The Effect of the Postnasal on the Gestural Overlapping between the Nasal and the Vowel in Saudi Arabic

by

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Abstract

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Thesis directed by Assistant Professor Rebecca A. Scarborough

Production and perception studies were conducted to investigate coarticulatory vowel nasalization in VNC sequences in Saudi Arabic. Previous studies have shown that the degree and pattern of vowel nasalization is influenced by the context in which the nasal and the neighboring vowel occur. The current study aims at investigating the effect of the postnasal consonant in the vowel-nasal-consonant sequence (VNC) on the production and perception of vowel nasalization in Saudi Arabic.

The production experiment provided acoustic analysis of the influence of the postnasal consonant manner on vowel nasality and the temporal interplay between the coarticulatory source (the nasal consonant) and the coarticulatory effect (vowel nasalization). In order to achieve this goal, vowel nasality, and temporal extent of the nasal consonants were measured in three different contexts: the pre-fricative context ($VNC_{\text{“fricative”}}$), pre-stop context ($VNC_{\text{“stop”}}$), and nasal context (VN). The analysis of acoustic and temporal results provided evidence for the cross-context variation in the degree of nasality on vowel and the duration of the nasal consonant, indicating a temporal interplay between the extent of coarticulatory source, nasal consonant, and that of its effect, vowel nasalization. The cross-context variation in the nasality degree on the vowel and the duration of nasal source was attributed to aerodynamic properties of the postnasal consonant, such as the presence of frication noise, which result in differences in the temporal alignment of the nasal gesture with the vowel gestures.

The perception experiment was designed to confirm the findings of the production study. A forced-choice preference task tested listeners’ preference for the large and small size of overlapping between the nasal and the vowel in VNC words in order to find whether listeners would be able to identify the following nasal based on the nasality on vowel. The results revealed a bias for the VNC words with increased vowel nasalization (i.e. large overlapping between N and V). This finding suggests that coarticulatory vowel nasalization can be beneficial for the listeners and facilitate the process of speech perception.

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CHAPTER1

INTRODUCTION

When two neighboring sounds overlap, the result will be a new coarticulatory variant that will introduce a different acoustic realization of the phonological categories. Since coarticulation forms an integral part of normal speech, the novel variant that results from coarticulation is attributed a significant role in the investigation of speech sound systems and communication. Despite the additional complexity that the overlapping segments cause, coarticulation is also considered systematic and predictable. Listeners consider the additional acoustic information introduced by coarticulation as beneficial and informative in making linguistic judgments about what the speaker intends to say (Beddor and Krakow, 1999; Scarborough, 2013; Beddor, 2009). However, investigation of the role of coarticulation in the speaker-listener interaction has shown that the confusability caused by coarticulation may result in differences in the interpretation of coarticulation outcomes and eventually lead to sound change (Ohala, 1981, 1993). Additionally, since coarticulation is cross-linguistically variable and is influenced by several factors, its effects tend to show language-specific patterns (Beddor, Harnsberger and Lindemann, 2002).

In this thesis, I investigate the role of the postnasal consonant on the temporal interaction between the coarticulatory source and its target, and how this interaction contributes to the emergence of contextual differences in coarticulation. The focus is on the coarticulatory vowel nasalization in VNC sequence in Saudi Arabic and the variation in the degree of coarticulation as a result of the temporal interplay between coarticulatory source (i.e. nasal consonant) and its effect (i.e. vowel nasalization). Vowel nasalization is influenced by several factors related to the nasal source and the target vowel, such as the presence of the nasal segment (Krakow and

Beddor, 1990), or the quality and length of the vowel (House and Steven, 1956; Delvaux et al., 2008), but factors associated with the phonetic context, namely the manner of the postnasal consonant, also appear to exert influence on vowel nasalization. In the current paper, it has been found that aerodynamic properties of the postnasal consonants affect the degree of overlapping between the nasal and the vowel in Saudi Arabic. Also, the source of variability between the nasal and the vowel has been shown to originate from differences in the organization of the corresponding gestures. This finding allows us to articulate a model that would account for the pattern of vowel nasalization in Saudi Arabic, based on the temporal relations between the gestures.

1.1 The Current Study:

Among the many factors that seem to affect coarticulatory vowel nasalization, the manner of the postnasal consonant appears to be the least examined and investigated. The current study investigates the role of postnasal consonant in the emergence contextual variation in the degree of nasal-to-vowel coarticulation in Saudi Arabic. It postulates that this pattern of coarticulation stems from differences in the synchronization of the temporally stable nasal gesture with the vowel in different contexts— a process which leads to a series of temporal and systematic interplays between the nasal and the neighboring vowel, and between the nasal and vowel nasalization. The study also assesses the claim that the increase in vowel nasality is a characteristic of the aerodynamic properties of the postnasal fricative.

The study targets vowel nasalization in VNC sequence in Saudi Arabic. Vowel nasality and the temporal interaction between the nasal and the nasal vowel are investigated in three phonetic contexts ($VNC_{\text{“fricative”}}$, $VNC_{\text{“stop”}}$, VN). I predict that vowels will be most nasal in pre-fricative context and least nasal in pre-stop and pre-nasal context. Relying on an intergestural timing account, I also predict that the most nasal vowel will cooccur with short nasal consonant while the least nasal vowel will be followed by a long nasal consonant.

Early onset of velum lowering in a pre-fricative context is attributed to aerodynamic and articulatory factors. The noise associated with postnasal fricatives exerts masking effect on the adjacent nasal (Ohala & Busà 1995). To resist the masking effect and preserve nasality, speakers tend to lower their velum initiating nasalization during the production of the preceding vowel. According to the intergestural timing approach which postulates a nasal gesture of a constant size, early initiation of the velum lowering will lead to short nasal consonant and long vowel nasalization. This account is consistent with the interaction between N and V nasalization in Saudi Arabic VNC sequences differing in the manner of the postnasal C. Nasal gestures in final position have temporal stability while N in pre-fricative or pre-stop contexts shows variation in duration.

Nasality in Saudi Arabic and the question of whether vowel nasality will be influenced by the postnasal consonant have not been addressed in previous studies. In addition to that, the claim that the increase in vowel nasality is a specialization of the articulatory features of the postnasal fricative may have some novelty.

1.2. Gestural Account to Coarticulation:

Based on the current analysis of coarticulation, all languages that have been analyzed exhibit some type of coarticulation, leading it to be considered a universal phenomenon (Farnetani and Racasens, 2010). Although coarticulation is found cross-linguistically, its effect and the degree of overlapping between the coarticulated segments tend to differ among languages (Farnetani and Racasens, 2006), and even among contexts within one language (e.g. Beddor, 2009). This variability in the degree and pattern of coarticulation constitutes a part of what comes to be called the lack of invariance problem in speech acoustic signal. That is, the processes of speech production and perception do not seem to show a one-to-one mapping between the extensively variable acoustic signal and the invariant discrete units (i.e. phonological categories) of speech sounds. While explaining the origin and function of coarticulation has been the aim of coarticulation theorists, the goal of coarticulation models have been to describe the details of the process, including the contextual variation in coarticulation, by trying to associate the phonetic variation resulting due to acoustic and articulatory modifications with the discrete units (Farnetani and Racasens, 2006). In this section, I will discuss some of the gestural models that attempt to approach the contextual variation in coarticulation.

The gestural account to coarticulation can be seen in the coproduction theory that has been outlined in the works of Fowler (1980) and Bell-Berti and Harris (1981). The theory is motivated by the inadequacy of the current account to speech production due to the lack of the connection between the phonological categorization of speech and what the speaker is actually saying. According to Fowler (1980), the account to speech production requires translation process between the cognitive domain that provides the abstract, discrete phonological unit and the physical domain that specifies the variable, context-dependent biomechanical movements that are characterized by the large number of the potential degrees of freedom. An approach to address the problem caused by the separation of the cognitive domain that specifies the abstract phonological unit from the physical domain that defines the temporal and spatial structure and the mechanical consequence of the system is to view the phonological unit as an articulatory unit or gesture. Instead of considering the temporal and spatial configuration as characterization of the physical domain and consequently separating the temporal structure from the phonological unit, the articulatory unit or the gestures in the coproduction theory are considered to have their own intrinsic temporal and spatial structure. Therefore, when two neighboring gestures are coarticulated, one gesture will not be altered by the other, but the two will be coproduced allowing their temporal and spatial extents to overlap.

The coproduction theory is similar to the articulatory phonology proposed by Browman and Goldstein (1992, 1995). In their approach, the separation between the cognitive and the physical domain in speech is accounted for by viewing speech as a system with two dimensions. Speech is characterized by 1) the low-dimensional (macroscopic) phonological form and 2) the large number of the (microscopic) degrees of freedom in the articulation of this form in the high-dimensional description. Articulatory phonology views the units of speech production as series of actions and therefore these units are dynamic and not static. Thus, like the coproduction theory, the basic phonological unit is the articulatory gesture which is defined as a dynamical system with a set of parameter values. Defining the gestures dynamically can provide a principled link between macroscopic and microscopic properties of speech because the dynamical parameters of the gesture defines the macroscopic phonological unit, and the system specifies the intrinsic time-varying microscopic pattern of the gesture. Coarticulation, in articulatory phonology, is seen as the result of the overlapping of the adjacent gestures. The degree of the overlapping is determined by the phasing of the virtual cycles of the articulations of the two gestures. The movement onset of the gesture is at the phase 0 degree, while the achievement of the constriction of the gesture occurs at phase 240 degree. So two gestures will be phased when their movement onsets are synchronized, that is, 0 degree is phased to 0 degree.

Thus coarticulation can be viewed as timing relations between the overlapping gestures (e.g. Cho, 1998; Yun, 2007; Beddor, 2009; Delvaux et al., 2012). This approach is firmly grounded in the view that in coarticulation like anticipatory vowel nasalization the size of the gesture (e.g. velum lowering) will be relatively stable but the timing of the gesture with the oral articulators will be different across contexts (Beddor, 2009; Delvaux et al., 2012). So, the degree of the overlapping between the coarticulatory source (N) and its target (V) is determined in systematic and predictable ways by adjusting the temporal alignment of the nasal gesture (i.e. velum lowering) with the oral gestures of the vowel (i.e. tongue position and the glottis). Thus, coarticulatory variation is explained in terms of the temporal relations between the gestures or the intergestural timing relations, in particular between the coarticulatory source and its effect. For example, Beddor (2009) found that the variation in the degree of vowel nasality between the sequence $VNC_{voiceless}$ and the sequence VNC_{voiced} stemmed from the temporal alignment of the nasal gesture with gestures of the vowel. Delvaux et al. (2012) investigated the pattern of vowel nasalization in two dialects of French and found that the variation is attributed to the synchronization of the nasal gesture with the gestures of the vowel and the following postnasal consonant.

1.3. Target language:

The data used in the experiment parts of this study is taken from Saudi Arabic. The term Saudi Arabic refers to a vast array of regiolects spoken in several parts Saudi Arabia. These regiolects include Hijazi Arabic, Najdi Arabic, Southern dialect of Tihama, dialect of Ruwaili and Hail, Eastern dialect, and Bedouin Arabic. However, it has been found that based on the similarity in their phonological and morphological properties, this wide range of regiolects can be divided into two major group dialects: the Najdi and Eastern region dialect, and the Hijazi and

Tihami dialect (Prochazka, 1988). To limit cross-dialect variation, the current investigation was confined to the Najdi and Eastern region dialect.

The Najdi and Eastern region dialect is spoken in a large geographical part of central and eastern Saudi Arabia. It is the major dialect of the country capital city Riyadh, and the most widely spoken in the country. Due to the large political and socioeconomic status that the capital city has, Najdi and Eastern dialect is heavily influenced by the dialect of Riyadh.

Like most dialects of Saudi Arabia, the consonantal inventory of the Najdi and eastern region dialect is characterized by the retention of most of the consonants found in Classical Arabic. The Najdi and Eastern Arabic system differs from Classical Arabic in three aspects: the merger of the pharyngealized voiced stop /dˤ/ and the dental fricative /ðˤ/ into the pharyngealized dental fricative /ðˤ/; the absence of the glottal stop *hamza* /ʔ/ in non-initial position; and the introduction of the two allophones [ts] and [dz] which alternate with the phonemes /k/ and /g/ (Ingham, 2012). With these exceptions, the consonantal system of Najdi and Eastern Saudi Arabic is similar to that of Classical Arabic. **Table 1-1** illustrates the consonantal inventory of Najdi Saudi Arabic.

	Labial	Labio-dental	Dental		alveolar		Platal	Velar	Uvular	Pharyngeal	Glottal
			Plain	Emphatic	plain	Emphatic					
Plosive	b				t d	tˤ		k g	q		ʔ
Nasal	m				n						
Trill					r						
Fricative		f	θ ð	ðˤ	s z	sˤ	ʃ		χ ʁ	ħ ʕ	
Affricate					ts dz		ɟ				
Approximate	w						j				
Lateral					l						

Table 1-1: Summary of the consonantal inventory of Najdi and Eastern dialect of Saudi Arabic

Najdi and Eastern Saudi Arabic has a small vowel inventory. The vowel system includes three vowel qualities: /i/, /u/ and /a/.

CHAPTER2

THE ACOUSTICS OF VOWEL NASALIZATION IN VNC SEQUENCES

2.1. Introduction:

The new coarticulatory variant introduced by the overlapping acoustic signals shows a very systematic and context-dependent behavior. However, when the overlapping of the acoustic signals does occur in the language, the patterns of coarticulation tend to be language-specific (Beddor, Harnsberger, and Lindemann, 2002; Keating, 1990), and the degree of the overlapping would vary widely in time and space depending on several factors (Cohn, 1990; Delvaux et al., 2008; Delvaux et al., 2012; Beddor, 2009, 2012; Busà, 2007). This type of coarticulatory variation is attributed to the interaction between the coarticulatory source and the target segment. Investigations in the coarticulatory variation show that speakers produce roughly constant-sized gestures but differ in the alignment and organization of these gestures, which results in a temporal and spatial interplay between the coarticulatory source and its effect (Beddor, 2009, 2012; Busà, 2007; Delvaux, 2012). This chapter investigates the acoustic properties of vowel nasality in Saudi Arabic and provides in-depth investigation of the coarticulatory patterns of anticipatory vowel nasalization in VNC sequence.

One of the objectives of this paper is to provide a detailed gestural account to the variation in the coarticulatory vowel nasalization in Saudi Arabic. The study targets anticipatory vowel nasalization in three phonetic contexts: pre-fricative, pre-stop, and pre-nasal position, where the trade-off between the coarticulatory source (N) and its effect (V) will vary depending on the context they occur in. Several studies have found that systematic variation in the temporal and spatial extent of the coarticulatory vowel nasalization will depend on the phonetic context in which the nasal consonant occurs (Cohn, 1990; Busà, 2007; Delvaux et al., 2008; Delvaux, 2012; Beddor, 2009, 2012), the quality and length of the vowel (Delvaux et al., 2008) and prosodic context (Cohn, 1990; Krakow 1993). Thus, investigation of the effect of postnasal manner on the interaction between the temporal extent of the coarticulatory source (N) and that of the coarticulatory vowel nasalization in Saudi Arabic will shed further light on the factors that trigger the pattern of coarticulatory nasalization.

There are two goals for this chapter: first, confirm the findings of the previous studies by Busà (2007), Beddor (2009, 2012), and Delvaux (2012) that coarticulatory variation is the outcome of the variability in the timing of constantly-sized gestures, which results in a temporal and spatial interplay between the coarticulatory source and its effect; second, report the study findings that the patterns of anticipatory vowel nasalization in Saudi Arabic is sensitive to the manner of the post-nasal consonant.

2.1.1. Research Hypotheses:

This chapter addresses two critical questions: first, whether the patterns of coarticulation will show temporal and spatial interplay between the coarticulatory source and that of its influence; second, whether the phonetic context in which the nasal consonant source and the vowel target occur will shape the coarticulatory patterns of vowel nasalization in Saudi Arabic. In order to address these questions, we formulated and tested the following hypotheses:

Hypothesis 1a:

In VNC sequences, there is greater nasality on vowels in a pre-fricative context than vowels in pre-stop.

Hypothesis 1b:

There is less nasality on vowels that are followed by nasal than vowels that are followed by a cluster of nasal plus consonant.

The previous hypotheses predict that the manner of the post-nasal consonant will affect the degree of nasality on vowels. Thus, the vowels in pre-fricative (VNF) context will be more nasalized than the vowels preceding nasal-stop sequences (VNT) or nasal (VN). The prediction that the fricative context will trigger greater nasality on the vowel is related to the acoustic properties of frication in overlapping speech signals. The noise introduced by fricative occurring in consonantal cluster exerts masking effect on the adjacent sounds (Ohala and Busà, 1995). In the case of vowel nasalization in VNC sequence, the masking effect of the fricative on the adjacent nasal gesture will lead to the early initiation of the velum lowering during the production of the nearby vowel to preserve the nasality information. This masking effect will not be available when the vowel is followed by a nasal, or is in a pre-stop context, which will decrease the degree of the overlapping between the gestures. To determine whether the increase in nasality degree is a specialization of the noise associated with the fricative consonants, the hypotheses also tested the pattern of the vowel nasality in another postnasal context, specifically the final stop. The hypotheses predict that the vowel nasality will increase when the vowel and the nasal gesture is followed by a postnasal stop.

Although these hypotheses test the pattern of coarticulatory vowel nasalization, they do not test the prediction about the interplay between the temporal and spatial extent of the coarticulatory source (N) and that of its effect (V). Thus, the following hypotheses are formulated to address this question:

Hypothesis 2a:

The nasal consonant duration in a pre-fricative context is shorter than that in pre-stop.

Hypothesis 2b:

The nasal consonant duration in pre-consonantal context is shorter than that in final position.

The prediction illustrated in the hypotheses 2a and 2b suggests that the degree of vowel nasalization will be inversely related to the temporal extent of the nasal consonant. Therefore, the shortest nasal consonant duration will co-occur with the most nasalized vowel, and the longest with least nasalized vowel.

2.2. Method:

2.2.1. Speakers:

Six male subjects participated in this study. They were in their mid twenties and early thirties. All participants were native speakers of the central Saudi Arabic dialects that are closely related and have identical phonological inventory. They were also members of the University of Colorado-Boulder community. The subjects were capable of producing all the Saudi Arabic speech sounds comfortably, and none of them reported speech- or hearing-related problems.

2.2.2. Procedure:

All recording were made in the Phonetics Lab at the University of Colorado-Boulder. The subjects were seated in a sound-attenuating booth and were asked to speak to a special headmounted microphone. The recorded words were presented to the subject as Microsoft PowerPoint (Microsoft Corp., 1987) slides using a monitor placed in the quiet room and connected to a Macintosh computer located outside. Each slide displayed only one sentence. Subject were instructed to read the sentence that appeared in the monitor in a normal conversational pace and move on to the next slide by pressing a key on the keyboard. Using an Apple Macintosh desktop computer and the audio editing and recording software Audacity (Audacity Team, 2014), each subject was digitally recorded at a 44KHz sampling rate.

2.2.3. Stimuli:

The set of stimuli consists of real Saudi Arabic words that contain a sequence of VNC or VN in which the post-nasal consonant in VNC sequences belonged either to the class of fricative ([f], [s], [z], [ʃ], [sˤ]; 17 words) or stop ([b], [t], [d], [ɟ], [tˤ]; 17 words), and the nasal in both sequences was the alveolar ([n]; 16 words). The vowels in these sequences were [a], [i], and [u]. A list of the words is provided in Appendix 1.

The words were balanced cross consonant type, vowel type, and syllable type. Minimal pairs across VNF and VNT words were used when they are available, and the place and manner of articulation of the non-target consonant that precedes the sequence of the vowel and the nasal in the test words was matched as much as possible. Checking the frequency of the test words and matching them for lexical frequency was not possible due to the lack of the corpus which would reveal information about the frequency of these words. However, the words were familiar to the subjects who expressed no complaints in regards to them.

The words were represented in the carrier phrases "gul _____ bisurʔah" ("say ___ quickly"). Subjects said each word twice.

2.2.4. Acoustic analysis:

2.2.4.1. Preparation:

Both N and V in all the words are annotated and segmented using Text-Gridding feature in Praat (Boersma and Weenink 1992). Annotation was performed manually by the author. The target vowel and nasal consonant were determined by investigating their spectrograms and waveform representations. The tokens are saved in a Text-Grid file to be used by the Praat auto-measure script.

Locating the boundary between the nasal and the vowel varies across in the three-context types. While the boundary between the nasal and the vowel can be immediately identified from the spectrogram and waveform representation in $VNC_{\text{"stop"}}$ and VN tokens, it is more difficult to identify the boundary between the nasal and the vowel in $VNC_{\text{"fricative"}}$, suggesting greater gestural overlapping between the nasal and the vowel. The nasal stop [n] is produced by a resonant tube formed by the nose and the pharynx, and a side tube open at one end formed by the mouth cavity. Therefore, the nasal [n] is characterized by the nasal resonance (or the murmur) at 200-400 Hz and the antiresonances (or the anti-formants) introduced by the side mouth cavity. Based on the calculation of the frequencies of the mouth cavity, the nasal [n] is expected to have an antiresonance frequency at about 1600 Hz and another at about 4800 Hz (Johnson, 2012). The antiresonance can be seen as white band in the spectrogram, but if the antiresonance and the formant occur at the same frequency, the antiresonance results in the weakening of that formant peak. So the strategies I used in order to identify the nasal segment are the presence of the nasal formant (or the nasal bar) at the 200-400 Hz, and the presence of the anti-formants.

2.2.4.2. Nasality Measurements:

Vowel nasalization occurs when the velum is sufficiently lowered to allow acoustic coupling between the nasal passage and the main vocal tract. As a result of this acoustic coupling, the production of nasalized vowels involves simultaneous use of two resonant systems, one determined by the pharynx cavity plus the nasal cavity and the other by the pharynx cavity plus the oral cavity. In the acoustic theory of speech production, each of these two systems will have its own resonant frequencies which will appear as formants, spectral peaks in the spectrum of a nasalized vowel (Fant 1960, Maeda 1993). This will lead the nasal vowels to have more spectral prominences than the non-nasal vowels.

Although the acoustic coupling between the pharyngo-nasal tract and the pharyngo-oral tract results in a complicated spectral structure of the nasal vowels, the location of the nasal spectral peaks introduced by the coupling between the nasal cavity with main vocal tract can be estimated and predicted when we know their frequency range (Chen, 1997). In non-nasal vowels, the formants, the spectral peaks, in the vowel spectrum are determined by the position of the tongue and the shape of the lips in the oral cavity. Unlike the oral cavity which can have different configurations, the nasal cavity does not seem to have different configuration since speakers have a limited control over the size and shape of their nasal cavity, and the only articulator that speakers can control during the production of nasalized vowels is the velopharyngeal port opening area. Thus, since Speaker cannot change the configuration of the nasal cavity, the location of the nasal formants, i.e. the nasal spectral peaks in the spectrum of the nasal vowel, can be estimated by calculating the transfer function of the velopharyngeal opening port area (Maeda, 1993) and the frequencies that resonate in the nasal cavity (Chen, 1997). Based on various studies of vowel nasalization, the first nasal formant (Fn1) is estimated to fall between

250 Hz and 400 Hz, while the second nasal formant (Fn2) is expected to be around 1000 Hz (Hattori, Yamamato, and Fujimura, 1958; House and Stevens, 1956; Maeda, 1993; Chen, 1997).

Calculation of the degree of vowel nasalization can be achieved by the acoustic investigation of the influence of the extra nasal peaks, Fn1 and Fn2, introduced by the coupling of the nasal tract and oral tract, on the overall spectrum of the nasal vowel. Chen (1997) finds that in nasal vowels there is a complex interplay between the amplitude of the nasal formants and that of the oral formants. In that interplay, it is demonstrated that the nasal formant peaks will be amplified as the degree of nasalization increases in the acoustic signal of the vowel. The amplification of the nasal formants will be accompanied by a damping of the amplitude of the oral formants appearing in the spectrum of the nasal vowel. Due to this inverse relationship between the nasal formant and oral formant amplitudes, Chen (1997) suggests that the degree of vowel nasalization can be quantified by calculating the relative difference in amplitude between the nasal formants and the oral formants of the nasal vowels. In this study, the relative difference in amplitude of the nasal and oral formants is obtained by subtracting the amplitude of the first nasal formant (P0) from the amplitude of first oral formant, referred to as (A1), which will give us the measure (A1-P0) that decreases as nasality increases.

All the nasality measurements were automatically measured in Praat (Boersma and Weenink 1992) by using the Automated Nasality Measurement Script Package[1] developed by the Phonetics Lab in University of Colorado-Boulder. For each time-point, the script extracts a complete cycle and repeats it until the cycle reaches 50 ms. From that newly created chunk, the script gets the frequencies of the pitch (f0) and the first formant (F1) by using the Linear

[1] The script was developed by Will Styler, based on an earlier version generated by Rebecca Scarborough.

Predictive Coding (LPC) envelope. The script then uses the estimated (f0) and (F1) frequencies and LPC to determine the frequencies and amplitudes of the first harmonic (H1), the second harmonic (H2) and the highest peak in the first formant region (A1). The A1-P0 value is obtained by subtracting A1 from the higher peak of the two first harmonic. The data along with the A1-P0 value is stored in an output file for further analysis.

For the purpose of this study, multiple measurements of vowel nasalization were taken for every vowel. Since we want to know the relationship between nasality degree and the phonetic context, vowels were measured at three evenly spaced time-points: beginning, mid, and end. As we measured all the nasality tokens, tokens in which A1-P0 equals 0 were deleted since this indicates that the same spectral peak was selected as a nasal formant and first oral formant.

2.2.4.3. Temporal Measures:

Measures for the duration of the target vowels and nasal consonants were also obtained by the use of same script based on hand-generated text grids. The data are stored in an output file for the analysis.

2.3. Results:

2.3.1. Vowel Nasality:

2.3.1.1. Variation in Vowel Nasality between VN and VNC Sequences:

The calculation of the mean of the overall A1-P0 values (all three points) in the three contexts indicates that lowest A1-P0 value is to be found in the fricative context (means= -0.79 dB; SD=5.08 dB). The average A1-P0 value then increases as we go from stop context to the nasal context (stop context: means=0.90 dB; SD=4.05 dB. Nasal context (VN): means=1.42 dB; SD=3.92 dB).

The average of the A1-P0 values is also calculated for each time point to get an accurate evaluation of the coarticulatory direction of nasalization. The result of the average A1-P0 values for all the time point in the three contexts (VNC$_{\text{“fricative”}}$, VNC$_{\text{“stop”}}$, VN) is illustrated in **Figure 2-1**.

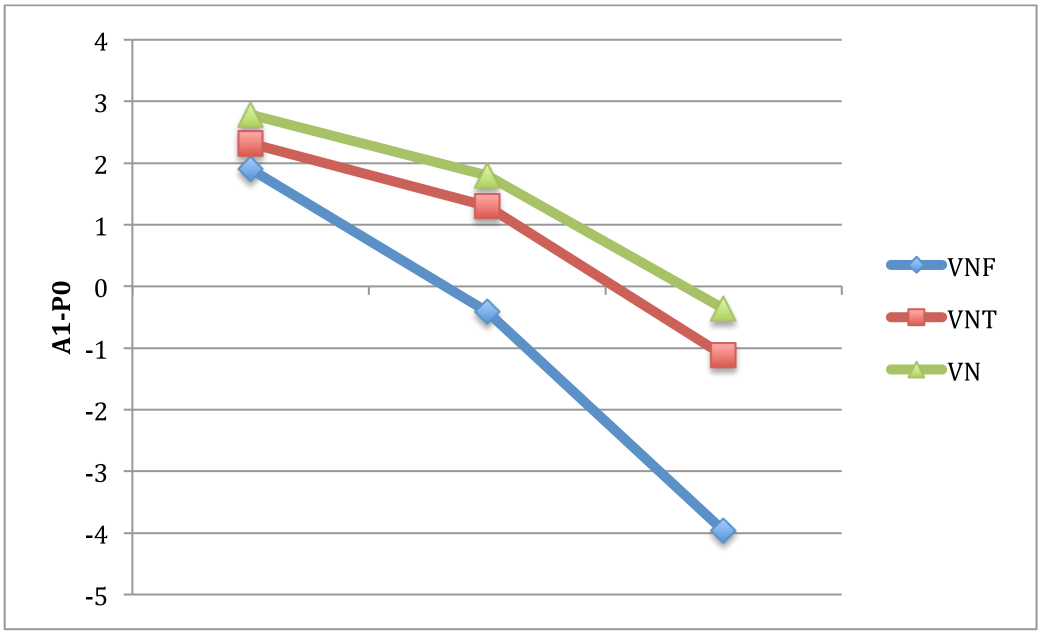

Figure2-1: Average A1-P0 values for vowels in pre-fricative context, pre-stop context, and pre-nasal; measurement taken at three time points.

The average A1-P0 value was highest in the first time point in all of the three contexts (fricative: means=1.90 dB, SD=4.61 dB; stop: means=2.31 dB, SD=3.74; nasal: means=2.78 dB, SD=3.94). Further, the average A1-P0 values in all contexts decreases as we go right to the mid point (fricative: means= -0.40 dB; stop: means=1.29 dB; nasal: means=1.80 dB) until the average values reach their lowest at the last point (fricative: -3.96 dB; stop: -1.12 dB; nasal: -0.36 dB). Although standard deviation for the calculated mean in the three points is still high, the increased deviation is consistent and constant in all time points of the different contexts.

A linear mixed-effects model was used to analyze the data from A1-P0 values of the vowels in the three contexts. The analysis was performed by R (R Core Team, 2014) using *lmer()* function in the *lme4* package designed for the program. In this model, nasality degree of the vowel was modeled as a function of context, vowel and time point, so A1-P0 values were used as our dependent variable while phonetic contexts ($VNC_{“fricative”}$, $VNC_{“stop”}$, VN), vowel type ([a], [i], [u]), and time points (start, mid, and end) were the explanatory variables or fixed effects. To control the effect of subjects' individual differences and word-specific variations on the results, both of subjects and words were listed as random intercepts in the model. Adding subjects and words as random effect will allow the model to analyze A1-P0 values and minimize any interference of word or subject idiosyncratic variations by assigning different nasality level for each speaker and each word. **Table 2-1** provides the fixed-effects predictors obtained from the linear mixed-effects model we fit on the nasality degree data.

predictor	β	Std. Error	*t* value	P-value
(Intercept)	3.06554	1.16113	2.640	0.02998
Contextfricative	0.29479	0.72907	0.404	0.68753
Contextstop	0.33839	0.73135	0.463	0.64539
Voweli	-1.05940	0.73290	-1.445	0.15349
Vowelu	0.01113	0.72972	0.015	0.98788
Timepointend	-3.22549	0.38777	-8.318	2.22e-16
Timepointmid	-0.79639	0.38389	-2.075	0.03818
Contextfricative:Timepointend	-2.81043	0.43134	-6.516	9.55e-11
Contextstop:Timepointend	-0.49070	0.44630	-1.099	0.27172

Contextfricative:Timepointmid	-1.28935	0.42648	-3.023	0.00254
Contextstop:Timepointmid	-0.13906	0.43501	-0.320	0.74925
Contextfricative:Voweli	-2.49252	0.97434	-2.558	0.01393
Contextstop:Voweli	-1.15269	1.00275	-1.150	0.25627
Contextfricative:Vowelu	-0.99426	0.97144	-1.023	0.31176
Contextstop:Vowelu	-1.61129	0.97346	-1.655	0.10505
Voweli:Timepointend	0.37711	0.44893	0.840	0.40103
Vowelu:Timepointend	-0.38263	0.42269	-0.905	0.36548
Voweli:Timepointmid	-0.46933	0.44116	-1.064	0.28755
Vowelu:Timepointmid	-0.61818	0.41531	-1.488	0.13682

Table2-1: Summary of coefficients of the fixed effects predictors from the linear mixed-effects model used to analyze vowel nasality in VNC and VN sequences.

The linear mixed-effect model shows that at the start point (beginning) of the vowel neither context nor vowel type significantly affects the A1-P0 values in vowels followed by nasal consonants. It is worth mentioning that the high vowel [i] noticeably dropped the value of A1-P0 at an early stage of the vowel duration, yet the effect of the vowel [i] on the anticipatory nasality was not significant. After that, the result starts to make sense and we can see some statistical significance as we concentrate on the effect of time on A1-P0 values. Specifically, the A1-P0 value at the mid point in the vowels in pre-nasal context has a negative coefficient (-0.79639) and a fairly high t-value (t=-2.075, p=0.03818). There is also another more negative coefficient (-3.22549) associated with the A1-P0 values for the vowel endpoint in the pre-nasal context, and this sharp drop in the A1-P0 at the vowel end is accompanied by a large t-value (t=-8.318, p=2.22e-16). The negative coefficients associated with the mid and end points in the vowels indicates that the A1-P0 value decreases –indicating increase in nasality degree– in the vowel in the pre-nasal context as the vowel becomes closer to the following nasal consonant. In addition to the significant effect of time on A1-P0 values, the model demonstrates that there is some significant interaction between context type and time. In this interaction, the fricative context strongly affects the A1-P0 values at the vowel mid and end point. Consequently, The vowel mid point in pre-fricative context has a negative coefficient (-1.28935) accompanied with a large t-value (*t*=-3.023, *p*=0.00254). Then, the vowel at the last point has another negative coefficient (-2.81043) with a larger t-value (*t*=-6.516, *p*=9.55e-11). These negative coefficients indicate that the vowel A1-P0 values sharply decreases (=nasality increases) at the mid- and endpoint as the vowel becomes closer to the nasality source. There is also another significant interaction associated with context and vowel type. The high vowel [i] shows a negative coefficient (-2.49252) that has a moderate *t*-value (*t*=-2.558, *p*=0.01393). The indication of this negative coefficient of the vowel [i] in pre-fricative context is that [i] increases the degree of nasality in pre-fricative context. Except for the high vowel [i] in the fricative context, none of the other interactions between vowels and context types shows any statistical significance.

The analysis shows that there is no significant effect of the adjacent nasal consonant on the vowel A1-P0 values at the start point, but in the sequences $VNC_{\text{“fricative”}}$ and VN the effect of the anticipatory vowel nasality becomes significant beginning from the vowel mid- and endpoint. This suggests that for vowels occurring in pre-nasal (=VN) and pre-fricative contexts nasality degree significantly increases over time as the vowel becomes closer to the nasality source. The model also illustrates that the vowel in pre-fricative context is more nasal than vowel adjacent to a nasal in VN sequences. This suggests that the postnasal fricative in VNC sequences significantly increases the degree of nasality in vowel at the mid and end point.

2.3.1.2. Variation in Nasality Associated with VNF and VNT:

While the previous statistical analysis predicts the significant effect of the postnasal fricative in VNC sequence over the A1-P0 value, it does not demonstrate whether this effect will remain significant when the vowel A1-P0 in $VNC_{\text{“fricative”}}$ is compared to another VNC sequence but with a different postnasal consonant. In other words, the current model shows that the postnasal fricative affects nasality degree but it does not show the difference between the effect of the postnasal fricative context and that of the postnasal stop context on the degree of nasality. As stated in §5.1.1, the average of the overall A1-P0 values for vowels in the pre-fricative context are lower than the average A1-P0 for vowels in the pre-stop context. Therefore, statistical analysis is needed to determine whether the variation in the A1-P0 value between the two contexts, fricative and stop, is significant.

Figure 2-1 illustrates that the average A1-P0 is relatively stable at the beginning of the vowel for both of the stop and fricative contexts. The A1-P0 for vowels in both postnasal contexts gradually decreases, as the vowel gets closer to the nasal consonant. Further, the difference in A1-P0 between the stop and fricative becomes salient as we reach the vowel midpoint where the A1-P0 values are noticeably lower for the fricative context. The lowest A1-P0 values are to be noticed near the end of the vowel in the pre-fricative context, suggesting greater nasality at the point adjacent to the nasal consonant.

To determine the effect of the postnasal fricative relative to the other postnasal consonant, another linear mixed-effects model was used. In this model, the dependent variable is the A1-P0 values, and the fixed-effects are ‘context type’ (with two categories: $VNC_{\text{“fricative”}}$, $VNC_{\text{“stop”}}$), ‘vowel type’ (with three categories: [a], [i], and [u]) and ‘time points’ (with three categories: ‘start’, ‘mid’, and ‘end’). By fitting this model, we can see whether the effect of the fricative context is statistically significant relative to the other postnasal context, namely the stop context. **Table 2-2** provides the fixed-effects predictors from the second linear mixed-effects model we fitted on the anticipatory nasality data with postnasal consonants.

predictor	β	Std. Error	*t* value	P-value
(Intercept)	3.42123	1.17054	2.923	0.0175
Contextfricative	-0.03691	0.80072	-0.046	0.9635
Voweli	-2.27590	0.86763	-2.623	0.0123
Vowelu	-1.59854	0.81774	-1.955	0.0579
Timepointend	-3.73585	0.44087	-8.474	< 2e-16
Timepointmid	-0.96502	0.43280	-2.230	0.0260
Contextfricative:Timepointend	-2.34174	0.45884	-5.104	3.92e-07
Contextfricative:Timepointmid	-1.15037	0.44859	-2.564	0.0105
Contextfricative:Voweli	-1.34904	1.10950	-1.216	0.2337
Contextfricative:Vowelu	0.61496	1.07371	0.573	0.5713
Voweli:Timepointend	0.63483	0.57459	1.105	0.2695
Vowelu:Timepointend	-0.47992	0.53807	-0.892	0.3726
Voweli:Timepointmid	-0.47874	0.56520	-0.847	0.3972
Vowelu:Timepointmid	-0.52272	0.52633	-0.993	0.3209

Table 2-2: Summary of coefficients of the fixed effects predictors from the linear mixed-effects model used to analyze vowel nasality in VNF and VNT sequences.

The model shows some significant context-time interaction in which the fricative context significantly affects the A1-P0 values at the vowel mid- and endpoint. Thus, the A1-P0 for the vowel midpoint in pre-fricative context has a negative coefficient (-1.15037) accompanied with a high t-value (t=2.564, p=0.0105). Then, the vowel at the endpoint has another negative coefficient (-2.34174) with a larger t-value (t=-5.104, p=3.92e-07). The negative coefficients for the vowel A1-P0 in pre-fricative context indicate that the A1-P0 for vowels in pre-fricative context relative to the vowel A1-P0 in pre-stop context significantly decreases over time as the vowel becomes closer to the nasal consonant. This suggests that vowel nasality in pre-fricative context is significantly greater than the nasality on vowel in pre-stop context.

The model suggests that when the A1-P0 values for vowels in pre-stop context are compared with the A1-P0 values for vowels in pre-fricative context, the A1-P0 in pre-stop significantly increases over time as the vowel comes closer to the nasality source. This increase in A1-P0 values indicates that the nasality degree for vowels in pre-fricative context is greater than the nasality degree for vowels in pre-stop context.

2.3.2. Nasal Duration:

The duration of the nasal consonant source was measured for all tokens in three phonetic contexts. **Figure 2-2** show the average duration of the nasal consonant in the three contexts.

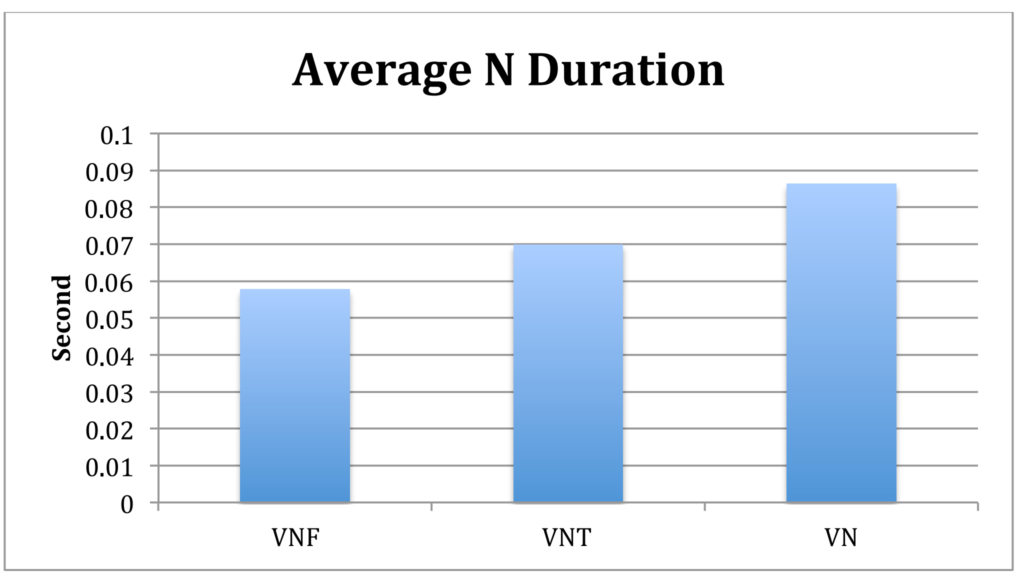

Figure 2-2: the average nasal consonant duration in the three contexts. The duration is shown in seconds.

The shortest nasal duration is found in the pre-fricative context. The average nasal duration then increases in the pre-stop context and increases even more in the VN context. Linear mixed-effects model was run on the nasal duration data to analyze the effect of the context on the duration of the nasal consonant. In this model, the duration of the nasal consonant was used as the dependent variable while the context was the independent variable. Speakers and words were included as random effects to make sure that speakers' idiosyncrasies and word-specific variation would not interfere with the analysis. The fixed-effects predictors of the model we ran on the duration data is illustrated in **Table 2-3**.

predictor	β	Std. Error	*t* value	P-value
(Intercept)	0.113358	0.005014	22.61	5.03e-08
Contextfricative	-0.080989	0.003172	-25.53	< 2e-16
Contextstop	-0.037744	0.003229	-11.69	4.44e-16

Table 2-3: Summary of coefficients of the fixed effects predictors from the linear mixed-effects model used to N duration data

Table 2-3 summarizes the result from the linear mixed effect model we fitted on the nasal consonant duration data. The model shows that the nasal consonant in pre-fricative context has a very low coefficient (-0.080989) with a very large *t*-value (t=-25.53, p=< 2e-16), indicating shorter duration of the nasal consonant. There is also another negative coefficient (-0.037744) with a large *t*-value (t=-11.69, p=4.44e-16) associated with the nasal consonant in pre-stop context. The negative values in the analysis indicate decrease in the duration of the nasal consonant.

The analysis of the nasal duration data indicates that the phonetic context significantly affects the duration of the nasal consonant. The model suggests that nasal consonant is longest when it occurs in VN context. The shortest nasal consonant is found in the fricative context. The duration of the nasal then becomes longer in prestop context.

2.3.3. Vowel Duration:

The duration of the vowel was measured for all the tokens in the three contexts. **Figure 1-3** shows that the average duration of the vowel is different for the three contexts.

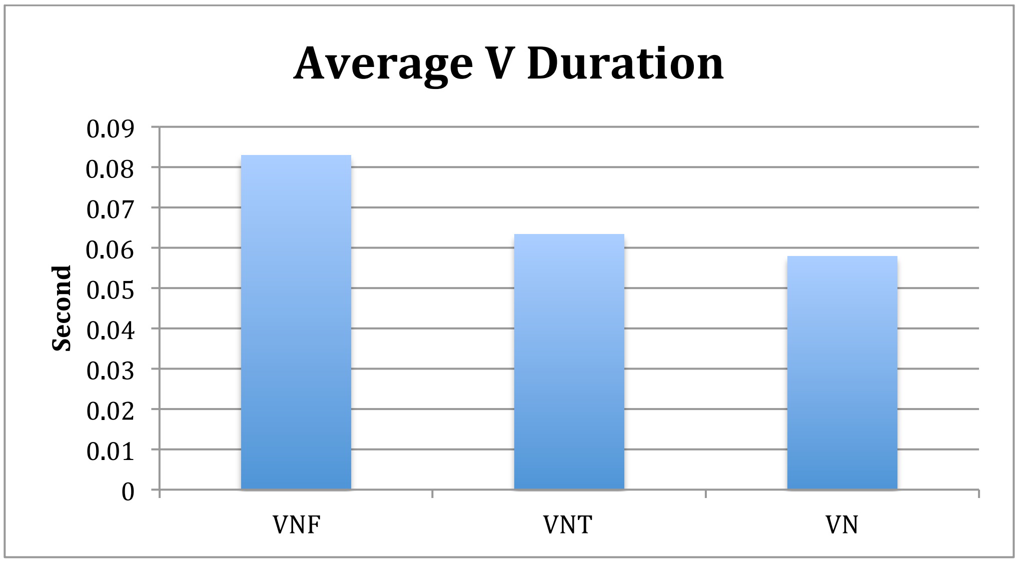

Figure 2-3: the average duration of the vowel in sec.

The shortest duration of the vowel cooccurs with the nasal context, and then the average duration of the vowel increases from stop context to the fricative context. The data from the vowel duration were analyzed using a linear mixed-effects model in which the vowel duration was the dependent variable, and the context was listed as the independent variable. To minimize the effect of subjects' or words' idiosyncratic variation, speakers and words were added as random effects. **Table 2-4** provides a summary of the predictors of the fixed-effects in the linear mixed-effects model used on the vowel duration data.

predictor	β	Std. Error	*t* value	P-value

(Intercept)	0.057877	0.004150	13.946	3.74e-08
Contextfricative	0.025152	0.003400	7.397	1.13e-09
Contextstop	0.005323	0.003418	1.557	0.126

Table 2-4: the predictors of the fixed-effects in the linear mixed-effects model used on the vowel duration data

Table 2-4 illustrates the predictors of the fixed-effects in the linear mixed-effects model used on the vowel duration data. The analysis indicates that the vowel duration is significantly affected by the post-nasal fricative. The linear mixed effects model demonstrates that the vowel duration significantly increases in pre-fricative context, as the fricative context in the model is associated with a positive high coefficient (0.025152) and a large *t*-value (t=7.397, p=1.13e-09). There is a very slight increase in the duration of the pre-stop vowel, but that increase is insignificant (t=1.557, p=0.126).

2.4. Discussion:

2.4.1. Summary:

The result confirms the prediction proposed in the first hypothesis that the degree of vowel nasality varies depending on the phonetic context in which the nasal consonant occurs. As predicted, the vowels in pre-fricative context have greater nasality than the vowels in the pre-stop context. Also, the result shows that the prediction that the vowel preceding a cluster of nasal and fricative is more nasalized than the vowel preceding a final nasal was true. However, unlike what we would expect for the vowels in $VNC_{\text{“stop”}}$, the coarticulatory vowel nasalization does not increase when the nasal occurs in pre-stop context since there was no significant difference in vowel nasality between the vowels in pre-stop context and the vowels before nasal in VN sequences. This suggests that the increase in vowel nasality is a characteristic of the noise associated with the fricative consonants.

Although nasality varies based on different contexts in which the nasal consonant occurs, the result indicates that the coarticulatory pattern of vowel anticipatory nasalization is predictable. Thus, The vowel is most nasal at the point adjacent to the nasal consonant, i.e. the coarticulatory source. However, while the pattern of vowel anticipatory nasality is intuitively going from least nasal to most nasal as the vowel becomes close to the nasality source, it is illustrated that the difference in nasality on vowel at start point is not significant between the vowels in the three contexts. This is not surprising given that the set of stimuli are less than ideal and there is the coarticulatory effect of the consonant preceding the vowel, plus the vowel at the start point is far from the nasal and the effect of nasality is not evident at the start point.

The investigation of the anticipatory vowel nasalization in Saudi Arabic also reveals that the phonetic context exerts significant influence on the duration of the nasal consonant. Throughout the result, it is illustrated that the nasal consonant becomes significantly shorter when it occurs in a pre-consonantal position. There is also difference in the length of the nasal segment between the nasal in a pre-fricative context and the nasal preceding a stop. The duration of the nasal consonant in a pre-fricative context was shorter than the nasal consonant that occurs before a stop. In addition to the change in the duration of the nasal consonant, the investigation shows change in the duration of the vowel. The vowel is longest in the pre-fricative context, while there is no significance difference in the duration of the vowel in the pre-stop and pre-nasal contexts. It's not clear why the duration of the vowel would be longer in the pre-fricative context. But I think the reason is related to the issue of the boundary between the vowel and nasal being harder to find in the fricative context.

The result also supports the predictions related to the trade-off relationship in the anticipatory vowel nasalization between the coarticulatory source, namely the nasal consonant, and the coarticulatory effect, i.e. vowel nasalization. As described previously, the duration of the nasal consonant was inversely related to the degree of nasality on the adjacent vowel. Thus, there is greater anticipatory nasality on vowels that are adjacent to short nasal consonants like the vowel in the fricative context. In contrast, the degree of nasality tends to decrease when the vowels are followed by relatively long nasal consonants like those that occur in coda or before postnasal stops. The following section attempts to provide a theoretical account for this systematic interplay between the nasal consonant and the adjacent vowel.

2.4.2. Coarticulatory Variation and the Temporal interplay between N and Ṽ:

One of the main findings reported in this study can be seen in the complex but very systematic interactions in the anticipatory vowel nasalization between the nasal consonant or the coarticulatory source and the adjacent vowel, the target of coarticulation. This finding also provides support for the study main hypothesis, described in chapter 1, the variability in anticipatory vowel nasalization in Saudi Arabic depends on the timing relations between the corresponding gestures. This gestural account for the variation in coarticulatory patterns of vowel nasalization is based on the approach to coarticulatory variation proposed by Beddor (2009) and Devlaux et al. (2012) who suggest that under normal conditions speakers tend to produce gestures of constant duration, yet the alignment of the temporal extent of these gestures would vary depending on many language-specific factors. In coarticulatory vowel nasalization, for example, the nasal gesture (i.e. velum lowering) tends to have a constant size in all the coarticulatory variants, yet the different patterns of synchronizing the same-sized velum lowering gesture with the oral gestures of the adjacent vowel would introduce coarticulatory variation. Consequently, the delay in synchronizing the velum lowering gesture relative to the vowel gestures would lead a small part of the vowel to be nasalized and the nasal consonant to be lengthened. On the other hand, early initiation of the nasal gesture with respect to the oral articulators would result in a short nasal consonant but extensively nasalized vowel.

Beddor (2009) found that coarticulatory variation in anticipatory vowel nasalization in American English could be attributed to the temporal interplay between the coarticulatory source (N) and its effect (Ṽ). This case of coarticulatory variation due to the different timing of nasal gesture with the gestures of the vowel might be considered as a precursor to the stage that precedes the process of phonologization of vowel nasalization. In much the same way, Delvaux and colleagues (2012) provided account for the dialect-specific variability in French nasal vowels by comparing the different timing of the nasal gesture relative to the glottal and oral gestures in the nasal vowels of Northern and Southern French. Not only does the analysis by Delvaux and colleagues (2012) offer a comparative gestural account for the nasal vowels in Northern and Southern French dialects, but also it supports the argument that the nasal vowels in Southern French have /Ṽ/ as their underlying representation but their phonetic representation is realized as [$\tilde{V}_{n}$C] as a result of the temporal desynchronization of the nasal gesture with the gestures of the adjacent vowel and consonant.

My account of the cross-context coarticulatory variation by means of differently timed gestures is similar to those proposed by Beddor (2009) and Delvaux et al. (2012). The result of the current study suggests that the variation in the patterns of anticipatory vowel nasalization in Saudi Arabic VNC sequences stems from the difference in the temporal alignment of the nasal gesture with the oral articulators in the three different contexts ($VNC_{\text{“fricative”}}$, $VNC_{\text{“stop”}}$, VN). The result shows that in fricative context, in which the nasal consonant duration is found to be short, a large extent of the velum lowering gesture is aligned with the vowel gestures, leaving a large part of the vowel nasalized. Therefore, the vowels in pre-fricative context have greater nasality degree than the vowels in the other contexts. On the other hand, in the sequences of VN and VNT, the nasal consonants are relatively long and cooccur with decreased vowel nasality, indicating that the speakers align a small part of nasal gesture with the vowel gestures when they produce the vowel in VN or VNT sequences.

2.4.3. Why Fricative Contexts trigger N Shortening and Extensive Vowel Nasality:

In Saudi Arabic, manner of the postnasal in VNC sequences shows a pattern of vowel nasalization that is similar to the effect of voicing in English VNC sequences investigated by Beddor (2009). Her study revealed that the voicing properties of the postnasal stop in the VNC sequences led to differences in the duration of the preceding N. Investigation of the anticipatory nasality on the vowel then demonstrated that there was an inverse relationship between the duration of the nasal consonant and the duration of nasality on the neighboring vowel. Therefore, the duration of N in $VNC_{\text{“voiceless”}}$ is shorter than the duration of N in $VNC_{\text{“voiced”}}$. Additionally, the short N in pre-voiceless stop tends to cooccur with long vowel nasalization while the longer N in the pre-voiced stop is preceded by short duration of vowel nasalization.

My investigation of the interaction between nasal consonant and vowel nasalization in three different contexts ($VNC_{\text{“fricative”}}$, $VNC_{\text{“stop”}}$, VN) reveals that the shortest nasal duration is to be found in pre-fricative context, and the longest nasal duration when the nasal is in final position. Consistent with the prediction of the gestural alignment approach, I found that the most nasalized vowel co-occurs with the short nasal consonant. This trade-off between the duration of the nasal consonant and the nasality on the adjacent vowel suggests cross-context variability in the temporal alignment of the same-sized velum lowering gesture with the oral gestures.

However, while the gestural alignment approach provides an account for associating short nasal with extensive vowel nasalization, it does not yet explain why a specific context, namely fricative, causes the nasal consonant to be short and vowel nasalization to be extensive.

Early onset of velum lowering in a pre-fricative context is attributed to aerodynamic and auditory factors. When the air escapes through a narrow constriction to produce fricative sounds, turbulent airflow introduces high-intensity aperiodic noise to the speech acoustic signal (Johnson, 2012). In VNF sequences, the intense noise associated with the postnasal fricative interferes with the adjacent nasal and consequently masks nasality cues in the signal (Ohala & Busà 1995). In the current data, this might account for the observed pattern of coarticulatory vowel nasalization and the temporal interplay between the coarticulatory source (N) and the effect (Ṽ) in VNC sequence. I suggest that due to the masking of nasality cues by the postnasal fricative in VNF sequences speakers will estimate their listeners' need for the nasality information to be high. To resist the masking effect and preserve nasality, speakers promptly lower their velum initiating nasalization during the production of the preceding vowel to provide listeners with sufficient nasality information. According to the gestural timing approach which expects the nasal gesture to have constant duration, early initiation of the velum lowering during the vowel will lead to a short nasal consonant and long vowel nasalization. This account is consistent with the temporal interaction between the nasal consonant and vowel nasalization observed in Saudi Arabic VNC sequences differing in the manner of the postnasal consonant. Thus, in a pre-stop or VN context where there is no masking effect, the duration of nasal consonant is lengthened, and the extent of vowel nasalization is shortened, indicating that the constant-sized nasal gesture in these context is aligned for a small part with the vowel.

This account for the acoustic effect of the postnasal fricative on the temporal interaction between the preceding nasal and vowel nasalization in VNC sequences is consistent with Lindblom's (1990) model of Hypo- & Hyper-speech. H&H model postulates that in communication speakers adjust their speech depending on their estimation for their listeners' informational needs. As in H&H model, the gestural alignment approach predicts that speakers will vary the alignment of nasal gesture in accordance with their estimation for the listeners' need for nasality information. Coarticulation such as vowel nasalization has been found to be informative and beneficial for the listener as the overlapping between the source and the target provides additional acoustic cues that inform the listener about the coarticulatory source (Beddor, 2009; Scarborough 2013). Assuming the overlapping of the gestures will be perceptually useful for the listeners, I argue that speakers will change their articulation to produce short or long nasal consonant based on the amount of the nasality information available on the vowel, i.e. the degree of the gestural overlapping between the nasal and the vowel.

Therefore, when the nasality cues are easy to perceive due to the extensive nasalization of the nearby vowel, speakers will adjust their articulation to reduce N duration. But, when the nasality cues available on the vowel are expected to be weak, speakers will produce longer N to provide the listeners with sufficient nasality information. The reduction of the nasal consonant when there is sufficient nasality information on the vowel represents a form of the low-cost, system-oriented behavior to which speakers adjust their articulation in order to minimize the articulatory effort when they estimate listeners' informational needs to be low.

The previous discussion suggests that the variation in the degree of the overlapping between the nasal and the vowel in the three difference contexts can be seen as a type of the adaptive behavior of speech production– a process in which speakers tune their articulation to listener-directed speech to accommodate for the listener's informative needs or the speaker-directed speech to minimize articulatory effort. However, such claim that speakers are helpful and adjust their speech to maximize intelligibility of their listener requires evaluation of the listeners' perception of the varying degrees of vowel nasalization. If speakers are regarded to be helpful and accordingly change their articulation to increase the nasality on vowel when the nasal consonant is short (as in VNC "fricative"), I predict that the increased degree of nasality on the vowel will be informative and will facilitate the perception of the following short nasal consonant. Conversely, in VNC "stop" sequence in which the nasality on the vowel is low but the nasal consonant is long, I expect the vowel nasality to be perceptually less informative for the listeners. The perception study in the following chapter attempts to address these predictions.

CHAPTER 3

PERCEPTION OF NASALITY IN VNC SEQUENCES

3.1. Introduction:

In speech perception, the fundamental task of the listener is to determine the speaker's intended meaning– a process whereby the listener associates certain linguistic knowledge to the acoustic signal produced by the speaker. However, listener's task of deriving phonetic details (or recovering auditory cues) from the signal can be difficult, as the acoustic signal is characterized by the complexity and variation in its components. In normal speech communication, for instance, speakers tend to produce adjacent sounds less distinctly causing the acoustic signals of these sounds to overlap. Consequently, the pronunciation of these sounds will be modified, and new variants will be introduced to the phonetic realization of each sound. An interesting problem in speech perception is to examine the way in which this acoustic variation introduced by the overlapping signals affects listeners' judgment of the speakers' intended meaning. In other words, the research in speech perception is concerned with the question of what acoustic information listeners really use in perception of the new coarticulatory variants.

In nasal vowels, the coupling of the nasal cavity with the oral passage introduces new acoustic consequences to the signal. These acoustic changes in the signal influence listeners' judgment of vowel nasality (House and Stevens, 1956; Hattori, Yamamato, and Fujimura, 1958). Listeners' judgments of vowel nasality were also influenced by other vowel properties such as vowel duration (Whalen and Beddor, 1989) and phonetic context in which the vowel occurs (Beddor and Krakow, 1999). Beddor and Krakow (1999) found that nasal vowels were more accurately perceived as nasal when spliced and presented in non-nasal context ([CṼC]) than when presented in their original nasal context ([NṼN]).

The acoustic experiment demonstrated that the phonetic context in which the vowel occurred influenced vowel nasality in Saudi Arabic. The acoustic investigation of coarticulatory vowel nasalization (vowel nasality) in Saudi Arabic VNC and VN sequences revealed that acoustic variation in coarticulatory vowel nasalization among these contexts was attributed to the different patterns of the temporal organization of a same-sized nasal gesture with the oral articulators required for the production of the vowel. Thus, in the context with the most nasalized vowel, that is $VNC_{\text{“fricative”}}$, a large part of the nasal gesture is aligned with the vowel. On the contrary, the $VNC_{\text{“stop”}}$ sequence, where the measured nasality on the vowel is lower than the nasality on vowel in the sequence $VNC_{\text{“fricative”}}$, aligns a small extent of the nasal gesture with the vowel. The goal of this chapter is to find evidence from perception that supports the stability of the nasal gesture in varying contexts. Evidence of the stability of the gesture will be obtained when the listener considers the increased nasality on vowel as an informative cue of the following nasal.

The main question asked in this chapter is whether Saudi Arabic listeners use nasality on the vowel in contexts where a large part of velum lowering gesture is aligned with vowel to identify the following nasal. To address this question, we designed a forced-choice preference task that tested listeners’ preferences for stimulus pairs containing words with VNC sequence, which differ in the presence or absence of the nasal consonant. If listeners are able to identify the deleted nasal segment from the coarticulatory cue on the vowel, then this will provide support for the claim that speakers increase the degree of overlapping between the nasal and the vowel to compensate for the short nasal consonant by providing sufficient nasality information on the vowel.

3.1.1. Research Hypothesis:

The experiment in this chapter addresses the question whether the nasalized vowels with greater nasality will be better auditory cues for Saudi Arabic listeners than nasalized vowels with lower nasality in identifying the nasal that follows the vowel. The acoustic experiment in chapter 1 provided evidence for the temporal stability of the nasal gesture in Saudi Arabic that is differently timed relative the oral articulators depending on its phonetic context. Therefore, in the forced-choice preference task, we hypothesize that when the listeners are asked to choose the utterance they prefer, they will choose the extensively nasalized vowels in pre-fricative context over the less extensively nasalized vowels in pre-stop context.

3.2. Method:

3.2.1. Subjects:

Ten male subjects participated in this study. They were in their mid twenties and early thirties. All participants were native speakers of the central Saudi Arabic dialects that are closely related and have identical phonological inventory. Four subjects were from the Riyadh region, four from Qassim, one from Wadi al-Dwasir, and one from the western Riyadh. Six subjects from this group also participated in the production experiment in chapter 1. Because the stimuli from the perception experiment overlap with those from the production experiment, those listeners who also took part in the production experiment were asked to do the perception experiment before participating in the production experiment in order to avoid any effect of participants' previous knowledge on the perception task. The subjects were recruited in the Boulder area and were members of the University of Colorado-Boulder community. None of them reported speech- or hearing related problems.

3.2.2. Stimulus Materials:

The stimulus materials consist of real Saudi Arabic monosyllabic words that contain a sequence of VNC in which the postnasal consonant in VNC sequences belonged either to the class of fricative ([f], [s], [z], [ʃ], [sˤ] 18 words) or stop ([b], [t], [d], [ɟ], [tˤ]18 words). The vowels in these sequences were [a], [i], and [u]. The words were produced by a Saudi Arabic native speaker. The speaker was a 28 year-old male from Riyadh. A list of the words are provided in the Appendix.

The recorded words (18 $VNC_{\text{“fricative”}}$ words & 18 $VNC_{\text{“stop”}}$ words) were arranged in *three types* of pairs to be utilized in the forced-choice preference task. Each pair in the three pair-types has two degrees of vowel nasalization: a more nasalized vowel and a less nasalized one. The vowels with greater degree of vowel nasality are those that occur before fricatives, and the vowels with lower degree of vowel nasalization are those that occur before stops. The forced-choice preference task asked the listeners to choose the VNC word with the better pronunciation or the word that sounds more natural. This task was used because we could not examine the perception of vowel nasalization by using minimally contrastive pairs as they were not available.

The three types of stimulus pairs that were used in the forced-choice preference task are: (Type 1 *[more vowel nasalization with no nasal C* **vs.** *less nasalization with no nasal C]*: $\tilde{V}_{\text{“more nasal”}}C_{\text{“fricative”}}$ - $\tilde{V}_{\text{“less nasal”}}C_{\text{“stop”}}$; Type 2 *[more vowel nasalization with no nasal C* **vs.** *less vowel nasalization with nasal C]*: $\tilde{V}_{\text{“more nasal”}}C_{\text{“fricative”}}$ - $\tilde{V}_{\text{“less nasal”}}NC_{\text{“stop”}}$; Type 3 *[less vowel nasalization* *with no nasal C* **vs.** *more vowel nasalization with nasal C]:* $\tilde{V}_{\text{“less nasal”}}C_{\text{“stop”}}$ - $\tilde{V}_{\text{“more nasal”}}NC_{\text{“fricative”}}$). Three different conditions were created, and each condition consists of 18 trials. All of the three conditions involve removal of the nasal segment. So, each VNC word was duplicated, and one of the two copies had the nasal segment removed. The first pair presented the listeners with VNC words, where both words had no nasal consonant but differed in the nasality degree on the vowel (i.e. $\tilde{V}_{\text{“more nasal”}}C_{\text{“fricative”}}$ - $\tilde{V}_{\text{“less nasal”}}C_{\text{“stop”}}$). The second pair compared words that had increased vowel nasalization but no nasal consonant with words that have decreased vowel nasalization and a long nasal consonant ($\tilde{V}_{\text{“more nasal”}}C_{\text{“fricative”}}$ - $\tilde{V}_{\text{“less nasal”}}NC_{\text{“stop”}}$). The last stimulus pair presented the participants to VNC words that have decreased vowel nasalization and no nasal segment and other VNC words with increased vowel nasalization and short nasal consonant ($\tilde{V}_{\text{“less nasal”}}C_{\text{“stop”}}$ - $\tilde{V}_{\text{“more nasal”}}NC_{\text{“fricative”}}$).

To confirm that vowel nasality in VNC “fricative” is greater than vowel nasality in VNC “stop”, nasality was measured for vowels in the stimuli. The result of the measured nasality in the two contexts demonstrated that the average A1-P0 for vowels in $VNC_{\text{“fricative”}}$ words is lower than the average A1-P0 for vowels in $VNC_{\text{“stop”}}$ words ($VNC_{\text{“fricative”}}$: means=-0.22; $VNC_{\text{“stop”}}$: means= 2.51). This indicates that the condition $VNC_{\text{“fricative”}}$ is more nasal than $VNC_{\text{“stop”}}$.

3.2.3. Procedure:

The edited stimuli for the forced-choice preference task were presented to the subjects via Microsoft PowerPoint (Microsoft Corp., 1987) slides with integrated sound files. Each slide presented listeners with a pair of WAVE files that contained recordings of single VNC words. Subjects listened to the recorded VNC words only once. They were instructed to first listen to the recorded words in each stimulus pair and then choose the VNC word with the better pronunciation or the word that sounds more natural. Subjects' responses to the task were listed in a specific handout designed for the task that was distributed before the task.

The experiment was conducted in the Phonetics Lab of the University of Colorado-Boulder. Subjects were seated comfortably in a sound-attenuating booth and asked to listen to the stimuli over the headphones. The Microsoft PowerPoint (Microsoft Corp., 1987) slides were displayed using a monitor that was connected to Apple Macintosh desktop computer located outside the booth. After listening to the pair of VNC words and choosing the one with the better pronunciation, subjects moved to the next slide by pressing a key on a quiet keyboard in the booth.

3.3. Results:

The percentage of listeners' responses to the forced-choice preference task was calculated. As expected, the listeners' responses to type 1 trials ($\tilde{V}_{\text{“more nasal”}}C_{\text{“fricative”}}$ - $\tilde{V}_{\text{“less nasal”}}C_{\text{“stop”}}$), the no-nasal pair, indicated preference for the increased nasality condition represented by the sequence ($\tilde{V}_{\text{“more nasal”}}C_{\text{“fricative”}}$) over the decreased nasality condition of the sequence ($\tilde{V}_{\text{“less nasal”}}C_{\text{“stop”}}$) (60.3% for ($\tilde{V}_{\text{“more nasal”}}C_{\text{“fricative”}}$)) to 39.7% for ($\tilde{V}_{\text{“less nasal”}}C_{\text{“stop”}}$)). For the other two types of trials, listeners' responses revealed strong preference for the nasal-present condition version of the ($\tilde{V}$NC) word over the nasal-less condition version ($\tilde{V}$C). However, the degree of preference differed depending on the degree of nasality on the vowel in the nasal-less condition in each trial. Thus, subjects' preference for the nasal-present condition version ($\tilde{V}_{\text{“less nasal”}}NC_{\text{“stop”}}$) with less vowel nasalization over the nasal-less condition version ($\tilde{V}_{\text{“more nasal”}}C_{\text{“fricative”}}$) with more vowel nasalization (63.5% for $\tilde{V}_{\text{“less nasal”}}NC_{\text{“stop”}}$ to 36.5 for $\tilde{V}_{\text{“more nasal”}}C_{\text{“fricative”}}$) was smaller than their preference for the nasal-present condition with increased nasality on the vowel over the nasal-less condition version with decreased nasality on the vowel (82% for $\tilde{V}_{\text{"more nasal"}}NC_{\text{"fricative"}}$ to 18% for $\tilde{V}_{\text{"less nasal"}}C_{\text{"stop"}}$). **Figure 3-1** illustrates the calculated percentage of the listeners' responses to the three types of trials in the forced choice preference task.

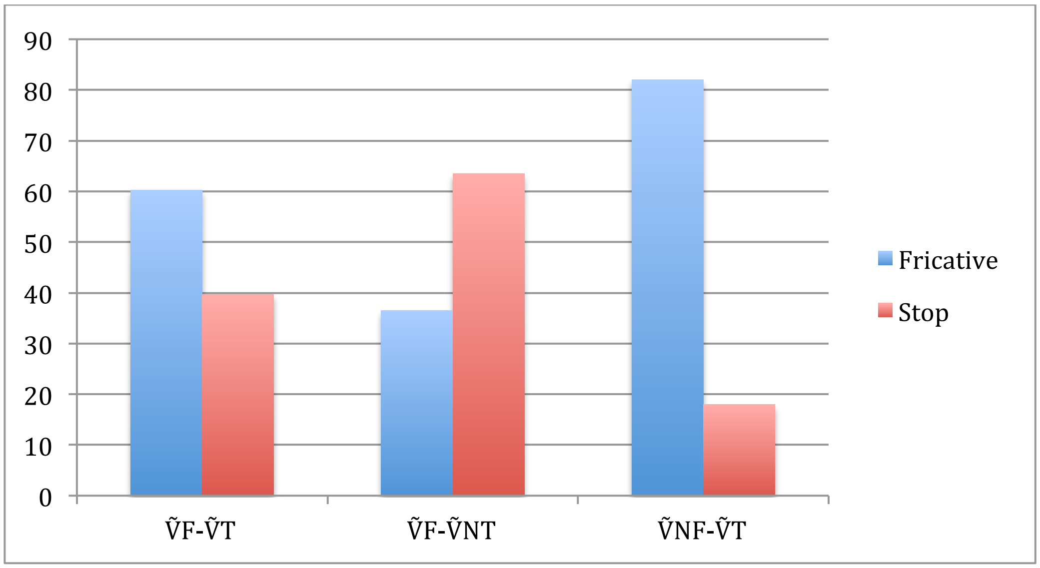

Figure 3-1: summary of the listeners' response to the three types of conditions (ṼF-ṼT; ṼF-ṼNT; ṼNF-ṼT). In these trial-types, (F) refers to a fricative, (T) to a stop. The vowel in the pre-fricative position is always more nasal than the vowel in the pre-stop position.

The calculated percentage of the listeners' responses to the no-nasal trials suggested that the more nasalized vowels in the fricative condition ($\tilde{V}_{\text{"more nasal"}}C_{\text{"fricative"}}$) were preferred over the less nasalized vowels in the stop condition ($\tilde{V}_{\text{"less nasal"}}C_{\text{"stop"}}$). This result, however, is not sufficiently convincing since the reason for preferring the more nasalized conditions ($\tilde{V}_{\text{"less nasal"}}C_{\text{"fricative"}}$) over the less nasalized one ($\tilde{V}_{\text{"less nasal"}}C_{\text{"stop"}}$) might also be attributed to the phonetic context in which the nasalized vowel is presented to the listeners. That is, the cause that led listener to prefer the more nasalized vowels over the less nasalized ones might be related to how the listeners like the vowel to be presented before certain postnasal consonant rather than the degree of nasality on the vowel.

3.4. Discussion:

The results from the forced-choice preference task support the hypothesis that extensively nasalized vowels are preferred more than the vowels with low nasality. The analysis of the listeners' responses in the no-nasal pairs ($\tilde{V}_{\text{"more nasal"}}C_{\text{"fricative"}}$ - $\tilde{V}_{\text{"less nasal"}}C_{\text{"stop"}}$) showed that Saudi Arabic listeners preferred the fricative condition ($\tilde{V}C_{\text{"fricative"}}$) which represents the pair member with extensive nasality over the slightly nasalized member of the pair, the stop condition ($\tilde{V}C_{\text{"stop"}}$).

The results of this perception study are also consistent with the results reported in the acoustic study. The results from the perception displayed some effects of phonetic contexts on the perception of nasalized vowel that are similar to the effect of phonetic context on the acoustics of vowel nasality. For example, the acoustic study found that A1-P0 values in vowels in prefricative context were significantly lower than the A1-P0 values in vowels in prestop context, indicating that nasality on pre-fricative vowels is greater than nasality in pre-stop vowels. Consistent with the acoustic results from the production experiment, the listeners' responses to the perception experiment indicated preference for the vowel in the fricative condition over the vowel in the prestop condition.

The results from the listeners' responses to the no-nasal trials ($\tilde{V}_{\text{"more nasal"}}C_{\text{"fricative"}}$ - $\tilde{V}_{\text{"less nasal"}}C_{\text{"stop"}}$) are inconclusive as the reason for the preference for the fricative condition over the stop condition might also be attributed to the phonetic context in which the nasalized vowel is presented to the listeners (see § 3.3.). Rather than saying that listeners preferred the pre-fricative vowels more than the pre-nasal vowels because the pre-fricative vowels are more nasalized (or listeners generally prefer more nasalized vowels over less nasalized ones), another possible interpretation of the results could be that listeners prefer the vowel in a pre-fricative position to be presented with more nasality and in a pre-stop position with less nasality. Unfortunately, the hypothesis of the listeners' preference for different degrees of nasality on the vowel depending on the phonetic context in which the vowel occurs cannot be tested by the current set of stimuli I used in this experiment, as the current stimuli are not designed in a way that would allow us to examine listeners' preference for two degrees of vowel nasality (heavy and low) occurring in the same phonetic context, that is before the same postnasal consonant. In order to see whether listener generally prefer the more nasalized vowel or they prefer to hear different degrees of nasality in different context, I need to add new conditions in which each stimulus pair presents two degrees of vowel nasalization followed by the same postnasal consonant. To control the effect of the postnasal consonant I need create the following conditions: $\tilde{V}_{\text{“more nasal”}}C_{\text{“fricative”}}$ - $\tilde{V}_{\text{“less nasal”}}C_{\text{“fricative”}}$ and $\tilde{V}_{\text{“more nasal”}}C_{\text{“stop”}}$ - $\tilde{V}_{\text{“less nasal”}}C_{\text{“stop”}}$.

Another reason for the preference of the fricative condition over the stop condition may be related to the difference in the duration of the vowels in these conditions. The vowels in the pre-fricative context are longer than the vowels in the pre-stop context. The duration issue might be considered as one of the factors influencing the listeners' responses in the perception experiment. When I removed the nasal consonant from the two contexts to prepare the conditions, I cut more of the $VNC_{\text{“stop”}}$ words more than of the $VNC_{\text{“fricative”}}$ words since the vowel in the pre-fricative context is longer than the pre-stop vowel. This would cause the $VNC_{\text{“fricative”}}$ words to be longer and sound more natural than the $VNC_{\text{“stop”}}$ words.

The results of the forced-choice preference task support the prediction that variation in the nasality degree on vowel affects the perception of the following nasal in Saudi Arabic. The forced-choice preference task demonstrated that when the nasal consonant is removed, the extensive nasality on the vowel in the VNC sequence represented a better version of the given word than the low vowel nasality did. Listeners' responses to the task showed noticeable preference for the fricative condition ($\tilde{V}C_{\text{“fricative”}}$) which has a heavily nasalized vowel over the stop condition ($\tilde{V}C_{\text{“stop”}}$) in which nasality on the vowel decreases.

This study also provides evidence for the effect of the differences in the alignment the nasal gesture with the oral articulators on the perception of anticipatory vowel nasalization in Saudi Arabic VNC sequences. Consistent with the acoustic results from the production experiment, the results of the preference task showed that listeners preferred the fricative condition where a large part of the nasal gesture is aligned with the vowel over the stop condition in which the temporal extent of nasal gesture aligned with the vowel appears to be small.

CHAPTER 4

IMPLICATIONS AND GENERAL DISCUSSION

The goal of this chapter is to match the findings from the production and perception experiments with theories about the interaction between the speaker and the listener and the interface between phonology and phonetics. The results from both experiments show that the manner of the postnasal consonant influences the degree of the overlapping between the nasal and the vowel in Saudi Arabic. To start with, I will provide a brief summary of the findings of the two experiments. Then, I will attempt to account for the pattern of coarticulatory vowel nasalization in Saudi Arabic and discuss its implications to the phonetic-phonology interface. Then, the implication of this account on the interaction between the speaker and the listener will be discussed. Finally, the effect of coarticulation on the perception process will be discussed and evaluated.

4.1. Summary of Findings:

In this work, I conducted production and perception experiments in order to investigate the influence of the postnasal consonant on the anticipatory vowel nasality in Saudi Arabic.

By examining vowel nasality in three different contexts ($VNC_{\text{"fricative"}}$, $VNC_{\text{"stop"}}$, VN), the results from the production study show that the vowels in pre-fricative context have greater nasality than the vowels in the pre-stop context and in VN sequences. The temporal measures of the nasal segments in three contexts also reveal that the phonetic context exerts significant influence on the duration of the nasal consonant. Throughout the result, it is illustrated that the duration of the nasal consonant is inversely related to the degree of nasality on the adjacent vowel. Thus, there is greater anticipatory nasality on vowels that are adjacent to short nasal consonants like the vowel in the fricative context. In contrast, the degree of nasality tends to decrease when the vowels are followed by relatively long nasal consonants like those that occur in VN sequences or before postnasal stops.

The findings about the inverse relationship between the nasal consonant duration and the nasality degree on the neighboring vowel suggest that the coarticulatory pattern of vowel nasalization in Saudi Arabic can be explained by using a gestural model. In this model, the variability in the degrees of the vowel nasalization is seen as a consequence of the differences in the coordination of the nasal gesture of a constant size and the gestures of the vowel.

The perception study examines whether the extra nasality information on the prefricative vowel, as explained in the production study, will be perceptually helpful for the listener to identify the following nasal. The results from the forced-choice preference task show that extensively nasalized vowels are preferred more than the vowel with low nasality. The analysis of the listeners’ responses in the no-nasal pairs showed that Saudi Arabic listeners preferred the fricative condition ($\tilde{V}C_{\text{“fricative”}}$) which represents the pair member with extensive nasality over the slightly nasalized member of the pair, the stop condition ($\tilde{V}C_{\text{“stop”}}$).

The results of this perception study are also consistent with the results reported in the acoustic study. The results from the perception displayed some effects of phonetic contexts on the perception of nasalized vowel that are similar to the effect of phonetic context on the acoustics of vowel nasality. For example, the acoustic study found that A1-P0 values in vowels in prefricative context were greater than the A1-P0 values in vowels in prestop context. Consistent with the acoustic results from the production experiment, the listeners’ responses to the perception experiment indicated significant preference for the vowel in the fricative condition over the vowel in the prestop condition.

4.2. Intergestural Timing Account for the Pattern of Coarticulatory Nasalization:

The results from the production study demonstrated that the degree of nasality on vowel and the temporal extent of the nasal consonant would vary systematically depending on the phonetic context in which the nasal gesture and its coarticulatory target, the adjacent vowel, would occur. Additionally, the investigation of the anticipatory vowel nasalization in in Saudi Arabic in three different contexts ($VNC_{\text{"fricative"}}$, $VNC_{\text{"stop"}}$, VN) revealed that the cross-context variation in the coarticulatory vowel nasalization displayed a systematic interplay between the degree of anticipatory nasality on the vowel and the duration of the following nasal consonant. Therefore, the vowel in pre-fricative context will be characterized by increased degree of nasality and short nasal consonant. Conversely, the vowel in the pre-stop or prenasal context will have low nasality but the duration of the following nasal will be prolonged. This section of the paper will attempt to address the questions of how the Saudi Arabic speakers vary the degree of nasality on vowel, and why the degree of nasality on the vowel varies in the different contexts.

The interplay between the nasality on vowel and the nasal consonant fits an intergestural timing model like the ones proposed by Beddor (2009) and Delvaux et al. (2012), Lin, Beddor & Coetzee (2014). In fact, applying the intergestural timing relations to account for the cross-context variation in vowel nasality is not surprising since the temporal interactions between gestures have been proven to be a useful tool to examine coarticulation (Browman and Goldstein, 1995; Fowler, 1977, 1980). We know coarticulation as the overlapping of adjacent segments where the components of the acoustic signal of one segment will be added to those of the other. In the intergestural timing model, nonetheless, coarticulation is defined as the overlapping between the corresponding gestures. So, according to this definition, a more precise description of the coarticulation would be obtained by examining the degree of the overlapping between these gestures. In coarticulatory vowel nasalization, therefore, the degree of nasality on the vowel is determined by the differences in the alignment of a constant-sized nasal gesture along the spatial extent of the adjacent vowel gestures.

Our analysis of the results from production study reveals that the nasality degree on vowel was inversely related to the duration of the following nasal consonant. So, when the vowel is extensively nasalized like the vowels in pre-fricative context, the nasal consonant will be shortened. However, when the nasality on vowel is low like the vowels in pre-stop or pre-nasal context, the nasal consonant appears to be considerably longer. This tradeoff between the duration of the nasal consonant and the nasality on the adjacent vowel can be seen as an indication for the stability of the nasal gesture across the three contexts. Since the data in the production study shows no correlation between long nasal consonants and increased degree of vowel nasalization, there is no reason to think that Saudi Arabic speakers, like American English speakers as found by Beddor (2009), produce a relatively same-sized nasal gesture in the three contexts ($VNC_{\text{“fricative”}}$, $VNC_{\text{“stop”}}$, VN), but they vary in the temporal alignment of the nasal gesture along the spatial extent of the vowel gestures. It is by investigating these timing relations between the nasal gesture and the gestures of adjacent vowel that we can provide a thorough description of the variability in the degree of vowel nasalization in Saudi Arabic.

But why would Saudi Arabic speakers do that? The findings show that the degree of vowel nasality will show cross-context variability depending on the manner of the postnasal consonant. We argue that this variability in the degree of the gestural overlapping is based on the effect of the phonetic properties of the postnasal consonant on the nasal gesture. Thus, increased degree of overlapping of the velum lowering gesture with the oral gestures of the vowel in a pre-fricative context occurs due to reasons associated with the aerodynamic properties of the fricatives, namely the high-intensity aperiodic noise. In $VNC_{\text{“fricative”}}$ sequences, the intense noise associated with the postnasal fricative interferes with the adjacent nasal and consequently attenuates nasality cues in the signal (Ohala & Busà 1995). However, the increase in nasality found in pre-fricative vowels occurs when the speakers lower the velum to initiate nasalization during the production of the vowel in an attempt to save nasality from being masked by the loud noise from the adjacent fricative. According to the intergestural timing model which expects the nasal gesture to have constant duration, early initiation of the velum lowering during the vowel will lead to a short nasal consonant and long vowel nasalization. This account is also consistent with the temporal interaction between the nasal gesture and the postnasal consonants with no noise component in Saudi Arabic VNC sequences. Thus, in the pre-stop context where there is no masking effect, the duration of nasal consonant is lengthened, and the extent of vowel nasalization is shortened, indicating that, in this context, a small portion of the constant-sized nasal gesture is aligned with the vowel.

4.3. Intergestural Timing Relations and the Speaker-Listener Interaction:

The findings from the experiments in chapter 2 demonstrated that Saudi Arabic speakers systematically would vary the degree of the overlapping between the nasal gesture and the adjacent vowel depending on the phonological structure of the postnasal consonant. Further investigation of this systematic coarticulatory variation in vowel nasality revealed a tradeoff relationship between the duration of nasal segment and the degree of nasality on the adjacent vowel, and another (tradeoff relationship) between the temporal extent of the nasal segment and that of the vowel. The findings are also consistent with the listeners’ responses in the perception experiment. Listeners’ performance in the perception task showed preference for the vowels that displayed a greater degree of overlapping between nasal and vowel (i.e. the prefricative vowels).

These findings about the complex temporal interplays that characterize vowel nasalization in Saudi Arabic suggest an account for the variation in coarticulatory vowel nasalization based on the difference in the synchronization of the gestures. As suggested by Lindblom (1990), we argue that the temporal interaction between gestures is an adaptive behavior by the speaker in response to the communicative demands on the listener.

According to Lindblom (1990), speakers vary their motor control along a continuum of hypo- and hyperspeech in accordance with their estimation for the communicative demands on their listeners. Consistent with Lindblom's (1990) H&H model, our intergestural timing model predicts that speakers will vary the alignment of the nasal gesture with oral gestures of the vowel to accommodate for the listeners' need for nasality information. Thus, in acoustic environments such as the fricative context that is characterized by the noise and the masking of the nearby sounds (Ohala &Busa, 1996), speakers estimate the listeners' need for the nasality information to be high and accordingly increase the coarticulation between the nasal and the vowel to provide their listeners with sufficient nasality information or cues. On the contrary, in contexts such as the VNT sequence where there is no masking of nasality by the postnasal segment, speakers estimate listeners' need for nasality to be low and consequently adjust their speech motor control to the low-cost form of behavior with a decreased degree of the overlapping between the vowel and the nasal. Consequently, in VNC sequences, when the nasality cues are easy to perceive due to the extensive nasalization of the nearby vowel in the prefricative context, speakers will adjust their articulation to reduce N duration. But, when the nasality cues on vowels are expected to be weak, as is the case with the vowels in prestop contexts, speakers will produce longer N to provide the listeners with sufficient nasality information.

In addition to suggesting that speakers have access to the listeners' linguistic knowledge and its contribution to speech perception, the acoustic investigation of the temporal interaction between gestures revealed that speakers adjust their articulation of the nasal vowel in prefricative contexts to enhance the acoustic salience of nasality. Based on evidence drawn from analyzing tongue movements, nasal airflow, and acoustic data, Shosted et al. (2012) concluded that Hindi speakers displayed fine oral articulatory changes during the production of series of phonemic nasal vowels either to reinforce the acoustic nasality on vowels or to increase the acoustic distinctiveness in the nasal and oral vowel pairs. Nonetheless, while the findings showed that manipulation of the intergestural timing relations reinforces the acoustic property of nasalization of the nasal vowel, it did not explain the causes that lead to the enhancement of nasalization over the loss of its acoustic property.

Speakers' behavior that showed enhancement of the acoustic nasality on the nasal vowel in prefricative context suggests preference for providing additional information in the acoustic signal. This argument is supported by the production study evidence that speakers concomitantly increase or decrease nasality on vowel depending on the amount of information provided by the nasal segment (=the duration of the nasal consonant). The next section will explain whether this additional information in the acoustic signal is beneficial for the listener.

4.4. Coarticulation as Informative to the Listener:

As explained in chapter 3, additional acoustic information in the signal facilitates the process of perception. Accordingly, listeners' responses in the preference task revealed bias for the vowels with increased degree of nasalization. Since additional information in the stimuli is the result of the increased coarticulation between the nasal segment and the preceding vowel, the forced-choice preference task which showed preference for the vowels in the increased-coarticulation condition suggests that coarticulation could provide informative cues for the listeners.

The view of coarticulation as informative to the listener apparently conflicts with some of the theories of speech perception (e.g. Lindblom, 1990; Ohala, 1993) as coarticulation of segments results in a form of reduction or a novel version that requires additional effort from the listener to be perceived. According to Lindblom (1990), speech perception is facilitated when the speakers adjust their articulation to the listener-oriented speech (hyperspeech) which aims at maximizing intelligibility of the utterances. Coarticulation which belongs to the speaker-oriented speech (hypospeech) is a low-cost form of behavior and aims at minimizing articulatory effort and thus cannot facilitate speech perception. For Ohala (1993), coarticulation cannot be viewed as informative for the listener since the overlapping between the segments results in new coarticulatory forms that are usually subject to misparsing or misperception by the listener.

Unlike what the previous studies suggest, coarticulation does not seem to conflict with speech perception. Furthermore, coarticulation is found in clear speech which is supposed to be clearer and more directed to the listener (Scarborough, 2004; Bradlow, 2002). Scarborough (2004) found that not only coarticulation did increase in low frequency words that were carefully articulated, but also it facilitated the perception of these words. Additionally, Beddor (2009) found that listeners use the acoustic effect of coarticulation to identify the coarticulatory source. Therefore, increased coarticulation between the nasal and the vowel in the prefricative context can be seen as informative and beneficial for the listeners.

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APPENDICES

APPENDIX 1

Stimuli- Production experiment

Carrier phrase: "gul _____ bisurʔah" ("say ___ quickly")

Word	Gloss	Target consonant	Vowel
ʔanf	*nose*	f	a
ʃanf	*earring*	f	a
kans	*sweeping*	s	a
kanz	*treasure*	z	a
ʕanz	*goat*	z	a
lanʃ	*motorboat*	ʃ	a
qansˤ	*hunting*	sˤ	a
sˤinf	*type*	f	i
ɟins	*class*	s	i
ʔins	*human beings*	s	i
ɟinz	*jeans*	z	i
ʔinʃ	*inch*	ʃ	i
ʕunf	*violence*	f	u
ʔuns	*amiability*	s	u
funs	*flat nose (Pl)*	s	u
brunz	*bronze*	z	u
ʔunsˤ	*go directly (IMP)*	sˤ	u
ʔant	*you*	t	a
ʔhant	*insult*	t	a

wzant	*weigh*	t	a
zand	*arm*	d	a
band	*item*	d	a
banɟ	*anesthesia*	ɟ	a
zantˤ	*strangling*	tˤ	a
bint	*girl*	t	i
lint	*I became nice*	t	i
hind	*sword*	d	i
zinɟ	*fence*	ɟ	i
narinɟ	*orange*	ɟ	i
kunt	*be (PAST, 2 Sg)*	t	u
χunt	*betrayed (PAST, 2 Sg)*	t	u
sˤunt	*take care of (Pl)*	t	u
ɟund	*soldiers*	d	u
ʁunɟ	*seduction*	ɟ	u
ʔan	*moan*	n	a
fan	*art*	n	a
ʃan	*initiate*	n	a
san	*sharpen*	n	a
kan	*inhale*	n	a
ran	*ring*	n	a
zan	*nagging*	n	a
din	*embrace faith*	n	i
sin	*tooth*	n	i

zin	*weight*	n	i
bin	*son*	n	i
ɟin	*jinn*	n	i
bun	*coffee bean*	n	u
sˤun	*take care of (IPM)*	n	u
ðˤun	*doubt (IMP)*	n	u
sun	*sharpen (IMP)*	n	u

APPENDIX 2

Stimuli- Perception experiment

Vowel	Words	Context
a	ʔant	VNT
a	lhant	VNT
a	zand	VNT
a	wzant	VNT
a	band	VNT
a	banj	VNT
a	sˤank	VNT
a	bank	VNT
a	zantˤ	VNT
i	zint	VNT
i	lint	VNT
i	hind	VNT
i	zinɟ	VNT
i	bint	VNT
i	narinɟ	VNT
i	zink	VNT
u	sˤunt	VNT
u	xunt	VNT
u	kunt	VNT
u	brunz	VNT
u	ʁunɟ	VNT
a	ʔanf	VNF
a	Kans	VNF
a	kanz	VNF
a	shanf	VNF
a	ʕanz	VNF
a	lanʃ	VNF
a	tˤanx	VNF
a	zanx	VNF
a	qansˤ	VNF
i	sˤinf	VNF
i	ʔins	VNF
i	ɟinz	VNF
i	winʃ	VNF
i	jins	VNF
i	ʔinʃ	VNF
i	ʔinx	VNF
u	ʕunf	VNF
u	ʔuns	VNF

u	funs	VNF
u	jund	VNF
u	ʕunʃ	VNF