Abstract

This aerodynamic study investigates velum activity during the production of nasal and pharyngeal consonants, using airflow, and during the production of vowels adjacent to nasal and pharyngeal consonants, using airflow and nasalance, in Moroccan Arabic (MA). The results indicate that the velum is lowered during the production of pharyngeals and that this overlaps on adjacent vowels. However, nasalance patterns on vowels suggest that nasality is greatest on the portion of the vowel opposite the actual pharyngeal. Examination of both oral and nasal airflow patterns on vowels indicates that actually oral airflow is increasing significantly towards the pharyngeal, due to extreme jaw lowering for this articulation, which accounts for the observed nasality patterns. This study highlights the importance of separating out the relative contribution of the oral and nasal tracts when investigating nasality patterns.

Index Terms: nasality, airflow, nasalance, pharyngeals

1. Introduction

It has been argued that nasalization systematically co-occurring with a non-nasal obstruent cannot exist: in order to build up or maintain sufficient air pressure required to produce oral stops or fricatives the velum must remain closed. Yet, there is potentially no articulatory constraint on velum closure during the production of consonants that are articulated further back from the position of the velum, also known as non-buccal consonants, since air pressure would be unaffected by velum activity. Indeed, studies have found spontaneous nasalization in vowels adjacent to glottal consonants in various languages, though notably this is usually restricted to low vowels (e.g., Thai and Piraha, [1]). More interesting, however, are situations where non-buccal consonants are systematically produced with velum lowering, even in non-nasal contexts. The pharyngeal consonants, in particular, have been shown in numerous articulatory studies to be systematically produced with velopharyngeal port opening.

The focus of the current study is the articulation of velum lowering with the pharyngeal consonants in Moroccan Arabic (MA). Previous articulatory studies have found consistent velopharyngeal port opening with the production of these consonants in other dialects of Arabic and other languages ([2], [3]). Yet, this has never been explicitly examined in MA. More important, however, is examining the production of nasalization as a systematic, sub-phonemic property of consonants where it is neither articulatorily precluded nor possibly phonemically contrastive.

The goal of this study is to describe the airflow patterns during the production of the pharyngeal consonants in MA.

Additionally, since any velum lowering gesture would presumably also be realized on adjacent vowels due to coarticulatory overlap this study also aims to examine the airflow patterns on vowels adjacent to pharyngeal consonants in MA.

2. Methods

2.1. Speakers and Stimuli

Two native MA speakers (both male, aged mid-late 30s) participated in this experiment. Both speakers reported no physiological impairments that would hinder the flow of air from either the nose or the mouth.

Twenty-six monosyllabic CVC words were elicited for this study, controlled for vowel (/a/, /i/, /u/), target consonant direction (word-final, word-initial) and consonant type (/ʕ/, /h/, /n or m/, and oral). Target oral consonants consisted of bilabial or alveolar stops. All non-target consonants were controlled for place of articulation (either bilabial or alveolar) to avoid interaction with the velum. The stimuli were repeated twice around a carrier phrase, gal ___ daba “say ___ now,” designed to contain no nasal segments.

2.2. Equipment and Procedures

Nasal and oral airflow data is obtained by channeling the air into a device that measures pressure and converts it to a time-varying digital signal [4]. An oro-nasal dual chamber pneumotachograph mask (split mask) was connected to two separate oral and nasal Glottal Enterprises PT-2E wide-band transducers. The oro-nasal mask, designed to be circumferentially vented to reduce voice muffling [5], fits over both the nose and mouth and measure separate oral and nasal airflow while reducing the cross-leakage of sound between the oral and nasal chambers. Both pressure transducers were connected to a Glottal Enterprises MS-110 transducer A-D converter unit, which was connected directly to a computer where recording was initiated.

Calibrations were performed for each transducer before the recording of each subject. The zero level was adjusted by the experimenter at the beginning of every recording session and checked regularly during the session. Unfortunately, during the zero setting for some word elicitation the zero was set with some degree of drift resulting in the collection of negative airflow measures. These measurements were not included in analysis.

Care was taken to ensure that the oro-nasal mask sealed around the subject’s face for each recording to prevent leakage of airflow during elicitation. If the mask slipped in any observable way, or if the speaker pointed their head downward causing the mask to be tilted, which may affect the pressure...
signal collected by the transducers, the recording of that token was repeated.

After recording, the output of both transducers was low-pass filtered at 40 Hz, with a smoothing of 5 Hz, in Praat. Nasal and oral airflow measures for each segment were automatically segmented into seven equally spaced intervals and the values of oral and nasal airflow at each time point were automatically collected. These seven equidistant time point measures were taken in order to analyze the aerodynamic data from all segments over the same relative duration.

2.3. Measurements

Two types of aerodynamic parameters are reported in this study: airflow (nasal airflow, oral airflow, and total (nasal+oral) airflow) and nasalance (proportion of nasal to total airflow). The units used in this study are liters per second (l/s). Variations of stress [7] or oral tract configurations [8]. Nasalance reflects capacity, cf. [6]), as well as due to contextual effects such as overall airflow can vary by speaker (due to difference in lung

Results were analyzed using a linear mixed-effects model with consonant type (oral, nasal, pharyngeal) as the fixed effect. All the predictors in the oral airflow model for vowels have high t-values, indicating a significant main effect of consonant type on adjacent vowel oral airflow. Pharyngeal-adjacent vowels are associated with a negative coefficient (β=-0.0146, p<.01), which is larger than the negative coefficient associated with nasal-adjacent vowels (β=-0.0209, p=.001), indicating P-adjacent vowels have more oral airflow than N-adjacent vowels.

The nasal airflow model for vowels computed a high t-value for nasal airflow in vowels adjacent to pharyngeal consonants, with a positive coefficient (β=0.0108, p=.01), indicating that vowels adjacent to pharyngeal consonants have reliably more nasal airflow than vowels adjacent to both oral and nasal consonants. That nasal-adjacent vowels are not associated with significantly larger coefficients is either indicative of the variability in the data or the systematic change in nasal airflow rates over time in nasal-adjacent vowels.

The nasal and oral airflow averages, over normalized time, for vowels following oral, nasal and pharyngeal consonants are
displayed in Fig. 4. The data indicate that vowels following word-initial pharyngeal consonants display consistently greater nasal airflow than vowels following oral consonants. Vowels following nasal consonants show a large amount of nasal airflow at the beginning, adjacent to the nasal consonant, yet subsequently the nasal airflow rate drops steadily over the duration of the vowel until the level of nasal airflow is similar to that of oral vowels, at the opposite end.

![Figure 4: Nasal (left) and Oral (right) Airflow (l/s).](image)

With respect to oral airflow, oral and nasal vowels show the reverse of the nasal airflow pattern—oral vowels have the greatest degree of oral airflow and nasal vowels have the lowest degree of oral airflow. Meanwhile, pharyngeal-adjacent vowels have greatest degree of oral airflow directly following the pharyngeal consonant and a large drop in oral airflow at the end. The distinct patterns of oral and nasal airflow for vowels adjacent to the different target consonant types suggest that nasalance is an important measure for vowels, since it can reflect changes in nasal airflow compared to overall airflow. Fig. 5 displays the average nasalance values for vowels following nasal and pharyngeal consonants over normalized time.

![Figure 5: Nasalance on P- and N-adjacent vowels.](image)

Nasalance patterns on N-adjacent vowels follows from what we might expect—nasalance is greatest directly following the nasal consonant and decreases steadily over the duration of the vowel. On the other hand, the nasalance pattern for P-adjacent vowels is surprising—nasalance is low directly following the pharyngeal consonant and increases to become greatest on the point of the vowel furthest away from the pharyngeal. Separate linear mixed-effects models computed for nasalance on vowels with carryover and anticipatory consonant type (O, N, P) and time point indicate that nasalance in P-adjacent vowels does increase over time away from the pharyngeal.

Nasalance was also analyzed by vowel quality. The vowel quality nasalance model computed /i/ as a significant predictor, with a positive coefficient ($\beta =19.45$, p<.05), indicating nasalance is greater (more nasal) for this vowel overall. The interaction of vowel /i/ and carryover context is associated with a positive coefficient ($\beta =38.24$, p<.01), indicating that position /i/ has much greater nasalance (is more nasal) following a P or N.

## 4. Discussion

### 4.1. Airflow

This aerodynamic study indicates that there is indeed nasal airflow during the production of pharyngeal consonants, without being in the context of a nasal segment. Relative to oral consonants, pharyngeals are articulated with systematically greater nasal airflow. This indicates that there is indeed velum lowering during the production of pharyngeal segments in MA. Furthermore, unlike nasal stops, which have the greatest amount of nasal airflow, pharyngeal segments are produced with a great amount of oral airflow.

With respect to the patterns of oral airflow associated with the pharyngeal consonants, it is documented that the jaw is actively involved in the production of the pharyngeal consonants. Specifically, it has been reported that there is an extreme degree of jaw opening during the articulation of pharyngeals [3]. This was shown to be greater than jaw opening for any other segment (including vowels). And, this jaw lowering does have coarticulatory influence on adjacent vowels: the lowered positioning of the jaw accounts for the substantial amount of oral airflow reported in the present study for pharyngeal. Also, it is consistent with the reported nasalance patterns of vowels adjacent to pharyngeals, wherein the jaw opens over the duration of the vowel toward to pharyngeal consonant resulting in greater oral airflow relative to nasal airflow at that point.

The total airflow patterns reveal that pharyngeals are produced with greatest overall airflow. This indicates that there is a great degree of airflow diverted through the mouth during pharyngeals. This accounts for greater nasal airflow during vowels adjacent to pharyngeals compared to during pharyngeal consonants—vowels have more oral constriction, more raised jaw height, than pharyngeals, so more airflow is diverted through the nose since the velum is lowered from the pharyngeal.

With respect to coarticulatory overlap of nasality, vowels adjacent to nasals show substantial nasal airflow, which decreases further away from the nasal. Meanwhile, P-adjacent vowels show a steady overall level of nasal airflow, greater than in Oral-adjacent vowels. However, in P-adjacent vowels, the change in proportion of nasal airflow to overall airflow can be attributed to the difference in jaw height between vowels and pharyngeal consonants. Nasalance changes over the course of the vowel duration in pharyngeal contexts. Surprisingly, nasalance is greatest at the point opposite the actual pharyngeal, due to a substantial decrease in oral airflow at that point.

This study found nasal airflow during the production of pharyngeals, indicating that the velum is lowered during pharyngeal articulation in MA. Furthermore, the results indicate that there was less nasality present for pharyngeal consonant production than nasal consonant production. However, unlike nasal stops, pharyngeal consonants are not produced with full closure—they have been described as approximates in MA [8], and this study indeed reported substantial oral airflow for pharyngeals. Thus, it may be that the velum lowering gesture present during the production of pharyngeal consonants is not categorically different in degree than that for nasal consonants, since the lack of complete oral closure could be diverting air from a similarly-sized velopharyngeal port opening resulting in less net nasal airflow. That pharyngeal consonants are produced with greater total airflow supports this explanation. Nonetheless, the amount of nasal airflow present during the
production of pharyngeal consonants is systematically less than that for nasal consonants, but systematically more than for oral consonants, thereby providing a finding of systematically gradient degrees of nasal airflow during consonant production.

4.2. Nasalance and Vowel-Specific Patterns
With respect to overlapping velum lowering from pharyngeal consonants, nasal airflow was found during production of adjacent vowels. Yet, pharyngeal-adjacent vowels displayed a steady, flat pattern of nasal airflow— not the dynamic pattern of nasal airflow on vowels adjacent to nasal consonants. So, is the velum lowered before the onset of the pharyngeal-adjacent vowel and then does not move for the duration of the vowel? No—when we look at the patterns of nasal and oral airflow together the interaction of velum movement and oral constriction that results in this pattern is apparent.

Critically, oral airflow increases over the duration of the pharyngeal-adjacent vowel since there is an opening of the oral cavity towards the pharyngeal: the jaw is lowered during the production of the pharyngeal and coarticulation results in this jaw lowering to overlap on the production of adjacent vowels. The greatest degree of oral constriction on the other side of the pharyngeal consonant has the least amount of oral airflow for the vowel. Yet, there is still some degree of velum lowering in anticipation of (or carryover from) the pharyngeal. This is evident since we have nasal airflow at this position— the change in the amount of oral airflow is telling us that there is a change in overall airflow, but it is being diverted from the oral cavity to the nasal passage. Essentially, there is a trade-off between oral constriction and velum lowering which makes nasal airflow appear steady.

The oral and nasal airflow data together show 1) oral airflow decreases over the vowel away from the pharyngeal; and 2) rather than an unchanging velopharyngeal port opening, the velum is dynamic and changing (i.e., in the process lowering in anticipation of, or carryover from, the pharyngeal articulation) during the articulation of vowels, but since an increasing amount of airflow is being diverted through the velopharyngeal opening as the oral cavity is being obstructed the nasal airflow remains constant. This interpretation would account for the nasalance results, where pharyngeal-adjacent vowels have greatest nasalance on the portion of the vowel opposite the actual pharyngeal segment.

The analysis of the interaction of velum movement and oral constriction also accounts for the vowel-specific patterns we observe in pharyngeal-adjacent vowels. X-ray studies have shown that the velum is intrinsically lower for low vowels than for high vowels due to the physiological connection of the soft palate and the jaw [10]—when the jaw lowers, the velum lowers—so we might predict a low vowel to have greater nasal airflow than the high vowels. However, the finding was a greater proportion of nasal airflow in the high vowels /a/ and /i/, compared to the low vowel /æ/, in pharyngeal contexts. This is consistent with the interpretation that greater degree of oral constriction results in more airflow through the nose when the velum is lowered. Also, the same basic vowel-specific patterns were observed in the context of nasal consonants, further confirming that greater proportion of nasal airflow to overall airflow is relevant to oral constriction required for the vowel.

In this study, the high vowels /i/ and /u/ showed the greatest average amount of nasal airflow, compared to the low vowel /æ/, in contextual nasal and pharyngeal conditions. This is a different pattern reported in [3]—it was found that /a/ had the greatest degree of velopharyngeal port opening in the context of a pharyngeal, followed by /u/, then /i/. Previous results, with respect to variations in the degree of velopharyngeal port opening by vowel height, report that e.g. in English non-high vowels (/æ/) have inherently lower intrinsic velum position than higher vowels (e.g., /i/)—when the jaw is lowered as required by a low vowel, the soft palate is intrinsically lower, too [10]. Along these lines, it was reported that velum lowering varied by vowel type, with /æ/ observed to have the greatest degree of velum lowering, /u/ next greatest, and /i/ the least amount of velum lowering [3].

Yet, in MA, both the nasal airflow and nasalance patterns are greater for the high vowels than the low vowel and we argue that this pattern is language-specific. Similar results for nasalance have been reported in other languages. For example, in French, high vowels have a greater degree of nasalance, greater amount of nasal airflow, and lower amount of oral airflow compared to the non-high vowels [7]. Similar results are reported for Gujarati and Hindi [11]. The trade-off between nasal and oral airflow in high vowels is consistent with the interpretation of nasalance and airflow during vowel production that we provide—the greater degree of constriction in the oral cavity for high vowels results in a diminution of oral airflow and augmentation of nasal airflow.

5. Acknowledgements
Thanks to Rebecca Scarborough, Rachid Ridouane and anonymous reviewers for helpful comments and suggestions.

6. References

INTERSPEECH 2012 2681