high	o	0.00	0.85	0.13
high	i	-9.09	-3.63	-8.40
high	y	-6.93	-3.77	-6.59
high	u	-5.61	-3.82	-5.43
central	ɨ	-1.16	-0.79	-1.05
central	ə	0.89	0.61	0.95

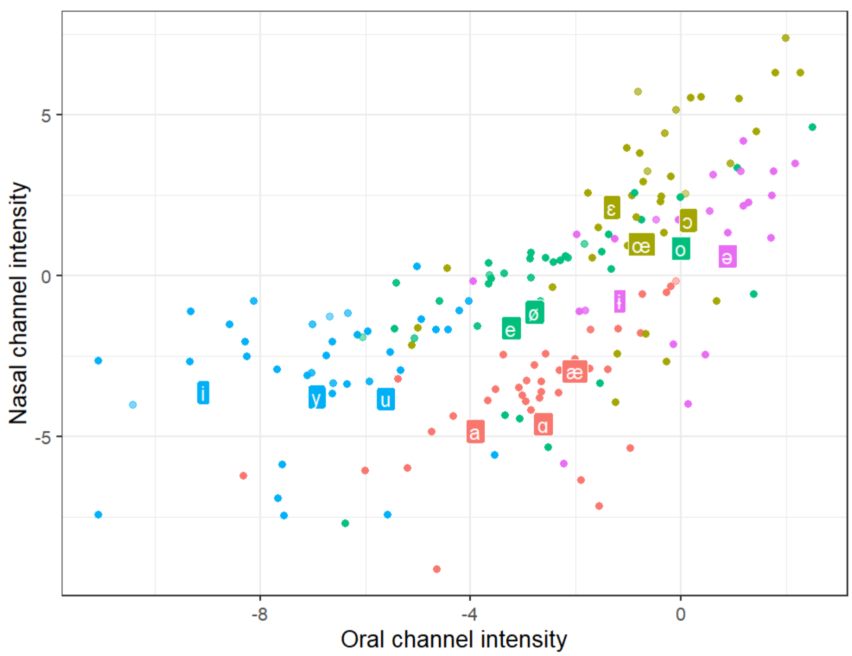

Figure 5. Mean relative intensity by channel and vowel identity, oral vowel tokens

Table 2. Mean intensity (dB) of nasal vowels relative to reference low vowel, by oral & nasal channels and combined signal

Class	Vowel	Oral	Nasal	Combined
low	æ	-2.48	-1.60	-1.75
low	a	-2.70	-2.25	-2.25
low	ɑ	-2.03	-2.06	-1.87
mid-low	ɛ	-3.36	0.62	-0.37
mid-low	œ	-2.34	-0.18	-0.72
mid-low	ɔ	-0.70	0.84	0.50
mid-high	e	-5.31	0.24	-0.95
mid-high	ø	-3.16	0.41	-0.48
mid-high	o	-0.90	0.40	0.11
high	i	-8.81	1.36	-0.39
high	y	-6.75	1.09	-0.46
high	u	-5.59	-1.19	-2.25
central	ɨ	-3.65	0.15	-0.77
central	ə	-1.68	-0.14	-0.47

tensity values in the nasal channel. Figure 6 plots the mean values of each token, along with the mean values per vowel quality. The disparity between [i, y] and mid vowels is most notable not in terms of nasal-channel intensity but in terms of relative oral-channel intensity.

The two types of vowels (oral and nasal) are compared in Figure 7, this time with respect to overall (combined-signal) intensity (x-axis) and the difference of the oral-channel intensity from that of the nasal channel (y-axis). Increasing values of the latter indicate that nasal-channel intensity is greater, though not necessarily due to an increase in nasal-channel intensity. (Compare, for instance, high front vowels with mid vowels in the nasal panel; the greater difference in the former is due to the lower oral-channel intensity of the latter, as we can confirm in Figure 6.) As usual, points indicate the mean values for a given token, while labels indicate the mean values for that vowel quality.

Especially in comparison with oral vowels, nasal vowels are densely packed with respect to overall amplitude (again, along the x-axis of Figure 7) and less clearly delineated than oral vowels. A slight distinction of [u] + low vowels < [i, y] + mid vowels may emerge. Meanwhile, the categories reflected by the oral vowel results reflect neither the standard hierarchy nor Parker's (2008) results, namely in that central and certain mid vowels have higher average intensity than low vowels.

Differential intensity (y-axis in Figure 7) can tentatively be seen as creating a hierarchy of high > mid + central > low vowels, though the significance of these differences is not probed here. Meanwhile, in oral vowels, this factor at best separates low from non-low vowels.

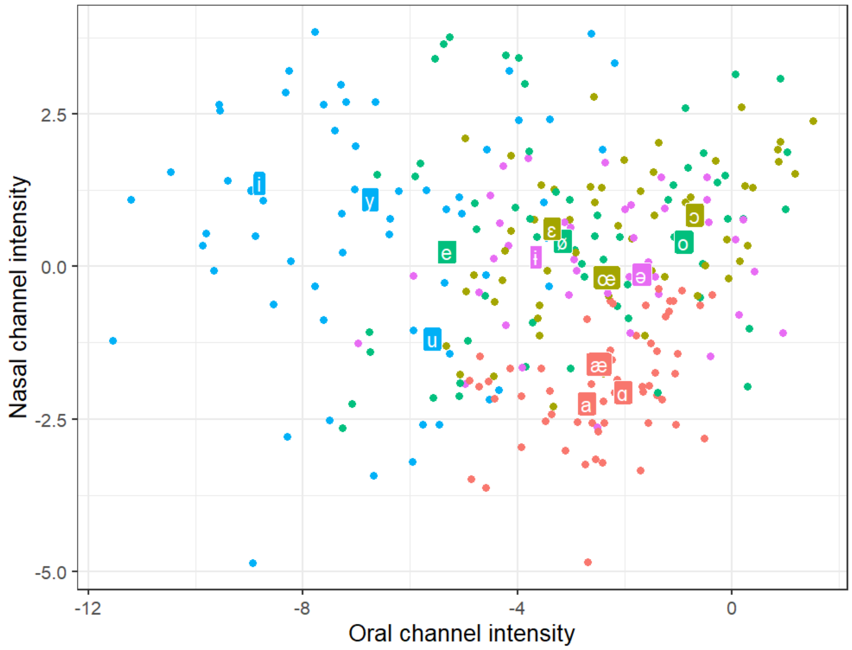

Figure 6. Mean relative intensity by channel and vowel identity, nasal vowel tokens

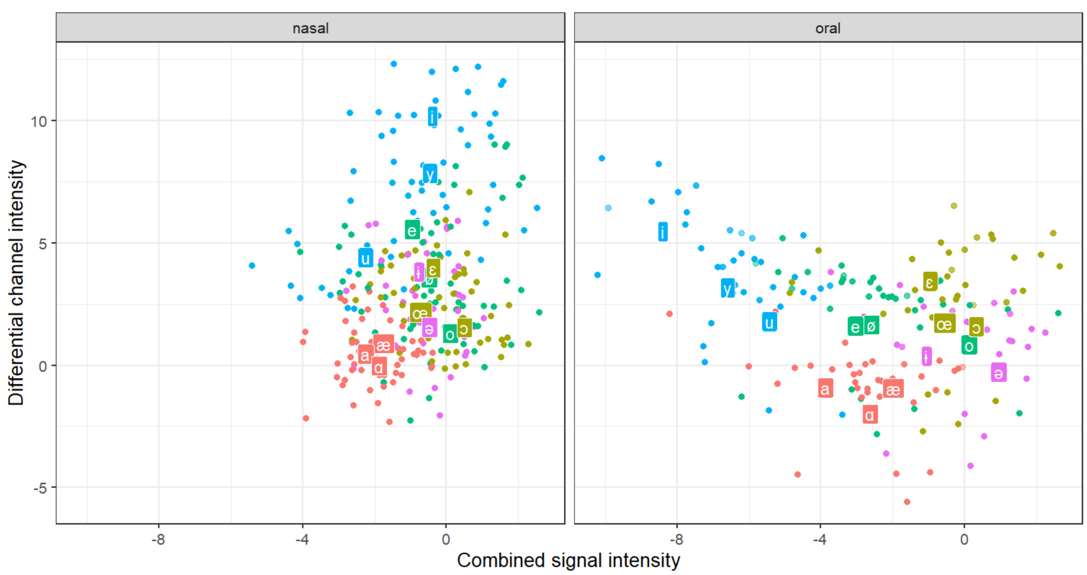

Figure 7. Differential (nasal – oral) intensity vs. intensity of the combined signal, oral and nasal vowels

5. Discussion

As stated earlier, the intensity results should be interpreted with caution, due to the lack of use of a carrier phrase. In addition, while the task was metalinguistic and designed for a trained linguist, it remains to be seen if similar trends will hold in other speakers, especially those of other linguistic backgrounds. That said, some tentative trends emerge from the data.

Most importantly, in each set of vowels (oral and nasal), a main distinction between a specific set of vowels and the rest can be seen. In oral vowels, high vowels had the lowest oral intensity without the proportionate decrease in nasal intensity seen in other vowels. In terms of overall (combined-signal) intensity, this translated into a notable gap between non-high vowels and high vowels. Meanwhile, in nasal vowels, low vowels (and potentially [u]) distinguished themselves as having much lower nasal intensity than non-low vowels. While this can be seen to a certain degree in the combined-signal intensity, nasal vowels are densely clustered in this respect, corroborating observations in the literature concerning the dampening effects of nasal coupling. Future work may be able to bring in formant readings and transfer functions (e.g., Feng and Castelli 1996) in order to explore a potential link between nasal vowel categories and combined-signal intensity.

The oral vowel results do not converge neatly with those of Parker (2008), most notably in that low vowels have intermediate intensity values, and that central vowels are among those with the largest average intensity. In agreement with the literature, however, high vowels had by far the lowest intensity, and some semblance of a hierarchy emerged.

Returning to the phonetic aspect of the scenarios entertained earlier, if we consider solely combined-signal intensity, nasal vowels appear to form a cohesive class with its own internal structure (in terms of differential intensity), arguing against scenario 1 and most immediately for scenario 2. Due to the differing reference vowels, comparison of values between oral and nasal vowels is not advised, which does not allow us to test the differing predictions made by scenarios 2 and 3.

This small study was necessarily based in a few working assumptions that will need to be explored in further research. First, intensity was chosen as the phonetic factor with the *highest* correlation to sonority. These results have shown us at the very least that the coupling of the nasal cavities as an additional resonator transform the much neater correspondence between oral vowel qualities and amplitude. It is entirely possible that another correlate such as air pressure, whether in conjunction with or in lieu of (split-channel) intensity, will yield a more coherent picture of sonority.

Second, it was assumed that the phonetic and phonological evidence will be in agreement with each other. For the moment, though raw evidence is likely robust, little appears to exist in terms of aggregated phonological evidence, apart from inventory surveys such as (Ruhlen 1975). One can deduce from his survey of phonemic nasal vowels that only low vowels are implied by other classes, which could be integrated with theories of markedness such as (De Lacy 2006) to infer that low nasal vowels are the least marked, due to their being most sonorous. Another piece of evidence is found in languages such as

Zuberoan Basque (Egurtzegi 2015) and Guaraní (Kaiser 2008), in which vowel nasality is contrastive only in stressed positions. If interpreted as a ban on nasal vowels in unstressed position (rather than an analysis via licensing in stressed positions), such a finding may suggest that nasal vowels as a class have a high degree of sonority, that is, a version of Figure 3 in which oral and nasal vowels are inverted. (This analysis is, however, speculative and offered merely for the sake of argument.)

Finally and most crucially, it was assumed that nasal vowels are admissible into the sonority hierarchy. Should a more thorough examination of the literature reveal that nasal vowels in general do not participate in the same, sonority-driven phenomena as oral vowels, we might infer that sonority does not apply to nasal vowels, or more specifically, "precedes" their nasality at a deeper level of structure. This could have implications, then, not for the study of sonority but for the larger representation of vowel nasality. Given, though, the evidence for differing types of representation (e.g., the biphonemic representation of French nasal vowels, such as /VN/ in (Paradis and Prunet 2000), instead of a more concrete representation of $\tilde{N}$/), it is more likely that these questions must be addressed at the language-specific level, or groups of languages, rather than universally.

6. Conclusion

This paper set out to begin a discussion on the notable absence of nasal vowels from the standard sonority hierarchy, despite the finding of intensity as a significant correlate of sonority, on one hand, and the knowledge of the consequences of nasal coupling for intensity, on the other. Three scenarios were offered for the integration of nasal vowels into this hierarchy, within a certain set of idealized conditions. Finally, the results of a phonetic investigation via a metalinguistic task were presented.

It was found that nasal vowels, unsurprisingly, were little differentiated in terms of overall intensity. However, some degree of organization and structure emerged from a look at intensity according to separate oral and nasal signals, singling out low vowels in particular as having lower nasal-channel intensity. High front nasal vowels proved to have both the lowest oral-channel intensity and the highest nasal-channel intensity. Before these results can be interpreted in terms of sonority, phonological evidence needs to be compiled, and more phonetic data needs to be examined. Ultimately, this investigation may have important impact on our understanding of the nature of sonority and/or vowel nasality.

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