A CROSS-LINGUISTIC STUDY OF THE ROLE OF THE JAW IN CONSONANT ARTICULATION

DISSERTATION

Presented in Partial Fulfillment of the Requirements for
the Degree Doctor of Philosophy in the
Graduate School of The Ohio State University

By

Sook-hyang Lee, B.A., M.A.

The Ohio State University
1994

Dissertation Committee:
Mary E. Beckman (Chair)
Michel T.T. Jackson
Elizabeth V. Hume

Approved by

Mary Beckman
Advisor
Department of Linguistics
Copyright by
Sook-hyang Lee
1994
To my parents and my advisor, Prof. Mary E. Beckman
ACKNOWLEDGEMENTS

I am grateful to many people, without whose advice, criticism, and encouragement I could not have completed this dissertation.

First, I thank my advisor, Mary E. Beckman for her academic enthusiasm in her work leading me to be fascinated by phonetics. I also thank her physical and emotional assistance and support by being always available when I had any problem and lending a shoulder to cry on. Especially for the last month after I came back from Korea, she has taken care of me by arranging things for me to keep up mental and physical stamina to complete my dissertation.

I also thank the two members of my committee. I thank Michel Jackson for his care and encouragement, for offering the anatomy course which led me to work on the jaw, and especially for writing much of the programs for data analysis for this study. I thank Beth Hume for her generous help with the phonological aspects of the dissertation.
I am grateful to many other people as well. In particular, I thank:

In-Tae Jun and Prof. Yong-Jin Song for invaluable advice on the mathematics and necessary physics for me to understand some of the literature on the jaw movement. Prof. Song also helped me send up files for my dissertation via e-mail from Korea to my committee members during the last three months.

Lutfi Hussein for his help on gathering the Arabic data and finding subjects. He served as a subject himself and was always willing to help me. Without his help, I would not be able to run the experiment on Arabic.

Sergey Zhupanov, Lupe Silva, and my husband, Yongkyoon No for writing parts of the programs for data analysis for this dissertation.

All the labbies for helping me in many ways: Sun-Ah Jun, Monica Crabtree, Shuhui Peng, Gayle Ayers, Kevin Cohen, and Stefanie Jannedy. Especially, Jennifer Venditti for taking care of my daughter in the lab and also elsewhere, e.g., ice-rink, while I needed to concentrate on my work. Kevin Cohen and Leslie Kent for their encouragement and concern for my daughter and also for me.

Ken de Jong and Keith Johnson for their care as Big Brothers and as colleagues. Ken, particularly, for e-mailing me about the all latest developments in research
on jaw movement.

Many Korean friends here in Columbus, especially Hyeree Kim and No-Ju Kim for their always being with me while I needed to work in school all night.

Sangjik Rhee, Hyunju Yoo, and Prof. Soonkyung Kahng for their generosity in sharing their offices or homes and computers with me during the three months in Korea before I defended my dissertation.

My family, and in-law family for their support for me to keep on working for such a long time here. Especially, my mother-in-law, who even in her illness did not demand from me the care I owed her as a daughter-in-law, and instead supported me fully to finish this study.

Chung-A No, my daughter and my friend, for spending many days and nights in the lab and for putting up with playing by herself and being bored.

My husband for his support and care, who has always kept me widely awake by both encouragement and criticism.

This dissertation was supported by Grant IRI-8858109 to Mary Beckman.
VITA

1976-1980  B.A., English Education,  
            Seoul National University, Seoul, Korea

1980-1984  M.A., English Education,  
            Seoul National University, Seoul, Korea

1980-1981  Graduate Research Assistant, Language Research Center  
            Seoul National University, Seoul, Korea

1981-1983  English teacher at Yeongseo Middle School  
            Seoul, Korea

1984-1985  Research Associate,  
            Department of Linguistics,  
            Seoul National University, Seoul, Korea.

1987-1993  Graduate Research Assistant/Graduate Teaching Assistant,  
            Department of Linguistics, The Ohio State University

PUBLICATIONS

Sook-hyang Lee (to appear) 'Orals vs. gutturals, and the jaw,' in Bruce Cornell  
and Amalia Arvaniti, eds., Papers in Laboratory Phonology IV. Cambridge  
University Press.

43, Dept. of Linguistics, The Ohio State University.


FIELDS OF STUDY

Major Field: Linguistics

Studies in Phonetics and Phonology
TABLE OF CONTENTS

DEDICATION........................................................................................................... ii

ACKNOWLEDGEMENTS .................................................................................... iii

VITA ......................................................................................................................... vi

LIST OF TABLES ................................................................................................... xi

LIST OF FIGURES ................................................................................................ xii

ABSTRACT ............................................................................................................. xv

CHAPTER I: INTRODUCTION .................................................................................. 1

1.1 The Anatomy of the Jaw .................................................................................. 2
1.2 Earlier Studies of the Jaw ................................................................................ 5
1.3 Modeling the Relationship Between Phonological and
    Phonetic representation..................................................................................... 8
1.4 Keating’s Window Model .............................................................................. 10
1.5 Brownman and Goldstein’s Articulatory Phonology .................................... 14
1.6 Preview .......................................................................................................... 17

CHAPTER II: Experiment: methods and summary of results .............................. 20

2.1 Subjects ........................................................................................................... 21
2.2 Material ......................................................................................................... 21
2.3 Data Acquisition .......................................................................................... 24
2.4 Data Processing ............................................................................................ 27
2.5 Correction of Head Movement ..................................................................... 28
2.6 Coordinate Transformation to the Occlusal Plane ..................................... 28
2.7 Statistical Analysis and Summary of Results ............................................. 31
CHAPTER III: ARTICULATORY TARGETS IN THE WINDOW MODEL ....40

3.1 Establishing Vowel and Consonant Windows Based on Actual Data.................................................................43
3.2 Prediction of the Window Model about the Jaw Trajectories for VCV Utterances Based on the Size of Segment's Windows........48

3.2.1 Speaker A1 ..........................................................49
3.2.2 Speaker A2 ..........................................................49
3.2.3 Speaker A3 ..........................................................50
3.2.4 Speaker F1 ..........................................................51
3.2.5 Speaker F2 ..........................................................52
3.2.6 Speaker F3 ..........................................................52
3.2.7 Speaker K1 ..........................................................53
3.2.8 Speaker K2 ..........................................................53
3.2.9 Speaker K3 ..........................................................54
3.2.10 Summary ..........................................................54

CHAPTER IV: ARTICULATORY PHONOLOGY AND THE DISTINCTION BETWEEN GUTTURALS AND ORALS ..........69

4.1 The Problem of the Gutturals ............................................70

4.1.1 Phonological Behavior of Gutturals in Arabic -- Patterning as a Natural Class .........................................................70
4.1.2 Explanations for Phonological Patterning of Gutturals as a Natural Class in Arabic......................................................74

4.1.2.1 Traditional SPE Classification...................................................74
4.1.2.2 Non-linear Approach - McCarthy (1991) ..............................75
4.1.2.3 Goldstein's Approach .........................................................77

4.2 Evaluating the Observed Jaw Positions ..............................78

4.2.1 Predictions ..........................................................78
4.2.2 Evaluating the Results ................................................81

4.3 Inter-speaker Differences ................................................103

CHAPTER V: CONCLUSION ..................................................110
# LIST OF TABLES

<table>
<thead>
<tr>
<th>TABLE</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1 Description of the speakers</td>
<td>21</td>
</tr>
<tr>
<td>2.2 List of consonants used in target and foil words</td>
<td>24</td>
</tr>
<tr>
<td>2.3 List of vowels used in target and foil words</td>
<td>24</td>
</tr>
<tr>
<td>4.1 Consonant chart of Palestinian Arabic</td>
<td>84</td>
</tr>
<tr>
<td>4.2 List of the slope, its standard error, and results of a t-test comparing the slope to 0, the intercept, and the correlation coefficient for the regression between the jaw height during consonants and jaw height during the preceding vowel</td>
<td>85</td>
</tr>
</tbody>
</table>
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>FIGURES</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1 Anatomy of the jaw and temporomandibular joint. a) Schematic of temporomandibular joint, b) illustration of translatory movement of the mandibale, and c) rotational movement .................................................4</td>
</tr>
<tr>
<td>1.2 Sequence of schematic jaw windows for /stræ/, with contour .............13</td>
</tr>
<tr>
<td>2.1 Schematic drawing of (a) the top view of the setting for data recording and (b) profile view played on TV monitor .........................26</td>
</tr>
<tr>
<td>2.2 Schematic drawing of measurement of angle between the splint and occlusal plane ..........................................................................................30</td>
</tr>
<tr>
<td>2.3 Mean jaw height for consonants across vowels for each speaker in all three languages .................................................................32</td>
</tr>
<tr>
<td>2.4 Mean jaw protrusion/retraction for consonants across vowels for each speaker in all three languages ......................................................36</td>
</tr>
<tr>
<td>3.1 Hypothetical jaw trajectories with different sizes of windows along with different height of the windows ........................................42</td>
</tr>
<tr>
<td>3.2 Windows for segments for Arabic speakers ........................................44</td>
</tr>
<tr>
<td>3.3 Windows for segments for French speakers .......................................45</td>
</tr>
</tbody>
</table>
3.4 Windows for segments for Korean speakers ........................................46

3.5 Mean and standard deviations for jaw heights during all ten consonants in all three vowel contexts for speaker A1 .........................56

3.6 Mean and standard deviations for jaw heights during all ten consonants in all three vowel contexts for speaker A2 .......................58

3.7 Mean and standard deviations for jaw heights during all ten consonants in all three vowel contexts for speaker A3 .......................60

3.8 Mean and standard deviations for jaw heights during all seven consonants in all four vowel contexts for speaker F1 ........................................62

3.9 Mean and standard deviations for jaw heights during all seven consonants in all four vowel contexts for speaker F2 ........................................55

3.10 Mean and standard deviations for jaw heights during all seven consonants in all four vowel contexts for speaker F3 ........................................55

3.11 Mean and standard deviations for jaw heights during all six consonants in all four vowel contexts for speaker K1 ..............................55

3.12 Mean and standard deviations for jaw heights during all six consonants in all four vowel contexts for speaker K2 ..............................55

3.13 Mean and standard deviations for jaw heights during all six consonants in all four vowel contexts for speaker K3 ..............................55

4.1 (a) Feature specification of consonants in SPE system and (b) Feature geometry proposed by McCarthy (1991) .................................76

4.2 Hypothetical situation of correlation of jaw height during consonants with their preceding vowels predicted by Goldstein’s proposal ....80

xiii
4.3 Jaw height during consonants against jaw height during preceding vowels for speaker A1 ......................................................... 82

4.4 Jaw height during consonants against jaw height during preceding vowels for speaker A2 ......................................................... 83

4.5 Jaw height during consonants against jaw height during preceding vowels for speaker A3 ......................................................... 84

4.6 Means and standard deviations for jaw heights for Arabic /s/ vs. /b/ and those for their surrounding high and low vowels for speaker A2 ........................................................................... 88

4.7 Jaw height during consonants against jaw height during preceding vowels for speaker F1 ......................................................... 95

4.8 Jaw height during consonants against jaw height during preceding vowels for speaker F2 ................................................................ 96

4.9 Jaw height during consonants against jaw height during preceding vowels for speaker F3 ................................................................ 97

4.10 Means and standard deviations for jaw heights during the pharyngeal fricative and the glottal stop in high and low vowel contexts for some Arabic speakers: a) for the pharyngeal fricative for speaker A2, b) for speaker A3, and c) for the glottal stop for speaker A2 ................................................................. 100

4.11 Actual and predicted jaw trajectories for velars and pharyngeals ... 101

4.12 Schematic drawing of the palate for speaker A2 and A3 ............... 105

4.13 Mean and standard deviation of jaw heights during /p/, /t/, /s/ for speakers K1 and K2 ................................................................. 107
ABSTRACT

A CROSS-LINGUISTIC STUDY OF THE ROLE OF THE JAW IN CONSONANT ARTICULATION

by

Sook-hyang Lee, Ph.D.

The Ohio State University, 1994

Professor Mary E. Beckman, Advisor

This thesis investigates the role of the jaw in the articulation of Arabic, French, and Korean consonants. Using jaw position data, it tests two recently developed theories of the relationship between phonological and phonetic representations: Keating's Window model and Browman and Goldstein's Articulatory Phonology framework. It also tests Goldstein's (1991) specific proposal within the Articulatory Phonology framework that the jaw's common function in the coordinative structures for labial, coronal, and dorsal constrictions differentiates these oral consonants from guttural consonants, which behave as a natural class in Arabic phonology.

The data are generally much less compatible with the Window model (which assumes invariant targets for the jaw, i.e., ranges of observed spatial values
with contextual variability) than with the Articulatory Phonology model (which says 'gestures', or constrictions involving vocal tract variables are the targets in speech and treats the jaw as only a member of the coordinative structure for the constrictions). The data, however, suggest that the Articulatory Phonology model might be improved by allowing for the direct control for an individual articulator, the jaw, during strident fricatives, where targets might need some consideration of acoustic or auditory effects of shapes besides those involved in the constriction proper.

Also jaw involvement in the articulation of some guttural consonants for some speakers provides evidence against Goldstein's specific hypothesis. An alternative is suggested: rather than such a categorical binary distinction (the jaw does or does not participate), there is a continuum of degrees of participation and also varied roles.
CHAPTER I
INTRODUCTION

The relationship between discrete and abstract phonological information and continuously varying physical events has been one of the central issues in phonetics. Phonological information for adjacent segments, which is supposed to be discrete and abstract, is realized in an actual utterance as continuous, and overlapping, so that each segment carries some information about its neighboring segments for a given articulatory or acoustic dimension. There have been many attempts to model this relationship, 'coarticulation', within several different frameworks, e.g., the undershoot model (Lindblom, 1963), the Gesture model within the Articulatory Phonology framework (Browman & Goldstein, 1986, 1990) and the Window model (Keating, 1990a). This dissertation addresses the issue using jaw position data as the given phonetic dimension.

Models of jaw movement are important in phonetics and phonology because the tongue and lower lip rest on the jaw, and therefore, movements of these articulators for speech will not be described accurately without considering
the role of the jaw. Previous studies of jaw movement have been largely confined to English and Swedish, and there have been no extensive studies of consonants in which the primary constriction cannot be related intuitively to jaw raising. This dissertation reports on an extensive cross-linguistic study of jaw movement during the production of consonants in Arabic, French, and Korean.

1.1 The Anatomy of the Jaw

The anatomy of the articulator of interest is portrayed in Fig 1.1. It is the mandible, or "lower jaw". The lower jaw is connected to the temporal bone at the temporomandibular joint. This is a "double" joint because the condyle is separated from the mandibular fossa by an articular disc providing a connecting surface both between the disc and the jaw and the disc and the skull. Due to the double nature of this joint, the jaw can rotate and also translate. The upper joint between articular disc and articular eminence (the thickened anterior part of the mandibular fossa) performs translation where all parts of the jaw moves in the same direction by movement of the articularatory disc and the condyle as a unit. The lower joint between the condyle of the mandibular and the disc performs rotation, where the condyle and the body of the jaw move in an opposite direction. The jaw can perform both rotational and translational movements at the same time (Zemlin, 1988).

Edwards and Harris (1990) summarize research such as that of Sarnat
(1964) and Gibbs and Messerman (1972) about differences in jaw movement between speech and non-speech as follows: in non-speech, the jaw performs all three translational movements while in speech it performs virtually no lateral movement. A more recent study (cf. Vatikiotis-Bateson and Ostry, 1993) shows some lateral jaw movement and rotation in other planes during speech but this movement is very small by comparison to the downward-forward and upward-backward movements in the sagittal plane. The range of jaw opening and closing is considerably less in speech compared to the non-speech movement such as mastication. In speech, the teeth normally do not touch even when the lower jaw is at maximum closing, nor is maximum opening as wide as it can be in mastication.
Figure 1.1 Anatomy of the jaw & temporomandibular joint. a) Schematic of temporomandibular joint, b) illustration of translatory movement of the mandible, and c) illustration of rotational movement (from Zemlin, 1988; p256, 259)
Edwards & Harris (1990), using a two-dimensional rigid-body model to describe jaw movement in speech, decomposed the observed movements into three subcomponents -- (1) vertical and (2) horizontal translations of the condyle and (3) rotation about the condyle -- and found that the component which contributes most in speech in terms not only of absolute but also of relative magnitude, is the movement due to the rotation. They also proposed that a two-point model (e.g., a model of which combines rotation and translation) rather than a single-point model (a pure translation or pure rotation model) is more accurate in describing jaw movement (see also Westbury, 1988).\(^1\) In this discussion, I will be concerned mainly with comparison of jaw height (a measure which reflects primarily jaw rotation and to a lesser extent, vertical translation). I will also be concerned to a considerably lesser extent with differences in jaw protrusion or retraction (a measure which reflects both jaw rotation and horizontal translation).

1.2 Earlier Studies of the Jaw

In earlier studies, phoneticians have proposed various linguistic roles for the jaw. In the articulation of vowels, for example, Sussman et al. (1973) found that the jaw is implicated in vowel height: they found that low front vowels showed

\(^1\) Their model is saturated in a sense that three is as many components as we could ever get from the kind of data they have, thus there is no simplification in the description of jaw movement.
lower jaw position than high front vowels. Other studies also report this finding (e.g., Johnson, et al., 1993). Macchi (1988) proposes that jaw height during consonants reflects both a passive coarticulation with neighboring vowels and an active suprasegmental specification. In her study, the jaw peak during the consonant was higher in the high vowel context than in the low vowel context, and it was also higher in stressed syllables, apparently to accomplish a higher target attributable to stress. Edwards et al. (1991) examined jaw movement to differentiate various lengthening effects and found that accentual lengthening is a result of a later phasing for the closing gesture relative to the opening gesture, while phrase-final lengthening is a consequence of a less stiff gesture, i.e., an 'actual targeted slowing down'. Schulman (1989) compared peak jaw displacement during stressed vowels in normal and loud productions and found bigger jaw displacement in loud productions compared to normal productions.

These studies relate jaw height in consonants only to features of neighboring vowels or of the prosodic context. Some studies which examine jaw height in relationship to consonant features as such also relate it primarily to prosodic context -- in this case the context of syllabic position and sonority. For example, Lindblom (1983) suggests that sonority has to do with ease of coarticulation: segments that are more difficult to coarticulate appear far away from each other in the syllable, whereas more compatible sounds tend to appear closer to each other. He tested this assumption with an articulatory parameter, jaw displacement, and found that there was a 'clear correlation between sonority
and jaw position’ with consonants higher on the sonority scale having lower jaw positions. He interpreted these jaw data as suggesting that the jaw position of the consonant indicates the propensity for coarticulation of the consonant with the vowel.

A different but related proposal is that of Keating (1983), who proposes that consonants are specified as having contrasting, relatively fixed jaw positions, and are ordered according to those positions so that the jaw can open smoothly. For example, in English, [s] and [z] have higher jaw positions than stops, in keeping with the voiceless fricative’s potential for occurring before stops in syllable-initial position and both fricatives’ potential for occurring after stops in syllable-final position in languages such as English.

The first approach to the role of the jaw in consonant articulation which refers directly to consonant features for their own sake is taken by Browman and Goldstein (1990), who use the role of the jaw in forming constrictions as one criterion for grouping the gestures of articulators or differentiating some group of consonants from others. In their Articulatory Phonology model, they identify the jaw as the common articulator unifying gestures in the oral system. That is, the oral gestures involving the lips, tongue tip, and tongue body share the jaw. Furthermore, Goldstein (1991) proposes that the jaw serves as the common articulator to differentiate oral consonants from gutturals which behave phonologically as a natural class in Arabic (McCarthy, 1991). He does so under the assumption that the jaw has a common function in the coordinative structures
for labial, coronal, and dorsal constrictions, but does not participate in the articulation of gutturals.

1.3 Modeling the relationship between phonological and phonetic representation

Crosscutting all of these studies is the issue of the relationship between phonological specification and phonetic specification -- the relationship between discrete symbolic phonological representations and continuously varying phonetic representations of physical events. There have been many attempts to model this relationship. One of the oldest models assumes qualitatively different targets or "coarticulated allophones". For example, Hammarberg (1976), a recent proponent of their model, proposes that the rounding in /s/ and /p/ in the word *spoon* is intentional and not the result of sloppy or inefficient articulation. Thus, allophones are still mental entities. In Hammarberg's model, phonetic representations are also discrete and symbolic, in the same way as phonological representations are, since coarticulatory phenomena are nothing but the results of certain phonological rules, assimilation rules.

The target and undershoot model (e.g., Lindblom, 1963), on the other hand, assumes an invariant phonetic target for each phoneme segment, and accounts for variable realizations as an artifact of the spacing between neuro-motor commands for the targets in time. If there is only a short duration for a given articulator to reach the target to which it is aiming, the target may be apparently reduced to a
continuously varying extent -- as a function of time. As a result, segments are affected by the surrounding segments. Thus this model accounts for observed coarticulation as 'undershoot' of the target due to physiological limits on articulator velocity.

However, this fixed velocity is not consistent of all observed phenomena. For example, observed differences in velum height for oral vowels and consonants in nasal consonant contexts cannot be easily explained in this model (Keating, 1990a). Slightly lower velum position during vowels in nasal consonant contexts in casual speech can be accounted for by undershoot of the target assuming that the maximum rate of velum movement is still very slow. However, fast movement of the velum during oral consonants in a nasal context is observed, which contradicts the necessary assumption for the case of vowels. As Lindblom (1983) mentioned, this model has been challenged by several studies such as Kuehn and Moll (1976) which show that 'undershoot is not an inevitable consequence of short duration'. At a fast speech rate, speakers can either speed up to reach the target or allow a decrease in the displacement.

As an alternative uniform mechanism to the undershoot model to account for coarticulation, Keating (1990a) has developed the Window model in which the target is a range of spatial values rather than a single value. Another more radically different approach is that of Browman and Goldstein (1986, 1990). In their model, the notion of a linear series of target values or targeted ranges of spatial values for any given articulator is replaced by a more complex organization
of "gestures", constrictions which harness flexible groupings of articulators. Since both of these models refer to the jaw in one application or another, it is possible to use the jaw to contrast their claims about the relationship between articulators and phonetic invariants.

1.4 Keating's Window model

As a generative grammarian, recognizing that the phonetic component must be included in the grammar to explain language-specific phonetic detail, Keating (1985, 1990a) tries to formalize coarticulation in the phonetic component as a final stage of derivation in speech production. She proposes the 'window' model as a mechanism to derive continuous articulatory movement contours from 'extrinsic allophones' (Keating, 1990a) or the 'categorical phonetic representation' (Keating, 1990b) which are the output of phonological rules. For a given physical dimension, the possible range of values, the 'window', is assigned to each feature value of a segment after phonological rules are applied. The 'window' is defined as follows:

"... a range of possible spatial values, i.e., a minimum and maximum value that the observed values must fall within. ... this window is not a mean value with a range around that mean, or any other representation of a basic value and variation around that value. It is an undifferentiating range representing the contextual variability of a feature value. For some segments this window is very narrow, reflecting little contextual variation; for others it is very wide, reflecting extreme contextual variation. ... There is no other "target" associated with a segment; the target is no more than this entire contextual range." (Keating, 1990a, p.455)
In an actual utterance, there will be a sequence of windows determined on the basis of the empirical data associated with each segment’s feature values and an interpolation process connects up these windows and finds a path through a sequence of windows with some constraints such as continuity, smoothness, and minimal articulatory effort.

With the window model, Keating attempts to account for the fact that segments show many more degrees of variability than can be accounted for by a simple dichotomy between fully specified target (as in Hammarberg, 1976) and phonetic nonspecification (as in Pierrehumbert’s (1980) proposal for tone in unaccented syllable in English). Keating claims that in her model, the apparently continuous variation in phonetic specification can be expressed easily without actual specification, since window size is continuous reflecting the degree of observed variability. For example, /h/, whose phonological description is placeless (Steriade, 1987), has associated with it the widest possible window for any place-related phonetic dimension, with no specification, while /s/, which shows almost no coarticulatory effects from its neighboring segments, will have its own specification reflected in a very narrow window. For an intermediate degree of variability such as velum height during English oral vowels (velum lowering during vowels anticipating the following nasal consonant but not to a degree which suggests a phonological rule changing them to [+nasal]) can be accounted for by association of vowels with a window which will reflect the coarticulatory effect from their neighboring nasal consonants with respect to velum lowering.
Figure 1.2 shows an example of windows for jaw position proposed by Keating for the sequence /stræ/. The consonant /s/ has the narrowest and high window, /t/ a similar but slightly wider window, /r/ a middle and medium window, and /æ/ a low and widest window. By an interpolation process these windows are connected up smoothly with /s/ exerting the most influence on the trajectory.

Even though a 'window' is defined as the range of spatial values and not as a single value, this model can be interpreted as assuming a target of each articulator. However, Keating does not explain why each articulator has its own target. Especially, it is not clear why there should be targets for the jaw. In other models such as Articulatory Phonology (Browman and Goldstein, 1986), the jaw has been treated as only a secondary articulator which may help the primary articulator (the tongue, the lower lip, etc.) to reach its aiming target. However, Stevens (1990), in the commentary on Keating's (1990a) paper, suggested that the jaw must be controlled with 'various degrees of precision' depending on acoustic requirement for the production of segments. For example, a low vowel will have a wide window for the jaw because change of the jaw position in the low vowel will exert only a small influence on the acoustic output. On the other hand, accurate position of the jaw is required for the production of strident fricatives since lower incisors play a role as an obstacle which the jet of air from the tongue constriction impinges upon, resulting in large amplitude turbulence noise (Amerman, Daniloff and Moll, 1970; Shaddle, 1991).
Figure 1.2 Sequence of schematic jaw windows for /stræ/, with contour (from Keating, 1990a, p464).
1.5 Browman and Goldstein’s Articulatory Phonology

Contrasting to Keating’s model which assumes a target (window) for each individual articulator, Browman and Goldstein (1986, 1990) have developed the Articulatory Phonology framework with a radically different concept for a 'target' in speech production -- 'gesture' or 'constriction'. Articulatory Phonology is an attempt to provide 'explicit and formal representations of articulatory organization appropriate for use as phonological representations'. It has been developed in conjunction with the computational model, 'task dynamics' (e.g., Saltzman & Munhall, 1989). Browman and Goldstein’s assumption about the relationship between phonological and phonetic structures, especially articulatory structure, can be seen very clearly in the following paragraph.

"we represent linguistic structures in terms of coordinated articulatory movements, called gestures, that are themselves organized into a gestural score that resembles an autosegmental representation. ... As abstract, discrete, dynamical linguistic units, the gestures are invariant across different contexts. Yet, because the gestures are also inherently spatio-temporal, it is possible for them to overlap in time. ... much coarticulation and allophonic variation occurs as an automatic consequence of overlapping invariant underlying gestures." (Browman and Goldstein, 1990, pp.341-342)

Each gesture involves the coordinated activity of a set of articulators that are coupled into a single functional structure. For example, a gesture for 'bilabial closing' involves the coordinated activity of the upper lip, the lower lip and the
jaw. Gestures overlap each other in time and space, resulting in gestures being hidden or blended with each other. When two gestures overlap in time across articulator tiers, a gesture on one tier can be hidden by a gesture on the other tier. One of examples they used to illustrate this type of overlap is the cross-word /ktm/ sequence in 'perfect memory'. In casual speech, 'alveolar closing gesture' for /t/ in 'perfect' is hidden by 'bilabial closing gesture' for /m/ in 'memory' and as a result, listeners cannot perceive /t/ even though its gesture is present. When gestures are overlapped in time within a tier, the two gestures are blended with each other. Possible types of 'blending' they assume are averaging, suppressing, and adding (Saltzman and Munhall, 1989). For example, production of /iki/ involves a 'palatal gesture' for /i/ and 'velar closing gesture' for /k/. Both gestures are represented under the 'Tongue Body' tier since they involve the same articulator, tongue body. They are blended with each other and the constriction location for /k/ is altered by that for /i/ without changing its location degree (Öhman, 1966). In Saltzman and Munhall (1989), the change of the /k/’s constriction location by that for its surrounding vowel was modeled by implementation of averaging-blend, while the lack of alteration in /k/’s constriction degree was modeled by implementation of suppressing-blend, i.e., suppression of vowels by velars. Degree of overlap is continuous, from the gestures being fully realized without being hidden or blended at all to being completely hidden or blended.

Gestures can be grouped hierarchically based on the criterion of
articulatory independence (Browman and Goldstein, 1989), similar to the hierarchical organization of phonological features recently developed in Autosegmental Phonology frameworks (e.g., Clements, 1985; Sagey, 1986). According to Browman and Goldstein, 'because the gestures characterize movements within the vocal tract, they are effectively organized by the anatomy of the vocal tract.' For example, the tongue tip and tongue body gestures are grouped together under a tongue gesture node based on the fact that the tongue tip and tongue body share the tongue body and jaw. At the next higher level, the tongue gesture is grouped with the lip gesture together to define a class of oral gestures, since both the tongue and lip share the jaw.

In addition to the role of the jaw as unifying oral gestures, Goldstein (1991) in this framework, suggests that the jaw differentiates orals from gutturals. McCarthy (1991) and others point out that in Arabic, gutturals -- uvular fricatives, pharyngeal fricatives and laryngeals -- behave phonologically as a natural class in terms of phonological phenomena such as guttural lowering rules and co-occurrence restrictions. McCarthy discusses the inappropriateness of the traditional SPE approach and proposes the [pharyngeal] feature for gutturals in feature geometry. However, the feature is defined as involving an "orosensory pattern of constriction" rather than as involving an active articulator, because gutturals do not share a single articulator. Goldstein (1991), on the other hand, proposes that gutturals do share an articulator. He proposes that the jaw can differentiate the gutturals from oral consonants, because the jaw is a member of
the coordinative structures of the oral gestures (i.e., gestures involving lips, tongue tip, and tongue body) but not of the gutturals.

1.6 Preview

This study takes Keating's Window model and Goldstein's proposal concerning gutturals as its point of departure. It presents measurements of jaw height during consonants and addresses the following questions: How can the observed various jaw trajectories in this study be accounted for in the Window model? What is the role of the jaw in the articulation of consonants, especially with respect to different places of articulation? Are the data consistent with the claim made by Goldstein (1991) about the role of the jaw -- unifying the oral consonants in opposition to gutturals in Articulatory Phonology?

During discussion on these questions, the following issues also are raised. Why would the jaw have a target in the Window model? Is the notion of binary participation/no participation compatible with the anatomy?

On the first point, Keating does not make it clear why the jaw has a target but assumes that all articulators have targets, e.g., velum for nasal feature. As mentioned earlier in this section, Stevens (1990) provides some acoustic considerations on this issue.

On the second point, Fujimura (1990) criticizes Browman and Goldstein (1990), saying that there can be some 'basic and inherently nonlinear
characteristics of articulatory control' which are not captured quantitatively by the simple coupling between articulators in a coordinative structure. Thus, modeling articulation without detailed consideration of anatomy would not work out very well. In particular, if we consider the Edwards and Harris's (1990) finding that the greatest contribution of the jaw displacement in speech is the movement due to the rotation of the jaw and conjecture from this finding that effect of jaw rotation movement on the production of the consonants produced in the back cavity (pharyngeal cavity) should be different from effect on production of consonants produced in the front cavity, it is not difficult to suspect that Goldstein's proposal is too simple. Rather than a simple dichotomy of participation versus no participation, we might predict a continuum of degrees of contribution of the jaw in the articulation of oral consonants based on the distance of the consonant constriction place from the center of rotation movement, i.e., the farther from the condyle a consonant is produced, the more the jaw would be involved, and vice versa. On the other hand, for the back consonants (except for laryngeals which are phonologically characterized as "placeless"), lowering of the jaw might be expected since jaw rotational movement might cause retraction of the tongue root that aids in constriction for back consonants.

Chapter 2 describes the experiment (the methods used to record, process, and analyze the data) and summarizes the results. Chapter 3 discusses how well the Window model can account for the observed jaw trajectories and what kinds of problems it has. Chapter 4 tests Goldstein (1991)’s proposal about the role of
the jaw in unifying oral gestures and differentiating oral consonants from gutturals by examining the jaw positions for consonants relative to the preceding vowels in the VCV utterances. The first part of Chapter 4 motivates Goldstein's hypothesis in more detail by reviewing briefly the phonological problem and previous solutions to the classification. The second part of the chapter then reanalyzes the data presented in Chapters 2 and 3 in several ways to see how well they conform to various predictions entailed by Goldstein's proposal.
CHAPTER II

THE EXPERIMENT: METHODS AND SUMMARY OF RESULTS

This study investigated jaw heights in VCV sequences, at all consonant places of articulation in Arabic, French, and Korean. Arabic has a wide range of consonant places in the back cavity and was chosen specifically to test Goldstein’s (1991) proposal about the role of the jaw differentiating gutturals from orals. French also has a uvular fricative. It was chosen to see how it behaves compared to the uvular fricative in Arabic which patterns with other gutturals. Korean has no consonants posterior to the velar place, but it has three high vowel places to coarticulate with [k]. If the jaw is tied tightly together with the tongue body, then coarticulation of the tongue body in the production of the velar consonants adjacent to these vowels will be reflected in jaw position. The general method was to record jaw position using a video camera. This chapter describes the method in detail and then presents an overview of the results, which will be discussed in more detail in conjunction with the predictions of Keating’s Window model and Goldstein’s proposal in Articulatory Phonology framework in Chapters 3 and 4.
2.1 Subjects

Three native speakers each of Korean, Arabic, and French served as subjects. Descriptions of the speakers are given in Table 2.1.

<table>
<thead>
<tr>
<th>language</th>
<th>speaker</th>
<th>sex</th>
<th>dialect</th>
<th>educational level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Korean</td>
<td>K1</td>
<td>F</td>
<td>Seoul</td>
<td>post-doc.</td>
</tr>
<tr>
<td></td>
<td>K2</td>
<td>M</td>
<td>Seoul</td>
<td>graduate student</td>
</tr>
<tr>
<td></td>
<td>K3</td>
<td>F</td>
<td>Seoul</td>
<td>graduate student (myself)</td>
</tr>
<tr>
<td>French</td>
<td>F1</td>
<td>F</td>
<td>Moroccan¹</td>
<td>graduate student</td>
</tr>
<tr>
<td></td>
<td>F2</td>
<td>M</td>
<td>Belgian</td>
<td>post-doc.</td>
</tr>
<tr>
<td></td>
<td>F3</td>
<td>F</td>
<td>Belgian</td>
<td>elementary school teacher</td>
</tr>
<tr>
<td>Arabic</td>
<td>A1</td>
<td>M</td>
<td>Palestinian</td>
<td>undergrad.</td>
</tr>
<tr>
<td></td>
<td>A2</td>
<td>M</td>
<td>Palestinian</td>
<td>graduate student</td>
</tr>
<tr>
<td></td>
<td>A3</td>
<td>M</td>
<td>Palestinian</td>
<td>undergrad.</td>
</tr>
</tbody>
</table>

2.2 Material

Obstruent consonants from each place of articulation from the three languages were chosen and put in intervocalic position in /VCV/ words for French and Korean, and in */VCV/ words in Arabic where vowel-initial words are

¹ This speaker was born in Spain and grown up in Tunisia (North Africa). She attended French school from primary to college in Tunisia. She studied in Paris, France (1982 - 1986) in college. Although her mother tongue is Spanish, she speaks French more than Spanish. She had no quality difference between front and back low vowels but keeps length difference.
phonotactically ill-formed. In all three languages, voiceless consonants were chosen if consonants were in contrast with respect to voicing in the same place of articulation. For surrounding vowels, all high and low vowels were chosen with the vowels being the same on either side of the consonant. The reason why high and low vowels and both front and back high vowels were chosen is to capture the maximum range of contextual effects of the neighboring vowels on the consonant since these vowels delimit the vowel space in each language. These criteria yielded thirty target word types (10 consonants x 3 vowels) for Arabic, twenty-eight (7 consonants x 4 vowels) for French, and twenty-four (6 consonants x 4 vowels) for Korean.

/?VCV/ words were used in Arabic because Arabic does not allow vowel-initial words. /?/ was used rather than another consonant because it seemed likely to have minimal coarticulatory effects on the adjacent vowel. Perkell (1990) shows that tongue pellet positions for vowels in /h/ and /b/ contexts are different from those in /?/ context or nonvowel context: 'the tokens containing /h/ mostly occupy the ventral (lower) half of the ellipse and the tokens containing non consonant or glottal stop mostly occupy the dorsal (upper) half’ (p. 273) and articulation of bilabial consonants requires upward and forward positioning of the mandible.

There is a report that glottal stop causes vowel lowering (/i/ --> [a]) in some dialects of Arabic such as Maltese (Hume, 1992). I checked with a Palestinian Arabic speaker and found that Palestinian Arabic does not have the
vowel lowering except for a/i Ablaut for Measure 1 (Herzallah, 1990).

I used existing words if possible. However, there were only few real words available in each language that fit the structure and most words used here are nonsense words.

Ten tokens of the target words randomized across consonants and vowels were written on 4 by 6 inch index cards in the script of the language. On each card, two foil words were placed before and after four target words. For the foil words, the same syllable structure (VCV sequence) and consonants as in the target words were used and three mid vowels, /e, ø, o/ and /æ, o, ð/ were used for French and Korean, respectively. For the foil words in Arabic, I used all ten consonants and the same three high and low vowels (instead of mid vowels) again because short mid vowels are phonologically absent in Palestinian Arabic. The list of target and foil words with glosses for real words are given in Appendix A. The reasons why foil words were used in each cards were as follows: first, I did not want speakers to know what the purpose or intention of the experiment. Second, I wanted speakers to read target words with the same intonation pattern and same degree of smoothness. Speakers generally tended to read all six words in a card in one breath group and the last word was read with a different intonation pattern, a falling tone, with others being read with a rising tone. The first word on each card also was read with some mistake or hesitation. The list of consonants and vowels used in the target and foil words, and the number of
real words out of whole target and foil words listed in Appendix A are given in

Table 2.2 and Table 2.3.

Table 2.2 List of consonants used in target and foil words.

<table>
<thead>
<tr>
<th></th>
<th>labial</th>
<th>coronal</th>
<th>velar</th>
<th>uvular</th>
<th>pharyngeal</th>
<th>laryngeal</th>
<th>Non-oral (guttural)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Korean</td>
<td>p</td>
<td>t</td>
<td>s²</td>
<td>tf</td>
<td>k</td>
<td></td>
<td>h</td>
</tr>
<tr>
<td>French</td>
<td>p</td>
<td>f</td>
<td>t</td>
<td>s</td>
<td>j</td>
<td>k</td>
<td>t</td>
</tr>
<tr>
<td>Arabic</td>
<td>b</td>
<td>t</td>
<td>s</td>
<td>j</td>
<td>k</td>
<td>q</td>
<td>Χ</td>
</tr>
</tbody>
</table>

Table 2.3 List of vowels used in target and foil words.

<table>
<thead>
<tr>
<th></th>
<th>high</th>
<th>mid</th>
<th>low</th>
<th>number of real words</th>
</tr>
</thead>
<tbody>
<tr>
<td>Korean target</td>
<td>i</td>
<td>u</td>
<td>a</td>
<td>5/24</td>
</tr>
<tr>
<td>foil</td>
<td>æ</td>
<td>θ</td>
<td>0</td>
<td>1/18</td>
</tr>
<tr>
<td>French target</td>
<td>i</td>
<td>y</td>
<td>u</td>
<td>1/28</td>
</tr>
<tr>
<td>foil</td>
<td>e</td>
<td>ø</td>
<td>o</td>
<td>8/21</td>
</tr>
<tr>
<td>Arabic target</td>
<td>i</td>
<td>u</td>
<td>a</td>
<td>3/30</td>
</tr>
<tr>
<td>foil</td>
<td>i</td>
<td>u</td>
<td>a</td>
<td></td>
</tr>
</tbody>
</table>

2.3 Data Acquisition

A splint similar to those used in Edwards (1985) was custom made for each subject and attached to the subject’s lower teeth. Using the splint magnifies jaw movement since the visible part of it is located farther away from the center of the rotation of the jaw than the most anterior point on the jaw, thus allowing

² In Korean /s/ changes into /ʃ/ before vowel /i/.
a finer spatial measurement resolution. A plaster cast of each subject’s lower teeth was made using dental impression material, and acrylic was molded to the teeth with a stiff round wire being embedded in it. The acrylic and the wire were trimmed to make a comfortable fit for the subject. Three points were marked on the wire with contrasting paint.

Video and audio signals were simultaneously recorded as each subject read the list in a double-walled sound-treated booth. A video-camera was used to take a profile view of the subject, as shown in Fig. 2.1. The camera was leveled using the bubble level on the supporting tripod. The distance between camera and subjects’ faces ranged from 13.5 to 14.5 inches. The camera’s zoom function was then used to enlarge the picture of the jaw and lips as much as possible. Screen measurements were calibrated using a plumb line hanging from the ceiling of the booth with known distance marked on it. By placing the plumb line in the same sagittal plane as the splint, measurement errors due to projection distortion were minimized.

Recording was done in a single session for each speaker. For calibration, the subject was recorded with the jaw in clench position before and after the speech recording. The lists of words were presented on cards held at eye level so that subjects did not have to move their heads to read comfortably. The subject sat in an Ear-Nose-Throat chair and subject’s head was secured to the chair’s head rest with a strap to minimize head movement. To record any head motion, a white wire with two reference points marked on it was attached to the
Figure 2.1. Schematic drawing of (a) the top view of the setting for data recording and (b) profile view played on TV monitor.
subject's forehead with tape above the subject's nose.

2.4 Data Processing

After recording, frame numbers (1/30 sec.) were added in a space away from the measurement points of interest, and used to select measurement frames. I chose appropriate frames for the preceding vowel, consonant and following vowel by eye. That is, scanning through the frames for each VCV token, I chose a frame which showed the lowest point during each of the vowels and a frame which showed the highest point during the consonant. The selected frames were digitized with the image processing boards, DT 2851 & DT 2858 and IRIS software. Using IRIS software, digitized images in IRIS format were converted to TIFF format. Positional values in screen pixels for five points -- two points on the wire on the nose and three on the wire on the splint -- were logged for each selected frame with programs which were developed in the OSU phonetics laboratory. About ten frames showing the marked plumb line were also chosen from each session's recording. The positions of two points on the plumb line (known to be 60 mm apart) were logged from the digitized video frames and a pixel to mm conversion formula was formulated, and used to convert screen pixels for the target points into distance in mm from the first point on the wire on the nose, which was chosen as the origin in a Cartesian space.
2.5 Correction for head movement

After all the positional values of the data points were converted to mm, they were corrected for head movement by using the reference points on the wire attached to the subject’s nose. All measurements were taken relative to the position of the head and jaw in the clenched position for that speaker. The frame of the clenched position for each speaker was used as the reference. The algorithm used for head-movement correction removes the effects of sagittal-plane rotational and translational displacement.

2.6 Coordinate transformation to the occlusal plane

Close examination of data from this experiment showed that speakers oriented their heads differently while reading, making inter-speaker comparisons difficult. In order to solve this problem, the angle between occlusal plane and splint for each speaker was measured and all the data were rotated so as to make the x-axis parallel to the occlusal plane. To measure the angle between occlusal plane and the splint, the impression of the lower teeth used to make the splint for each speaker was used. Stiff cardboard was cut to cover all the teeth and to extend to the same length as the wire of the splint. The angle was measured with a protractor taking the intercept as the point where the first point of the wire and
the cardboard met each other, as illustrated in Fig 2.2. Angles measured ranged from -13 degrees to +14 degrees. A program then recalculated resultant jaw height and degree of protrusion/retraction. The program source code is provided in Appendix D.
Figure 2.2. Schematic drawing of measurement of angle between the splint and occlusal plane.
2.7 Statistical Analysis and Summary of Results

For each subject, ANOVA was used to examine the jaw position in consonants for effects of consonant identity and vowel environment. Post-hoc tests for differences between the mean jaw positions for different consonants were also performed. The significance level in this study is $p < 0.01$ unless otherwise specified.

Mean jaw heights averaged over all vowel contexts for all consonants for each speaker are given in Fig 2.3. Means calculated separately for each consonant in each vowel context for each subject are shown and discussed in Chapter 3. Although there were some inter-speaker differences, generally coronals, especially coronal fricatives and affricates have the highest jaw positions; bilabials, velars, and uvulars intermediate; and pharyngeals and laryngeals the lowest jaw positions. All speakers from all three languages showed a significant main effect of consonant with respect to jaw height.
Figure 2.3 Mean jaw height for consonants across vowels for each speaker for all three languages. V indicates the mean jaw height of the preceding vowels. Zero on y-axis means the clench position and larger positive number means the higher jaw position. (a) for Arabic, (b) for French, and (c) for Korean.
Mean jaw protrusion/retraction for each consonant for each speaker is given in Fig 2.4. All speakers from all three languages also showed a significant main effect of consonant with respect to degree of jaw protrusion/retraction, although the effect was clearly smaller for K2 and K3. Again although there were some inter-speaker differences, generally coronal fricatives showed the largest jaw protrusion: coronal stops, labials, and velars showed intermediate values; and uvulars, pharyngeals and laryngeals showed the most retraction.
Figure 2.4 Mean jaw protrusion/retraction for consonants across vowels for each speaker for all three languages. V indicates the mean jaw protrusion of the preceding vowels. Zero on the y-axis means the clench position. A positive number means more jaw protrusion and a negative number means more jaw retraction. (a) for Arabic, (b) for French, and (c) for Korean.
The mean position of each consonant was compared to that of the preceding vowel by t-test. This analysis showed a general tendency for oral consonants to have significantly higher and more protruded jaw position than the preceding vowels. Gutturals and uvular stops had lower and more retracted jaw position compared to those of the preceding vowels even though the differences were not always significant. These effects will be important for the evaluation of Keating's Window model in the next chapter.
CHAPTER III

ARTICULATORY TARGETS IN THE WINDOW MODEL

The data on jaw position described in Chapter 2 can be considered in light of the Keating’s (1990) Window model. Recall that this model attributes coarticulatory effects of adjacent segments to a process of deriving an optimal path through a succession of target windows of varying segment-specific width. The model allows for an infinite number of different sizes of window because window width itself is a phonetic parameter, which might be chosen arbitrarily in the phonetic component of the language’s grammar. For jaw height, however, she made a prediction about window width. Based on the actual data from English and Swedish, Keating made a generalization that ‘overall higher segments (segments whose average jaw position is higher) vary less than overall lower segments’ (e.g., vowels vary more than consonants). Fig 3.1 illustrates predictions of this model about the jaw trajectories for VCV sequences with three qualitatively different sizes for consonants -- narrow, medium, and wide windows.
The narrow and medium width windows also might have different overall average jaw heights -- high, middle, and low although (given Keating's discussion of jaw height) we might expect there to be a relationship between window width and height. That is, we might expect segments with generally high jaw position to have narrower windows than segments with intermediate mean heights. The widest windows, on the other hand, would span the total jaw-height range -- hence, no distinction is possible in window height. This would correspond to a completely unspecified segment in alternative models of phonetic implementation, such as that of Pierrehumbert and Beckman (1988).
Fig 3.1. Hypothetical jaw trajectories for VCV sequences with surrounding identical high, middle, and low vowels. The columns show narrow, medium, and wide window widths for medial consonants and the rows show different heights of the windows -- i.e., a) narrow and high window, b) narrow and middle window, c) narrow and low window, d) medium and high window, e) medium and middle window, f) medium and low window, and g) wide window.
3.1 Establishing Vowel and Consonant Windows Based on Actual Data

Keating defines a ‘window’ as ‘a range of possible spatial values, i.e., a minimum and maximum value that the observed values must fall within ... not a mean value with a range around that mean or any other representation of a basic value and variation around that value ’ (Keating, 1990a, p455). According to this principle, determining the window means determining the range of spatial values for a given segment. These ranges of jaw positions for each segment for each speaker are given in Fig 3.2, 3.3, and 3.4. That is, each of the lines shows minimum and maximum values of jaw positions for each segment from the actual data. In Fig 3.4, the range for [J] is for /s/ in the environment of /i/ in Korean. The reason why the range for this allophonic variant of /s/ is given separately is that Keating proposes that her model derives continua of articulatory movements contours from allophones which are the output of the phonological rules. As predicted by the Window model, segments with windows located in a higher range showed narrower windows. For example, coronal consonants (and labials for some speakers) showed the highest and narrowest windows (similar to Keating et al.’s experimental results). Also high vowels generally have higher and narrower windows as predicted (e.g., speaker K1, K2, K3, and F3), although some high vowels for some speakers do not show much difference from low vowels in width of windows (e.g., /i/ speakers A2, A3, and F2). The window for French /i/ is wider and/or lower than those for /u/ and /y/. Furthermore, vowels generally show
Figure 3.2 Windows for segments for Arabic speakers. (a) for A1, (b) for A2, and (c) for A3.
Figure 3.3 Windows for segments for French speakers. (a) for F1, (b) for F2, and (c) for F3.
Figure 3.4 Windows for segments for Korean speakers. (a) for K1, (b) for K2, and (c) for K3.
wider windows than most front consonants, and similar width windows to back consonants. However, the window for /a/ is wider than for back consonants except for the window for /h/ for A3.

Based on the data given in Fig 3.2 - 3.4, window width and height for each segment can be established. As has been suggested elsewhere (e.g., Keating, et al., 1989), coronals in English and Swedish show relatively little contextual variability with a consistently high jaw position. The data show that the same is true of the Arabic, French, and Korean coronal fricative and affricate except for F2’s /f/. (Generally, /l/ shows a wider and/or slightly lower window.) In Keating’s model, this is accounted for by assuming that coronals have a relatively small and high window of allowable values.

The data here show that the range of spatial values allowed for glottals is very wide (except for /l/ for speaker A2) but narrower than the low vowel /a/ (except for K3). The wide window for glottals accords with the phonetic and phonological description of them as having no specification for the features that characterize place of articulation (Steriade, 1987), implying that these consonants simply take the jaw positions of the surrounding vowels.

The data here also show that generally the windows for labials, although considerably smaller than for glottals, are larger and lower than for coronals. However, the window for A1’s labial is larger but not lower than that for coronals. Furthermore, the labiodental fricative /f/ for speakers F1 and F2 shows a smaller window than the bilabial stop /p/ for the same speakers.
The range of spatial values allowed for velars also is intermediate between glottals and coronals. It is larger and lower than for labials with the exception that F2’s /k/ shows larger but not lower window.

The range of spatial values allowed for uvulars is almost the same as that for velars, but it spans medial target values with one exception — A2’s velar shows a lower window than his uvulars. Uvular fricatives for A1 and F3 show smaller windows than their velars. That window widths for uvulars are as narrow as for velars contradicts to minor prediction of the Window model that the higher the window is located, the narrower the window is, and vice versa.

The pharyngeal fricative in Arabic has a similar range of spatial values to the glottal fricative for A1 and A2, and a very large window for A3 that is even wider than his /a/.

3.2 Prediction and Evaluation of the Window Model about the Jaw Trajectories for VCV Utterances Based on the Size of Segments’ Windows

Having established the windows for various vowel and consonant types on the basis of the observed ranges of jaw position, we could predict general patterns of jaw movement for consonants out of and into the vowels according to the principles of contour continuity and smoothness, and minimal articulatory effort. Then, we could evaluate the Window model comparing the predicted jaw movement patterns with the observed real data.
3.2.1 Speaker A1

From Fig 3.2a, the Window model would predict that jaw trajectories for coronal fricatives in the low vowel context will have peaks during the consonant since the top of the range for the low vowel /a/ is lower than the bottom of the range for these fricatives. However, jaw trajectories for the other consonants in VCV sequence will be straight lines since the ranges for the vowels and the consonants overlap with each other.

As can be seen in Fig 3.5, the Window model predicts the jaw trajectories for the coronal fricatives in the low vowel context correctly, showing peaks during these consonants. It also predicts correctly that there is no change in jaw position during his glottal stop.

However, the model cannot account for the peaks observed during the coronal fricatives in the two high vowel contexts. Moreover, it cannot account for the peaks during labials, velars, uvulars, and pharyngeals in high or low vowel contexts. Instead of such peaks, the Window model predicts a straight line throughout these VCV sequences.

3.2.2 Speaker A2

Again, the Window model would predict that the jaw trajectory for the two coronal fricatives will have a small peak during the consonant in low vowel
contexts since the top of the range for the low vowel /a/ is somewhat lower than the bottom of the range for either of these consonants. However, jaw trajectories for these same consonants in high vowel contexts and the other consonants in all vowel contexts will be straight lines since ranges for vowels and consonants overlap with each other.

As can be seen in Fig 3.6, this model predicts the peak during /s/ and /ʃ/ in the low vowel context correctly. It also predicts correctly a straight line throughout VCV sequence in the case of /h/ in the low vowel contexts and /q/ in the /i/ vowel context. However, it cannot account for the observed peaks for the coronal fricatives in the high vowel contexts and for the peaks during many other consonants in any vowel environment. It also cannot account for shallow valleys during /b/ and /k/ in /u/ and /i/ vowel contexts and the valley during /q/ in the /u/ vowel context, and for /h/ in all vowel contexts.

3.2.3 Speaker A3

The Window model would predict that jaw trajectories for /b/, /t/, /s/, and /ʃ/ will have peaks during the consonant in low vowel contexts. However, jaw trajectories for the other consonants in VCV sequence will be straight lines since ranges for vowels and consonants overlap with each other.

As can be seen in Fig 3.7, the Window model predicts correctly peaks during /b/, /t/, /s/, and /ʃ/ in low vowel contexts. It also predicts correctly a
straight line for /h/ in the /i/ vowel context and /?/ in all vowel contexts.

However, this model cannot account for peaks during /b/, /d/, /s/, and /f/ in high vowel contexts, peaks during /k/ in all vowel contexts, and peaks during /q/ and /k/ in the /u/ and /a/ vowel contexts. It also cannot account for valleys during /q/ and /k/ in the /i/ vowel context and valleys during /n/ in all vowel contexts.

3.2.4 Speaker F1

The Window model would predict that jaw trajectories for /f/, /d/, /s/, and /f/ will have peaks during the consonant in the low vowel contexts. However, jaw trajectories for the other consonants in VCV sequence will be straight lines since ranges for vowels and consonants overlap with each other.

As can be seen in Fig 3.8, the first of these predictions is true. Also, there is a straight line for /l/ and /k/ in the /u/ vowel context and for /p/ and /l/ in the /u/ and /y/ vowel contexts.

However, the model cannot account for peaks during /l/, /s/, and /f/ in high vowel contexts, peaks during /p / in the /i/ and /a/ vowel contexts, a peak during /k/ in the /a/ vowel context, and a peak during /l/ in the /i/ vowel context. It also cannot account for valleys during /R/ in all vowel contexts and /k/ in the /y/ and /i/ contexts.
3.2.5 Speaker F2

For this speaker, the Window model would predict that jaw trajectories for all consonants in any vowel contexts will be straight lines since ranges for all vowels overlap with ranges for all consonants. However, as can be seen in Fig 3.9, the Window model predicts correctly only the straight lines for /s/ in the /u/ and /y/ vowel contexts and for /R/ in the low vowel context. The model cannot account for peaks during /s/ in other vowel contexts and peaks during /l/, /ʃ/, /ɹ/, and /p/ in all vowel contexts. It also cannot account for valleys during /k/ and /R/ in the high vowel contexts.

3.2.6 Speaker F3

Similarly for speaker F2, the Window model would predict that jaw trajectories for all consonants in any vowel contexts will be straight lines, since the ranges for all vowels overlap with ranges for all consonants. As can be seen in Fig 3.10, however, there are unpredicted peaks for /l/, /ʃ/, /ɹ/, /p/, and /k/ in all four vowel contexts. There are also unpredicted valleys during /R/ in the three high vowel contexts and a peak in the low vowel context.
3.2.7 Speaker K1

For speaker K1, the Window model would predict that the jaw trajectories should show peaks for /u/, /s/, /f/ and /tʃ/ in the low vowel context. As can be seen in Fig 3.11, however, there are peaks for many more consonants and many more vowel contexts. Only /h/ in all vowel contexts shows a straight line. The model cannot account for peaks during coronals in the high vowel contexts, and for all other consonants in any vowel contexts.

3.2.8 Speaker K2

As for speakers F2, and F3, the Window model would predict for K2 that jaw trajectories for all consonants in any vowel contexts will be straight lines since ranges for vowels and consonants overlap with each other. As can be seen in Fig 3.12, however, the Window model predicts correctly only the straight lines for /h/ in any vowel contexts and for the other consonants in the high vowel contexts. It cannot account for the overall peaks during the other consonants in the low vowel context.
3.2.9 Speaker K3

For speaker K3, the Window model would predict that jaw trajectories for /l/, /s/, and /ʃ/ will have peaks during the consonant in the low vowel contexts and straight lines elsewhere. As can be seen in Fig 3.13, there are straight lines for /l/, /s/, and /k/ in the high vowel contexts and for /h/ in all vowel contexts. However, there are peaks during all consonants except for /h/ in the low vowel context. The window model also cannot account for the peak in [ʃ], i.e., the /s/ in the /i/ vowel context.

3.2.10 Summary

In sum, comparison of the observed jaw trajectories shown in Fig 3.5 - 3.13 with the predicted ones shows that the Window model does not seem to account for the observed jaw trajectories at all well. The model predicts correctly the jaw trajectories for labial or coronal consonants especially in the low vowel contexts for some speakers. It also predicts correctly the jaw trajectory for glottals for some speakers. However, it cannot not account for observed peaks during many other consonants such as the coronals for F2 and F3 and /k/ for all speakers. Furthermore, it cannot not account for observed valleys during uvular consonants in the high vowel contexts and peaks in the low vowel contexts for most Arabic and French speakers. It cannot not account for the observed
downward deflection during the pharyngeal consonant for speakers A2 and A3 and the glottal stop for speaker A2. In all of these cases, the model incorrectly predicts a straight line through the overlapping sections of the adjacent vowel and consonant ranges.
Figure 3.5 Means and standard deviations for jaw heights during all ten consonants in all three vowel contexts for speaker A1.
Figure 3.5 (continued)
Figure 3.6 Means and standard deviations for jaw heights during all ten consonants in all four vowel contexts for speaker A2.
Figure 3.6 (continued)
Figure 3.7 Means and standard deviations for jaw heights during all ten consonants in all your vowel contexts for speaker A3.
Figure 3.7 (continued)
Figure 3.8 Means and standard deviations for jaw heights during all seven consonants in all four vowel contexts for speaker F1.
Figure 3.9 Means and standard deviations for jaw heights during all seven consonants in all four vowel contexts for speaker F2.
Figure 3.10 Mean and standard deviations of jaw heights during all seven consonants in all four vowel contexts for speaker F3.
Figure 3.11 Mean and standard deviations of jaw heights during all six consonants in all four vowel contexts for speakers K1.

- /Ci/
- /Cu/
- /Ci/
- /aCa/

V1 C V2
Figure 3.12 Mean and standard deviations of jaw heights during all six consonants in all four vowel contexts for speaker K2.
Figure 3.13 Means and standard deviations of jaw heights during all six consonants in all four vowel contexts for speaker K3.
There could be at least two reasons I can think of why the Window model is unsuccessful. First, determination of target window size simply based on the minimum and maximum spatial values might be too simple compared to complexity of articulation in speech. Furthermore, this method of determining the windows does not exclude spatial values which may be unfluent -- i.e., it does not consider the possibility of simple mistakes or random error. In order for this model to include only values for possible contextual variability and exclude the accidental outliers from the productions for a given segment, it might be necessary to consider not only the minimum and maximum values of the range but also the mean and standard deviation. That is, the window for a consonant might better be the range of means for the different vowel context or the range of means with some allowance for random variation in the standard deviations.

Second, vowels and consonants seem to accommodate to each other’s jaw positions in the way which cannot be captured by the Window model. It is likely that the jaw is not directly involved in the articulation of vowels or any consonants except for strident fricatives (where there may be a controlled jaw target to position the lower incisors precisely as an obstacle to the air from the tongue constriction to produce a large turbulence noise). Results from biteblock experiments provide evidence only for the indirect involvement of the jaw in the production of most segments (cf. Gay et al., 1981). Some more sophisticated notion of phonetic targets and the jaw’s relationship to them is needed.
CHAPTER IV

ARTICULATORY PHONOLOGY AND THE DISTINCTION BETWEEN GUTTURALS AND ORALS

In this chapter, the jaw position data described in Chapters 2 and 3 are used to examine the role of the jaw proposed in Goldstein (1991) -- namely its uniform participation in oral places of constriction as opposed to nonparticipation in gutturals. At the same time, this chapter examines how the observed jaw trajectories can be accounted for in the Articulatory Phonology framework in general, apart from this specific application of the framework.

The problem that Goldstein (1991) addressed with his proposal is how to explain the phonological grouping of gutturals -- i.e., uvular fricatives, and the pharyngeal and laryngeal consonants. McCarthy (1991) and others point out that in Arabic, gutturals behave phonologically as a natural class in terms of phonological phenomena such as guttural lowering rules and co-occurrence restrictions. This behavior is a problem for earlier articulator-based feature geometry representations (e.g., Sagey, 1986) because gutturals do not share a single primary articulator. Goldstein (1991) proposes an alternative: namely, that

69
the jaw can differentiate the gutturals from oral consonants because the jaw is a member of the coordinative structures of all oral gestures, -- i.e., gestures involving lips, tongue tip, and tongue body -- but not of the coordinative structures for the gutturals. This chapter tests this hypothesis about the role of the jaw by examining the jaw positions for consonants in VCV utterances. If Goldstein's hypothesis is correct, we would expect the jaw to be high during oral consonants and to show a consistent movement pattern out of and into the surrounding vowels, but would expect no jaw movements into and out of gutturals that cannot be accounted for simply by vowel-to-vowel trajectories. Section 4.1 motivates Goldstein's hypothesis in more detail by reviewing briefly the phonological problem and previous solutions to the classification. Sections 4.2 and 4.3 then reanalyze the data presented in Chapters 2 and 3 in several ways to see how well they conform to various predictions entailed by Goldstein's proposal.

4.1 The Problem of the Gutturals

4.1.1. Phonological Behavior of Gutturals in Arabic - Patterning as a Natural Class

Arabic has seven consonants which are produced at the back part of the vocal tract behind the velar place of articulation, as can be seen in the consonant system of Palestinian Arabic given in Table 4.1.
Table 4.1. Consonant chart of Palestinian Arabic.

<table>
<thead>
<tr>
<th>labial</th>
<th>dental</th>
<th>alveolar</th>
<th>palato-alveolar</th>
<th>palatal</th>
<th>velar</th>
<th>uvular</th>
<th>pharyngeal</th>
<th>laryngeal</th>
</tr>
</thead>
<tbody>
<tr>
<td>b</td>
<td>d</td>
<td>t</td>
<td>t</td>
<td>k</td>
<td>q</td>
<td>?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>f</td>
<td>θ</td>
<td>s</td>
<td>s</td>
<td>ξ</td>
<td>η</td>
<td>η</td>
<td></td>
<td></td>
</tr>
<tr>
<td>δ</td>
<td>θ</td>
<td>z</td>
<td>z</td>
<td>ξ</td>
<td>η</td>
<td>η</td>
<td></td>
<td></td>
</tr>
<tr>
<td>l</td>
<td>m</td>
<td>r</td>
<td>n</td>
<td>y</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Phonetically these back consonants seem to include a striking diversity of sounds. Laryngeals have no consonantal constriction above the glottis and hence show almost no acoustic effects on adjacent vowels. Pharyngeals are produced with the primary constriction in the lower pharynx showing the narrowest constricton between the epiglottis and the pharyngeal wall. The articulation of these consonants also involves backward movement of the root of the tongue at the bottom of the pharynx (Laufer and Baer, 1988). Creakiness in the production of the voiced pharyngeal fricative and larynx raising in the production of pharyngeal consonants are also reported in Ghazeli (1977). They are characterized by high F1 acoustically (e.g., Al-Ani, 1970; Alwan, 1989). Uvulars are produced with a narrow constriction in the upper part of the pharyngeal cavity, and involve a circular movement -- backward horizontal movement and then raising of the
tongue root for constriction in the upper pharynx (Delattre, 1971). Acoustically, uvulars are characterized by lower F1 than that for pharyngeals and wide bandwidth of F1 (Alwan, 1989).

Despite this seeming phonetic heterogeneity, six of the consonants -- namely, the uvular fricatives, the pharyngeals, and the laryngeals -- behave phonologically as a natural class in terms of three phonological phenomena characteristic of many dialects of the language (McCarthy, 1991): co-occurrence restrictions, vowel lowering rules, avoidance of syllable-final gutturals. (Interestingly, the uvular stop /q/ does not pattern consistently with the six guttural consonants.)

The first of these phenomena characterizes the Classic Arabic lexicon. Basically, homorganic consonants rarely occur together within the same root. One of the consonant sets which should be treated as homorganic in Arabic is the guttural consonant group. Roots containing two gutturals are significantly rarely observed. These co-occurrence restrictions apply more or less productively to the modern dialects as well.\(^1\)

The second phenomenon is a class of vowel lowering rules. In Measure 1 of the Arabic verb, a derivational category which has CVCVC for a triliteral root or CVCCVC for a quadriliteral root as its prosodic template, the last vowel

---

\(^1\) Actually, uvular fricatives show a dual patterning in terms of the co-occurrence restrictions: they occur neither adjacent to other guttural consonants nor adjacent to some of non-guttural consonants -- velar and uvular stops.
of the stem shows an alternation between perfectives and imperfectives.\textsuperscript{2} There are five classes of alternation of this thematic vowel in Standard Arabic, but only two classes, /a/ and a/i, are inherited in Palestinian Arabic (Herzallah, 1990). In this dialect, when an /i/ for imperfectives in a/i class is adjacent to guttural consonants, it changes into /a/, which McCarthy (1991) has accounted for by spreading [+low] (or [pharyngeal]) for gutturals to the preceding vowel. Examples from Palestinian Arabic (from Herzallah, PP. 174-175) are given in (1) and (2).

In (1), /a/ appears instead of /i/ when it is adjacent to guttural consonants. On the other hand, in (2), /i/ does not change into /a/ because there are no gutturals adjacent to it.

\begin{tabular}{lll}
(1) & Perfective & Imperfective & 3rd m. sg. \\
& sa?al & yis?al & 'asked/asks' \& nahab & yinhab & 'robbed/robs' \& faraχ & yifraχ & 'screamed/screams' \end{tabular}

\begin{tabular}{lll}
(2) & hamal & yihmil & 'neglected/neglects' \& abas & yi\v{c} bis & 'imprisoned/imprisons' \end{tabular}

\textsuperscript{2} According to Herzallah (1990), 'Measure' corresponds to the Hebrew term 'Binyaan' meaning different forms of the Arabic verb, whether derived from three or four consonant roots. In the Palestinian Arabic, there are ten Measures for the triliteral verb and two for the quadriliteral verb.
The third phenomenon is avoidance of the gutturals in syllable final position. When the morphology puts a guttural in coda position, the guttural becomes an onset by vowel epenthesis. Thus, a sequence of \( C_1VC_2VC_3V \) becomes \( C_1VC_2VC_3V \) where \( C_2 \) is a guttural. Examples from Negev Bedouin Arabic (from McCarthy 1991, p.39) are given in (3). Underlined /a/ is an inserted vowel by vowel epenthesis.

(3)

<table>
<thead>
<tr>
<th>Plain Roots</th>
<th>Guttual Roots</th>
</tr>
</thead>
<tbody>
<tr>
<td>ya`arb ‘he drinks’</td>
<td>yahar`e ‘he speaks’</td>
</tr>
<tr>
<td>a`rab ‘I drink’</td>
<td>ah`alam ‘I dream’</td>
</tr>
<tr>
<td>ta`arb ‘you drink’</td>
<td>a`xabar ‘I know’</td>
</tr>
</tbody>
</table>

4.1.2. Explanations for the Phonological Patterning of Gutturals as a Natural Class in Arabic

4.1.2.1. Traditional SPE Classification

As shown in Fig.4.1a, gutturals have traditionally been specified [-anterior, -high] in the SPE system. The features [low] and [back] distinguish the uvulars, pharyngeals and laryngeals from one another. However, this analysis suffers from phonetic unrealism. The features [low] and [back] in the SPE system are defined in terms of tongue body position. Yet laryngeals which are said to be
[+low], cannot involve the tongue at all, and pharyngeals, which are said to be
 [+low, +back], involve the tongue root instead of the tongue body (McCarthy, 1991).

4.1.2.2. Non-linear Approach -- McCarthy (1991)

The specification of gutturals also provides problems in feature geometries
developed within non-linear phonologies such as Clements (1985), and Sagey
(1986). First, if we translate SPE feature specifications directly into a feature
geometry analysis, the use of [anterior] for gutturals is impossible since in these
frameworks, [anterior] is supposed to be used for specifications only for coronal
consonants. The more crucial problem for these frameworks, especially for
articulator-based feature geometry frameworks such as Sagey's (1986), is that
gutturals do not share a single major articulator. Therefore, McCarthy (1991)
proposes a [pharyngeal] place feature on par with [labial], [coronal], and [dorsal]
in the articulator-based feature geometry. However, he defines [pharyngeal] not
as involving any articulator but rather as the "orosensory pattern of constriction
anywhere in the broad region of the pharynx", an idea which is adopted from
Perkell's (1980) suggestion that distinctive features may involve such sensory
feedback. Furthermore, to account for guttural transparency in vowel assimilation
in Arabic, he proposes that the [labial], [coronal], and [dorsal] be grouped
together under an Oral class node with both the Oral class node and [pharyngeal]
Figure 4.1. (a) Feature specification of consonants in SPE system and (b) Feature geometry proposed by McCarthy (1991).
being dominated by the Place node as shown in Fig.4.1b.

4.1.2.3 Goldstein’s Approach

Goldstein (1991) questions McCarthy’s proposal, listing two advantages of defining each basic place feature in terms of an active articulator opposed to an "orosensory pattern". First, this view is compatible with the idea that speech is composed of 'gestures formed by the independently controllable articulator sets within the vocal tract' as in Browman and Goldstein’s (1989) Articulatory Phonology framework. That is, Goldstein suggests that phonetic goals should be related to coordinated motor structures for tasks such as forming a labial constriction. Second, it is not clear whether [coronal] and [dorsal] can be defined in purely orosensory terms as well as in terms of a primary articulator.

Goldstein then proposes two alternative accounts, the more striking of which is that the jaw serves as the common articulator to differentiate oral consonants from gutturals, under the assumption that the jaw has a common function in the coordinative structures for labial, coronal, and dorsal constrictions, but does not participate in the articulation of gutturals. Specifically, given the mechanical coupling between the jaw and the lower lip and between the jaw and the tongue, raising the jaw will contribute to constrictions of lips, tongue tip, and tongue dorsum.
4.2 Evaluating the Observed Jaw Positions

4.2.1 Predictions

The same jaw data discussed in the previous chapters is reanalyzed in a different way here to test Goldstein’s hypothesis. Since Goldstein’s proposal concerns patterns based on Arabic phonology, this reanalysis will concentrate primarily on the data for the Arabic speakers. However, if feature geometry is universal, the same distinction should apply to French /R/ versus its oral sounds. Therefore, French data will also be discussed where relevant.

Goldstein’s proposal predicts two things about consonant jaw position: First, if his proposal is correct, jaw position during oral consonants will be higher than during guttural consonants, because his proposal is based on the assumption that raising the jaw contributes to constrictions for oral consonants but not for guttural consonants. Second, jaw position during oral consonants will be higher than during the neighboring vowels while there will be no change in jaw position throughout the VCV sequence for guttural consonants because his proposal assumes no jaw involvement in the articulation of gutturals.

To summarize the trends reported in Chapter 3, jaw height during consonants is plotted against jaw height during preceding vowels to see how highly they are correlated with each other. If Goldstein’s proposal is correct, we expect high correlation in the case of the gutturals but poor correlation in the case of oral consonants, as schematized in Fig 4.2. If the jaw is not involved in the
production of guttural consonants, it should simply maintain the jaw position of preceding vowels. This would give a high correlation close to 1 and datapoints clustered on or close to the x=y line as shown in Fig 4.2a. If the jaw is involved in the production of orals, it should move away from its position during the vowel in whichever direction it needs to do to help the other articulator involved in the constriction. This would give a poor correlation, with slope close to 0 and datapoints generally above the highest values for adjacent vowels as shown in Fig 4.2b.
Figure 4.2 Hypothetical situation of correlation of jaw height during consonants (a) for Goldstein's proposal, (b) for Goldstein's vowels predicted by Goldstein's proposal, and (c) for vowels.
4.2.2 Evaluating the Results

As described in Chapter 2, coronal fricatives and affricates (and the coronal stops for some speakers) showed the highest jaw positions, while pharyngeals and laryngeals showed the lowest positions, even though some differences among speakers were observed.

These results partially support Goldstein's hypothesis in that orals showed higher jaw positions than gutturals even though the uvular stop (a non-guttural) showed a similar pattern to the other guttural uvulars. However, the patterns of relationship to values during the vowel do not completely support Goldstein's claim, as can be seen in Table 4.2 and Fig 4.3, 4.4., and 4.5. The figures plot jaw height during each consonant against jaw height during the preceding vowel for each of the three Arabic speakers. The table summarizes the relationships in the plots by listing, for each consonant for each speaker, five relevant characteristics of a simple regression: (1) the slope, (2) its standard error, (3) results of a t-test comparing the slope to 0, (4) the intercept, and (5) the correlation coefficient for the regression.
Figure 4.3 Jaw height during consonants against jaw height during their preceding vowels for speaker A1. a) for gutturals and b) for orals.
Figure 4.4 Jaw height during consonants against jaw height during their preceding vowels for speaker A2. a) for gutturals and b) for orals.
Figure 4.5 Jaw height during consonants against jaw height during their preceding vowels for speaker A3, a) for gutturals and b) for orals.
Table 4.2. The slope, its standard error (SE), and results of a t-test comparing the slope to 0 (T(H0)), the intercept, and the correlation coefficient (corr.) for the regression between jaw height during consonants and jaw height during the preceding vowels are provided. ** indicates significance level at $\alpha = .01$ and * at $\alpha = .05$.

<table>
<thead>
<tr>
<th>spk</th>
<th>cons</th>
<th>slope</th>
<th>SE</th>
<th>T(H0)</th>
<th>intcpt</th>
<th>corr</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>/b/</td>
<td>.23</td>
<td>.06</td>
<td>3.97**</td>
<td>3</td>
<td>.63</td>
</tr>
<tr>
<td></td>
<td>/t/</td>
<td>.22</td>
<td>.04</td>
<td>5.50**</td>
<td>2</td>
<td>.73</td>
</tr>
<tr>
<td></td>
<td>/s/</td>
<td>.13</td>
<td>.03</td>
<td>4.78**</td>
<td>2</td>
<td>.67</td>
</tr>
<tr>
<td></td>
<td>/s/</td>
<td>.15</td>
<td>.05</td>
<td>2.88**</td>
<td>4</td>
<td>.48</td>
</tr>
<tr>
<td></td>
<td>/k/</td>
<td>.26</td>
<td>.04</td>
<td>6.16**</td>
<td>-3</td>
<td>.76</td>
</tr>
<tr>
<td></td>
<td>/q/</td>
<td>.23</td>
<td>.11</td>
<td>2.10*</td>
<td>-6</td>
<td>.37</td>
</tr>
<tr>
<td></td>
<td>/r/</td>
<td>.23</td>
<td>.05</td>
<td>4.88**</td>
<td>-6</td>
<td>.68</td>
</tr>
<tr>
<td></td>
<td>/h/</td>
<td>.70</td>
<td>.09</td>
<td>7.43**</td>
<td>1</td>
<td>.81</td>
</tr>
<tr>
<td></td>
<td>/l/</td>
<td>.69</td>
<td>.05</td>
<td>13.19**</td>
<td>-2</td>
<td>.93</td>
</tr>
<tr>
<td></td>
<td>/r/</td>
<td>.91</td>
<td>.1</td>
<td>9.16**</td>
<td>0</td>
<td>.87</td>
</tr>
<tr>
<td>A2</td>
<td>/b/</td>
<td>.22</td>
<td>.04</td>
<td>4.94**</td>
<td>-2</td>
<td>.68</td>
</tr>
<tr>
<td></td>
<td>/t/</td>
<td>-.05</td>
<td>.06</td>
<td>-.75</td>
<td>2</td>
<td>.14</td>
</tr>
<tr>
<td></td>
<td>/s/</td>
<td>-.13</td>
<td>.05</td>
<td>-2.74*</td>
<td>6</td>
<td>.47</td>
</tr>
<tr>
<td></td>
<td>/s/</td>
<td>.01</td>
<td>.03</td>
<td>.39</td>
<td>7</td>
<td>.07</td>
</tr>
<tr>
<td></td>
<td>/k/</td>
<td>.43</td>
<td>.05</td>
<td>8.74**</td>
<td>-3</td>
<td>.86</td>
</tr>
<tr>
<td></td>
<td>/q/</td>
<td>.43</td>
<td>.08</td>
<td>5.39**</td>
<td>-1</td>
<td>.71</td>
</tr>
<tr>
<td></td>
<td>/r/</td>
<td>.60</td>
<td>.05</td>
<td>12.26**</td>
<td>-1</td>
<td>.92</td>
</tr>
<tr>
<td></td>
<td>/h/</td>
<td>.93</td>
<td>.09</td>
<td>10.84**</td>
<td>-1</td>
<td>.90</td>
</tr>
<tr>
<td></td>
<td>/h/</td>
<td>.83</td>
<td>.04</td>
<td>19.59**</td>
<td>-1</td>
<td>.97</td>
</tr>
<tr>
<td></td>
<td>/r/</td>
<td>.88</td>
<td>.04</td>
<td>19.79**</td>
<td>-2</td>
<td>.97</td>
</tr>
<tr>
<td>A3</td>
<td>/b/</td>
<td>.15</td>
<td>.05</td>
<td>2.95**</td>
<td>-7</td>
<td>.49</td>
</tr>
<tr>
<td></td>
<td>/t/</td>
<td>.10</td>
<td>.04</td>
<td>2.15*</td>
<td>-7</td>
<td>.38</td>
</tr>
<tr>
<td></td>
<td>/s/</td>
<td>.03</td>
<td>.04</td>
<td>.84</td>
<td>-1</td>
<td>.16</td>
</tr>
<tr>
<td></td>
<td>/s/</td>
<td>.02</td>
<td>.05</td>
<td>.54</td>
<td>-2</td>
<td>.10</td>
</tr>
<tr>
<td></td>
<td>/k/</td>
<td>.43</td>
<td>.04</td>
<td>10.05**</td>
<td>-6</td>
<td>.88</td>
</tr>
<tr>
<td></td>
<td>/q/</td>
<td>.56</td>
<td>.04</td>
<td>15.39**</td>
<td>-9</td>
<td>.95</td>
</tr>
<tr>
<td></td>
<td>/r/</td>
<td>.75</td>
<td>.06</td>
<td>13.15**</td>
<td>-6</td>
<td>.93</td>
</tr>
<tr>
<td></td>
<td>/h/</td>
<td>1.14</td>
<td>.08</td>
<td>14.54**</td>
<td>4</td>
<td>.94</td>
</tr>
<tr>
<td></td>
<td>/h/</td>
<td>1.02</td>
<td>.05</td>
<td>22.14**</td>
<td>-1</td>
<td>.97</td>
</tr>
<tr>
<td></td>
<td>/r/</td>
<td>1.02</td>
<td>.03</td>
<td>36.06**</td>
<td>1</td>
<td>.99</td>
</tr>
</tbody>
</table>
As can be seen in the top third of Table 4.2 and in Fig 4.3b, orals for speaker A1 behave as predicted, showing poor or moderate correlations and very flat slopes (.13 - .26) with data points generally above the x=y lines. This suggests that the jaw is a member of a coordinative structure for the constriction of those consonants.

As can be seen in Table 4.2 and Fig 4.3a, gutturals except for /χ/ also generally behave as predicted for this speaker, in that they show high correlations with the preceding vowels. However, unlike the other two speakers which will be discussed later, this speaker shows jaw involvement -- jaw raising -- and shows it not only in the production of pharyngeals but also in the glottals. That is, most data points for gutturals for this speaker are above the x=y line indicating that the jaw is somewhat higher in the consonant than in the preceding vowel. Interestingly, the guttural uvular fricative /χ/ for this speaker shows a different pattern from the rest of guttural consonants. Instead of a close correlation to the vowel, it shows a flat slope, similar pattern to his nonguttural uvular stop /q/. The two uvulars show a poor correlation between the jaw height during these consonants and jaw height during the preceding vowels and, moreover, they show the same value for slopes (.23) and intercepts (-6). Both uvulars in fact look very much like /k/ except for its higher intercept (-3).

The jaw involvement in the production of gutturals and the different pattern of the uvular fricative from the rest of the gutturals provide evidence against Goldstein's hypothesis that the jaw does not participate in the production
of gutturals.

As can be seen in the middle third of Table 4.2 and in Fig 4.4b, coronals for speaker A2 also behave as predicted, showing poor correlations between these consonants and the preceding vowel. The slopes of the regression lines are also low compared to those for his gutturals. Examination of data points across the x-axis in Fig 4.4b shows that jaw height during vowels for coronals are in a higher range (around -9 to 9) than for the other orals (around -12 to 4) indicating that the jaw lowering component of the coordinative structure of vowels was coopted by the jaw raising for the coronal constriction. This pattern of higher average jaw height during vowels around coronals is also clear in the means in Fig 3.6 in Chapter 3. The relevant figure is reproduced here in Fig 4.6.
Fig 4.6 Means and standard deviations for jaw heights for Arabic /s/ vs. /f/ and those for their surrounding high and low vowels for speaker A2.
However, the velar stop for this speaker shows a slightly higher correlation compared to other orals (.60), although its slope is not so steep compared to his gutturals (0.43 for velars vs. 0.93, 0.83, and 0.88 for /χ/, /h/, and the two glottals). The labial stop, the uvular stop, and the velar stop together, for this speaker show correlation values intermediate between those for other orals (coronals) and gutturals. These consonants also show somewhat complicated patterns. They show lower jaw positions compared to the coronal consonants. Moreover, they show a lower jaw position than that for the preceding vowel in the high vowel contexts (i.e., here their data points are below the x=y line) and a higher jaw position in low vowel contexts (i.e., here their data points are above the x=y line). This complicated pattern also provides evidence against Goldstein’s hypothesis, which assumes jaw raising during oral consonants to help in the oral constriction, but cannot account for the jaw lowering.

The gutturals generally behave in unexpected ways. Although they show high correlations and high values for the slope of the regression lines as predicted, they show jaw involvement in the production of gutturals like speaker A1, but in this case, it is jaw lowering that is involved -- most data points for gutturals except for some for the uvular fricative are below the x=y line. Again, this provides evidence against Goldstein’s hypothesis.

Again, like speaker A1, speaker A2 shows the uvular fricative patterning more with the uvular stop in terms of the slope of the regression lines (.43 for /q/ .60 for /χ/), which are much lower than those for other gutturals, (even though the
former shows a higher correlation than the latter).

Even more clearly than the other two speakers, speaker A3 shows a continuum from coronal fricatives through the coronal stop, the labial stop, the velar stop, and the uvular stop to gutturals in terms of the degree of their correlation to the preceding vowels, the slope of the regression lines, and the jaw position. Fig 4.5a and 4.5b show poor correlation for coronal fricatives, intermediate for other orals with continuously different correlations, and high correlation for gutturals. Those figures show flat slopes for coronal fricatives, intermediate slopes for other orals, and steep slopes for gutturals. Finally, Fig 4.5b shows a high jaw position for coronal fricatives, intermediate jaw position for the coronal and bilabial stops, and low jaw position for velar and uvulars. Like other speakers, this speaker also shows the uvular fricative patterning with the uvular stop rather than patterning with other gutturals. Both uvulars show correlations as high as those for other gutturals, but the velar also has a high correlation. Also the uvular fricative shows a slope (.75) closer to the slope for the uvular stop (.56) than to the slopes for other gutturals (1.14 and 1.02 for the pharyngeal fricative and the two glottal consonants). Again, the velar’s slope also is not much closer to 0.

In sum, the data generally support the idea that the jaw has a common function in the coordinative structures for labial, coronal, and dorsal constrictions of raising to augment the raising of a primary articulator (tongue or lower lip) toward the roof of the mouth or toward the upper lip. By comparison to the
gutturals, the orals -- particularly the coronals -- show high jaw positions raised away from surrounding vowels. However, we do see some problems for the idea that this common function differentiates orals from gutturals. For example, the jaw lowers during some oral consonants in high vowel contexts, which is not expected from Goldstein's hypothesis. Furthermore, the jaw raises from its position in adjacent low vowels in some gutturals, such as the uvular fricative for A2 and A3, and the jaw always lowers from its position in adjacent vowels in pharyngeals for A3 and A2, which provides evidence against the second part of Goldstein's account: that the jaw does not participate in the gutturals. A more accurate characterization would be that rather than such a categorical binary distinction (the jaw does or does not participate), there is a continuum of degrees of participation and also varied roles as described in more detail below.

Two extreme cases were observed. Coronals, particularly, coronal fricatives, showed clear and relatively invariant jaw positions, as the near-zero slopes of their regression lines indicate. Glottal consonants on the other hand, showed the widest range of values for jaw height. Here the jaw simply maintained whatever the position it had adopted in aiding the gesture of the adjacent vowel.

The invariant jaw values for the coronal fricatives might be interpreted as indicating that the jaw must be directly controlled for some aspects of these consonants. In other words, the jaw raising may not be only a subpart of the coordinative structure for coronal constriction gestures but also a necessary gesture
with its own fixed task. What could the extra gesture be? Whatever this task is, it must involve more than the simple seal for the coronal stop.

Two potential candidates are suggested in the literature on coronal fricatives. First, there may be some physiological requirement of stiffness of the tongue for these consonants. Stone (1991), and Stone, Faber, Raphael & Shawker (1992) show that /s/ is produced with a midsagittal groove along the entire length of the tongue and much contact of the tongue with the anterior portion of the palate and that /ʃ/ was produced with an oblique tongue shape at the anterior and dorsal portions of the tongue and a midsagittal groove and much tongue contact with the posterior portion of the palate only in the posterior tongue. They speculate that the groove shape would be made by bracing the tongue against the palate so that the tongue can stiffen and take on surface shapes that would otherwise be impossible. This finding can be interpreted as implying that the jaw should be in a fixed position to support the specific tongue shape.

The second task may involve the lower teeth as a necessary obstruction to shape and amplify the noise source for the coronal fricative /s/ (Stevens, 1990; Shaddle, 1991). Positioning the teeth in this way would require that jaw height be controlled directly and not only as a member of the coordinative structure for the tongue tip raising gesture. Jaw protrusion in production of this consonant may also be involved in positioning the lower teeth as an obstruction in front of the noise source.

In addition to these two clearly contrasting cases -- coronals and
laryngeals -- two intermediate patterns were observed. The first pattern is in labial and velar consonants. Although they did not show such invariant positional values as the coronals, still there was a fairly consistent pattern of movement out of the preceding vowel. As the relationship of their curve to the $x=y$ line indicates, the jaw during these consonants is higher than in the preceding vowel (i.e., data points are above the $x=y$ line), indicating that the tongue or the lower lip for these consonants must be higher than in the preceding vowel.

Similarly, both the uvular stop (which is considered to be a non-guttural) and the uvular fricative (which is considered to be a guttural) showed some movements for the consonants out of the preceding vowel, even though the direction of the movement was different from that for the labials and velars in high vowel contexts. The jaw moved downwards from preceding high vowels and upwards from low vowels, as the pattern of the data points in the plot indicates. This pattern indicates that the targeted constrictions for the uvulars are between the targets for the high vowel and targets for the low vowels. In these cases, the jaw seems to cooperate with the tongue to achieve the target of the uvular-closing gesture with accommodation to the jaw's participation in the tongue body gestures for the surrounding vowels.

Further support for this interpretation comes from the comparable data for the French speakers, shown in Figs 4.7 - 4.9. The French uvular fricative showed a similar pattern to the two uvulars in Arabic. For F2 and F3, the jaw was lower compared to the surrounding vowels in the high vowel contexts while it
was higher than the surrounding vowels in the low vowel contexts. This suggested medial tongue constriction of the uvular consonants is contradictory to the observations of Jackson (1989) whose factor analysis of midsagittal tongue surface shapes for the velars and uvulars showed that both velars and uvulars should be treated as [+high]. Rather, it supports the traditional description of the uvulars as [-high] and [-low].

The other intermediate pattern involves the pharyngeal fricative for A2 and A3 and glottal stop for A2. As can be seen more clearly in Fig 4.10 repeated from Chapter 3, these consonants for these subjects show a downward deflection of the jaw during the consonant even though the amplitude of the movement is small compared to movements for orals or uvular consonants. This pattern of jaw lowering relative to the adjacent vowels is different from the patterns for glottal consonants, which showed straight lines. The jaw seems to participate in such a way that it cooperates with the tongue to achieve some targeted tongue position that is lower than that of any vowel. Such an interpretation is most intuitive for the pharyngeals, which are specified to have a tongue root constriction low in the pharynx.

The unexpected jaw involvement in A2’s glottal stop on the other hand, might be a merely passive byproduct of a non-lingual target. Suppose that the larynx must be lowered to produce the laryngeal target for creaky voice (a common allophone of [?]). The larynx can be lowered as a result of the
Figure 4.7 Jaw height during consonants against jaw height during their preceding vowels for speaker F1.
Figure 4.8 Jaw height during consonants against jaw height during their preceding vowels for speaker F2.
Figure 4.9 Jaw height during consonants against jaw height during their preceding vowels for speaker F3.
contraction of the strap muscles in the neck. Thus the strap muscles may be part of the coordinative structure for producing this speaker's target realization of the glottal stop. Since the strap muscles are connected to the hyoid bone, contraction of the strap muscles causes pulling on the hyoid bone which can lower the jaw. This results in lowering the jaw along with /n/. If this is true, then the same mechanism might be at work in the production of pharyngeals, which showed lower position compared to any preceding vowel. Creakiness of the voiced pharyngeal fricative in Ethiopian languages has already been reported in studies such as Hayward & Hayward (1989). If the same is true of the variety of Arabic examined here, then the same physiological effect as for the glottal stop might be applied to jaw lowering in pharyngeals. However, Ghazeli's (1979) report of raising of the larynx instead of lowering in production of the pharyngeals makes it difficult to assume the same kind of physiological effect as for the glottal stop. Even if we assume that the jaw is a member of the coordinative structure for pharyngeal gesture in this way, there still remains one more problem to be solved. The behavior of the jaw in this coordinative structure is different from those in the coordinative structures for other consonants: unlike other consonants, especially velars, in which the context with the tongue furthest away triggers the most jaw cooperation, in pharyngeals, the context which appears to be furthest away from "goal" for pharyngeals does not trigger more jaw cooperation. In other words, in velars, we see the pattern shown in Fig 4.11a which would lead us to expect the pattern for pharyngeals to be like the pattern shown in Fig 4.11b. However,
instead we get the pattern shown in Fig 4.11c. So, the pharyngeals do not behave as though the jaw were simply part of the coordinative structure as it is in velars which behave as if there were an invariant equilibrium position which involves the jaw in its coordinative structure. There might be more complicated interaction among articulators involved in the production of pharyngeals than we expect. If we know how the jaw lowering in pharyngeals really affects pharyngeal constriction, it would be easier to solve this problem. If we consider the anatomical fact that the vertical displacement of the jaw is mostly due to rotation movement of the jaw, we might be able to find the answer: for the pharyngeal constriction, the jaw rotates a lot to pull the jaw downwards and backwards resulting in retraction of the tongue root.
Figure 4.10 Means and standard deviations for jaw heights during the pharyngeal fricative and the glottal stop in high and low vowel contexts for some Arabic speakers: (a) for the pharyngeal fricative for speaker A2 (b) for speaker A3, and (c) for the glottal stop for speaker A2.
Figure 4.11 Jaw trajectories for a) velars and b) pharyngeals expected from the jaw's being a member of the coordinative structure for velar closing gesture and pharyngeal closing gesture, respectively, and c) observed jaw trajectory for pharyngeals.
In sum, the jaw’s contribution to the articulation of consonants is not so simple as Goldstein (1991) claimed. Contribution of the jaw was observed in articulation of the orals but it was also observed in some guttural consonants such as the uvular fricative and pharyngeal consonants (A3 and A2) where no contribution of the jaw was expected according to Goldstein’s hypothesis. Consonants where jaw participation was observed showed some differences in the ways how the jaw participates. Coronals showed invariant jaw positions to which the surrounding vowels accommodated while other consonants did not show invariant jaw positions, and accommodated more to the lower tongue targets for the surrounding vowels than vice versa. We could apply Lindblom’s (1983) analogy of window cleaning to these different degrees of jaw participation. A window cleaner can move his feet to shift his body as well as stretch his arm away from his body in synergistic interaction. This interaction can show continuously different degrees of trade-off relationships between the amount of movement of the feet and the arm. In the same way, producing speech segments can show a relationship between the two mechanically coupled articulators, the jaw and the tongue or the jaw and the lower lip. For example, production of coronals is at one extreme end, where a large amount of jaw raising is perhaps accompanied by little tongue raising in a cooperative way. Production of uvulars involved lesser jaw involvement than for coronals but still the jaw seemed to cooperate with the tongue to achieve the tongue root constriction.

Thus, whatever the phonetic basis of guttural vs. oral distinction, it
cannot be simply that the jaw does not contribute to guttural articulation. However, results from this study can be interpreted as supporting Goldstein’s claim if we reinterpret his claim in a more sophisticated way. Rather than making a single binary distinction (participation vs. no participation), we can refer to how the jaw participates in guttural vs. oral consonant articulation: jaw raising for orals vs. no jaw raising (lowering or no participation) for gutturals. However, the problem of differentiating the uvular stop (oral consonant) from the uvular fricative (guttural consonant) in terms of how the jaw participates still remains unsolved.

4.3 Inter-speaker Differences

In this section, we turn to some inter-speaker differences that are somewhat problematic to Goldstein’s hypothesis. The velar stop for A2 showed different pattern from velars for the other speakers. Instead of raising of the jaw for velars in all vowel contexts, he lowered the jaw in the high vowel contexts showing similar pattern to uvular consonants. This inter-speaker difference might be explained by the different shape of the palates. As shown in Fig 4.12, A2’s palate was short and the back of the palate curved downward while A3’s palate was long and flat all the way to the back of the palate. A2 does not have to raise his tongue and the jaw much for constriction for the velar stop compared to other speakers. A similar pattern and interpretation are given in Ladefoged et
al. (1972). Ladefoged et al. found that the variability in jaw position and the degree of palate doming were related: those speakers who had shallowly domed palates showed a larger variability in jaw positions at vowel midpoint than those who had deeply domed palates.
Figure 4.12. Schematic drawing of the palate for speaker A2 and A3.
Another type of individual difference was also observed: the different degree of involvement of the jaw in the articulation of segments. Speaker K1 and speaker K2 showed different patterns in jaw movement as can be seen in Fig 4.13. When we compare the jaw trajectories for these speakers, some differences can be observed: first, the whole range of jaw movement for the consonants and their neighboring vowels for K1 is much larger than for K2 (K1:59.5 mm, K2:20.8 mm) implying that K1 uses the jaw more than K2 does. Second, K2 shows larger variability in jaw height during consonants, especially /p/, /t/, and /s/, than K2 does. It seems that in the case of K1, the jaw is not only a member of the coordinative structure for raising gestures for consonants but also an articulator which must be directly controlled (or has own specification). On the contrary, in the case of K2, the jaw is a member of the coordinative structure of the raising gestures for consonants as for K1, but not directly controlled. A similar pattern is reported in Johnson et al.(1993). Some of the speakers in their experiment showed both a higher jaw position and a higher tongue position for the tense vowel /u/ in 'do' than in its lax counterpart, /U/ in 'dood', while other speakers used only the tongue height difference for this pair with the fixed jaw height. Johnson et al. interpret these data as indicating that the jaw is 'more closely tied to the tongue body gesture' for speakers who used both the jaw height difference and tongue height difference than for speakers who used only the tongue height difference. This interpretation can be applied to the different pattern of the jaw
Figure 4.13 Mean and standard deviation of jaw heights during /p/, /β/, and /s/ in all four vowel contexts for speakers K1 and K2.
involvement in articulation of consonants between K1 and K2. For K1, the jaw is more closely tied to the tongue tip, tongue body, or lip gestures than K2. This different articulatory relationship between the jaw and the tongue or lip can be modeled at the interarticulatory level in the Task dynamic model, i.e., different interarticulatory organization as Johnson et al. suggested for the different pattern of the jaw involvement in tense/lax distinction among speakers.

A different degree of the jaw involvement in articulation was also observed in the articulation of labials. As can be seen in Fig 4.4b, A2’s labials also did not show raising of the jaw in high vowel contexts suggesting some active compensation of the upper lip for lip closure for /b/. This decreased involvement of the jaw in A2’s bilabial gesture also can be modeled at the interarticulatory level in the Task dynamic model, i.e., as different interarticulatory coordination.

The individual differences discussed so far seem to be related to the different degrees of participation among member articulators in the coordinative structures for achievement of the articulatory gestural target and they could be modeled as different interarticulator organization in the Task dynamic model. However, the different patterns of jaw involvement in production of the glottal fricative and the pharyngeal consonant for A1 and A2 might not be accounted for by the same mechanism as for individual differences discussed so far. Speaker A1 showed jaw raising out of the preceding vowel while speaker A2 showed jaw lowering. This difference should be accounted for by different gestural target. This type of individual difference provides support for the conclusion made by
Johnson et al. (1993) about the "goals" or "targets" of speech: they propose that 'universal articulatory phonetic hypothesis' might be wrong or cannot account for all possible inter-speaker variabilities. An alternative hypothesis that speakers use 'auditory goals' might be correct. However, to make any conclusive claim about the targets of speech, this study needs more speakers and more variety of analyses.
CHAPTER V
CONCLUSION

The present thesis reports cross-linguistic study on the role of the jaw in the articulation of consonants by investigating jaw position in consonants of three Arabic speakers, three French speakers, and three Korean speakers. This study focused on the two topics using the jaw position data as the given phonetic dimension. One is the relationship between phonetic specification and phonological specification which has been one of the central topics in phonetics. Another is the claimed role of the jaw differentiating a group of consonants from another group of consonants, especially in terms of places of articulation.

There have been many attempts to model the relationship between abstract and discrete phonological representation and continuously varying phonetic representation. This study tested two recently developed theories: Keating's Window model and Browman and Goldstein's Gesture model in the Articulatory Phonology framework.

The jaw position data did not support the Window model in which the
'target' for a segment in speech is 'a possible value of spatial values, i.e., minimum and maximum value that the observed values must fall within'. Based on the jaw position data gathered in this study, this model predicted that jaw movement patterns for most consonants in most VCV sequences would be straight lines. In particular, all back consonants overlapped in ranges with all vowels, and so did many oral consonants. These predictions held for some glottal consonants for some speakers, and some oral consonants especially in high vowel contexts. However, real data for most VCV sequences for most consonants showed peaks or valleys during consonants where none were predicted. The model also predicted peaks for many speakers during some oral consonants, particularly coronals in low vowel contexts, which fits to the observed jaw movement patterns for those given consonants for those speakers. However, real data showed peaks during the same consonants not only in the low vowel contexts but also in high vowel contexts. Furthermore, peaks were observed during other consonants in high and low vowel contexts for most speakers.

On the other hand, the Articulatory Phonology framework in which 'gesture' for vocal tract variables are the units for both the phonetic and phonological representations, accounts for the most observed jaw trajectories. In this framework, the jaw does not have any targets of its own, but jaw raising is involved in constriction gestures for oral places of articulation. The jaw peaks during oral consonants then would be explained by the jaw helping to raise the lower lip or tongue tip or body away from its lower position during the more open
oral tract for the vowel. However, there was an unexpected jaw movement pattern for pharyngeals, a downward deflection in all vowel contexts not apparently aiming at some common mid tongue height.

As an alternative to the previous proposals about phonological representation of gutturals which behave as a natural class in Arabic phonology, Goldstein (1991), in the Articulatory Phonology framework, proposed that the jaw differentiate orals from gutturals under the assumption that the jaw has a common function in the coordinative structures for labial, coronal, and dorsal constriction, but does not participate in the articulation of gutturals. The jaw position data partially supported his proposal. In plots of consonant position against the vowel, patterns of contextual dependence seem to differentiate oral consonants from gutturals. These patterns do support the idea that the jaw has a common function in the coordinative structures for labial, coronal, and dorsal constrictions of raising to augment the raising of a primary articulator (tongue or lower lip) toward the roof of the mouth or toward the upper lip. However, we do see some exceptions: for example, the jaw lowers during oral consonants such as velars and uvular stops in high vowel contexts, which is not expected from Goldstein’s hypothesis. Furthermore, the jaw raises from its position in adjacent low vowels in the uvular fricative for some speakers and the jaw always lowers from its position in adjacent vowels in pharyngeals for some speakers, which provides evidence against the second part of Goldstein’s hypothesis: that the jaw does not participate in the gutturals. A more accurate characterization would be that rather
than such a categorical binary distinction (the jaw does or does not participate), there is a continuum of degrees of participation and also varied roles.

In this continuum, coronals are at one extreme, showing clear and relatively invariant jaw positions with the narrowest range of values while glottal consonants are at the other extreme showing a wide range of values for jaw height and the jaw simply maintaining whatever position it had adopted in aiding the gesture of the surrounding vowels. The rest of the consonants are intermediate on the continuum showing various degrees of jaw involvement and also various types of jaw involvement depending on where the consonants are produced in the vocal tract. Labials showed a lesser jaw involvement than coronals, but more jaw involvement than velars. Velars showed a small degree of jaw involvement compared to the labials for most speakers, but jaw raising was generally involved in the production of both these consonants. On the other hand, in the uvular stop and fricative, jaw lowering was observed in the low vowel context while jaw raising was observed in the high vowel contexts. Pharyngeals, which are closer along the continuum to the glottals, showed jaw lowering in all vowel contexts for most speakers.

Some thought was given to possible reasons for why the Window model failed to account for the most observed jaw movement patterns. First, determination of target window size simply based on the minimum and maximum spatial values might be too simple compared to complexity of articulation in speech. Second, vowels and consonants seem to accommodate to each other in
a way which cannot be captured even by target windows for the jaw. It is likely that the jaw is not directly involved in the articulation of vowels and any other consonants except for strident fricatives.

Reviewing possible reasons for the apparently exceptional target-like behavior during strident fricatives, we are particularly taken by Steven's (1990) notion that the jaw must be high to position the lower incisors precisely as an obstacle to the air from the tongue constriction to produce a large turbulence noise. This direct control of the jaw also leads us to reexamine how the Articulatory Phonology framework treats the jaw in the coordinative structure for a given constriction. While the Window model assumes that the jaw has its own target and is directly controlled, the Articulatory Phonology framework assumes that the jaw is only one part of the articulator complex for making the tongue tip constriction.

The results from this study lead us to think that some more sophisticated notion of phonetic targets and the jaw's relationship to them is needed to improve on the Window model. Also, they lead us to reconsider the basic assumption of the Articulatory Phonology framework. The theory says that 'gestures', or constrictions involving vocal tract variables are the targets in speech. Our data suggest, however, that interarticulatory relationships in the coordinative structure need to be better studied for inter-speaker differences. Also the theory might be improved by allowing for the direct control for an individual articulator, the jaw,
during strident fricatives, where targets might need some consideration of acoustic
or auditory effects of shapes besides those involved in the constriction proper.
REFERENCES


Stone, M., A.Faber, L.J. Raphael, and T.H. Shawker (1992) 'Cross-sectional tongue shape and linguopalatal contact patterns in [s], [z], and [l],’ *Journal of Phonetics* 20, 253-270.

Sussman, H.M., P.F. MacNeilage, and R.J. Hanson (1973) 'Labial and mandibular dynamics during the production of bilabial consonants: preliminary observations,' *Journal of Speech and Hearing Research* 17, 397-420.


APPENDIX A

List of the target and foil words.

1. Target words

Arabic

/ FILIBI/ / FIUBU/ / FIA:BA/ 'to refuse'
/ FIITI/ / FIITU/ / FIA:TA/ 'he came'
/ FISTI/ / FIISU/ / FIA:SA/
/ FISTA/ 'a thing'
/ FISKI/ / FIUKU/ / FIA:KA/
/ FIQIS/ / FIQU/ / FIA:QA/
/ FISKI/ / FIYU/ / FIA:Ya/
/ FISHI/ / FIHU/ / FIA:HA/
/ FISHI/ / FIHU/ / FIA:HA/
/ FISHI/ / FIHU/ / FIA:HA/
/ FISHI/ / FIHU/ / FIA:HA/
/ FISHI/ / FIHU/ / FIA:HA/
/ FISHI/ / FIHU/ / FIA:HA/
### French

| /ipi/  | /upu/  |
| /ifi/  | /ufu/  |
| /iti/  | /utu/  |
| /isi/  | /usu/  |
| /ifi/  | /ufu/  |
| /iki/  | /uku/  |
| /iia/  | /ulu/  |
| /ypy/  | /apa/  |
| /yiy/  | /afa/  |
| /tay/  | /ata/  |
| /isy/  | /asa/  |
| /yiy/  | /afa/  |
| /kyi/  | /aka/  |
| /ya/   | /a/    |

### Korean

| /ipi/  | /upu/  |
| /iti/  | /utu/  |
| /isi/  | /usu/  |
| /tji/  | /ufu/  |
| /iki/  | /uku/  |
| /ihi/  | /uhi/  |
| /ipi/  | /apa/  |
| /iti/  | /ata/  |
| /isi/  | /asa/  |
| /tji/  | /afa/  |
| /iki/  | /aka/  |
| /hi/   | /aha/  |

- 'purchase'
- 'melancholy'
- 'a universe'
- 'death from hunger'
- 'a baby'
- 'Oh!'
2. Foil words

French

/epe/ ‘sword’ /øpø/ /opo/
/efe/ ‘effect’ /øfø/ /ofø/ ‘car’
/ete/ ‘summer’ /øtø/ /oto/ ‘hot’
/ese/ ‘try’ /øsø/ /oso/ ‘oral (pl.)’
/eje/ /øʃø/ /øʃø/ ‘happy’
/eko/ /øko/ /øko/ ‘oral (pl.)’
/eæe/ /ø ə ø/ ‘happy’

Korean

/æpæ/ /æpæ/ /æpæ/
/ætæ/ /ætæ/ /ætæ/ ‘in a hurry’
/æsæ/ /æsæ/ /æsæ/ /æsæ/ ‘in a hurry’
/ætʃæ/ /ætʃæ/ /ætʃæ/ /ætʃæ/ ‘in a hurry’
/ækæ/ /ækæ/ /ækæ/ /ækæ/ ‘in a hurry’
/æhæ/ /æhæ/ /æhæ/ /æhæ/ ‘in a hurry’

/æ/ /æ/ /æ/