Multi-dimensional Acoustic Analysis of Sociophonetic Nasality

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1 Introduction

This paper considers a method for the analysis of sociophonetic variation in coarticulatory vowel nasalization. The result of anticipatory velum lowering before nasal consonants [n], [m], [ŋ] during vowel production, English vowel nasalization is allophonic, as opposed to the phonemic nasal vowels found in many languages. Vowel nasalization has been researched fairly extensively in American English (Beddor et al. 2009, 2013, Labov 2006), and nasal voice quality more generally has been shown to be a salient, indexical feature of speech (Bucholtz 2010, Podesva et al. 2013). Existing studies of nasality in the UK are mostly impressionistic (Laver 1972, Trudgill 1974) but there is anecdotal perceptual evidence of regional and social differences in the UK with some supporting research (e.g. Stuart-Smith 1999). Additionally, there is a potential discord between lay perceptions of nasality and phonetic realities of nasalization. Wilhelm (2019) notes a common example of such an issue with the case of blocked nose speech.

To that end, there appears to be a lot to uncover in terms of how nasality behaves in English, and how listeners perceive it. As with any sociophonetic variable, this is best done by observing its behaviour in spontaneous, naturalistic speech, but established methods for measuring nasality range from inconvenient and/or expensive to highly invasive. Recently, promising acoustic methods have been developed for the quantification of nasality. This paper evaluates one of those approaches, the NAF method (Nasalization from Acoustic Features; Carignan 2021), with application to sociophonetic data in mind.

2 Approaches to Nasality Research

2.1 Nasality in the Sociolinguistic Landscape

Nasalization varies considerably across different varieties of English. In a sociophonetic analysis of Vancouver English, Esling (1991:126) concluded that vowel quality in middle class Vancouver English was characterized by lingual fronting and nasalization (in contrast to lingual retraction and velarization of upper working class speech). These differences were claimed to be more distinct in female speakers. Lawson (2011) postulated, based on anecdotal evidence, that one of the most commonly cited identifying features of a group of (lower) working class males in Glasgow, known as “neds,” is increased nasalization. Indeed, in her seminal work using vocal profile analysis (VPA) to analyze the speech of 32 speakers of Glasgow English, Stuart-Smith (1999) observed increased nasality in male speakers, but found no class-based differences. In Edinburgh, Chirrey (1999) claimed that vowel nasalization is common across all speakers, but Esling (1978) claimed nasality to be a feature of middle class Edinburgh speech. Laver (1972) also observed nasality as a feature of Received Pronunciation (RP),[1] while Trudgill (1974) conversely found nasality to be a vocal setting of working class speech in Norwich.

Of course, nasality variation is not limited to English. There is a fairly extensive body of research into the nasalization of the postponed determiner *la* in non-nasal contexts in Haitian Creole (HC): Dejean (1980) first observed it as free variation; further analysis in Valdman (1991) revealed a correlation between nasalization of the postponed determiner and speaker age, identifying more nasalization in younger speakers and suggesting it to be a change in progress. More recently, Tezil’s

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[1]An accent now arguably confined to upper class speakers in the UK, but at the time also attributed to middle class speakers.

(2019) doctoral thesis evinced that this nasalization had spread to speakers of different social status, and Tezil (2022) extended this line of analysis to demonstrate that monolingual speakers of HC "overuse" nasalization of the postponed determiner compared to bilingual HC and Haitian French speakers (p. 291). In some languages, it appears that nasality is associated with politeness. A frequently used example of this is Crystal's (1970) reference to the "ceremonial" function of nasalization in the Cayuvava language of Bolivia. In Tokyo Japanese, Ikuta (2013) observed "among young urban mostly female [sic] sales clerks... an emerging use of nasal voice quality" (pp. 61-2) in polite "service talk".

In English, though, it seems politeness is rarely the first thing that comes to mind when one thinks of "nasal voice". On the contrary, in a study of listener attitudes to various vocal settings, Addington (1968:502) concluded that "increased simulation of nasality by both sexes provoked such a wide array of socially undesirable characteristics as to make the isolation of any clear cut images difficult if not impossible". Shortly thereafter, however, Addington (1971) was able to identify that phonetically balanced reading passages recited using nasal and denasal voicing were rated as less credible than other phonation types assessed. Similar findings include those of Pittam (1987), whose listeners ranked nasal voice in Australian English lowest out of five phonation types for status, and later found nasalization to be negatively correlated with listener ratings of persuasiveness, status, and solidarity (Pittam 1990). Poyatos (1991) commented that nasalization performs generally negative interactional functions in every culture, positing also that nasality is a component of "whining" and "moaning" voice (p. 188). In a similar crosslinguistic approach, Payá Herrero (2019) noted that native speakers of languages in which nasalization is "strongly present [in the] phonological system" (p. 110; namely German and American English) perceived nasality more negatively than native speakers of Spanish.

The research highlighted in this section has given us a great deal of insight into the sociolinguistic significance of nasality, in a broad range of languages and contexts. There is however, one shared drawback of these previous studies: they all employ exclusively auditory methods.[2] The production studies involve exclusively auditory analysis, which is a valid, valuable method, but given the previously noted inconsistencies between productions and perceptions of nasality, warrants some objective corroboration. The perception studies rely on stimuli produced by speakers approximating "nasal voice", with only auditory validation of the stimuli. This is an issue especially for perception studies, as the validity of their results relies on the assumption that the researcher's concept of nasal voice and the listeners' concept of nasal voice are in alignment, which is not always the case.

2.2 Methods for the Phonetic Analysis of Nasality

The most direct way of measuring nasality involves recording the degree of movement of the articulators involved in the production of nasalization. Techniques for recording this sort of data include the use of cinefluorography (x-ray videos), originally used for the clinical study and diagnosis of conditions that cause abnormal nasalisation patterns (Massengill, 1966; Moll, 1965; Powers, 1960) and magnetic resonance imaging (MRI; Byrd et al. 2009, Carignan et al. 2019, Liao et al. 2023).

Less resource-heavy articulatory methods include nasography (Ohala, 1971) and velum tracing (Horiguchi and Bell-Berti, 1987). Nasography was developed by John Ohala (1971) in response to "popular" methods (such as those mentioned previously) that "necessitate[d] a huge amount of labour (and a certain amount of danger)" (p. 1). However, both nasography and velum tracing involve inserting a long cable or rod into the nose to reach the velum, which can be dangerous and nowadays requires the presence of a medical professional. Nonetheless, the use of nasography has led to several findings of cross-linguistic diferences in degree of velum aperture (Al-Bamerni 1983, Clumeck 1976, Solé 1992, Solé 1995), and Krakow (1989, 1993) used velum tracing to observe how syllable structure and stress influence vowel nasalization in American English, concluding that abstract prosodic structure affects degree of nasalization.

But how might we measure degree of nasalization without real risk to speakers? We may consider that the next best method for measuring nasalization is the measurement of airflow. In-

[2]Some of the studies, their contributions to the literature, drawbacks, and alternate methods are discussed in more detail in Dewhurst (2023).

creased velopharyngeal opening results in more nasalisation, and vice versa. This is because a larger velopharyngeal opening allows for more air from the lungs to travel through the nasal cavity as well as the oral cavity. So, airflow rates are a strong indicator of the extent of nasalization. The use of airflow to measure nasalization requires the separate recording of airflow rates from the nose and the mouth, which is achieved through the use of an oro-nasal screen-type pneumotachograph mask. The design of this type of mask is attributed to Rothenberg (1973). The mask is typically made of plastic, with a rubber baffle and seal creating separate oral and nasal chambers and avoiding leakage. Using an oronasal airflow mask, Merrifield and Edmondson (1999) confirmed and expanded upon auditory conclusions made in Merrifield (1963) about timing differences in lexically contrastive nasasalization in Palantla Chinantec.

Screen-type pneumotachograph masks provide a good proxy for tracking velopharyngeal opening, and Rothenberg (2013) has claimed they cause relatively low acoustic impedance. However, they have been shown to display sound leakage caused by the vibration of the internal separator (Rothenberg 2006) and Hertegård and Gauffin (1992) observed spectral attenuation near 2000 Hz. Thus, a further removed, but arguably equally reliable and less problematic method for indirectly quantifying the extent of nasalization is nasometry, the original system for which was named TONAR (The Oral Nasal Acoustic Ratio; Fletcher and Bishop, 1970). The system's original purpose, for which it is still widely used today, was to improve upon existing procedures involved in the diagnosis and treatment of cleft palates and related issues. Fletcher developed the highly innovative TONAR system to separately record acoustic outputs from the oral and nasal cavities during speech, the output of which could be easily interpreted by clinicians. Such a system uses separate amplitude measurements from the nose and mouth as a proxy for airflow (which itself is a proxy for velophoaryngeal aperture). It consists of a plastic baffle with an attached handle that the speaker holds to their face between their mouth and nose so that the signals from the mouth and nose can be recorded separately. Highly directional microphones are attached to the top and bottom of the baffle and amplitudes are extracted from the resultant acoustic signals and proportional nasal amplitude is calculated using Equation 1.[3] This is known as nasalance or the nasalance score, and is a representative measure of degree of nasalization.

Nasometry is used extensively in speech pathology (e.g. Luyten et al. 2012, Prathanee et al. 2003, Seaver et al. 1991). It is also used in phonetic research, as a less intrusive, more cost-friendly alternative to other methods for measuring nasality discussed here so far (Pouplier et al. 2023, Rodriquez et al. 2023). For the purposes of sociophonetic research, however, nasometry carries the same limitation as the rest of the methods discussed above, in that it does not allow for collection of "naturalistic" data. For this kind of data, we need measurements that require minimal disruption to the speaker and their surroundings. Thus, we turn to acoustics.

Research into the acoustics of nasalization have been ongoing for almost a century, and, perhaps a testament to the complexity of the process, the overarching consensus on the matter is that it is near impossible to identify a single acoustic feature or combination of features that adequately and consistently quantify nasalization across all speakers, languages, vowel qualities, and even lexical items (Scarborough 2013). This is because of velopharyngeal port coupling (VP-coupling), which introduces the nasal cavity as an additional resonator into the already interconnected and interdependent system of resonators in the sub-velic vocal tract. As such, the inclusion of the nasal cavity during phonation further convolutes the already complex acoustic system of the vocal tract.

Many acoustic features have been observed to correlate with nasalization (most of these are listed in Section 3.5, see Baken and Orlikoff 2010 for an overview). The most widely used acoustic method for measuring nasalization is A1-P0, the subtraction of the first nasal peak, P0, around 250Hz, from A1, the amplitude of the first formant (Chen 1995, 1997). Tamminga and Zellou (2015) observed systematic change in Philadelphia nasalization and Zellou and Tamminga (2014) found regional variation between speakers in Philadelphia, Pennsylvania and Columbus, Ohio using A1-P0. Other methods include the use of Mel-frequency Cepstral Coefficients (MFCCs; Liu et al. 2019), and other recent attempts to quantify nasalization using acoustics have also turned to multi-dimensional approaches. Styler (2017) assessed the success of 22 acoustic features of nasality as

[3] See Section 3.3.

predictors in linear mixed-effects regression, identifying A1-P0, F1 bandwidth, and spectral tilt (A3-P0) as the most promising. Carignan (2021) developed the NAF method for estimating nasality trajectory across the vowel, which predicted degree of nasality using the principal components (PCs) of both the acoustic features from Styler (2017) and 13 MFCCs. Validation of this method produced correlations between scores generated by the linear regression and nasalance of up to r = .94.

The latter method forms the basis of the analysis in this paper. As Carignan's data were obtained from trained phoneticians, recorded in a highly controlled environment, I aim to determine whether such high correlations can be found with nasalance data recorded from naive, untrained participants. Additionally, the 2021 paper sought to model the time-varying trajectory of nasality across vowels. I seek to confirm that such a method can be applied using only vowel midpoint measurements, in hopes of eventually applying it to sociolinguistic interview data to determine how speakers realize vowel nasalization in speech approximating everyday interactions.

3 Methods

3.1 Speakers

The speakers in this study were four female and four male speakers aged 15-16. Speakers were recruited from two schools in Greater Manchester. Four speakers were monolingual; languages spoken by the remaining multilingual speakers were not languages that employ contrastive nasalization. Future analysis will take into account other speakers in my dataset who do speak languages with nasalization contrasts (e.g. French, Punjabi, Yorùbá). Speakers were also evenly stratified by social class, and the balance of speaker ethnicities was four white speakers, three black speakers, and one Southeast Asian speaker. These categories will be discussed briefly in this paper, but future work with a larger sample will consider these macrosocial categories in more detail. Anecdotal evidence suggests that these characteristics are significant predictors of nasality variation in Greater Manchester, which is corroborated by preliminary analysis elsewhere.

3.2 Stimuli

The stimuli used in this study were designed to elicit increasing degrees of nasalization across eight vowel contexts. Vowels were elicited in between two oral consonants (CVC; "bed"), following an oral consonant and preceding a nasal consonant (CVN; anticipatory nasalization; "Ben"), and in between two nasal consonants (NVN; carryover and anticipatory nasalization, or *maximal nasalization*; "men"). Oral consonants were voiced to reduce any potential effect of consonant voicing (or lack thereof) on vowels in the oral tokens compared with nasal tokens. Ten repetitions of each word were elicited, totalling 240 tokens in each environment. Five repetitions of 19 distractor tokens were interspersed throughout the wordlist, which was presented randomly to the speakers.

3.3 Nasometry and Nasalance

Recordings were made with a nasometry system designed in the Lancaster University Phonetics Laboratory, using AKG CK99L BK lavalier cardioid microphones. The resulting oral and nasal amplitudes, extracted using a Praat script written by Henning Reetz, were used to calculate the proportion of the total amplitude that could be attributed to the nasal passage. The equation used to calculate proportional nasal amplitude (nasalance) is as follows:

$$nasalance = \frac{nasal\ amplitude}{nasal\ amplitude + oral\ amplitude} \qquad (1)$$

3.4 Data Processing

Recordings were downsampled to 22.05 kHz and lowpass-filtered to 11.025 kHz, transcribed in Praat, and segmented using the Dartmouth Linguistic Automation (DARLA) forced-alignment software[4] (Reddy and Stanford, 2015; Kendall and Thomas, 2010; McAuliffe et al., 2017; Rosenfelder et al., 2014). The resulting TextGrids were checked and corrected manually,[5] and non-vowel related information was removed. The NasalityAutomeasure Praat script[6] was used to extract acoustic correlates of nasality (Styler, 2016). Further data wrangling was carried out in R.

3.5 Adapting the NAF Method

The method used in this work follows that proposed by Carignan (2021). A total of 31 acoustic features were obtained in Praat at the midpoint of the vowel portion of each token. Eighteen of the 31 features were extracted using the NasalityAutomeasure Praat script: frequency, amplitude, and bandwidth of F1–F3; P0 and P1 amplitude; P0 prominence; A1-P0 and A1-P1, as well as their formant-compensated analogues; A3-P0; and H1-H2. As A1-P0 and A1-P1 typically exhibit an inverse relationship with degree of nasalization. These values were inverted for easier comparison with the nasalance signal, so that a higher A1-P0 value corresponds to a higher degree of nasalization, and vice versa. The remaining features consisted of 13 MFCCs, calculated in Praat using a script written by Sam Kirkham. MFCCs are highly accurate at approximating vocal tract dimensions, and preserve information from the acoustic signal that parameters in linear representations do not (Davis and Mermelstein, 1980).

For each speaker, all 31 acoustic features underwent principal component analysis (PCA) using the R `princomp` function, following scaling and centering. Nasalance values were also scaled and centered. PCA was carried out in order to avoid the high degree of multicollinearity that would result from the "raw" acoustic features, which were created specifically for the purpose of measuring vowel nasalization, as independent variables in a regression. All resulting PCs thus replaced the original acoustic features as independent variables in a linear regression. The total number of tokens for each vowel quality for each speaker was split via random sampling into training and testing sets, with a 75%-25% training-testing split. Then, nasalance data from the training tokens were separated into the lower and upper quantile for each speaker; these observations were considered as maximally oral and maximally nasal data for the purpose of training, and remaining data was discarded. This resulted in an average of 180 data points in each of the oral and nasal categories for each speaker (SD = 71). As in the original NAF implementation, oral data were coded as "0" and nasal data were coded as "1." The coding was treated numerically, instead of categorically, meaning that it could be used as a continuous independent variable in a linear regression, rather than as a binary independent variable in a logistic regression, as one might expect from 0-1 coding. This was done in order to avoid the issue of binary classification being "too easy," and it also meant that the predictions based off the linear regression would give a more precise score of degree of nasalization. A combination of the corresponding PCs were used as predictors. As such, the models assume that the mapping between the PCA-transformed acoustic features and the degree of nasalization is linear, on a scale from 0-1. "Nasal scores" for the testing data were predicted from the linear regression.

4 Results

The method was validated here the same way it was in Carignan (2021) paper, by identifying the correlation between model predictions ("nasal scores") and "raw" nasalance values. A high correla-

[4]DARLA uses an American English pronunciation model, but MacKenzie and Turton (2020) found it to perform sufficiently well on varieties of British English.

[5]UK vowel contrasts not picked up by the American pronunciation model used by DARLA were manually coded.

[6]Written by Rebecca Scarborough and Will Styler and maintained by Styler, to be found here: https://github.com/stylerw/styler_praat_scripts/tree/master/nasality_automeasure

tion would suggest that the scores generated by the regression predictions adequately approximate nasalance rates, implying that this method is an acceptable replacement for collecting nasalance data for the analysis of nasalization. Due to the small sample size used here, correlations for each individual speaker are presented in Table 1, as well as an overall correlation.

Speaker	Correlation
F1	0.95
F2	0.92
F3	0.89
F4	0.87
M1	0.80
M2	0.85
M3	0.85
M4	0.88

Table 1: Correlations of model scores with nasalance values. F1-4 are female speakers, M1-4 are male speakers. All correlations were significant ($p < 0.01$).

Correlations for all speakers were strong, ranging from r = .80 to r = .95, and statistically significant ($p < 0.01$). The average correlation across all speakers was r = .87 (SD = 0.05). Such correlations suggest that the NAF method does, in fact, accurately approximate nasalance values in data recorded from naive, untrained participants, roughly to the same accuracy that it does on highly controlled data from trained phoneticians. Additionally encouraging is the method's efficacy on not only maximally oral and nasal stimuli, but with the inclusion as well of anticipatorily nasalized CVN tokens, which inevitably add noise to the training data. It also appears to work just as well approximating only vowel midpoint measurements instead of modelling the nasalization trajectory across the vowel. One peculiarity, so to speak, of the data reported here, which may be immediately noticeable to the reader, is that the correlations appear to be stronger for female speakers. Gender-based differences ($t(7) = 2.59$, $p = 0.04$), as well as class- ($t(7) = 2.41$, $p = 0.84$) and ethnicity-based ($t(7) = 0.28$, $p = 0.79$) differences, were found to be insignificant using independent t-Tests with Bonferroni-adjusted alpha levels of 0.017.

A notable distinction of this method from typical applications of PCA is the indifference towards what, exactly, the PC values represent in the original data. They are simply vehicles for de-correlation of a large number of acoustic features, giving this method a black box-like quality. Arguably, the lack of clarity as to what the values represent is not problematic, as the aim of the method is not to pin down how individual features contribute to vowel nasalization, but rather to harness the collective power of all related features to produce an accessible "nasality score". This is understandable, given how messy acoustic nasality is.

One aspect to consider with this method is the subject of principal component selection, or lack thereof. The typical procedure in principal component regression (PCR) is to select a small number of PCs that explain the majority of the variance in one's data (Mansfield et al. 1977, Mosteller and Tukey 1977). This is realised in many fields as the selection of the number of PCs it takes to explain 80% of the variance in the data (Dray 2008, Cowe and McNicol 1985, Sabharwal and Anjum, 2016). NAF does not require selection of PCs; instead, all the PCs generated are used as independent variables in the linear regression. As such, PCA should be seen as a way of including a wide range of acoustic measures in a way that avoids multicolinearity, rather than as a form of dimensionality reduction. As mentioned previously, one downside of this is reduced interpretability, and there are also potential risks of model instability due to the inclusion of any non-relevant PCs (Adragni and Cook 2009, Massy 1965).

An alternative approach is to use PCA as a form of dimensionality reduction by only including a selection of PCs. For example, I re-fitted models containing only the PCs that cumulatively explain 95% of the data's variance (requiring from two to four PCs across speakers). Table 2 shows correlations for individual speaker models when only the most explanatory PCs are included in the regressions, compared with the original correlations displayed in Table 1.

Speaker	Correlation after PC selection	Correlation before PC selection
F1	0.69	0.95
F2	0.49	0.92
F3	0.52	0.89
F4	0.58	0.87
M1	0.4	0.80
M2	0.61	0.85
M3	0.65	0.85
M4	0.55	0.88

Table 2: Correlations of model scores with nasalance values before and after PC selection. All correlations were significant ($p < 0.01$).

When only the most explanatory PCs are selected for inclusion in the regressions, correlations of model output with raw nasalance values plummet quite dramatically. The majority sit somewhere between weak to moderate. Thus, PC selection garners disappointing correlation coefficients. This could suggest that the higher PCs included in the original method explain some small but consistent variances that collectively contribute important information to the acoustic signal, but in this case the possibility of overfitting cannot be ruled out, due to the small size of the dataset. Future work will consider using resampling techniques to avoid this possibility.

5 Conclusion

The present paper evaluated the success of the NAF method (Carignan 2021) for the acoustic analysis of vowel nasalization at the vowel midpoint when used on data from naive, untrained speakers, as opposed to laboratory data from trained phoneticians, in the hopes of applying the method to sociolinguistic interview data in future work. Using the same model structure as in the original implementation of the method, strong positive correlations were observed between scores from 0-1 generated in linear regression and "raw" nasalance data, suggesting that the method accurately approximates rates of nasal airflow. However, it was noted that the method in its current form uses PCA for decorrelating features, rather than dimensionality reduction. In an attempt to improve model stability, the analysis was rerun, using only the amount of PCs required to explain 95% of the variance in the data, resulting in a dramatic reduction in correlations. When initially all correlations were very strong, correlations from the new models ranged from weak to moderate. This suggests that the use of all PCs in the original NAF method could be capturing important aspects of the signal; future work should investigate this further, with a bigger dataset or resampling techniques.

The NAF method is a unique approach to the issues encountered in the acoustic analysis of nasality. This work has shown that it may be a good data-driven method, but there remain potential advances concerning interpretability and reduced dimensionality. Either way, it is clear that harnessing the power of the numerous acoustic correlates of nasalization, rather than aiming to identify one or a small number of key correlates (a pursuit which has repeatedly proven to be futile), is a positive contribution to the field.

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