ARE SYLLABLES UNITS OF SPEECH MOTOR ORGANIZATION?

—A Kinematic Analysis of Labial and Velar Gestures in Cantonese

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The University of Connecticut, 1995

Syllable level organization has been observed in articulatory movement patterns in American English (Krakow, 1989; Sproat & Fujimura, 1993; Browman & Goldstein, 1994). This study investigates the issue of universality of syllable structure from the aspect of articulatory phonetics. Articulatory characteristics and coordination patterns of two independent articulatory subsystems, velum and lower lip, and their acoustic manifestations, are examined during the production of Cantonese disyllabic nonsense utterances containing /m/ in one of three syllable positions, syllable-initial, syllable-final or syllabic. The results indicate consistent effects of syllable structure on both velar and lower lip movements, spatially and temporally, for the utterances examined. For utterances containing syllabic nasals, compared to those with syllable-final or syllable-initial nasals, durations of velar lowering and the low velar plateau were longer, displacement amplitudes of velar lowering were greater, and the positional minimum of the velum was lower; similarly, greater durations and displacement amplitudes of lower-lip gestures were also found for utterances with syllabic nasals. For utterances with syllable-final nasals, compared to those with syllable-initial nasals, greater displacement amplitudes of velar lowering, lower positional minima of the velum and longer durations of lower-lip plateau were found. Acoustic duration of nasal murmur also showed clear differences. Effects of syllable structure were also found on the coordination patterns between the velar and lower lip movement. For utterances with syllabic nasals, compared to those with syllable-final or syllable-initial nasals, velar movement began earlier and finished later relative to lower lip movement. In utterances with syllable-final nasals, although the downward velar movement began no later than those with syllable-initial nasals, the velum reached a relatively lower position than in those with initial nasals.

Comparisons of these findings to those for American English (Krakow, 1989) indicate that, while in both languages, articulatory movement patterns of velum and lower-lip systematically show evidence of syllable level organization, the actual patterning is quite different between the two. A syllable structure patterning model is proposed to account for the differences.

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A Dissertation

Submitted in Partial Fulfillment of the

Requirements for the Degree of

Doctor of Philosophy

at

The University of Connecticut

1995

UMI Number: 9541615

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300 North Zeeb Road
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APPROVAL PAGE

Doctor of Philosophy Dissertation

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ACKNOWLEDGMENTS

Preparation of this dissertation was supported in part by NIH grant DC-00121 to Haskins Laboratories, 270 Crown Street, New Haven, CT.

Making the right choice for your advisor is half instinct and half luck. I got an A in making my choice. I would like to express my deepest gratitude to my major advisor, Ignatius Mattingly, who has guided, supported and encouraged me in many ways during my years as a graduate student at the University of Connecticut. Through his constructive criticism and tireless correction, I have learned to think and write as a researcher. He was always ready to offer help when I needed it, academic or non-academic. I enjoyed so much of his wisdom as a teacher and a scholar, his humor and care as a friend, and his Volvo as a commuting partner.

I would like to thank my other committee members, Arthur Abramson, Katherine Harris and Rena Krakow for their guidance at every stage of this research project. Over the years, I have enjoyed listening to Arthur on various topics and benefited a great deal from his knowledge of languages; Kathy's questions have always kept me on my toes and made me think more critically; and Rena's previous work on syllable structure has inspired this project. Rena has done more than her share on this project by sitting at the terminal with me for long hours looking at the data and trying to make sense out of them, and arguing with me so that I would not get off the right track. She has been a strict teacher and a good friend.

I would also like to extend my gratitude to Freddie Bell-Berti, Anders Löfqvist and Walter Naito. Freddie has helped me tremendously with her expertise on Velotrace and velum movement which included offering herself as a guinea pig at the preparation stage of this project. She also gracefully served as my outside examiner for the defense. Anders has unselfishly taught me to write procedures that automated the signal processing and made the project manageable. Walter did a wonderful job on Velotrace insertions. Without their help, this project could not have been accomplished.

I would also like to thank the following people who have played important roles in my academic growth over the years: Diane Lillo-Martin, David Michaels, Cathi Best, Andrea Levitt, Doug Whalen, Philip Rubin, Vince Gracco, Carol Gracco, Len Katz, Leigh Lisker, Bruno Repp, and Michael Studdert-Kennedy.

I am very grateful for all the technical and administrative support I got from Haskins Laboratories and the University of Connecticut. Special thanks go to Ed Wiley, Donald Hailey, Yvonne Manning, Vincent Gulisano, Michael D'Angelo, William Scully, Fawn Wang, Judy Marcus, Alice Dadourian, Joan Martinez, Philip Chagnon, Betty Delise, and Lisa Fresa.

I would like to take the opportunity to thank my fellow Haskins buddies, for we all have had our frantic moments at times and kept the same weird hours at the Lab, Joaquín Romero, Doug Honorof, Dorothy Ross, Melanie Campbell, Pailing Hsiao, Alice Faber, Laura Koenig, Michele Sancier, Margaret Dunn, Dani Byrd, Rob Avery, and Sandra Chiang.

I admire my brave subjects for their devotion to science. Without their cooperation, this project could not have been accomplished. Thank you!

I would like to thank my friends Jean and Robert DeValve for their unconditional love and moral support, Paula and Peter Cappola for their friendship.

Last but not the least, my thanks go to my husband, Ping, for his love, understanding, support, endless trips to Haskins with me, and simply being there for me. I could have never finished this degree without him.

Finally, I would like to dedicate this thesis to my parents, who have given me so much and have always believed in me.

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CHAPTER ONE

INTRODUCTION

The purpose of this thesis is to present phonetic evidence for the syllable in Cantonese in both articulatory and acoustic dimensions, and to characterize its role in speech motor organization.

1.1 Background Review

The term *syllable* has been commonly used by phonologists, phoneticians, speech scientists, psychologists and speech pathologists. Many researchers have commented on the importance of the syllable in human communication: "All spoken languages are syllabic and constrain syllabic structure in terms of consonants and vowels. The syllable is a unit of timing in articulation, of contrast and compression in perception" (Studdert-Kennedy, 1977, p. 37); "......syllable structure is essential for efficient speech communication and not simply a concomitant linguistic structure" (Mattingly, 1981, p. 418). However, despite the importance of the syllable in linguistic analysis, as shown in a vast linguistic literature, and the ever increasing evidence for the linguistic functions of the syllable in languages, limited physical evidence has been found for the syllable as a general phonetic feature of human articulatory organization.

1.1.1 Evidence for the Syllable from Phonological Studies

Evidence for the syllable, as an abstract unit, has been found in phonological data in various languages. For example, the most basic phonological evidence of the phonotactic distribution of segments is found in most of the languages in the world. According to Bell and Hooper, "Languages are more likely to have initial consonant clusters than final clusters. The world's languages are split about evenly between those with initial clusters and those without. But less than half, perhaps as few as one-quarter, have final clusters" (1978, p. 9). Also there are many languages which allow some phonemes in syllable-initial position but not in syllable-final position. One such example is the distribution of the nasal consonants in Mandarin Chinese; the alveolar nasal /n/ is allowed both syllable-initially and syllable-finally, the bilabial nasal /m/ is allowed only syllable-initially, and the velar nasal /ŋ/ only syllable-finally. Similarly, in many languages, the distribution of allophones is based mainly on their position in the syllable. For example, in Cantonese, while the released forms of the phonemes /p', t', k'/ occur in syllable-initial position, their non-released counterparts, /p˺, t˺, k˺/, occur only in syllable-final position. In many varieties of English, the /l/ in syllable-initial position as in *lead* is defined phonologically as clear /l/ and is distinguished from its allophonic form in syllable-final position, the dark /ɫ/, as in *bill*. Many phonological processes are applicable only when the segments are in the "right" syllable position (see examples in Donegan & Stampe, 1978). And such "position sensitive" phenomena were found in the disordered speech of children as well. However, the phonological evidence for the syllable is at an abstract level and even the phonological analyses of the syllable have been shown to be problematic in many cases (e.g., Saib, 1978; Clements & Keyser, 1983). For example, Bell & Hooper (1978) pointed out that in English it is difficult to decide the syllable boundary when the intervocalic consonant or consonant cluster seems to belong equally to the preceding or following syllable as in *apple* or *attic*.

1.1.2 Evidence for the Syllable as a Psychological Reality

The existence of the syllable also gets support from empirical evidence, or in other words, the syllable is psychologically real. For example, it has been shown that a speaker of a language without any linguistic training usually has a very clear idea of the number of syllables in an utterance (Malmberg, 1963). Data collected on spontaneous word fragmentation in children, (two to three years old), showed that after being interrupted during the articulatory process, the children either restarted from the beginning of a word or from an intervocalic consonant directly preceding the place of interruption, which indicates that there may be syllable sized articulatory units (Wijnen, 1988). Evidence of a psychological basis of the syllable is also seen from studies reporting speech errors produced by normals (Fromkin, 1973; MacKay, 1978) and by children and adults with speech and language disorders. So and Dodd (1994) reported that several Cantonese-speaking children referred to their clinical service showed errors involving syllable-final position. One such error consistently produced by a 4-year-old child was that while he was able to produce the alveolar nasal /n/ correctly in syllable-initial position, he always velarized /n/ in syllable-final position, e.g., [fɐn]—>[fɐŋ], or [jɐn]—>[jɐŋ]. Phonological errors observed in adult aphasic speech also lend support to evidence for the syllable. For example, from spontaneous speech interviews, a 2000-word sample was obtained from each of 17 aphasic patients (Blumstein, 1978). While 42.4% of phoneme substitution errors made by the patients occurred syllable-initially, only 17.4% occurred syllable-finally. Recently, effects of syllable structure were also observed in two experiments exploring the internal structure of trisyllabic nonwords, one involving subjects performing a phoneme shift task with visually presented stimuli of trisyllabic nonwords, and the other a phoneme substitution game with auditorily presented trisyllabic nonwords, both in English. The results showed a clear performance difference between onsets and codas, and between rimes and consonant-vowel units, indicating a psychological basis for the syllable in the trisyllabic nonwords in English (Fowler, Treiman, & Gross, 1993).

1.1.3 Early Search for a Physiological Basis of the Syllable

Is the syllable only a psychological, or phonological unit, or does it have a physiological basis? The earliest work in search of a physiological basis of the syllable was done by R. H. Stetson (1951). He believed that "the existence of the syllable as a physiologic unit has often been denied or ignored," and therefore, "it is possible to obtain recordings showing the syllable pulse both in terms of the direct movements of the muscles themselves and indirectly in terms of the rapid fluctuations of air pressure within the chest"

(Stetson, 1951, p. 16). Stetson made recordings of muscle movements during speech using a kymograph and concluded from his findings that the syllable consisted of a ballistic movement of the intercostal muscles, that is, a distinct chest pulse for each syllable released (initiated) and arrested (terminated) by both internal and external intercostal muscles.

However, the work done by Ladefoged, Draper and Whitteridge (1958) to identify the basis of the syllable in the respiratory musculature showed conflicting results. According to Ladefoged, "we found that Stetson oversimplifies the situation by considering the activity of the intercostal muscles in terms of a series of 'ballistic movements', ...It is quite clear that there is no simple correlation between intercostal activity and syllables" (1967, p. 20). They also pointed out that there were two phenomena which could be correlated with the bursts of intercostal activity: one was the increased air flow during the production of some voiceless sounds, and the other the degree of stress change. They concluded that there were no discrete bursts of muscle activity, either in the internal or external intercostal muscles, corresponding to individual syllables. Therefore, in their opinion, "there is certainly insufficient basis for a chest pulse theory of the syllable in normal speech" (Ladefoged, 1967, p. 47). Thus, in contrast to Stetson, no evidence was found for any activity in the respiratory musculature at the chest level that could be identified as the physiological basis of the syllable.

1.1.4 Phonetic Evidence for the Syllable—from Acoustic Studies

Although no physical evidence of the syllable has been found in the activity of the respiratory musculature at the chest level, studies on acoustic properties of segments in different syllable positions have provided some physical evidence supporting phonological observations of the syllable, as well as some useful confirmation for some of the syllable-based phonological rules. One of the earliest studies was done by Malmberg (1955). Using hand-painted spectrograms and transferring them into sound on the Haskins Pattern Playback Synthesizer, he obtained three types of synthetic stimuli: [ipi], [odo] and [ɑgɑ]. Within each type, he had two variants, one with the formant transition (the author referred to them as "inflections") portion in the first vowel and one with this portion in the second vowel. He also varied the distance between the two parts of the stimulus in ten steps from 200 msec to 20 msec. He presented these stimuli to phonetically trained listeners and asked them to say whether the stop consonant belonged to the first vowel or the second vowel. Listeners identified the consonant as implosive (syllable-final) if the formant transition was in the preceding vowel, or as explosive (syllable-initial) if the formant transition was in the following vowel. Thus, an acoustically defined phonological boundary between the vowel and stop consonant was perceived and integrated into a phonologically defined syllable unit. A consistent acoustic difference was also found in allophonic /l/ in American English, a well-known phonological phenomenon (Lehiste, 1964). In this study, prevocalic /l/ was found to have a relatively low F_1 and a high F_2, while post-vocalic /l/ was found to have a higher F_1 and lower F_2. However, in another study investigating formant frequency changes between CV and VC syllables (stop consonant+vowel or vowel+stop consonant) in American English, the author did not find any consistent pattern as to whether formant frequency changed more in CV or VC syllables, although he found that on the whole, the degrees of spectral difference among the CV syllables were greater than those among the VC syllables, and as a result, the stops were better contrasted syllable-initially than syllable-finally (Haruko, 1982). Another widely reported acoustic finding that provides physical evidence for the phonologically defined closed syllable (CVC, e.g. s<u>ee</u>m) versus open syllable (CV, e.g. s<u>ee</u>) structure, is that the acoustic duration of a vowel segment is shorter in closed syllables than in open syllables (for example, Wiik, 1965 for English and Finnish; Han, 1964, for Korean; Ren, 1984, for Standard Chinese; all cited in Maddieson, 1985). Additional evidence for such syllable position effects on segments were also reported for Thai and Cantonese. Phonologically long vowels in closed syllables in Thai were found to be substantially shorter than the same vowels in open syllables (Abramson, 1962). In his study of Cantonese vowels, Lee (1983) found that the mean duration of long vowels in open syllables ranged from 233 to 270, to 345 msec for three different Hong

Kong Cantonese speakers, while the mean duration of the same long vowels in closed syllables with nasal endings for the same three speakers ranged from 170 to 171, to 238 msec., respectively. Since this experiment was designed to study the vowel system in two varieties of Cantonese, the durations of vowels reported were averaged over several phonologically long vowels and thus it is unclear from what was reported whether the difference was maintained for each individual vowel.

On the one hand, the examples cited above can provide certain physical evidence for the segmentally based syllable-position effects or syllable-based phonological rules. On the other hand, because studies of this fashion chop continuous speech signals into discrete segments and map them to phonologically defined phonemes, they fail to view the syllable as a unit of speech production and thus fail to provide an understanding of the basic question: what is the syllable?[1]

1.1.5 Phonetic Evidence of Syllable—from Articulatory Movement

Having failed to find the physiological basis of the syllable in the respiratory musculature at the chest level, and not satisfied with the acoustic findings on segmentally based syllable-position effects, researchers turned their attention to the articulatory dimension of speech production. Most early efforts were made to try to discover syllable boundaries by careful examination of the activity of the upper articulators. Kozhevnikov and Chistovich (1965) proposed the general concept of the *articulatory syllable*, which suggested that the motor instructions for each segment within the syllable are sent out simultaneously, unless being prevented by the competing articulations in a syllable. The articulatory syllable was the basic articulatory programming unit in the form of CV, with C being *any* number of consonants and V being *a* vowel. Thus, the boundary of a syllable would be marked in coarticulatory terms, which bore no relation to the common linguistic

[1] If acoustic information is mapped to the articulatory movement, rather than to the phonologically defined segments, it would allow us to observe how the temporally overlapped articulatory gestures manifested into acoustic signals and further our understanding of some basic mechanism or organization in speech production.

units. This proposal received both support and challenge from experimental studies. The concept of the articulatory syllable did account well for the coarticulatory effects observed for lip rounding for /u/ in string of CV, CCV and CCCV, even when there was a conventional syllabic boundary in the string (Kozhevnikov & Chistovich, 1965; Daniloff, 1967). The reason was that although the onset of lip rounding for the vowel /u/ began during the production of the first consonant in a string, it was considered, according to the theory, as part of the motor commands issued for the entire articulatory syllable.

The "trough phenomenon" (Bell-Berti & Harris, 1974; Gay, 1978) also lent support to the model of articulatory syllable. It was shown that during the production of a VCV sequence such as /ipi/ or /utu/, a trough separated the two vowel peaks in the tongue or lip muscle movement patterns, thus, marked the syllable boundary between the two vowels in /ipi/ or /utu/. If the "trough phenomenon" was a general syllable marker, it should be seen in other VCV sequences as well, argued Harris and Bell-Berti (1984). However, they did not find such a phenomenon in their study of /iʔi/ or /ihi/. One of their suggestions to account for the results was that "there is no coarticulatory definition of the syllable boundary". The notion that syllable boundaries were marked by articulatory boundaries was not well-supported by data obtained from several independent studies of coarticulation of velar lowering (Moll & Daniloff, 1971; McClean, 1973; Kent, Carney & Severeid, 1975). In all of these studies, it was found that the onset of velar lowering to the nasal consonant consistently occurred at, or slightly later than, the onset of the primary articulatory movement to the first vowel in a sequence of CVVN, ignoring the presence of a word boundary. If this onset of velar lowering marks the articulatory boundary of the syllable, according to the articulatory syllable model of Kozhevnikov and Chistovich, the resultant articulartory syllable VN or V_nN certainly violates their assumption that the basic articulatory programming unit was a C_nV syllable with *C* being any number of consonants followed by a vowel.

Although the articulatory syllable model of Kozhevnikov and Chistovich failed to reveal the true nature of the syllable, many other studies since then have observed syllable effects from articulatory movement, usually by comparing articulatory behaviors of one or two articulators during the production of one sound or sound sequence with respect to its varied syllable positions. For example, Macchi (1988) found that during the production of /p/ in contrasting syllable positions (e.g., syllable-initial versus syllable-final), while the lip movement was generally invariant, the jaw height differed with respect to the syllable position of /p/. In a recent study on timing of English clusters, Byrd (1994) found that the coproduction of articulatory movements between the consonants in a cluster varied as a function of its syllable affiliation. That is, less coproduction of articulatory movements between the two consonants in a cluster was observed if the cluster was in syllable-initial position than in syllable-final position. Consistent with the finding of less coproduction of articulatory movements, it was also observed that the initial clusters were longer in total duration than the final clusters. Fujimura, Miller and Kiritani (1977) reported systematic differences in velar height associated with syllable structure in their X-ray Microbeam study of articulations of nasal consonants, in both Japanese and English. They found that velum height was consistently greater for syllable-initial nasals than for syllable-final nasals in both languages. Similar conclusions for velar height of Japanese nasals associated with syllable structure were also independently reached by an electromyographic study (Ushijima & Hirose, 1974).

To explore the effect of syllable affiliation, Browman and Goldstein (1988) examined the intrasyllabic articulatory organization in American English. In their approach, they went beyond phonologically defined syllable boundaries to examine the temporal articulatory movement patterns in terms of *C-center* (consonant center). The findings indicate that syllable-initial and syllable-final consonants use different organizations, as defined by the *C-center* model. For syllable-initial consonants, the global organization is used while for syllable-final consonants, a local organization.

Krakow (1989) took a step further to investigate the syllable level organization of articulatory movement patterns by examining two different articulatory subsystems simultaneously, namely, the velum and lower lip, during the production of English bilabial nasal consonant. She argued that the previous research on searching for the physical evidence of the syllable had failed to consider that syllable did not delimit but rather shape the coarticulatory patterns, whether articulatory or acoustic. She hypothesized that "syllables *are* characteristic organizations of articulatory units and that they have no reference to externally imposed temporal boundaries" (Krakow, 1989). To test her hypothesis, she carried out a kinematic analysis of gestures of two independent articulators, velum and lip, during the production of bilabial nasal consonants contrasting in phonologically defined syllable-initial and syllable-final positions by two American English speakers. Analyzing these articulatory patterns, she was able to tease apart the effect of word structure from the effect of syllable structure on the velar and labial movement patterns. She was able to show that there were indeed different patterns of velar and lip movements and different patterns of labial-to-velar coordination associated with different positions of nasal consonants in a syllable. She observed that increased durations and displacement amplitudes of velar lowering and raising, as well as lower spatial minima of the velum, were all associated with syllable-final nasals. She also observed that the velum and the lower lip were coordinated in such a way that the end of velar lowering was closely timed with the beginning of the lower lip raising if the nasal was in syllable-final position, but with the end of lower lip raising if the nasal was in syllable-initial position. Subsequently, Browman & Goldstein (1992, 1995) reported their X-ray Microbeam data of timing patterns of temporal coordination between tongue-dorsum and tongue-tip for laterals in American English. They found that, parallel to what was found for the nasals (Krakow, 1989), for the syllable-initial /l/ as in *leap*, the end of the tongue dorsum retraction was closely timed with the end of tongue tip movement, while for the syllable-final /l/ as in *peal*, it was the beginning of tongue tip movement that was synchronous with the end of the tongue dorsum retraction. Sproat and Fujimura (1993) also reported similar results on their work of laterals in American English. In a study on articulatory gestural characteristics of bilabial stops in American English, Turk (1994) found that the syllable affiliation of word-medial intervocalic bilabial stops was largely dependent of the stress.

These findings suggest that there is a phonetic basis for the syllable in American English. Following these studies, two questions asked here are: (1). Is the syllable organization found in these studies just a language-specific phenomenon or is it a more general phenomenon of human articulatory organization, that is, do syllables act as basic units of motor organization for all languages? (2). If the syllable level organization is also found in another language, will it exhibit a temporal and spatial organization similar to those of English?

There have been studies indicating that although coarticulation has been found in every language studied, the actual patterns of coarticulation may be language-specific. For example, it was reported by Clumeck (1976) that the amount of assimilatory nasalization on vowels varied among different languages: among the six languages studied. The vowel following a nasal stop was heavily nasalized in American English and Brazilian Portuguese, but was only lightly so in Amoy Chinese (Clumeck, 1976)[2]. In another cross-language study (Henderson, 1984) of velopharyngeal function in oral and nasal vowels, differences were found in mid-vowel velar height for phonemically identical syllables when produced by speakers of two different languages, namely, American English and Hindi. The syllables were in the forms of /tVn/ and /nVt/, contrasting in the syllable position of the nasal consonants, with V being any of the five oral vowels tested. For the American English speakers, the mid-vowel velar position was lower in cases like /tin/ than those like /nit/, while for the Hindi speakers, no such difference in mid-vowel velar position was

[2]One may argue that the less nasalization of the vowel seen in Amoy Chinese is because it has distinctive vowel nasalization. However, the fact that both Brazilian Portuguese and American English, one with and one without distinctive vowel nasalization, show similar patterns in the coarticulation of nasal stop and the preceding vowel, makes this explanation unapplausable.

found. In other words, the final nasal has a greater influence than the initial nasal on velar position for the vowel in American English, but not in Hindi.

These differences may indicate that syllables are organized differently in different languages with respect to oral to velar timing. Thus, it is necessary to look at a language other than English for effects of syllable structure on articulatory movement patterns of the velum. The language proposed here is Cantonese. Different articulatory patterns may be expected in Cantonese from those of English. However, if characteristic articulatory patterns are observed for different syllable structure in Cantonese, it would indicate that the existence of the syllable itself is indeed universal.

1.2 Motivation and Objectives of the Study

The present study investigates whether syllables are the units of motor organization by examining articulatory characteristics and coordination patterns of two independent articulatory subsystems, i.e., the velum and the lips, during the production of the bilabial nasal consonant /m/ in Cantonese, a Chinese language unrelated to English and quite different in phonological structure. If evidence for the syllable as a unit of motor organization is also found in Cantonese, it will greatly increase the likelihood that the syllable is a universal feature of human phonetic organization.

It has been shown that in the case of English, the velum and lips are two independent articulatory subsystems with asynchronous activity in which the syllable acts as the core of the organization (Krakow, 1989). This study is a comparison study. It intends to compare the results obtained in American English (Krakow, 1989) for the articulatory organization between the velum and lips during the production of bilabial nasal consonant to those in Cantonese. By studying the velar and lip gestures and their inter-articulatory organization in a different language, we hope to shed some light on the question raised above: Is syllable level organization a more generalized phenomenon of human articulatory organization?

1.2.1 A Brief Review of Cantonese Phonology

Cantonese, part of the Chinese language family, is a tonal language spoken in the central and southwestern parts of Guangdong Province and the southern part of Guangxi Province as well as in the city of Canton and Hong Kong. The variety of Cantonese spoken in Canton and Hong Kong has been regarded as the standard form of Cantonese (Chao, 1947; Hashimoto, 1972). As in other dialects of Chinese, in Cantonese, the syllable as a rule coincides with a morpheme (Kao, 1971). The phonological structure of the Cantonese syllable consists of a nucleus, either nasal or vocalic, an optional onset, an optional coda, and a phonemic tone. There are two syllabic nasals in Cantonese, /m̩/ and /ŋ̍/ (Chao, 1947; Kao, 1971; Hashimoto, 1972). They behave differently from those syllabic consonants in English (Kao, 1971, p. 27): "The sonants /m n l/ in English function as syllabics only in unstressed syllables and are generally preceded by consonants; e.g., bottom [ˈbatm̩], button [ˈbətn̩] and bottle [ˈbatl̩]. The occurrence of a syllabic nasal in Cantonese, however, is never governed by stress, since stress is not a constituent of the syllable or word, and a syllabic nasal occurs as the sole component of a syllable." Also in the case of Cantonese syllabic nasals, a glide may be part of the transition from the vocalic to the nasal consonant, but not in the case of English.

There are eleven vowels in Cantonese, seven long and four short. There are seventeen consonants that can serve as onsets in Cantonese, /m n ŋ p t k (kw) p' t' k' (kw') c c' l f s h j w/, but only a subset of them, eight consonants, /m n ŋ p t k w/, can occur as codas (Kao, 1971). Also, only the two central vowels, /a: ə/, can combine with all codas (Light, 1976). All stop codas are unreleased and syllables with stop codas occur only in level tones. Cantonese has six phonemic tones: four noncontour tones, High level (HL), Mid level (ML), Mid-low level (MLL) and Low level (LL), and two contour tones, High rising (HR) and Low rising (LR) (Kong, 1987)[3]. Stress does not play a distinctive

[3]The tone description given by Kong is comparable to Chao's (1947) well-known system or the one given by Kao (1971).

role in the Cantonese phonological system (Chao, 1947; Kao, 1971; Hashimoto, 1972; Vance, 1976; Yip, 1990). Thus, Cantonese has a very limited number of syllables with codas, whereas in English, a comparatively larger number of syllables have codas. The bilabial nasal /m/ chosen for investigation functions in three different syllable positions, an onset as in [mi:t˺˩],'destroy', a coda as in [ts'i:m˩], 'diving', and a nucleus, that is, a syllable by itself as in [m̩], a negation morpheme with only one tone (the LL tone). Also according to Kao (1971), the two syllabic nasals (or nasal nuclei), /m̩/ and /ŋ̍/, although at a low frequency of distribution, have a high functional yield in Cantonese. No experimental work has been done previously on syllable structure in Cantonese.

1.2.2 Motivation and Objectives of the Study

As described above, the nasal /m/ occurs in three different syllable positions in Cantonese, but in only two in English (not counting the unstressed syllabics). Thus, the Cantonese nasal /m/ provides a rare opportunity, not available in Indo-European languages, for finding some unique articulatory characteristics associated with syllable structures. It is assumed here that there exists some kind of manifestation of syllable structure in Cantonese, since in a pilot perceptual study, native speakers of Cantonese were able to identify correctly phonemically identical sound sequences containing the nasal consonant /m/ in different syllable positions. It is also assumed that there are three possibilities. First, Cantonese might exhibit syllable level organization similar to that in American English. This would suggest that such an organization may be at a universal level. However, that would leave a question about the syllabic nasal: what is its position in the language? Second, no clear patterns of velar and lower-lip movement that reflect syllable level organization might be found. This would suggest that information used to distinguish nasals in different syllable positions may be at a level that is not being examined. Third, consistent effects of syllable structure, but not identical to those that have been found in American English, might be observed in the oral to velar timing pattern. This would suggest the physical reality of the syllable, but the difference would have to be accounted for.

Since a tone stretches itself over the voiced part of a syllable, /m/ also carries the tone. In this study, tone is being controlled as much as possible, but there will be also a chance to observe any possible interaction between syllable position of the nasal /m/ and the effect of tone, manifested on the velar and lip movement patterns (see Chapter 3). Again, to date, there is no information available for Cantonese on this point, either acoustically or perceptually associated with nasality and syllable structure.

Thus, a perceptual study and a production study, both in Cantonese Chinese, are proposed for this thesis to investigate the universality of the syllable and to provide physical evidence for the syllable. The proposed perceptual and production studies for Cantonese will focus on the following questions:

(1) Can native speakers of Cantonese reliably perceive the contrast between syllable-initial, syllable-final and syllabic /m/ in otherwise identical sound sequences?

(2) Are there any articulatory characteristics of velar and lip gestures and their coordination patterns that are associated with the syllable structure in Cantonese?

(3) Are there consistent interactions between syllable position and vowel type, or between syllable position and tonal type in Cantonese?

(4) How do any observed syllable effects in Cantonese compare to those found for American English?

The body of the thesis is divided into three separate chapters, following this introduction, Chapter 1. Chapter 2 consists of two perception experiments, addressing question (1) as well as providing some information needed in designing the stimuli for the kinematic study; Chapter 3 is the kinematic study, which also includes a summary and a brief discussion of the findings; and Chapter 4 provides a general discussion of the questions raised here based on the results of the perception and production studies.

CHAPTER TWO

PERCEPTUAL STUDY

2.1 Introduction

The purpose of this perceptual study are two. The first is to lay some foundation for constructing the stimuli for the kinematic study, and the second is to see whether native speakers can perceive the contrast between syllable-initial, syllable-final and syllabic nasal /m/ in otherwise identical sound sequences. Therefore, the perceptual study is divided into two parts.

Part I investigates whether native speakers of Cantonese are able to detect the difference between a pair of stimuli which are segmentally identical but morphemically different syllable sequences, i.e., one being a real word in the language, and the other, not; and whether they would perform differently when a nasal consonant /m/, being a part of the stimulus, is in different syllable positions. That is, would the word status, or syllable position, or both, of the stimuli, affect the perception in certain directions? The results of this part of perception study will have a direct application in the stimulus design for the planned kinematic study laid out in Chapter One. If, based on auditory information alone, subjects can reliably identify a word from its nonsense counterpart, or if they do better with stimuli with the nasal consonant /m/ in a particular syllable position, (hence, interaction between word status and syllable position), it would suggest that there must exist certain phonetic information in the auditory signal that correspond to the lexical property of being a word. However, if subjects can not identify a word from its nonsense counterpart just based on auditory information, it would be safe to use nonsense stimuli for the planned kinematic study without concern for confounding from the lexical status of the stimuli.

Part II investigate whether native speakers of Cantonese can detect the difference among identical segmentally sound sequences when the syllable position of the nasal consonant is varied systematically from syllable-initial to syllable-final to syllabic positions. If native speakers are able to hear the difference in the sound sequences as a result of varying the syllable position of the nasal consonant /m/, then, a difference in articulatory organization accounting for this change is expected if one believes that there exists a phonetic module which is a biologically coherent system specialized for both production and perception of phonetic structures, and that the objects of speech perception are the intended phonetic gestures of the speaker (Liberman & Mattingly, 1985).

2.2 Subjects

2.2.1 Production

A male subject who was born and grew up in Hong Kong served as the speaker on all testing tapes.

2.2.2 Perception

Nine subjects, 4 males and 5 females, participated in both parts of the perception study. They were native speakers of Cantonese, who were born and raised in Hong Kong, with exception of Subject 6, who was born in Hong Kong but emigrated to the United States in her teens, and were students of Yale University at the time of testing. None of them had any known speech or hearing problems.

2.3 Stimuli Design

There were two parts to the perceptual study. Part I examined the effect of word status versus syllable position; and Part II examined the effect of syllable position.

2.3.1 Stimulus Design for Part I

The utterances were six pairs of phonetically identical but morphemically different syllable sequences, ranging from two to four syllables. In each pair, one was a real word and the other was not. All pairs contained a bilabial nasal consonant /m/. For two of the six pairs, the nasal consonant /m/ was in syllable-initial position, for two in syllable final position, and for two in syllabic position. The detailed information of the stimuli used in this part of the experiment is given in Table 2.1.

TABLE 2.1 STIMULI — PERCEPTION PART I

Syllable status	Word status	Phonetic transcription	Chinese character	English translation
syllable-initial	word	sɐu˧˥ mɐt̚˩	手襪	glove
syllable-initial	nonword	sɐu˧˥ mɐt̚˩	首襪	
syllable-initial	word	tsiː˥ mɑː˩	芝麻	sesame
syllable-initial	nonword	tsiː˥ mɑː˩	之麻	
syllable-final	word	sɐm˥ t'ai˧	心態	state of mind
syllable-final	nonword	sɐm˥ t'ai˧	森態	
syllable-final	word	ts'iːm˥ tsiː˧˥	簽紙	signature
syllable-final	nonword	ts'iːm˥ tsiː˧˥	簽紫	
syllabic	word	m̩˩ sɐi˧˥ hak̚˧ hei˧	唔使客气	don't mention it
syllabic	nonword	m̩˩ sɐi˧˥ hak̚˧ hei˧	唔駛嚇器	
syllabic	word	m̩˩ tœy˧ lou˨	唔對路	not right
syllabic	nonword	m̩˩ tœy˧ lou˨	唔兑怒	

2.3.2 Stimulus Design for Part II

For Part II, the stimulus design was as the follows: There were eighteen nonsense utterances. Nine of them contained vowel /ɑ/, the other nine vowel /i/. Within the subcategory of vowel, the utterances further contrast with syllable positions of the bilabial nasal consonant /m/, syllable-initial, syllable-final, and syllabic. The detailed information of the stimuli used in this part of the experiment is given in Table 2.2.

2.4 Procedure

2.4.1 Recording

Each stimulus item was produced in a carrier phrase 罰 /fɐt̚ ˩/ ______ 塗字 /t'ou ˩ ts'i: ˧/ with the meaning "penalize______to paint characters". Six repetitions of

TABLE 2.2 STIMULI — PERCEPTION PART II

Vowel type	Type	Syllable status	Tone first syl	Tone mid syl	Tone last syl	Phonetic transcription	Chinese character
	T1	syllable-initial	LL		HL	ts'ɑ:˩ mɑ:˥	茶嗎
	T2	syllable-initial	HL		HL	ts'ɑ:˥ mɑ:˥	差嗎
	T3	syllable-initial	HL		HL	sɑ:˥ mɑ:˥	沙嗎
	T1	syllable-final	LL		HL	ts'ɑ:m˩ ɑ:˥	慚阿
/ɑ/	T2	syllable-final	HL		HL	ts'ɑ:m˥ ɑ:˥	參阿
	T3	syllable-final	HL		HL	sɑ:m˥ ɑ:˥	三阿
	T1	syllabic	LL	LL	HL	ts'ɑ:˩ m̩˩ ɑ:˥	茶唔阿
	T2	syllabic	HL	LL	HL	ts'ɑ:˥ m̩˩ ɑ:˥	差唔阿
	T3	syllabic	HL	LL	HL	sɑ:˥ m̩˩ ɑ:˥	沙唔阿
	T4	syllable-initial	LL		L[1]	ts'i:˩ mi:t̚˩	慈滅
	T5	syllable-initial	HL		L	ts'i:˥ mi:t̚˩	雌滅
	T6	syllable-initial	HR		L	si:˧˥ mi:t̚˩	使滅
	T4	syllable-final	LL		L	ts'i:m˩ i:t̚˩	潛熱
/i/	T5	syllable-final	HL		L	ts'i:m˥ i:t̚˩	簽熱
	T6	syllable-final	HR		L	si:m˧˥ i:t̚˩	閃熱
	T4	syllabic	LL	LL	L	ts'i:˩ m̩˩ i:t̚˩	慈唔熱
	T5	syllabic	HL	LL	L	ts'i:˥ m̩˩ i:t̚˩	雌唔熱
	T6	syllabic	HR	LL	L	si:˧˥ m̩˩ i:t̚˩	使唔熱

[1] Note that the L tone is a special case of the LL tone when the syllables end in /p t k/ (Kao, 1971; Yip, 1990).

each item (in the carrier phrase) were obtained. The subject was asked to speak at a normal speaking rate, one which he would normally use when talking to a friend. All utterances were recorded with the use of a condenser microphone and a digital recorder SV-3700PP-H in a sound-treated booth. After the recording was completed, the utterances were digitized using the Haskins PCM system (Whalen, Wiley, Rubin & Cooper, 1990) at 10 KHz sampling rate. Four of the six repetitions were chosen as representative of each stimulus, and each of these was extracted from the carrier phrase in which it had been produced. Four repetitions of each unique token were used for Part I (totaling sixteen presentations of each stimulus item), and three repetitions for Part II (totaling twelve presentations of each stimulus item). For Part I, tokens which were real words were paired with their nonsense counterparts. In half of these pairs, the real words occurred first in the pair, and in the other half, the nonsense ones. The randomized pairs (Part I) or tokens (Part II) were then recorded using the same digital recorder.

2.4.2 Testing

Answer sheets were prepared for the experiments. For Part I, an AB paradigm was used. For each pair of tokens heard, there was only one Chinese word or its nonsense counterpart printed in Chinese characters on the answer sheet followed by **"1"** and **"2"**. After listening to each pair of tokens, the subject was to decide which of the two tokens, the first one or the second one, matched the one in Chinese characters on the answer sheet. He or she then circled the number appropriate to his choice. For example, if he decided that the first token he heard matched the one on the answer sheet, he would circle **"1"**. Below is an example of the response form for a single presentation.

14. 芝麻 **1** **2**

For Part II, there were three choices reflecting the syllable positions of the nasal for each token presentation. The three choices were written in Chinese characters and the subject's task was to circle one of the three choices on the answer sheet for each token heard. Below is an example of the response form for a single presentation.

2. 茶嗎 嘶阿 茶唔阿

The testing was conducted in a sound-treated room. The testing stimuli were delivered via headphones with the experimenter controlling the tape recorder outside the room.

Before the real testing, each subject was given a short practice session which contained the instruction for the test and eight randomly chosen token presentations. The purposes were to help the subject find his/her comfortable listening level and to ensure that he or she understood the instructions.

2.5 Results

2.5.1 Results of Part I of the Perceptual Study

Figure 2.1 shows the effect of word status on the mean correct responses of the stimuli. While the real words were identified correctly 54% of the time, which is slightly above the chance level, their nonsense counterparts, only 46%, which is below the chance level.

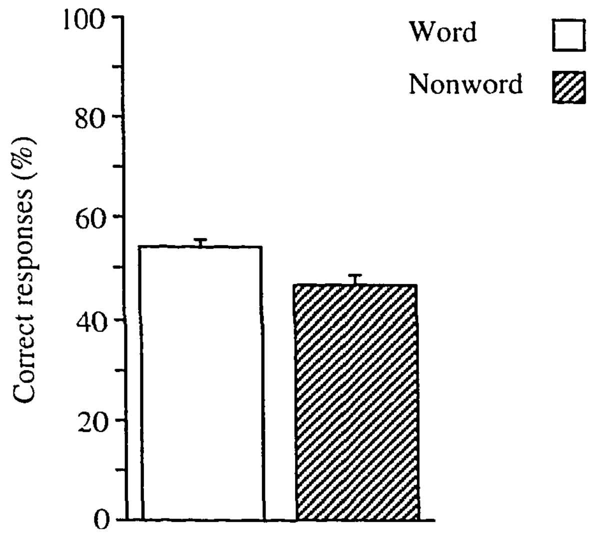

Figure 2.1 Effect of word status on percent of correct responses of the stimuli. The horizontal bars indicate standard error.

Figure 2.2 shows that the mean correct responses were at chance level for all three levels of syllable affiliations, 48.6% for syllable-initial, 51.9% for syllable-final and 50.9% for syllabic conditions.

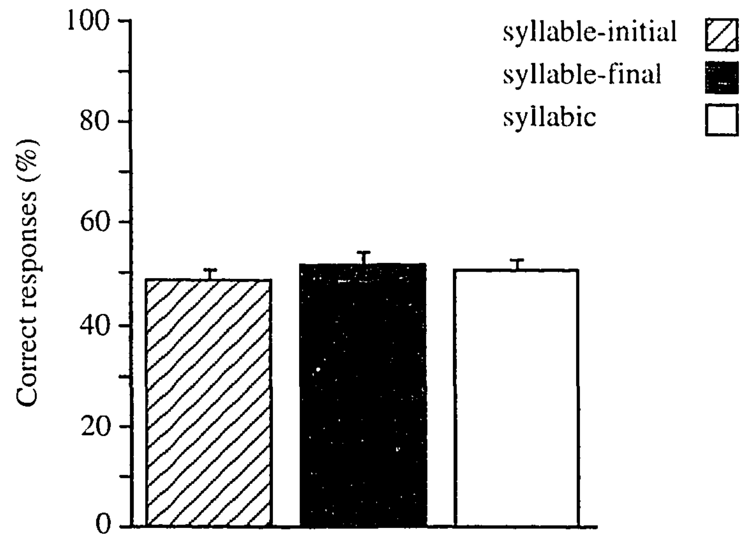

Figure 2.2 Effect of syllable position on percent of correct responses of the stimuli. The horizontal bars indicate standard error.

An ANOVA of repeated measures was conducted with word status (word or nonword), and syllable position (syllable-initial, syllable-final, and syllabic) as factors, and mean correct responses as dependent variable. The results show that neither of the main effects, i.e., word status and syllable position, were statistically significant. And further, there was no statistically significant interaction found between the word status and syllable position on the identification of the stimuli.

2.5.2 Results of Part II of the Perceptual Study

The original design for Part II had included two types of vowels, a low vowel /ɑ/ and a high vowel /i/, as shown in Table 2.2. In the low vowel condition, the Chinese morpheme, 阿, /ɑ/, which was the last syllable in the syllable-final and syllabic conditions, can be pronounced with either a high level tone, which was required by the experimental design, or a mid level tone. The high level tone was required in this case to keep the tone value consistent so that comparisons could be made without confounding from the tone. However, because the speaker produced this syllable with a mid level tone, which was about 12 Hz lower than the desired high level tone as later measurement showed, the perception data obtained with these stimuli were excluded from the analyses.

Figure 2.3 shows the mean correct responses for all three levels of syllable affiliations, 86.4% for syllable-initial, 93.5% for syllable-final and 96.3% for syllabic conditions.

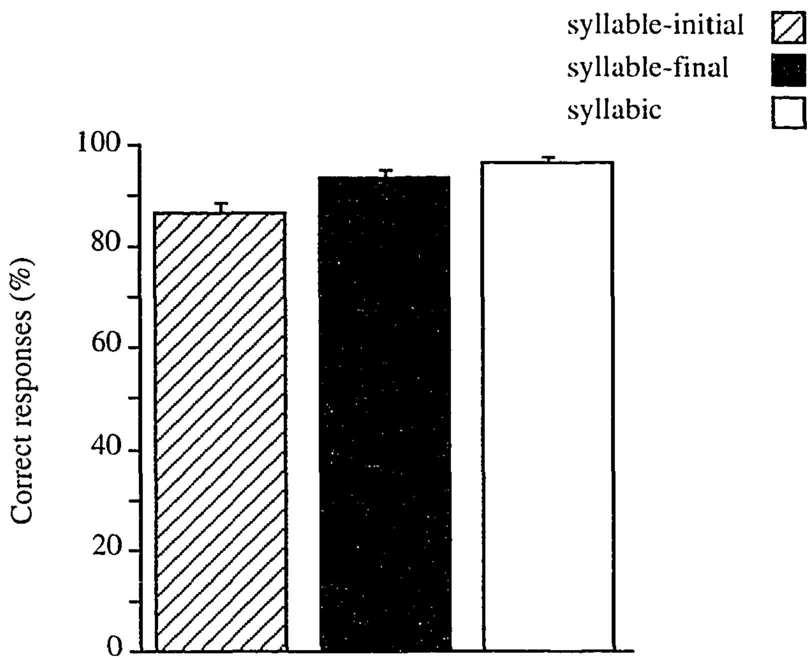

Figure 2.3 Effect of syllable position on percent of correct responses of the stimuli. The horizontal bars indicate standard error.

Figure 2.4 shows the mean correct responses for each of the three types of stimuli used in the study. As shown in Table 2.2, there were two sources of difference among the three types. The first one was the initial consonant for the first syllable: an affricate /ts'/ in Type 4 and Type 5, and a fricative /s/ in Type 6. The second one was the tone of the first syllable: a Low Level tone for Type 4, a High Level tone for Type 5, and a High Rising tone for Type 6. However, the tone of the first syllable was consistent within each type across different syllable positions of the nasal consonant /m/. The mean correct responses were 85.8% for Type 4, 94.8% for Type 5 and 95.7% for Type 6.

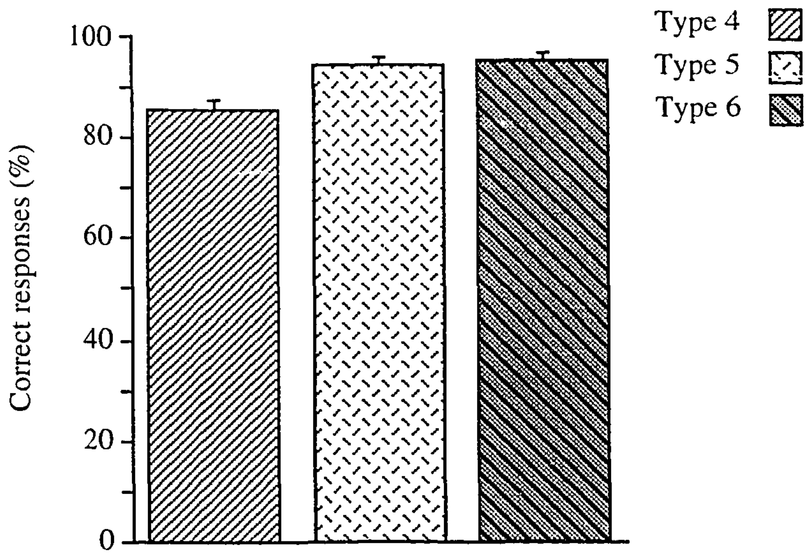

Figure 2.4 Effect of type on percent of correct responses of the stimuli. The horizontal bars indicate standard error.

An ANOVA of repeated measures was used to further evaluate these differences, with syllable (syllable-initial, syllable-final, and syllabic) and type (T4, T5 and T6) as factors, and mean correct responses as dependent variable. The results show that both main effects, i.e., syllable position and type, were statistically significant, with $F(2, 8) = 4.42$, $p < 0.05$ for syllable position and $F(2,8) = 4.94$, $p < 0.05$ for type. The interaction between syllable position and type was also significant, $F(4,8) = 2.99$, $p < 0.05$. As shown in Figure 2.5, for syllable-initial and syllabic conditions, the identification was the highest for Type 6 (syl-ini: 96.3% and syllabic: 100%), lowest for Type 4 (syl-ini: 75% and syllabic: 89.8%), with Type 5 in the middle (syl-ini: 88% and syllabic: 99.1%). For syllable-final condition, the identification pattern from the highest correct responses to the poorest was Type 5, Type 4 and Type 6.

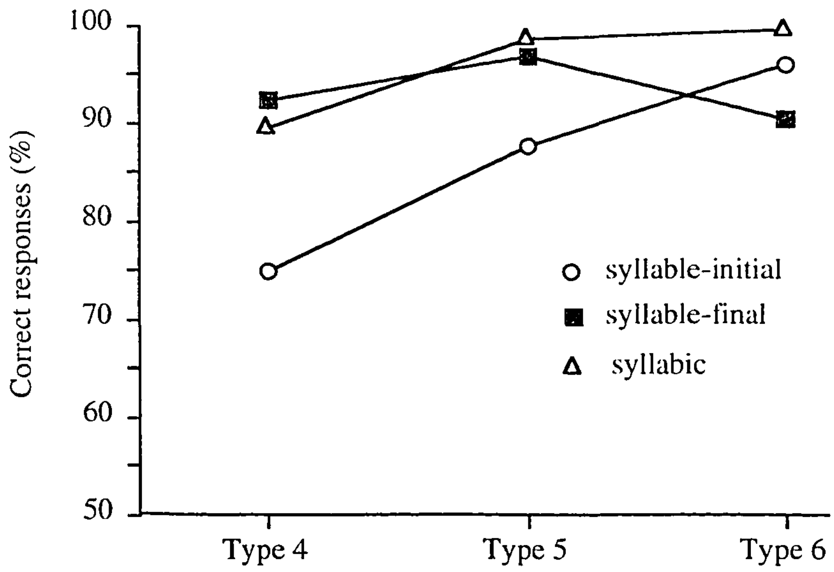

Figure 2.5 Interaction between syllable position and type on percent of correct responses of the stimuli.

Since Type 4 was the one that with no tonal changes from the first syllable to the last syllable (low level tone for all syllables), it was of interest to see how each individual subject performed on this type. It was found that there were two subjects, S1 and S6, who performed really poorly on Type 4. For S1, her two low scores were 50% for, syllable-initial and 33% for syllabic. For S6, the two low scores were 58% for syllable-initial and 33% for syllable-final. A further investigation of their linguistic background/experience showed some interesting findings. In the case of S1, she emigrated to the United States in her teens and spoke Cantonese only to her parents and friends at home; her primary language socially was American English. In the case of S6, although she was a native speaker of Cantonese, she was married to a native speaker of Mandarin Chinese for about ten years and she studied in Taiwan as a college student before she came to the U.S. four years ago. The only language spoken at her home was Mandarin Chinese since her husband did not understand Cantonese.

2.6 Discussion

2.6.1 Part I of the Perceptual Study

As it can been seen from Table 2.1, for each pair of words and its nonsense counterpart, the phonetic environment of consonant, vowel, and tone was well-controlled. The results of this part of the experiment demonstrated that subjects, given a well-controlled phonetic environment of consonant, vowel and tone (stress was not a concern here because it does not play a distinctive role in Cantonese, Chao, 1947; Vance, 1976), could not reliably distinguish a word from its phonologically identical but morphemically different nonsense counterpart, based on auditory information alone. And further, this inability to distinguish a word from its nonsense counterpart was not influenced by the syllable positions of the nasal consonant /m/, i.e., whether the nasal consonant was a syllable-initial nasal, syllable-final nasal, or syllabic nasal.

Therefore, based on the results from Part I of the perceptual experiment, if only nonsense stimuli are used in the kinematic study, any differences found in articulatory patterns of the stimulus could be safely attributed to syllable level structure not to word level structure.

2.6.2 Part II of the Perceptual Study

The results from this part of the perceptual study clearly demonstrated the following:

1. Native speakers of Cantonese could reliably identify the difference in the stimuli due to varying the syllable positions of the nasal consonant /m/;

2. The perception of the stimuli was an integration process in which all relevant phonetic information was being utilized;

3. Both consonant and tonal information play a role in the identification of the stimuli.

Even in the case where other phonetic information was truly consistent except for the syllable position of the nasal consonant, subjects were able to identify the stimuli with well above chance level accuracy, (75% for syllable initial, 93% for syllable final and 90% for syllabic nasals). Therefore, there must exist some detectable articulatory organizations/patterns that are responsible for the perceived differences.

CHAPTER THREE

PRODUCTION EXPERIMENT

3.1 Introduction

The primary purpose of this production study is to provide phonetic evidence in both the articulatory domain and the acoustic domain for the syllable. Different articulatory movement patterns of velum and lower lip were observed in American English to be associated with nasal consonants in different syllable positions (Krakow, 1989). For example, it was found that in American English, for bilabial nasal consonants, velar gestures were amplified in syllable-final position while labial gestures were amplified in syllable-initial position, and that significantly earlier velar lowering gestures were associated with syllable-final nasals but not with syllable-initial nasals (Krakow, 1989). If a language such as Cantonese, unrelated to American English and quite different in its phonological structure, exhibits similar syllable level organization, it would suggest that such an organization may be at a level that is universal; if no clear patterns of velar and lower lip movement that reflect syllable level organization are found, it would suggest that information used to distinguish these nasals of different syllable positions may be at a level that is not being examined; if consistent effects of syllable structure, but not identical to those found in American English, are observed, then, it would suggest the physical reality of a syllable, but the differences would require explanation. This study is intended to address the following questions:

- Are there any measurable differences in velar movement that characterize the syllable position of bilabial nasal consonants?
- Are there any measurable differences in labial movement that characterize the syllable position of bilabial nasal consonants?

- What are the coordination patterns between velar and lower lip gestures associated with syllable structure?
- Are there any vowel effects on the velar and lip movements which are associated with syllable structure?
- Are there any tonal effects on the velar and lip movements which are associated with syllable structure?
- What is the correlation between the articulatory movements and the acoustic outcome?

3.2 Subjects

Four native speakers of Cantonese, 2 males and 2 females, who were born and raised in Hong Kong, served as the subjects. All of the subjects were also fluent English speakers. None of the subjects had any known speech or hearing problems. None of them had any nose conditions, such as constant nose bleeding or severe allergy, that would make them unsuitable candidates for the experiment. All were between the ages of 20 and 24 and were students at either Yale University or the University of Connecticut at the time of the experiment (Table 3.1).

TABLE 3.1 — SUBJECT LIST

Subject code	Gender	Age	Year spent in the U. S.
JJL —S1	F	20	4
HW—S2	F	20	1
AH —S3	M	22	1
TF —S4	M	24	3

3.3 Stimulus Design

Different articulatory movement patterns of the velum and lower lip were observed in American English to be associated with nasal consonants in different syllable positions (Krakow, 1989). As discussed in the introduction, in order to observe the articulatory organization of the velum and lip associated with syllable structure, phonologically defined bilabial nasal consonants in three different syllable positions, syllable-initial, syllable-final and syllabic, have been chosen as the primary part of the stimulus design. It has also been shown in many languages (including Amoy Chinese) that oral vowel height has a direct relationship with velar height in both nasal and oral environments, that is, position is lower for low vowels than for high vowels (Clumeck, 1976; Henderson, 1984; Bell-Berti, Baer, Harris & Niimi, 1979). Thus, two vowels, a high vowel /i/ and a low vowel /ɑ/, were included in the design to see if and how velar height would interact with both vowel height and syllable position. It has been found that vowel duration varies among the six Cantonese tones in three groups. The longest duration group includes the high rising tone (HR) and the mid level tone (ML), the mid duration group includes the low rising tone (LR) and mid-low level tone (MLL), and the shortest duration group includes the high level tone (HL) and the low level tone (LL), (Kong, 1987). Between the two tones in the shortest duration group (HL and LL), the finding was that for the three speakers tested, two produced slightly longer duration for the HL tone and one produced slightly longer duration for the LL tone (Kong, 1987). The two tones in the shortest duration group were chosen for this study. Therefore, on the one hand, the tonal effect would be minimized, since both tones were in the same vowel duration group; on the other hand, it would still allow observations of tonal effects if there were any, since there were indications that they might differ slightly in duration between speakers (Kong, 1987).

A subset of the stimuli used in the perception study (Part II) was chosen for this study (See Table 3.2). There were twelve nonsense utterances. The consonant of the first syllable was /ts'/ for all twelve utterances. There were two vowels, V1 and V2, used in each target utterance, one preceded the bilabial nasal consonant and one followed it. In six of the utterances V1 and V2 were vowel /ɑ/, in the other six they were vowel /i/. Within the category of vowel, the six utterances contrast with respect to the syllable positions of the bilabial nasal consonant /m/, syllable-initial, syllable-final, and syllabic. The stimuli were further divided into two groups according to the tone of the first syllable in the utterance, LL or HL. In Cantonese, there is only one tone for the bilabial syllabic nasal, LL tone. Tones of the last syllable of all utterances were identical within each vowel category. They were necessarily confounded with the vowel type, that is, the HL tone was always used in the vowel /ɑ/ context, while the LL tone was always used in the vowel /i/ context. Therefore, whenever (from here on) the tone type is mentioned it the text, it refers to the tone of the first syllable in an utterance. The tonal effect is only explored with respect to the first part of the utterance.

TABLE 3.2 STIMULI — PRODUCTION EXPERIMENT

Vowel type	Syllable position	Tone first syl	Tone mid syl	Tone last syl	Phonetic transcription	Chinese character
	syllable-final	LL		HL	ts'ɑ:m˩ ɑ:˥	慚阿
	syllable-initial	LL		HL	ts'ɑ:˩ mɑ:˥	茶嗎
	syllabic	LL	LL	HL	ts'ɑ:˩ m̩˩ ɑ:˥	茶唔阿
/ɑ/	syllable-final	HL		HL	ts'ɑ:m˥ ɑ:˥	參阿
	syllable-initial	HL		HL	ts'ɑ:˥ mɑ:˥	差嗎
	syllabic	HL	LL	HL	ts'ɑ:˥ m̩˩ ɑ:˥	差唔阿
	syllable-final	LL		L[1]	ts'i:m˩ i:t̚˩	潛熱
	syllable-initial	LL		L	ts'i:˩ mi:t̚˩	慈滅
	syllabic	LL	LL	L	ts'i:˩ m̩˩ i:t̚˩	慈唔熱
/i/	syllable-final	HL		L	ts'i:m˥ i:t̚˩	簽熱
	syllable-initial	HL		L	ts'i:˥ mi:t̚˩	雌滅
	syllabic	HL	LL	L	ts'i:˥ m̩˩ i:t̚˩	雌唔熱

3.4 Instrumentation

The experiment was conducted at Haskins Laboratories in New Haven, a research institution affiliated with the University of Connecticut.

[1]See footnote on p. 18 .

3.4.1 The Velotrace

The velum movement was tracked using the Velotrace, a mechanical device developed by Horiguchi and Bell-Berti (1987) at Haskins Laboratories. As shown in Figure 3.1, the device consists of a curved internal lever that rests on the nasal surface of the velum, an external lever positioned outside the nose, and a push rod connecting the two levers. The internal lever is raised when the velum is raised. This upward (or downward) movement of the internal lever is then transmitted via the connecting push rod to the external lever which moves toward (or away from) the subject. Thus, the Velotrace monitors the changes in the vertical position of the velum. Since the linear distance between the fulcrum and tip is 30 mm for the internal lever, and 60 mm for the external lever, the movement of the external lever is twice as large as that of the internal lever. The Velotrace has been shown to be able to track relatively rapid velar movements accurately (Horiguchi & Bell-Berti, 1987).

The Velotrace was monitored with a position-sensitive optoelectronic transduction system, a modified version of the commonly-used Selcom SELSPOT system (Kay, Munhall, Vatikiotis-Bateson and Kelso, 1985). Two infrared light-emitting diodes (LEDs) were attached to the end of the external lever and the fulcrum of the external lever as shown in the diagram. The former allowd monitoring of the external lever, the latter served as a reference point. The positions of the LEDs were tracked by a planar diode located in the focal plane of a camera mounted on a tripod and placed approximately 25 inches from the subject. Thus, by means of these LEDs, the movement of the external lever and hence of the velum was recorded as an analog signal.

3.4.2 The Lip Movement Tracking System

As shown in Figure 3.1, two LEDs were attached midsagittally to the vermilion borders of the upper lip and the lower lip. A third LED was positioned on the bridge of the nose for reference. The positions of the LEDs were tracked by the same position-sensitive optoelectronic device used to track the LEDs on the Velotrace.

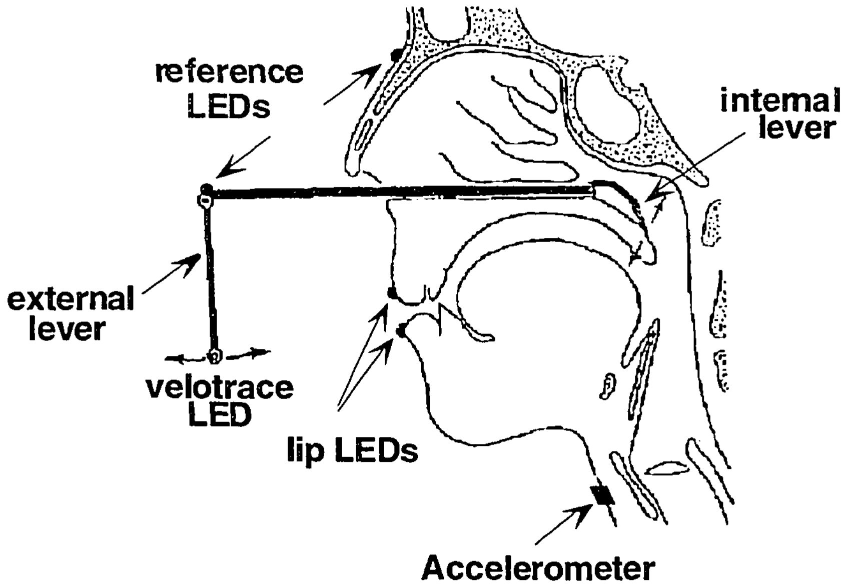

Figure 3.1 Experiment set-up

3.4.3 The Accelerometer and Acoustic Recordings

An accelerometer, Model BBN 501, whose output reflects vocal fold movement via the response of the body wall to the acoustic wave in the trachea, was placed on the pretracheal surface of the neck (Figure 3.1). The accelerometer signal was used for obtaining fundamental frequency.

3.5 Procedure

3.5.1 Experimental Protocol

Prior to the start of the experiment, the subject reviewed the stimulus list to see if she or he had any problems with the Chinese characters. Nobody had any difficulties.

Each subject sat in a dental chair. An adjustable headrest and an adjustable footstool were used to assist the subject in sitting in a stable and upright position for the duration of the experiment. First, an otolaryngologist examined the subject's nasal passages and chose the larger of the two for Velotrace insertion. Next, the LEDs were attached to lips midsagittally at the vermilion borders. Then, the accelerometer was attached on the pretracheal surface of the neck. Finally, the Velotrace was inserted by the otolaryngologist. The insertions for S1 and S2-S4 were done by Dr. Kiyoshi Oshima and Dr. Walter Naito, respectively.

Before the Velotrace was inserted, Prontocaine Hydrochloride 2%, a topical anesthetic, was sprayed into the nose, followed by Ephedrine Sulfate 3%, a nasal decongestant. Then, both solutions were in turn applied several times to the nasal mucosa with cotton swabs. Finally, Xylocaine jelly was squeezed onto the internal lever of the Velotrace and the Velotrace was inserted. The fulcrum of the internal lever was positioned in the nasal cavity above the end of the hard palate, while the internal lever rested on the nasal surface of the velum. The Velotrace was stabilized by a modified Nagashima fiberoptic-headlight headband. Figure 3.2 shows a subject with the Velotrace in position. A Sennheiser MKH816T microphone was positioned about 5 inches from the subject's mouth to record the speech signal, and a videotape recorder was used to obtain an audio-visual record of the entire experiment. There were a total of ten channel signals, which included Velotrace X, Y, Velotrace reference X, Y, upper lip Y, lower lip Y, nose reference X, Y, accelerometer and the acoustic signal. A real-time monitor was used to monitor all ten channel signals simultaneously during the entire experiment.

At the beginning and the end of the experiment and after every eighteen utterances, the subject was asked to produce a sustained /s/ and a sustained /m/. At the end of the experiment, a period of silence, i. e., resting position, was recorded. The sustained /s/ and the sustained /m/ (or rest) define the two extremes of the velum position, with the /s/

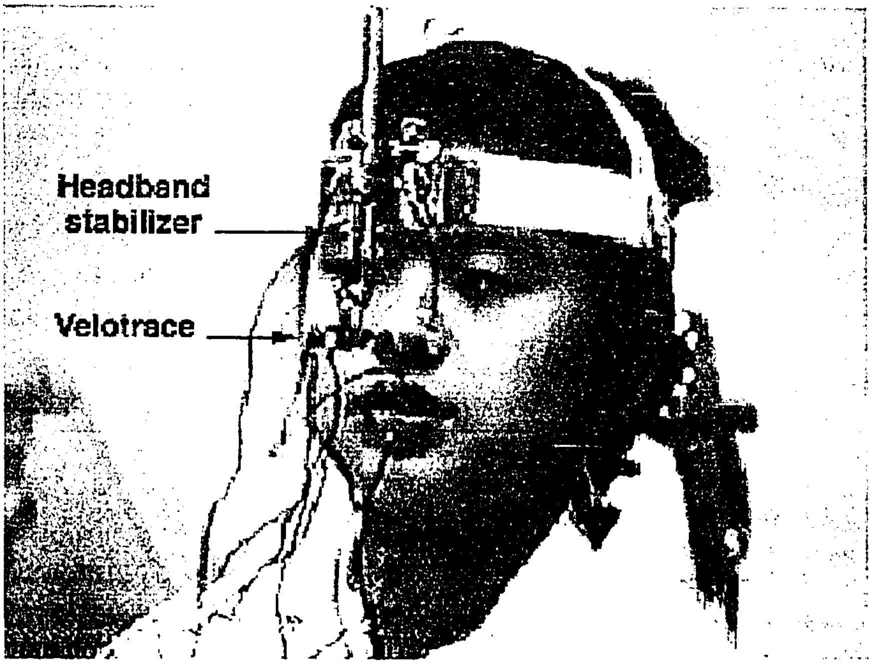

Figure 3.2. A subject with apparatus attached.

providing the maximum and /m/ the minimum. These maneuvers served three purposes: (1) as a baseline for monitoring during the experiment; (2) as a means to correct any possible baseline shifting after the experiment (these signals were recorded in the same way as the stimulus signals); and (3) as an indication of the full range of velum movement for each subject.

3.5.2 Obtaining Calibration Signals

The calibration values of the movements of the LEDs were obtained at the end of experiment in two different ways for the four subjects. For S1, a Selspot calibration device was used. The calibration values were collected by taking two different recordings of a diode using the same Selspot system: one with the diode in its original position and one after it was moved a distance of two centimeters in a focal plane from its original position.

For S2, S3 and S4, no such calibration device was employed. The two recordings were taken right after the experiment with the subject remaining silent in the same sitting position. One recording was taken before the camera was moved 2 centimeter to the left and the chair raised up 2 centimeters, and the other after these maneuvers. The reason for the change was that Haskins Laboratories upgraded its physiological input system from a SE-7000 14-channel instrumentation tape recorder to an on-line real time programmable input system, and the original calibration device was not compatible with the new system. However, in either case, the changes obtained corresponding to the two-centimeter movement in sampled values were applied to the relevant signal channels for the purpose of calibration in the same manner. Since the statistical analyses were done for each subject separately, this change of procedure did not affect the results of the experiment.

3.6 Data Collection

3.6.1 Data Acquisition

The stimuli were written in traditional Chinese characters, with each stimulus and a carrier phrase printed on a piece of 11 x 8 inch heavy paper. Each stimulus item was produced in a carrier phrase 罰 /fɐt˺ ˩/ ______ 塗字 /t'ou ˩ ts'iː ˧/ 'penalize______to paint characters'. The subject was asked to speak at a normal speaking rate, such as he/she normally would use when talking to a friend. The subject was also told to say the Chinese character, 阿, /ɑ/, which was the last syllable in the syllable-final and syllabic conditions of the low vowel part, with the HL tone, since this character can be pronounced with either a high level tone (HL) which was required by the design paradigm, or a mid level tone (ML). Twelve tokens were produced in two random orders for each stimulus in blocks of six repetitions of the same utterance.

For the first subject, the ten signals were recorded onto a SE-7000 14-channel instrumentation tape recorder along with digitally coded signals for synchronization. The signals were later digitized. For the other three subjects, the ten signals were digitized on-line real time by using the Haskins Laboratories Real-Time acquisition and analysis system (HART). Again, this change in procedure was due to the system upgrading in the Haskins Laboratories. However, for the digitizing itself, the same data acquisition/experiment control files were used in all four experiments to ensure the same filtering and sampling frequencies.

For all subjects, the velar and labial movement signals were low-pass filtered at 200 Hz and sampled at 1250 Hz. Both pre-gain and post-gain were set at 0 dB. The accelerometer signal was low-pass filtered at 2000 Hz and sampled at 5000 Hz. Both pre-gain and post-gain were set at 20 dB. The acoustic signal was low-pass filtered at 10 KHz and sampled at 20 KHz for S1 and S2, and filtered at 5 KHz and sampled at 10 KHz for S3 and S4.

3.6.2 Signal Processing

The signal processing was accomplished by using RTF, the Real-Time system file tool and the Haskins software package HADES, Haskins Analysis Display Experiment System (Rubin & Löfqvist, in preparation). Since the signals were digitized as multiplexed files which contained all 10 channels of a single burst, the first step was to demultiplex the signals into individual channels using RTF. Next, a series of HADES algorithms were used to calibrate, smooth, and correct the signals for head movement, and to derive velocity data from them. The signals were first calibrated by using the corresponding calibration values for each movement channel, and then smoothed using a triangular smoothing window of 33 samples or 25 milliseconds (see Kay et al. 1985). Next, these calibrated and smoothed signals from the above process were corrected for head movement (i.e., the reference signal Nose Y was subtracted from the lower lip and upper lip signals, and the Velotrace reference signals were subtracted from the corresponding Velotrace signals). Finally, the velocity traces were created from the corrected signals and smoothed with a triangular window of 33 samples or 25 milliseconds. After the above procedures, the signals were then extracted into single tokens including the carrier phrase for further processing.

3.6.3 Event Marking and Other Relevant Procedures

In order to assess the motor organization of the velar and lower lip movement patterns associated with the syllable structures, a series of articulatory events associated with the bilabial nasal consonant /m/ were marked after visual inspection of the velar and lower lip movement and velocity traces. Although the Velotrace data was obtained for both dimensions, X and Y, since the velum movement was mainly reflected in the X dimension, data on Velotrace Y which was obtained the purpose of confirmation, was not used in the analyses of this experiment for any of the subjects.

Peak Velocity — For each token, the moments of peak velocity for lowering and raising movements associated with the bilabial nasal /m/ were marked on the corresponding velocity traces of velum and lower lip.

Movement Onsets and Offsets — The onset and offset of velar lowering toward the low position for /m/ and the onset and offset of subsequent raising were marked. Similarly, the onset and offset of lower lip raising toward the high position for /m/ and the onset and offset of subsequent lowering were marked. Onsets and offsets of movement were determined based on velocity as follows:

The maximum peak velocities of velar lowering and raising were obtained from corresponding velocity trace for velar lowering and velar raising movements separately across all the utterances listed in Table 3.2. All movement onsets and offsets were identified using a computer algorithm written in SPIEL (the internal procedural language) and were carried out in HADES (Rubin & Löfqvist, in preparation). For both velar lowering and velar raising movements, movement onset was identified as the point at which the velar velocity reached 5% of maximum peak velocity. And movement offset was defined as the point at which the velar velocity fell below 5% of maximum peak velocity. Maximum peak velocities were obtained for both lower lip raising and lowering gestures across all the utterances. In the same fashion, for both lower lip raising and lowering movements, the movement onset was identified as the point at which the velocity reached 5% of maximum peak velocity. And movement offset was identified as the point at which the velocity fell below 5% of maximum peak velocity.

The 5% criterion was found necessary and appropriate for the present data because of the elastic properties of the velar and labial tissues. Using a zero-crossing point rather than the 5% criterion would result in identifications of onset and offset which were not closely associated with the movement of interest; that is, an onset would be identified before the real movement had started and an offset after the real movement had already effectively stopped. Figure 3.3 gives an example of how the criterion was used. (For discussion on similar decision making, see Gracco & Abbs, 1988).

Positional Minima/Maxima — The absolute vertical minimum (velum) and maximum (lower lip) points associated with the bilabial consonant /m/ were identified on the movement signals.

Acoustic Landmarks — There were two vowels in each token (Table 3.2). The onset of the first vowel, the onset and offset of the nasal murmur associated with the bilabial nasal consonant /m/, and the offset of the second vowel were identified in the acoustic waveform of each token for each utterance. The determination of the onset of the first vowel and the offset of the second vowel was made with the aid of the Accelerometer signals. There is no accelerometer signal unless there is voicing. Since the consonants before the first vowel and after the second vowel were voiceless, the onset of the first vowel and the offset of the second vowel were well defined on the accelerometer signal. The determination of the onset and offset of the nasal murmur was made by visually inspecting the decreased energy point in the waveform, the low frequency nasal bar in the wide-band FFT and by listening to the tokens. The marked onset of the nasal murmur also served another purpose by being the reference point for that token for obtaining ensemble averages for the utterance.

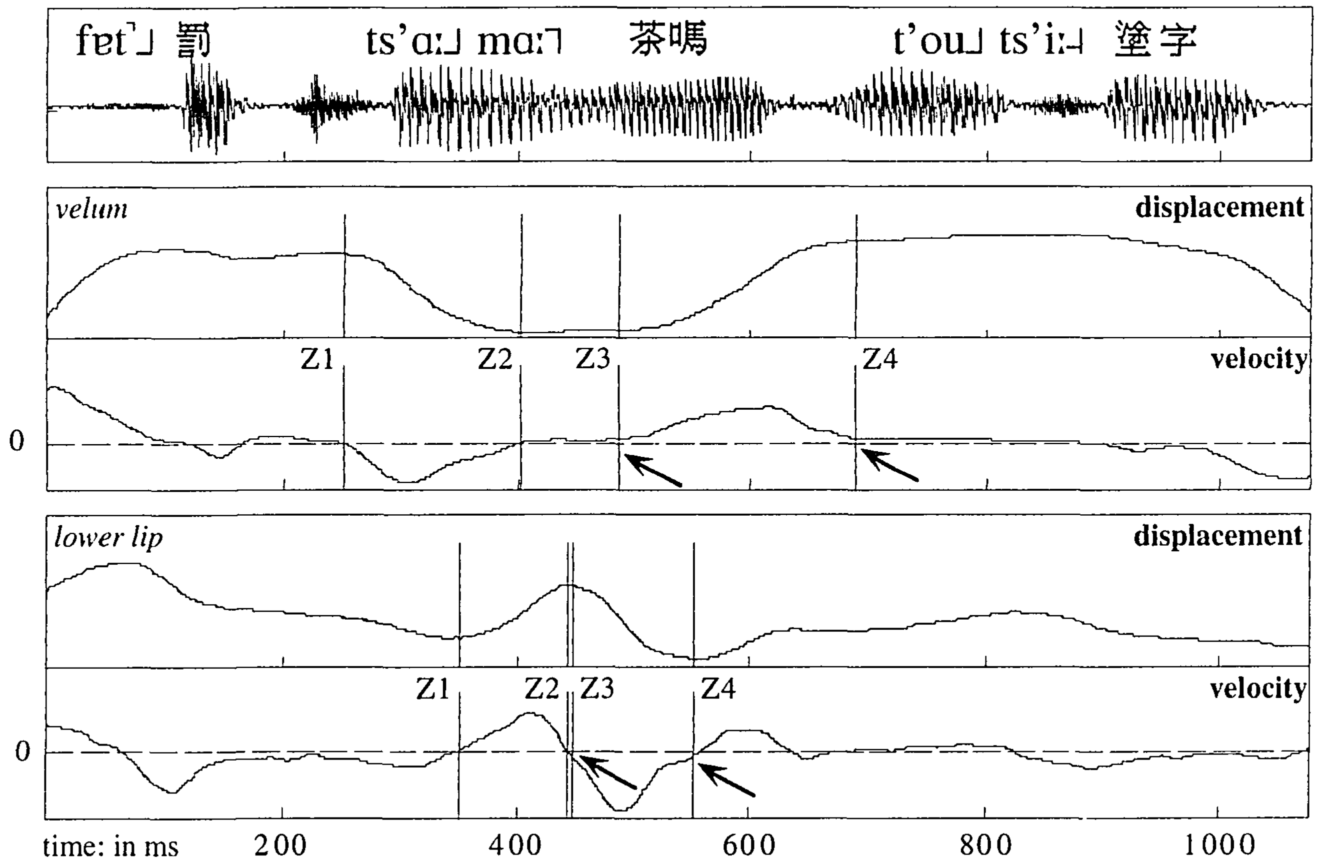

Figure 3.3 A single token (syllable-initial) produced by S3, demonstrating why it was necessary to use (pointed by arrows) 5% of the peak velocity as the noise criterion. Labels on movement traces mark the onsets and offsets of the movement as identified on the corresponding velocity traces (the 'Z' labels).

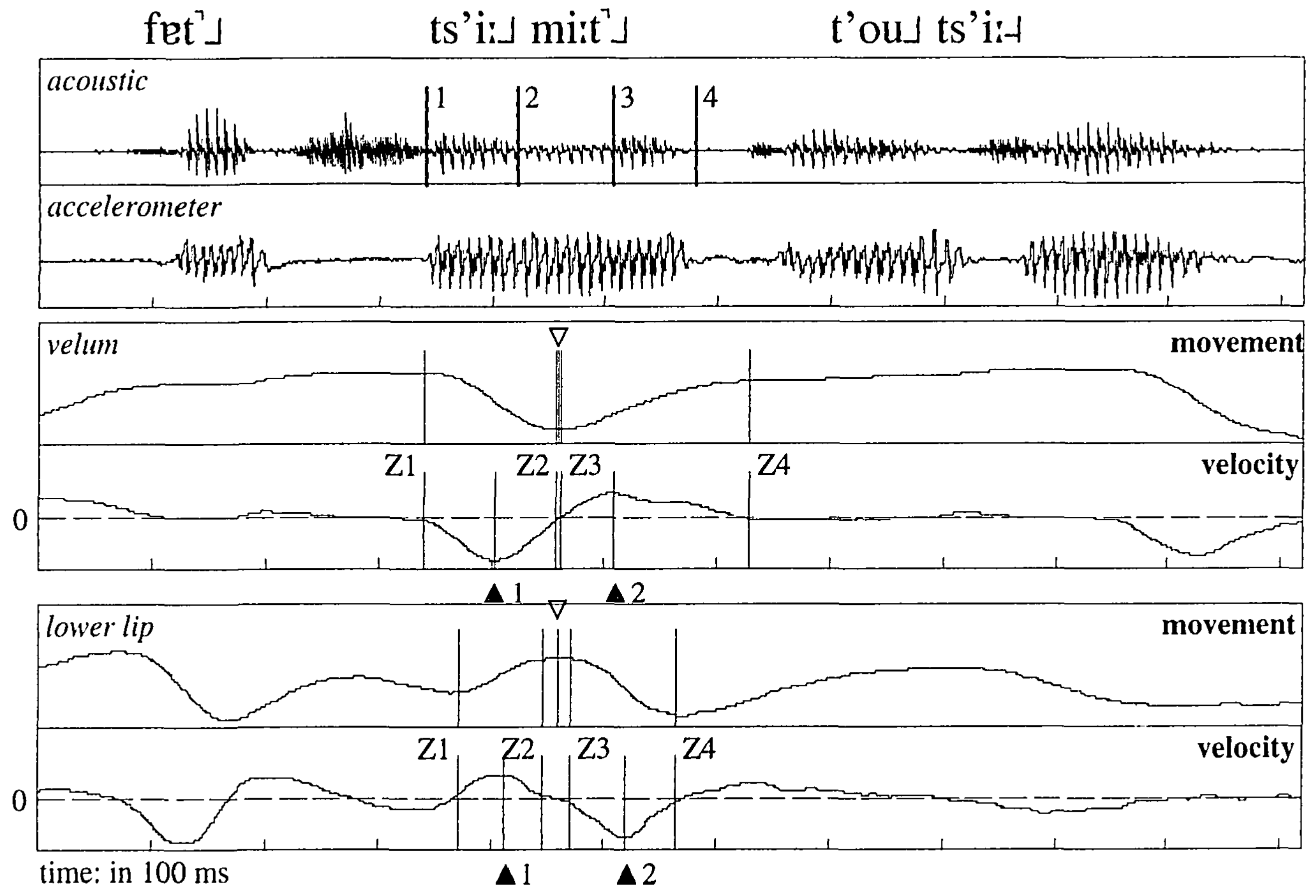

Figure 3.4 A single token (syllable-initial) produced by S4, illustrating events marked in the analyses. Z1 & Z2: onset and offset of velar lowering/lower-lip raising; Z3 and Z4: onset and offset of velar arising/lower-lip lowering. Filled triangles 1 & 2: peak moment velocity for velar lowering/lower-lip raising, and for velar raising/lower-lip lowering, respectively. Unfilled triangles: positional minimum & maximum of the velum, and the lower-lip, respectively. In acoustic signal, 1 & 2, and 3 & 4: onset & offset for vowels preceding and following the nasal.

The Criterion for Averaging of Displacement Data — An ensemble averaging signal was obtained over the ten tokens of each of the eighteen utterances (see 3.6.5), using an averaging window of 600 msec. For each token, the window starts from the point of 250 msec before and ends at the point of 350 milliseconds after the onset of the nasal murmur in the corresponding acoustic signal, totaling a window size of 600 msec.

The F0 — The F0 traces were derived from the Accelerometer signals using a HADES F0 algorithm. For each subject, the criterion of voice threshold was manipulated so that the algorithm would give the best-fit F0 trace. The reliability of a particular criterion was checked by running the program interactively so that F0 values obtained by the program could be evaluated against the ones calculated by measuring the period (F0=1/T).

3.6.4 Data Calculation

Peak Velocity — For each token, the peak velocity values of the lowering and raising movements associated with the bilabial nasal /m/ were obtained from the marked points on both velum and lower lip velocity traces without further processing.

Movement Duration and Displacement — For both velum and lower lip, the durations of the lowering and raising movements associated with the bilabial nasal /m/ were defined as the time between the moment of onset and moment of offset and were calculated accordingly. For both velum and lower lip, the displacements of the lowering and raising movements associated with the bilabial nasal /m/ were defined as the distance between the moment of onset and moment of offset and were calculated accordingly. The low velar plateau was defined as the time between the moment offset of the velar lowering gesture and the moment onset of the velar raising gesture and was calculated accordingly. For the lower lip, the movement durations and displacements of the raising and lowering gestures associated with the bilabial nasal /m/, and the high lower lip plateau were defined and calculated the same way as those for the velum.

Displacement Minima/Maxima — The values of the vertical absolute minimum (velum) and maximum (lower lip) points associated with the bilabial consonant /m/ were taken directly from the velar and lower lip movement signals without further processing.

Durations of Nasal Murmur and Vowels — The time difference between marked onset and offset of the nasal murmur provided the duration of that murmur. The time difference between the onset of the first vowel and the onset of the nasal murmur gave the duration of the first vowel and the time difference between the offset of the nasal murmur and the offset of the second vowel gave the duration of the second vowel.

The F0 — F0 value was obtained at the mid point of V1 from the corresponding F0 trace for each token. The mid point was determined using the onset and offset of the vowel marked on the acoustic waveform as reference. These F0 values were than averaged over the ten tokens for each utterance, the resulting mean F0 value was then taken as the corresponding tonal frequency for the first vowel (or vowel+nasal) for that utterance.

Figure 3.5 provides an example of the measurements of duration and displacement obtained for a single token.

3.6.5 Statistical Analyses

As it was described in 3.6.1, for each stimulus, twelve tokens were produced in two random orders for each stimulus in block of six repetitions of the same utterance by each subject. To avoid a possible block effect, the first token of each block of six repetitions was excluded from all analyses. All the statistical analyses were run for each subject separately because the differing anatomic structures of each subject made it inappropriate to pool the results. Descriptive statistical analyses were first used to eliminate any outliers whose differences from their group means were more than three times the standard deviation. An Analysis of Variance (ANOVA) was always conducted. For most of the measures, the independent variables are: syllable position, vowel type and tone type, and the dependent variable is a single measurement (e.g., duration of velar lowering or

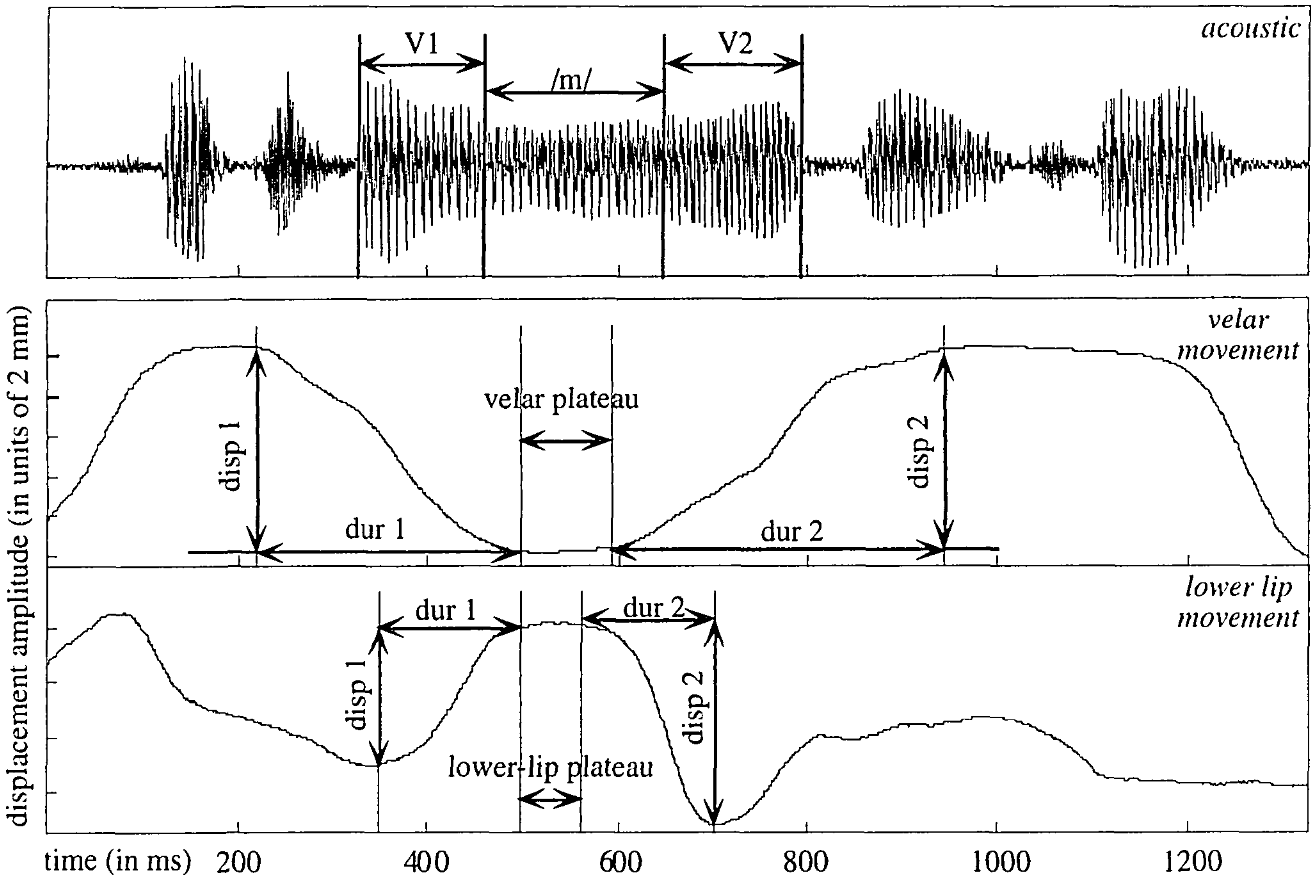

Figure 3.5 A single token, /ts'ɑː˩ m̩˩ ɑː˥/, (syllabic, LL tone), produced by S3, illustrating the measurements of durations and displacement amplitudes. In top panel, V1 and V2 represent the durations of the vowels preceding, and following the nasal, respectively. In bottom panel 1, dur 1 & disp 1: duration and displacement of velar lowering; dur 2 & disp 2: duration and displacement amplitude of velar raising. In bottom panel 2, dur 1 & disp 1: duration and displacement of lower-lip raising; dur 2 & disp 3: duration and displacement of lower-lip lowering.

displacement amplitude of lower lip raising). The ANOVA was employed to assess the effects of syllable position, vowel type, and tone type on the movements of, and coordination between, the velum and the lips. As Table 3.2 shows, the tone for the last CV sequence was kept constant within the vowel, that is, High Level tone (HL) for /ɑ/ and Low Level tone (L) for /i/; therefore, the tonal effect, if there was any, could not be teased apart from the vowel effect. Therefore, for statistical analyses of the measures *following the nasal consonant* (e.g., duration and displacement amplitude of velar raising, or duration and displacement amplitude of lower lip lowering), tone was not included as a main factor. A two-factor ANOVA was conducted for each subject with syllable position and vowel type as independent variables and a single measure as dependent variable. For any ANOVA test, if the main effect of syllable position was significant, pairwise comparisons were conducted to determine whether the significant effect was true for all pairwise comparisons between nasals in different syllable positions (i.e., syllable-final versus syllable-initial, syllable-final versus syllabic, and syllable-initial versus syllabic). The significance level of these pairwise comparisons is reported, but the pattern of difference is not since it is available from the figures provided. The Modified Bonferroni Test was used for the pairwise comparisons. Because the number of pairwise comparisons planned was always three, the approximate familywise error ($\tilde{\alpha}_{FW}$) was .15, and the rejection probability ($\tilde{\alpha}_{planned}$) was set at .05 (See Keppel, 1982). If a significant interaction (either two-way or three-way) was found, tests of simple effect were conducted to further assess the interaction in details. The pattern of difference of the three pairwise comparisons for effects of syllable position within each vowel context is summarized in tables for each measure for each subject. Interactions with a significance level of $p \leq .06$ were considered approaching significance and further analyses were conducted whenever it was felt necessary to help understand the effects.

3.7 Results

This section focuses on the effects of three factors, syllable position, vowel type and tone type, on the temporal and spatial measures of articulation, as well as acoustic duration and relative timing measures. For all subjects, for each measure, means are plotted in figures in the text as well as provided in tables in appendix. Unless indicated otherwise, the legend used is the same in all figures. Note that in the legend, beside representations for syllable position and vowel context that were self-explanatory, the tone of the first syllable of each stimulus was also indicated: 'LL' referring to the low level tone and 'HL' referring to the high level tone. In tables reporting ANOVA results, the three main factors of syllable position, vowel type and tone type were represented by S, V, and T, respectively.

3.7.1 Velar Movement Patterns

The results of analyses of velar movement are presented separately for the temporal and the spatial measures.

Temporal Measurements

Temporal measurements included durations of velar lowering for the bilabial nasal consonant, the low velar plateau, and velar raising away from the bilabial nasal consonant.

- **Duration of velar lowering**

The mean durations of the velar lowering are plotted in Figure 3.6 for all four subjects. ANOVA was conducted for each subject and the results are shown in Table 3.3.

For S1 (Figure 3.6), syllabic nasals had shorter durations of velar lowering in /ɑ/ context, but longer durations in /i/ context, than either syllable-final and syllable-initial nasals. Between syllable-final and syllable-initial nasals, syllable-final nasals had longer velar lowering duration in the LL tone condition, but shorter in the HL tone condition.

TABLE 3.3 ANOVA RESULTS FOR DURATION OF VELAR LOWERING

	S1			S2		
	DF	F	P	DF	F	P
S	2,106	2.876	.0608	2,107	76.608	<.0001
V	1,106	.015	.9012	1,107	242.542	<.0001
S*V	2,106	18.169	<.0001	2,107	36.355	<.0001
T	1,106	54.629	<.0001	1,107	32.169	<.0001
S*T	2,106	6.975	.0014	2,107	.18	.8355
V*T	1,106	.023	.8806	1,107	1.241	.2678
S*V*T	2,106	1.727	.1827	2,107	3.202	.0446
	S3			S4		
	DF	F	P	DF	F	P
S	2,106	42.466	<.0001	2,108	94.303	<.0001
V	1,106	148.866	<.0001	1,108	582.272	<.0001
S*V	2,106	2.915	.0586	2,108	.317	.7288
T	1,106	1.012	.3166	1,108	28.358	<.0001
S*T	2,106	.767	.4671	2,108	.52	.5960
V*T	1,106	.523	.4711	1,108	2.328	.1300
S*V*T	2,106	.376	.6874	2,108	3.981	.0215

Thus, the main effect of syllable position was intertwined with other two factors. The effect of main effect of syllable position was intertwined with other two factors. The effect of syllable position was not significant. The pairwise comparison of duration of velar lowering was significant between syllabic nasals and syllable-initial nasals ($p<.05$). As can be seen from Figure 3.6, the difference in duration between the two vowel types was inconsistent and the effect of vowel type was not significant. As expected, there was a significant interaction between vowel type and syllable position. Further testing of simple effect revealed that although the overall effect of syllable position was not significant in the vowel /ɑ/ context, the pairwise comparison between syllable-final and syllabic nasals was significant ($p<.05$). In the vowel /i/ context, the overall effect of syllable position was significant ($F[2,56]=10.427$, $p<.0001$), and two pairwise comparisons were significant (between syllable-final and syllabic nasals, $p<.0005$, and between syllable-initial and syllabic nasals, $p<.0001$). The vowel effect was significant only for syllabic nasals ($F[1,36]=26.765$, $p<.0001$), with longer duration in /i/ context. A clear tonal effect was also observed: For both vowel contexts and all three nasals of different syllable positions, the duration was consistently longer for the HL tone than for the LL tone condition. The

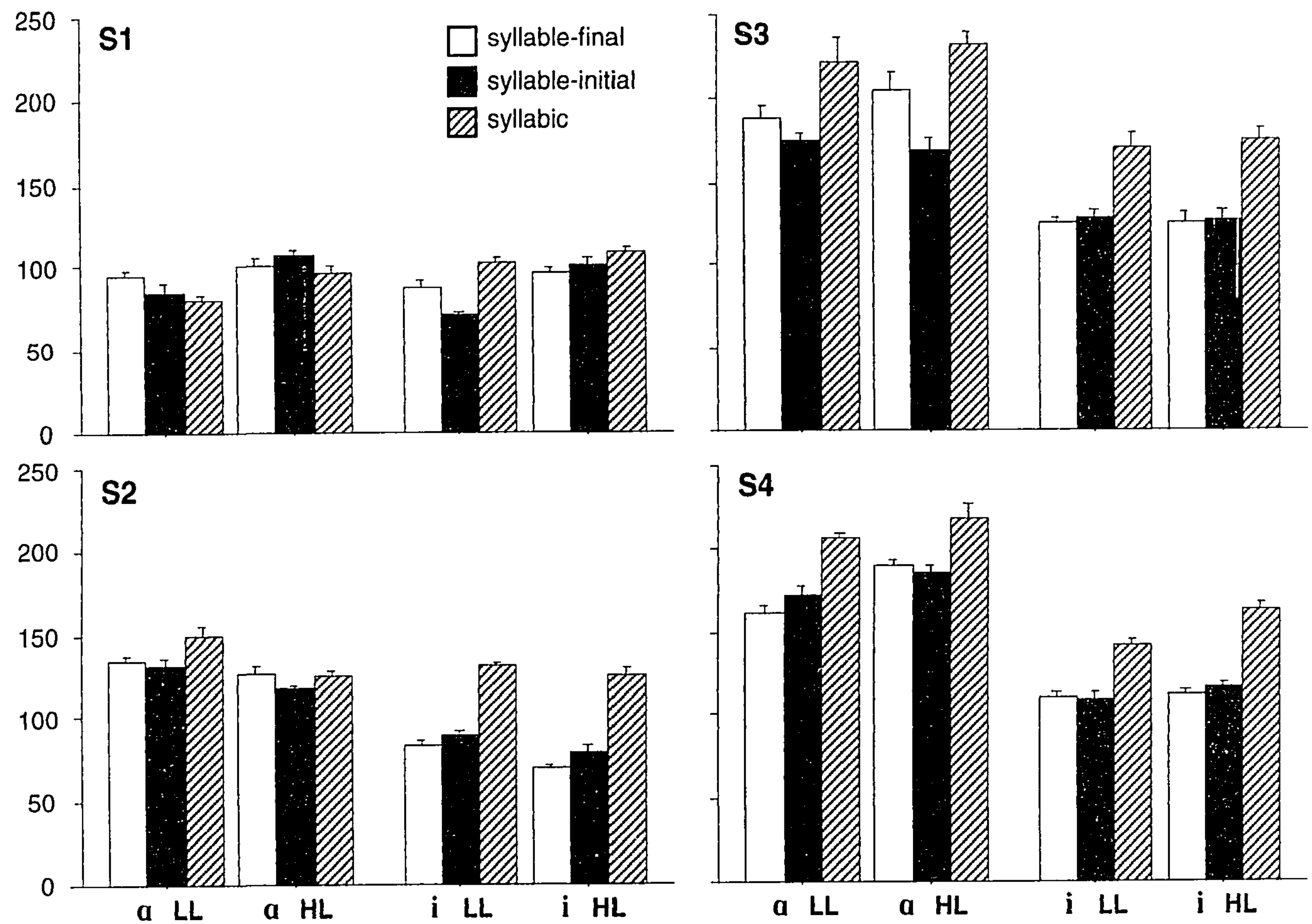

Figure 3.6 Duration of velar lowering (in msec).
The horizontal bars indicate standard error.

main effect of tone type was significant. There was a significant interaction between syllable position and tone type. More detailed analyses revealed that significant effect of syllable position was only found in the LL tone condition (F[2,55]=5.736, p=.0055). The pairwise comparisons conducted within the LL tone condition showed that both syllable-final and syllabic nasals had significantly longer durations of velar lowering than syllable-initial nasals (both p<.01). The results also indicate that significant tonal effect was found in nasals of all three syllable positions, with longer durations of velar lowering in the HL tone condition (for syllable-final nasals, F[1,38]=4.898, p=.0330, for syllable-initial nasals, F[1,38]=36.705, p<.0001, and for syllabic nasals, F[1,36]=7.749, p=.0085). No other significant interaction was observed.

For S2 (Figure 3.6), while the longest durations were found with syllabic nasals in three of the four utterances, the duration of velar lowering varied for syllable-final and syllable-initial nasals as the vowel context changed from /ɑ/ to /i/. In the vowel /ɑ/ context, the duration was longer for syllable-final nasals than for syllable-initial nasals while the opposite was found in the vowel /i/ context. Thus, significant main effects of syllable position was found. Pairwise comparisons were significant between syllable-initial and syllabic nasals (p<.0001), and between syllable-final and syllabic nasals (p<.0001), but not between syllable-final and syllable-initial nasals. Vowel type had observable influence on the duration of velar lowering. The duration of velar lowering was longer in the vowel /ɑ/ context than that in the vowel /i/ context and the main effect of vowel type was significant. The interaction was significant between syllable position and vowel type. Further tests of simple effect showed that the overall effect of syllable position was significant in both vowel contexts, with /ɑ/, F(2,56)=3.433, p=.0392, and /i/, F(2,57)=135.277, p<.0001. In /ɑ/ context, the pairwise comparisons showed that duration of velar lowering was significantly longer for syllabic nasals than syllable-initial nasals (p<.05). In /i/ context, all three pairwise comparisons were significant, with syllable-final nasals having shorter durations than either syllable-initial nasals (p<.05), or syllabic nasals (p<.0001), and syllable-initial nasals having shorter durations than syllabic nasals (p<.0001). For vowel effect, although longer duration in /ɑ/ context was observed for nasals of all three syllable positions, the effect was significant only for syllable-final and syllable-initial nasals (F[1,38]=255.719, p<.0001, and F[1,38]=82.97, p<.0001, for syllable-final and syllable-initial nasals, respectively), not significant for syllabic nasals. For the main effect of tone type, velar lowering duration was found longer in the LL tone condition than in the HL tone condition, and the effect was significant. There was a significant three-way interaction among the three main effects. Analyses of simple effect were conducted to assess it and the results were summarized in Table 3.4. '*' indicates that the effect was significant at the level of p<.05 in the specified condition.

TABLE 3.4 RESULTS OF ANALYSES OF SIMPLE EFFECT ON THE THREE-WAY INTERACTION (S2)

<table>
<tr><th>Effect</th><th colspan="6">Condition</th></tr>
<tr><td>Syllable position</td><td colspan="3">/ɑ/, LL, *</td><td colspan="3">/ɑ/, HL</td></tr>
<tr><td>Syllable position</td><td colspan="3">/i/, LL, *</td><td colspan="3">/i/, HL, *</td></tr>
<tr><td>vowel</td><td colspan="2">syllable-final, LL, *</td><td colspan="2">syllable-initial, LL, *</td><td colspan="2">syllabic, LL, *</td></tr>
<tr><td>vowel</td><td colspan="2">syllable-final, HL, *</td><td colspan="2">syllable-initial, HL, *</td><td colspan="2">syllabic, HL, *</td></tr>
<tr><td>tone</td><td colspan="2">syllable-final, /ɑ/</td><td colspan="2">syllable-initial, /ɑ/</td><td colspan="2">syllabic, /ɑ/, *</td></tr>
<tr><td>tone</td><td colspan="2">syllable-final, /i/, *</td><td colspan="2">syllable-initial, /i/, *</td><td colspan="2">syllabic, /ɑ/</td></tr>
</table>

The analyses of the three-way interaction indicate that both effects of syllable-position and vowel type were significant more often than the effect of tone type; and the tonal effect was significant more often in the vowel /ɑ/ context.

For S3 (Figure 3.6), syllabic nasals had longer durations of velar lowering than either syllable-final or syllable-initial nasals, similar to the general pattern of difference observed for S2. The duration of velar lowering was longer for syllable-final nasals than syllable-initial nasals in the vowel /ɑ/ context, but shorter in the vowel /i/ context. The main effect of syllable position was significant. The pairwise comparison was significant between syllable-final and syllable-initial nasals (p<.05), between syllable-final and syllabic nasals (p<.0001), and between syllable-initial and syllabic nasals (p<.0001). The duration of velar lowering, in general, was longer in /ɑ/ than in /i/ context. The main effect of vowel type was significant. The interaction between syllable position and vowel type was not significant, but approaching the significance. Further analyses of simple effect showed that the overall effect of syllable position was highly significant in both vowel contexts (for /ɑ/, $F[2,56]=15,98$, $p<.0001$, and for /i/, $F[2,56]=41.133$, $p<.0001$), and the only non-significant pairwise comparison was between syllable-final and syllable-initial nasals in the vowel /i/ context (all other five comparisons, three in /ɑ/ and two in /i/ context, were significant at $p<.01$). It was also shown by tests of simple effect that the vowel effect was significant for nasals of all three syllable positions (for syllable-final, $F([1,37]=108.488$, $p<.0001$; for syllable-initial, $F[1,37]=65.893$, $p<.0001$; for syllabic, $F[1,38]=26.314$, $p<.0001$). The main effect of tone type was not significant, and no other significant interactions between factors were found.

For S4 (Figure 3.6), similar to what was seen for S3, syllabic nasals had consistently longer velar lowering duration than syllable-final or syllable-initial nasals. Between syllable-final and syllable-initial nasals, the pattern of difference was inconsistent. Further, the difference was relatively smaller than those when comparisons were made between these two nasals and syllabic nasals. The main effect of syllable position was significant. The pairwise comparisons confirmed the observation: the differences in durations observed between syllabic and syllable-final nasals or syllable-initial nasals were significant (both $p<.0001$), but the difference between syllable-final and syllable-initial nasals was not. The velar lowering duration was always longer in /ɑ/ context than in /i/ context and the main effect of vowel type was significant. There was no interaction between the effect of syllable position and the effect of vowel type. The duration was longer in the HL tone condition than in the LL tone condition, thus, the main effect of tone type was significant. There was a significant three-way interaction among the three main effects. Analyses of simple effect were conducted to assess it and the results are summarized in Table 3.5. From the analyses of the three-way interaction, it was observed that both effect of syllable position and effect of vowel type were found to be significant much more often than the effect of tone type.

TABLE 3.5 RESULTS OF ANALYSES OF SIMPLE EFFECT ON THE THREE-WAY INTERACTION (S4)

Effect	Condition		
Syllable position	/ɑ/, LL, *	/ɑ/, HL, *	
Syllable position	/i/, LL, *	/i/, HL, *	
vowel	syllable-final, LL, *	syllable-initial, LL, *	syllabic, LL, *
vowel	syllable-final, HL, *	syllable-initial, HL, *	syllabic, HL, *
tone	syllable-final, /ɑ/, *	syllable-initial, /ɑ/	syllabic, /ɑ/
tone	syllable-final, /i/	syllable-initial, /i/	syllabic, /i/, *

Table 3.6 summarizes the results presented on duration of velar lowering for effect of syllable position. In the table, the pattern of difference is indicated between each pairwise comparison with reference to the first element in the pair.

To summarize, there was an overall effect of syllable position on duration of velar lowering. As shown in Table 3.6, syllabic nasals had longer duration of velar lowering than either syllable-final, or syllable-initial nasals in most of the cases. Between syllable- and syllable-initial nasals, when there was a significant effect of syllable position, it varied in the two vowel contexts. For S2 and S3, the pattern of difference was, although not always significant, that the syllable-final nasals had longer duration of velar lowering than syllable-initial nasals in the vowel /ɑ/ context, but shorter duration in the vowel /i/ context.

TABLE 3.6 PAIRWISE COMPARISON FOR DURATION VELAR LOWERING

	Pairwise Comparisons			
Subject	vowel	Syl-final vs. Syl-initial	Syl-final vs. Syllabic	Syl-initial vs. Syllabic
S1	ɑ	longer	longer	longer *
	i	longer	shorter *	shorter *
S2	ɑ	longer	shorter	shorter *
	i	shorter *	shorter *	shorter *
S3	ɑ	longer *	shorter *	shorter *
	i	shorter	shorter *	shorter *
S4	ɑ	shorter	shorter *	shorter *
	i	shorter	shorter *	shorter *

While for S1, syllable-final nasals always had longer durations than syllable-initial nasals, the opposite pattern was found for S4. Therefore, for two of the four subjects, durations of velar lowering for syllable-final and syllable-initial nasals were different in different vowel contexts, while for the other two subjects, there was no such interaction. There was a consistent vowel effect for three of the four subjects, with longer duration in the vowel /ɑ/ context. Significant tonal effects were found in three of the four subjects (S1, S2 and S4): two subjects showing a longer duration for the HL tone condition (S1, S4) and one subject showing the effect in the opposite direction (S2).

- **Duration of low velar plateau**

The mean durations of low velar plateau for each stimulus are plotted in Figure 3.7. The results of the ANOVA are presented in Table 3.6.

For S1 (Figure 3.7), syllabic nasals had longer velar plateau duration than either syllable-final or syllable-initial nasals. Between syllable-final and syllable-initial nasals, syllable-final nasals had longer velar plateau durations in /ɑ/ context, but shorter durations in /i/ context. The main effect of syllable position was significant. Pairwise comparisons were conducted to further assess the significant effect of syllable position.

TABLE 3.7 ANOVA RESULTS FOR DURATION OF VELAR PLATEAU

	S1			S2		
	DF	F	P	DF	F	P
S	2,107	100.687	<.0001	2,107	43.223	<.0001
V	1,107	1361.395	<.0001	1,107	17.869	<.0001
S*V	2,107	21.679	<.0001	2,107	2.699	.0719
T	1,107	.8390	.3618	1,107	3.948	.0495
S*T	2,107	4.788	.0102	2,107	2.742	.0689
V*T	1,107	7.232	.0083	1,107	1.634	.2039
S*V*T	2,107	5.778	.0041	2,107	1.657	.1956
	S3			S4		
	DF	F	P	DF	F	P
S	2,105	43.070	<.0001	2,106	49.558	<.0001
V	1,105	311.737	<.0001	1,106	975.423	<.0001
S*V	2,105	29.300	<.0001	2,106	29.019	<.0001
T	1,105	3.433	.0667	1,106	.075	.7848
S*T	2,105	8.023	.0006	2,106	1.988	.1420
V*T	1,105	2.149	.1457	1,106	1.041	.3099
S*V*T	2,105	6.698	.0018	2,106	.924	.4000

The results showed that the comparisons were significant between syllabic nasals and syllable-final or syllable-initial nasals (both p<.0001), but not significant between syllable-final and syllable-initial nasals. The velar plateau duration was consistently longer in /ɑ/ context than in /i/ context, and the main effect of vowel type was significant. There was a significant interaction between syllable position and vowel type. Further analyses of simple effect revealed that the overall effect of syllable position was highly significant in both vowel contexts, (for /ɑ/, $F[2,57]=54.377$, $p<.0001$, and for /i/, $F[2,56]=39.432$, $p<.0001$), and pairwise comparisons in both vowel contexts were significant (all three comparisons in /ɑ/ context were significant at $p<.01$, and all three comparisons in /i/ context were significant at $p<.001$). The significant difference in duration of velar plateau found between syllable-final and syllable-initial nasals was, as observed above, longer for syllable-final nasals in /ɑ/ context, but shorter in /i/ context. The duration of the velar plateau was significantly longer in vowel /ɑ/ context compared to /i/ context, for nasals of all three syllable positions (for syllable-final nasals, $F[1,37]=498.297$, $p<.0001$, for syllable-initial nasals, $F[1,38]=237.648$, $p<.0001$, and for syllabic nasals, $F[1,38]=430.115$, $p<.0001$). The main effect of tone type was not significant. However, the interactions between syllable position and tone type and between vowel type and tone type were significant. Results from tests of simple effect indicated that for interaction between syllable position and tone type, the effect of syllable position was significant only in the HL tone condition ($F[2,57]=6.517$, $p=.0028$), and the pairwise comparisons were significant between syllabic nasals and syllable-final or syllable-initial nasals (both $p<.01$). However, for nasals of all three syllable positions, no significant tonal effect was found, which was consistent with the findings of the ANOVA test. For the interaction between vowel type and tone type, it was shown that while vowel effect was significant in both tone conditions ($F[1,57]=275.244$, $p<0001$ for /ɑ/ context, and ($F[1,58]=160.655$, $p<0001$ for /i/ context), the tonal effect was not significant in either vowel context. There was a significant three-way interaction among the three main effects. Analyses of simple effect were conducted to assess it and the results were summarized in Table 3.8.

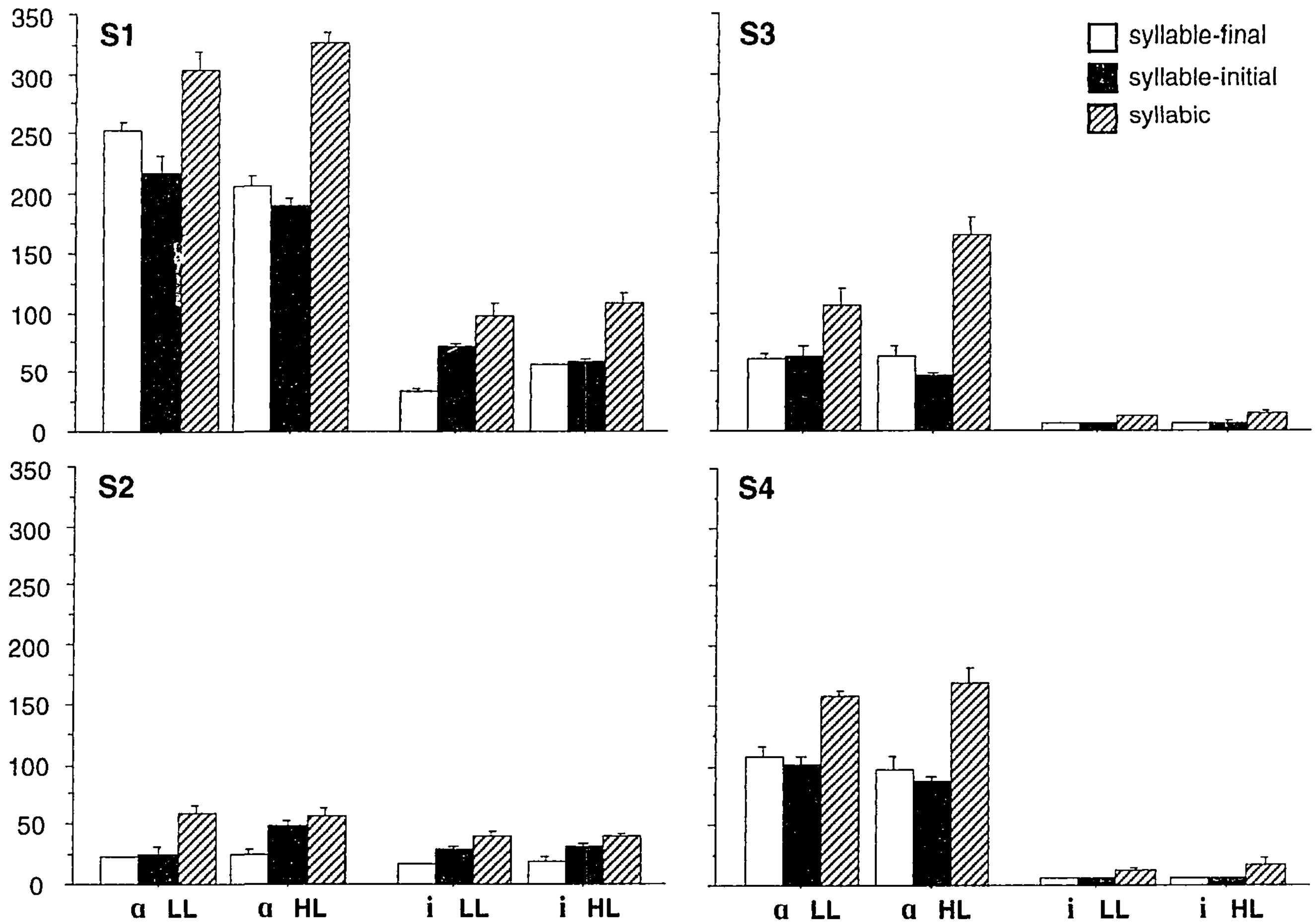

Figure 3.7 Duration of low velar plateau (in msec).
The horizontal bars indicate standard error.

TABLE 3.8 RESULTS OF ANALYSES OF SIMPLE EFFECT ON THE THREE-WAY INTERACTION (S1)

<table>
<tr><th>Effect</th><th colspan="6">Condition</th></tr>
<tr><td>Syllable position</td><td colspan="3">/ɑ/, LL, *</td><td colspan="3">/ɑ/, HL, *</td></tr>
<tr><td>Syllable position</td><td colspan="3">/i/, LL, *</td><td colspan="3">/i/, HL, *</td></tr>
<tr><td>vowel</td><td colspan="2">syllable-final, LL, *</td><td colspan="2">syllable-initial, LL, *</td><td colspan="2">syllabic, LL, *</td></tr>
<tr><td>vowel</td><td colspan="2">syllable-final, HL, *</td><td colspan="2">syllable-initial, HL, *</td><td colspan="2">syllabic, HL, *</td></tr>
<tr><td>tone</td><td colspan="2">syllable-final, /ɑ/, *</td><td colspan="2">syllable-initial, /ɑ/</td><td colspan="2">syllabic, /ɑ/</td></tr>
<tr><td>tone</td><td colspan="2">syllable-final, /i/, *</td><td colspan="2">syllable-initial, /i/</td><td colspan="2">syllabic, /i/</td></tr>
</table>

From the analyses of the three-way interaction, it is clear from Table 3.8 that both the effect of syllable position and the effect of vowel type were found significant much more often than effect of tone type. For the duration of low velar plateau, the effect of tone type was significant only for syllable-final nasals.

For S2 (Figure 3.7), for syllabic nasals, the pattern is similar to what was seen for S1, that is, syllabic nasals consistently had longer durations of low velar plateau than either syllable-final or syllable-initial nasals. Between syllable-final and syllable-initial nasals, syllable-final nasals had shorter duration than syllable-initial nasals. Thus, the main effect of syllable position was significant, and so were the three pairwise comparisons among nasals of different syllable positions (for all three comparisons, $p<.0001$). Overall, the velar plateau duration was longer in the vowel /ɑ/ context than in the vowel /i/ context, and the main effect of vowel type was significant. However, tests of simple effect showed that vowel effect was significant only for syllable-final nasals ($F[1,37]=255.719$, $p<.0001$) and syllable-initial nasals ($F[1,38]=82.97$, $p<.0001$), but not for syllabic nasals. No significant interaction between syllable position and vowel type was found. For syllable-final and syllable-initial nasals, the duration of low velar plateau seemed to be longer in the HL tone condition than in the LL tone condition, but no clear difference was seen between the two tone conditions in syllabic nasals, although the main effect of tone type was significant. Further testing showed that the tonal effect was significant only for syllable-initial nasals ($F[1,38]=9.236$, $p=.0043$), although syllable-final nasals also had longer mean durations in the HL tone condition, similar to what was observed for syllable-initial nasals. No significant interactions were found between factors.

For S3 (Figure 3.7), the pattern for syllabic nasals observed for both S1 and S2, is seen again. Syllabic nasals consistently had longer duration of low velar plateau than syllable-final or syllable-initial nasals. Syllable-initial nasals had longer durations of low velar plateau than syllable-final nasals in vowel /i/, but the pattern of difference between these two nasals was not consistent in /ɑ/ context. The main effect of syllable position was significant. Pairwise comparisons were significant between syllabic nasals and syllable-final or syllable-initial nasals (both $p<.0001$), but not significant between syllable-final and syllable-initial nasals. Therefore, although difference of velar plateau duration between these two nasals was observed, it was not consistent enough to be statistically significant. The velar plateau duration was consistently longer in vowel /ɑ/ context than in vowel /i/ context and the main effect of vowel type was significant. There was a significant interaction between syllable position and vowel type. Tests of simple effect revealed that the overall effect of syllable position was significant in both vowel contexts. In the vowel /ɑ/ context, ($F[2,55]=28.294$, $P<.0001$), the pairwise comparisons were significant between syllabic nasals and syllable-final or syllable-initial nasals (both $p<.0001$), but not significant between syllable-final and syllable-initial nasals; while in the vowel /i/ context, ($F[2,56]=36.782$, $P<.0001$), all three pairwise comparisons were significant, between syllable-final and syllable-initial nasals ($p<.05$), and between syllabic and syllable-final or syllable-initial nasals (both $p<.0001$). It was also shown by test of simple effect that the vowel effect was significant for nasals of all three syllable positions, (for syllable-final nasals, $F[1,37]=192.531$, $p<.0001$; for syllable-initial nasals, $F[1,37]=102.328$, $p<.0001$; and for syllabic nasals, $F[1,37]=87.195$, $p<.0001$). The main effect of tone type was not significant, but the interaction between syllable position and tone type was significant. Further analyses revealed that the overall effect of syllable position was significant only in the LL tone condition, ($F[2,55]=8.363$, $p=.0007$), and pairwise comparisons were significant between syllabic and syllable-final or syllable-initial nasals (both p<.01); and as for the effect of tone type, it was not significant for any of the three types of nasals. There was a significant three-way interaction among the three main effects. Analyses of simple effect were conducted to assess it and the results were summarized in Table 3.9.

TABLE 3.9 RESULTS OF ANALYSES OF SIMPLE EFFECT ON THE THREE-WAY INTERACTION (S3)

Effect	Condition		
Syllable position	/ɑ/, LL, *		/ɑ/, HL, *
Syllable position	/i/, LL, *		/i/, HL, *
vowel	syllable-final, LL, *	syllable-initial, LL, *	syllabic, LL, *
vowel	syllable-final, HL, *	syllable-initial, HL, *	syllabic, HL, *
tone	syllable-final, /ɑ/	syllable-initial, /ɑ/	syllabic, /ɑ/, *
tone	syllable-final, /i/	syllable-initial, /i/	syllabic, /i/, *

From the analyses of the three-way interaction, it was found that both effects of syllabic position and effects of vowel type were significant more often than effects of tone type. Recall that no significant tonal effect was found at any of the three levels of syllable position when the data were pooled across vowel context to assess the interaction between syllable position and tone, it is clear that the tonal effect was detected only when the assessment was done in each vowel context separately.

For S4 (Figure 3.7), again, regardless of the vowel context and tone context, syllabic nasals consistently had longer durations of the low velar plateau than either syllable-final or syllable-initial nasals. Between syllable-final and syllable-initial nasals, syllable-final nasals had longer durations of velar plateau in the vowel /ɑ/ context, but did not differ much from syllable-initial nasals on this measure in the vowel /i/ context. The main effect of syllable position was significant. Pairwise comparisons were significant between syllabic nasals and syllable-final or syllable-initial nasals (both p<.0001), but not between syllable-final and syllable-initial nasals. The velar plateau duration was consistently longer in the vowel /ɑ/ than in the vowel /i/ context; thus, the main effect of vowel type was significant. There was a significant interaction between syllable position and vowel type. Further analyses of simple effect revealed that the overall effect of syllable position was highly significant in both vowel contexts (for /ɑ/, F[2,57]=41.326, p<.0001; and for /i/, F[2,55]=17.899, p<.0001). Pairwise comparisons in both vowel contexts were significant between syllabic nasals and syllable-final or syllable-initial nasals (both p<.0001 in both vowel contexts), but not significant between syllable-final and syllable-initial nasals in either vowel context. The vowel effect was significant for nasals in all three syllable positions (for syllable-final nasals, F[1,38]=188.124, p<.0001; for syllable-initial nasals, F[1,37]=419.162, p<.0001; and for syllabic nasals F[1,37]=474.259, p<.0001). There was no tonal effect observed and the main effect of tone type was not significant. No other significant interactions were found.

Table 3.10 summarizes the results presented on the duration of low velar plateau for effect of syllable position.

TABLE 3.10 PAIRWISE COMPARISON FOR DURATION OF LOW VELAR PLATEAU

	Pairwise Comparisons						
Subject	vowel	Syl-final vs. Syl-initial		Syl-final vs. Syllabic		Syl-initial vs. Syllabic	
S1	ɑ	longer	*	shorter	*	shorter	*
	i	shorter	*	shorter	*	shorter	*
S2	ɑ	shorter	*	shorter	*	shorter	*
	i	shorter	*	shorter	*	shorter	*
S3	ɑ	longer		shorter	*	shorter	*
	i	shorter		shorter	*	shorter	*
S4	ɑ	longer		shorter	*	shorter	*
	i	longer		shorter	*	shorter	*

Thus, for durations of low velar plateau, a significant main effect of syllable position was observed for all four subjects. While syllabic nasals consistently had longer durations than either syllable-final or syllable-initial nasals as indicated in Table 3.10, the effect of syllable position varied for syllable-final and syllable-initial nasals as the vowel contexts varied for two of the four subjects. For S1 and S3, relatively longer durations of low velar plateau were found in syllable-final positions in vowel /ɑ/ context, but not in /i/ context. For S2 and S4, the pattern of difference between syllable-final and syllable-initial nasals did not vary between the two vowel contexts, although for S2, syllable-final nasals had significantly shorter duration of velar plateau regardless of the vowel context, while for

S4, syllable-initial nasals had longer duration than syllable-final nasals, but the difference was not statistically significant. For all four subjects, consistently longer durations of low velar plateau were found in the vowel /ɑ/ context. The difference found between the two vowel contexts was statistically significant for nasals of all three syllable positions, except for syllabic nasals for S2. Only S2 had significant main effect of tone type, although, as revealed by tests of simple effect, the tonal effect was significant for syllable-final nasals for S1, for syllable-initial nasals for S2, and for syllabic nasals for S4. The pattern of difference of the tonal effect was inconsistent in two vowel contexts for S1, consistent for both S2 and S4, with longer durations found in the HL tone condition in both vowel contexts.

- **Duration of velar raising**

The mean durations of velar raising for each stimulus are plotted in Figure 3.8. The results of the ANOVA test are presented in Table 3.11.

TABLE 3.11 ANOVA RESULTS FOR DURATION OF VELAR RAISING

	S1			S2		
	DF	F	P	DF	F	P
S	2,114	1.691	.1889	2,114	59.056	<.0001
V	1,114	40.492	<.0001	1,114	297.163	<.0001
S*V	2,114	12.209	<.0001	2,114	.85	.4302
	S3			S4		
	DF	F	P	DF	F	P
S	2,114	3.894	.0231	2,114	4.32	<.0155
V	1,114	39.387	<.0001	1,114	540.912	<.0001
S*V	2,114	.103	.9023	2,114	5.229	.0067

For S1 (Figure 3.8), apparently the effect of syllable position was intertwined with the effect of vowel type. Syllabic nasals had shorter durations of velar raising than syllable-final and syllable-initial nasals in the vowel /ɑ/ context, but longer durations in the vowel /i/ context. Between syllable-final and syllable-initial nasals, syllable-final nasals had consistently longer durations in /i/ context only. In the vowel /ɑ/ context, the pattern of difference between the two nasals was inconsistent. As one would expect from what was

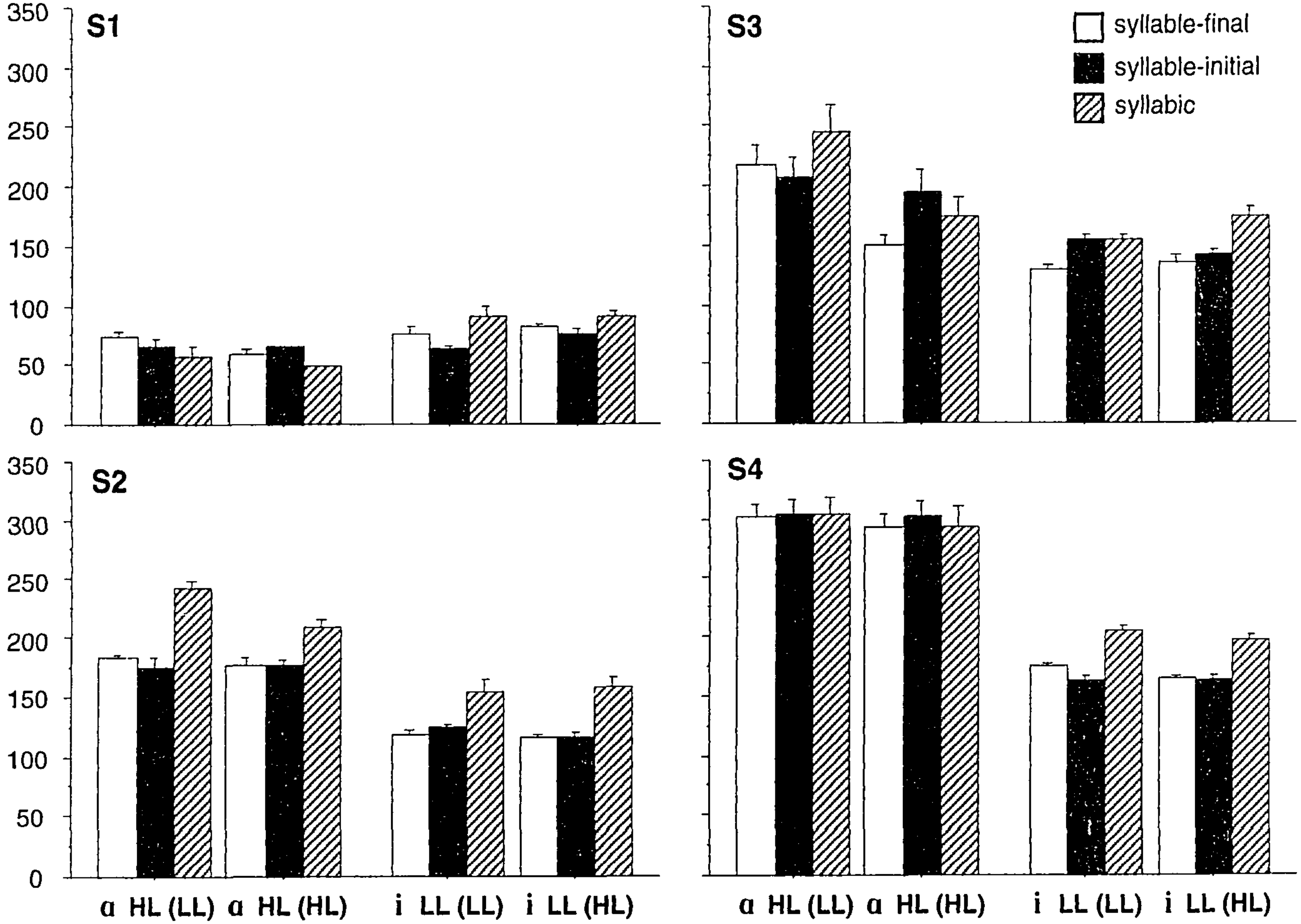

Figure 3.8 Duration of velar raising (in msec).
The horizontal bars indicate standard error.

seen above, the main effect of syllable position was not significant. As shown in Figure 3.8, consistently longer durations were found in the vowel /i/ context for syllable-final and syllabic nasals, thus, the main effect of vowel type was significant. Not surprisingly, the interaction between syllable position and vowel type was significant. Further analyses of simple effect revealed that the overall effect of syllable position was significant in both vowel contexts (for /ɑ/, $F[2,57]=45.743$, $p<.01$; and for /i/, $F[2,57]=7.795$, $p<.001$). In the vowel /ɑ/ context, pairwise comparisons were significant between syllabic nasals and syllable-final or syllable-initial nasals, ($p<.01$, and $p<.05$, respectively), but not significant between syllable-final and syllable-initial nasals; while in the vowel /i/ context, all three pairwise comparisons were significant: between syllable-final and syllable-initial nasals ($p<.05$), between syllabic and syllable-final nasals ($p<.05$) and between syllabic and syllable-initial nasals ($p<.001$). The vowel effect was significant for both syllable-final nasals, ($F[1,38]=7.421$, $p<.01$), and syllabic nasals, ($F[1,38]=40.885$, $p<.0001$), but not for syllable-initial nasals.

For S2 (Figure 3.8), syllabic nasals had consistently longer durations of velar raising than either syllable-final or syllable-initial nasals, which differed from each other inconsistently. The main effect of syllable position was significant. Pairwise comparisons were significant between syllabic nasals and syllable-final or syllable-initial nasals (both $p<.0001$), but not significant between syllable-final and syllable-initial nasals. Consistently longer durations were found in the vowel /ɑ/ context for nasals of all three syllable positions, thus, the main effect of vowel type was significant. And this significant vowel effect was consistent across nasals of all three syllable positions. No significant interaction was found between syllable position and vowel type.

For S3 (Figure 3.8), syllabic nasals had consistently longer durations of velar raising than syllable-final nasals. Between syllabic and syllable-initial nasals, although there was observable differences, the pattern of difference was inconsistent among utterances. Between syllable-final and syllable-initial nasals, syllable-initial nasals had longer durations in the vowel /i/ context, but the pattern of difference between these two nasals was inconsistent in the vowel /ɑ/ context. The main effect of syllable position was significant. Only pairwise comparison between syllable-initial and syllabic nasals was significant ($p<.05$). Durations of velar raising were longer in the vowel /ɑ/ context for nasals of all three syllable positions; thus, the main effect of vowel type was significant. This significant vowel effect was consistent across nasals of all three syllable positions. Thus, no significant interaction was found between the two main factors. Observation indicated that the pattern of difference between nasals of different syllable positions varied in different vowel contexts, therefore, tests of simple effect were warranted and the effect of syllable position was further assessed within each vowel context. The results showed that the overall effect of syllable position was significant only in the vowel /i/ context ($F[2,57]=13.363$, $p<.0001$). All three pairwise comparisons in /i/ context were significant: between syllable-final and syllable-initial nasals ($p<.05$); between syllable-final and syllabic nasals ($p<.0001$); and between syllable-initial and syllabic nasals ($p<.001$).

For S4 (Figure 3.8), durations of velar raising did not differ much among nasals of different syllable positions in the vowel /ɑ/ context. In the vowel /i/ context, syllabic nasals had longer duration than either syllable-final or syllable-initial nasals, while syllable-final nasals had longer duration than syllable-initial nasals. The main effect of syllable position was significant. Pairwise comparisons were significant between syllabic nasals and syllable-final or syllable-initial nasals, ($p<.05$, and $p<.01$, respectively), but not significant between syllable-final and syllable-initial nasals. The effect of vowel type was very prominent with longer durations of velar raising in the vowel /ɑ/ context. The main effect of vowel type was significant. The interaction between syllable position and vowel type was also significant. Further analyses of simple effect revealed that the overall effect of syllable position was significant only in the vowel /i/ context ($F[2,57]=38.818$, $p<.0001$), and pairwise comparisons were significant between syllabic nasals and syllable-final or syllable-initial nasals (both $p<.0001$). The vowel effect was significant for all three types of nasals with longer durations of velar raising in /ɑ/ context, (for syllable-final nasals, F[1,38]=283.221, p<.0001; for syllable-initial nasals, F[1,38]=237.77, p<.0001; and for syllabic nasals, (F[1,38]=89.937, p<.0001).

Table 3.12 summarizes the results presented on duration of velar raising for effect of syllable position.

TABLE 3.12 PAIRWISE COMPARISON FOR DURATION OF VELAR RAISING

		Pairwise Comparisons		
Subject	vowel	Syl-final vs. Syl-initial	Syl-final vs. Syllabic	Syl-initial vs. Syllabic
S1	ɑ	longer	longer *	longer *
	i	longer *	shorter *	shorter *
S2	ɑ	longer	shorter *	shorter *
	i	shorter	shorter *	shorter *
S3	ɑ	shorter	shorter	shorter
	i	shorter *	shorter *	shorter *
S4	ɑ	shorter	longer	shorter
	i	longer	shorter *	shorter *

To summarize, for duration of velar raising, syllabic nasals had consistently longer durations in the vowel /i/ context when compared to syllable-final or syllable-initial nasals, while in the vowel /ɑ/ context, the pattern of difference varied inconsistently among different syllable positions as well as among subjects. In /ɑ/ context, for S2, syllabic nasals had significantly longer durations than either syllable-final or syllable-initial nasals; while for S1, significant difference was found for syllabic nasals as well, but in opposite direction. That is, syllabic nasals had shorter durations than the other two types of nasals. As shown in Table 3.12, the difference in duration of velar raising between syllable-final and syllable-initial nasals was not very consistent, either. Most of the differences identified between syllable-final and syllable-initial nasals were not statistically significant. A significant vowel effect was found for all four subjects, although the difference patterned differently among subjects. For S1, longer duration of velar raising was found in /i/ context; but for the rest three subjects, longer duration of velar raising was found in /ɑ/ context.

Spatial Measurements

Spatial measurements included: displacement amplitude of velar lowering, positional minimum of the velum, and displacement amplitude of velar raising.

- **Displacement amplitude of velar lowering**

The mean displacement amplitudes of velar lowering are plotted in Figure 3.9 for all four subjects. The results of ANOVA analyses are presented in Table 3.13.

TABLE 3.13 ANOVA RESULTS FOR DISPLACEMENT AMPLITUDE OF VELAR LOWERING

	S1			S2		
	DF	F	P	DF	F	P
S	2,106	13.286	<.0001	2,108	49.124	<.0001
V	1,106	33.669	<.0001	1,108	207.336	<.0001
S*V	2,106	43.017	<.0001	2,108	25.998	<.0001
T	1,106	.02	.8875	1,108	101.011	<.0001
S*T	2,106	7.032	.0014	2,108	4.64	.0117
V*T	1,106	5.522E-3	.9409	1,108	13.732	.0003
S*V*T	2,106	.343	.7104	2,108	.488	.6152
	S3			S4		
	DF	F	P	DF	F	P
S	2,106	28.47	<.0001	2,108	62.483	<.0001
V	1,106	104.422	<.0001	1,108	50.06	<.0001
S*V	2,106	3.835	.0247	2,108	37.569	<.0001
T	1,106	.557	.4571	1,108	2.492	.1174
S*T	2,106	2.209	.1149	2,108	.547	.5801
V*T	1,106	5.198	.0246	1,108	2.755	.0998
S*V*T	2,106	.771	.4650	2,108	.589	.5566

For S1 (Figure 3.9), displacement amplitudes of velar lowering varied among nasals of different syllable positions. Syllable-final nasals always had greater displacement amplitudes than syllable-initial nasals in both vowel contexts, but had greater displacement amplitudes than syllabic nasals only in the vowel /ɑ/ context. The main effect of syllable position was significant. Pairwise comparisons were significant between syllable-final and syllable-initial nasals (p<.001) and between syllable-initial and syllabic nasals (p<.0001). Also in Figure 3.9, a clear vowel effect can be seen for nasals of all three syllable positions, but the pattern of difference was different for different nasals. For syllable-final and syllable-initial nasals, the displacement amplitudes were greater in /ɑ/ context; while for syllabic nasals, greater displacement amplitudes were found in /i/ context. The main effect

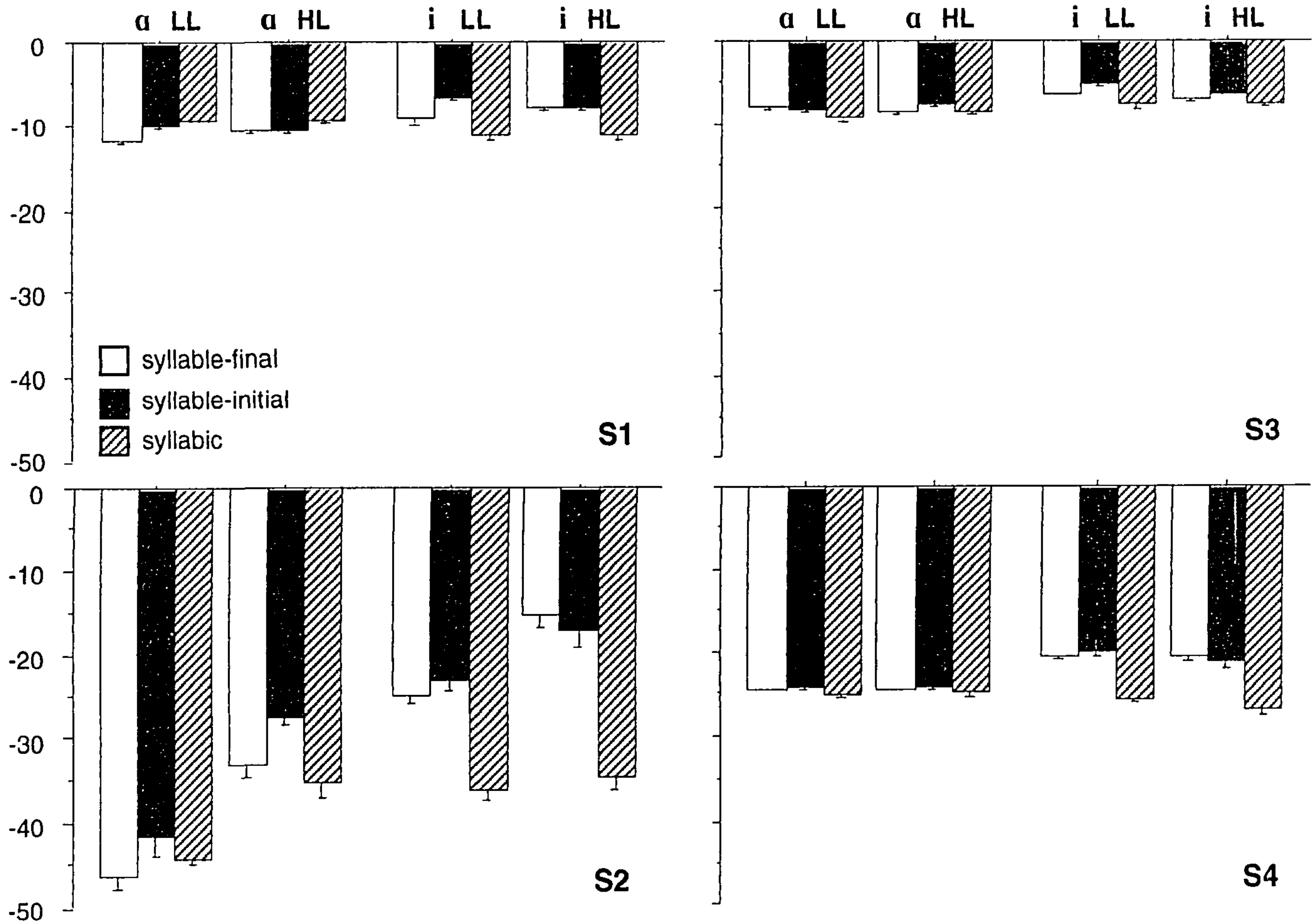

Figure 3.9 Displacement amplitude of velar lowering (in mm)
The horizontal bars indicate standard error.

of vowel type was significant. As discussed before, effect of syllable position varied to certain extent in the two vowel contexts. Thus, as expected, there was a significant interaction between syllable position and vowel type. Further tests of simple effect revealed significant effects of syllable position in both vowel contexts, for /ɑ/, $F(2,57)=18.313$, $p<.0001$; and for /i/, $F(2,55)=28.101$, $p<.0001$. All three pairwise comparisons in /ɑ/ context among nasals of different syllable positions were significant (all $p<.05$); and so were the three pairwise comparisons in /i/ context (all $p<.05$). The vowel effect was significant for all three types of nasals in the direction observed. Greater displacement amplitudes were found in /ɑ/ context for syllable-final and syllable-initial nasals ($F[1,37]=24.584$, $p<.0001$, and $F[1,38]=95.201$, $p<.0001$, respectively); while for syllabic nasals, greater displacement amplitudes were found in /i/ context ($F[1,37]=20.865$, $p<.0001$). Although the main effect of tone type was not significant, there was a significant interaction between syllable position and tone type. However, tests of simple effect revealed that effect of syllable position was significant only for the LL tone condition ($F[2,55]=7.515$, $p<.01$), and pairwise comparisons were significant between syllable-final and syllable-initial nasals, and between syllable-initial and syllabic nasals (both $p<.01$). No tonal effect was found for any of the three types of nasals. No other significant interactions were found.

For S2 (Figure 3.9), syllabic nasals had greater displacement amplitudes of velar lowering than either syllable-initial or syllable-final nasals in three of the four utterances examined. Except for one utterance in /i/ context, syllable-final nasals had greater displacement amplitudes than syllable-initial nasals. Not surprisingly, the main effect of syllable position was significant, and the three pairwise comparisons among nasals of different syllable positions were also significant (for comparison between syllable-final and syllable-initial nasals, $p<.05$, between syllable-final and syllabic nasals, $p<.0001$, and between syllable-initial and syllabic nasals, $p<.0001$). As shown in Figure 3.9, effect of vowel type was also observed. For nasals of all three different syllable positions, the displacement amplitude was greater in /ɑ/ context than in /i/ context. The interaction between syllable position and vowel type was significant. Tests of simple effect revealed that the effect of syllable position varied in degree in the two vowel contexts. In /ɑ/ context, the effect of syllable position was not significant. Pairwise comparisons were significant only between syllable-final and syllable-initial nasals ($p<.05$), and between syllable-initial and syllabic nasals ($p<.05$). In /i/ context, although the effect of syllable position was highly significant ($F[2,57]=50.105$, $p<.0001$), pairwise comparisons were significant only between syllabic and syllable-final or syllable-initial nasals (both $p<.0001$). It was also revealed by tests of simple effect that the vowel effect was significant for nasals of all three syllable positions (for syllable-final nasals, $F[1,38]=72.30$, $p<.0001$; for syllable-initial nasals, $F[1,38]=32.18$, $p<.0001$; and for syllabic nasals $F[1,38]=6.73$, $p<.01$). A tonal effect was also observed: displacement amplitudes were greater in the LL tone condition than in the HL tone condition. Thus, the main effect of tone was significant. The interaction between syllable position and tone type was significant. However, tests of simple effect revealed that while effect of syllable position was significant for both tone conditions, ($F[2,57]=3.196$ $p<.05$, for the LL tone condition, and $F[2,57]=15.977$, $p<.0001$, for the HL tone condition), not all pairwise comparisons were significant. For the LL tone condition, one significant pairwise comparison was found between syllable-initial and syllabic nasals ($p<.05$); and for the HL tone condition, the two significant pairwise comparisons were between syllabic and syllable-final or syllable-initial nasals, (both $p<.0001$). Significant tonal effects were found for nasals of all three different syllable positions (for syllable-final nasals, $F[1,38]=10.858$, $p<.01$; for syllable-initial nasals, $F[1,38]=11.183$, $p<.01$; and for syllabic nasals, $F[1,38]=10.74$, $p<.01$). The interaction between vowel type and tone type was significant. As revealed by tests of simple effect, significantly greater displacement amplitudes of velar lowering were found in the vowel /ɑ/ context for both tone conditions, (for the LL tone condition, $F[1,58]=94.504$, $p<.0001$; and for the HL tone condition, $F[1,58]=19.749$, $p<.0001$). Significant tonal effects were found in both vowel contexts with the significance level varied slightly (for /ɑ/, $p<.0001$, and for /i/, $p<.05$). No significant three-way interaction was found.

For S3 (Figure 3.9), the displacement amplitude of velar lowering was affected by the syllable position of the nasal consonants. Among them, syllabic nasals consistently had greater displacement amplitudes than either syllable-final or syllable-initial nasals. Between syllable-final and syllable-initial nasals, syllable-final nasals tended to have greater displacement amplitudes, though, in one utterance in /ɑ/ context, the displacement amplitudes did not differ much between them. As can be seen from Figure 3.9, the effect of syllable position was more prominent in /i/ context. The main effect of syllable position was significant. The differences seen between the nasals of different syllable positions were also statistically significant by pairwise comparisons. For the comparison between syllable-final and syllable-initial nasals, $p<.01$; between syllable-final and syllabic nasals, $p<.0001$; and between syllable-initial and syllabic nasals, $p<.0001$. As for the effect of vowel type, the displacement amplitudes were greater in the vowel /ɑ/ context, and the main effect of vowel type was significant. There was a significant interaction between syllable position and vowel type ($F[2,106]=3.835$, $p=.0247$). Tests of simple effect revealed that the effect of syllable position was significant in both vowel contexts. In /ɑ/ context, the effect of syllable position was significant ($F[2,56]=7.131$, $p=.0017$), and pairwise comparisons were significant only between syllabic and syllable-final or syllable-initial nasals ($p<.01$ and $p<.05$, respectively); while in /i/ context, not only was the effect of syllable position highly significant, $F[2,56]=20.419$, $p<.0001$, but also all three pairwise comparisons were significant (all $p<.01$). The vowel effect was also shown to be significant for nasals of all three different syllable positions, (for syllable-final: $F[1,37]=49.705$, $p<.0001$; for syllable-initial, $F[1,38]=57.566$, $p<.0001$; and for syllabic, $F[1,37]=11.602$, $p=.0016$). Although no tonal effect was observed, the interaction between vowel type and tone type was significant. Tests of simple effect were conducted to assess the interaction, and the results showed that significantly greater displacement amplitudes of velar lowering were found in /ɑ/ context for both tone conditions, (for the LL tone condition, $F[1,57]=39.396$, $p<.0001$, and for the HL tone condition, $F[1,57]=26.957$, $p<.0001$), however, no significant tonal effect was found in either vowel contexts. No significant three-way interaction was found.

For S4 (Figure 3.9), just as observed for S3, among nasals of three different syllable positions, syllabic nasals had greater displacement amplitudes than either syllable-final or syllable-initial nasals. Between the latter, syllable-final nasals tended to have greater displacement amplitudes. The main effect of syllable position was significant. Pairwise comparisons among nasals of different syllable positions were significant between syllabic nasals and syllable-final or syllable-initial nasals (both $p<.0001$), but not significant between syllable-final and syllable-initial nasals. As can be seen in Figure 3.9, vowel type had an effect on displacement amplitudes of velar lowering. Relatively greater displacement amplitudes of velar lowering were observed for syllable-final and syllable-initial nasals in /ɑ/ context than in /i/ context; while for syllabic nasals, greater displacement amplitudes were found in /i/ context. The main effect of vowel was significant. As expected, the interaction between syllable position and vowel type was significant ($F[2,108]=37.569$, $p<.0001$). Further testing of simple effect showed that the effect of syllable position varied in the two vowel contexts. While it was not significant in /ɑ/ context, it was highly significant in vowel /i/ context ($F[2,57]=66.774$, $p<.0001$). Pairwise comparisons were significant between syllabic nasals and syllable-final or syllable-initial nasals in /i/ context (both $p<.0001$). Also revealed by tests of simple effect was the significant effect of vowel type for nasals of different syllable positions. For syllable-final and syllable-initial nasals, significantly greater displacement amplitudes were found in /ɑ/ context, ($F[1,38]=76.83$, $p<.0001$ and $F[1,38]=35.461$, $p<.0001$, for syllable-final and syllable-initial nasals, respectively). For syllabic nasals, significantly greater displacement amplitudes were found in /i/ context, ($F[1,38]=13.536$, $p=.0007$).

No tonal effect was observed and the main effect of tone was not significant. No other significant interactions were found.

Table 3.14 summarizes the results presented on displacement amplitude of velar lowering for effect of syllable position.

TABLE 3.14 PAIRWISE COMPARISON FOR DISPLACEMENT AMPLITUDE OF VELAR LOWERING

		Pairwise Comparisons					
Subject	vowel	Syl-final vs. Syl-initial		Syl-final vs. Syllabic		Syl-initial vs. Syllabic	
S1	ɑ	greater	*	greater	*	greater	*
	i	greater	*	smaller	*	smaller	*
S2	ɑ	greater	*	smaller		smaller	*
	i	smaller		smaller	*	smaller	*
S3	ɑ	greater		smaller	*	smaller	*
	i	greater	*	smaller	*	smaller	*
S4	ɑ	greater		smaller	*	smaller	*
	i	greater		smaller	*	smaller	*

To summarize, the displacement amplitudes of velar lowering were affected by syllable positions of the nasals. Except for the utterances in /ɑ/ context for S1, syllabic nasals always had greater displacement amplitudes of velar lowering than either syllable-initial nasals or syllable-final nasals. The main effect of syllable position was significant for all subjects. More often than not, greater displacement amplitudes of velar lowering were found for syllable-final nasals than for syllable-initial nasals, although the magnitude of difference did not always reach the pre-defined significance level. For all four subjects, significantly greater displacement amplitudes of velar lowering were found for syllable-final and syllable-initial nasals in the vowel /ɑ/ context than in the vowel /i/ context. For syllabic nasals, although a significant vowel effect was always found, the direction of this significance was not uniform among subjects. That is, for two subjects, significantly greater displacement amplitudes of velar lowering were found in /ɑ/ context, but for the other two subjects, in /i/ context. As for the effect of tone type, only S2 exhibited significant tonal effect on displacement amplitude of velar lowering. The pattern of the difference was consistent for nasals of all three syllable positions, that is, significantly greater displacement amplitudes were always observed in the LL tone than the HL tone condition.

- **Positional minimum of the velum**

It was observed that for the velar movement, the velar height where the lowering gesture started, as well as the velar height where the lowering gesture ended were different among nasals of different syllable positions. For most of the utterances examined (in both vowel contexts), the general pattern was that syllabic nasals tended to start and end at a relatively lower velar position than either syllable-final or syllable-initial nasals, and syllable-final nasals tended to start and end at a relatively lower velar position than syllable-initial nasals. This observed difference in velar position at the starting and ending points of velar lowering gesture was paralleled by the measure of positional minimum of the velum presented here. The mean minima of the velum are plotted in Figure 3.10 for all four subjects. The results of ANOVA analyses are presented in Table 3.15.

TABLE 3.15 ANOVA RESULTS FOR POSITIONAL MINIMUM OF THE VELUM

	S1			S2		
	DF	F	P	DF	F	P
S	2,107	67.021	<.0001	2,108	83.199	<.0001
V	1,107	162.05	<.0001	1,108	150.244	<.0001
S*V	2,107	13.836	<.0001	2,108	11.335	<.0001
T	1,107	.458	.4998	1,108	65.891	<.0001
S*T	2,107	3.727	.0273	2,108	2.461	.0901
V*T	1,107	9.629	.0025	1,108	13.297	.0004
S*V*T	2,107	1.408	.2490	2,108	1.687	.1899
	S3			S4		
	DF	F	P	DF	F	P
S	2,108	36.999	<.0001	2,108	33.762	<.0001
V	1,108	338.192	<.0001	1,108	384.986	<.0001
S*V	2,108	22.978	<.0001	2,108	31.926	<.0001
T	1,108	.421	.5177	1,108	.043	.8360
S*T	2,108	.583	.5602	2,108	2.787	.0660
V*T	1,108	6.132	.0148	1,108	5.093	.0260
S*V*T	2,108	.295	.7449	2,108	.455	.6354

For S1 (Figure 3.10), syllabic nasals reached the lowest positional minimum among the nasals of three different syllable positions and this was true in both vowel contexts. While between syllable-final and syllable-initial nasals, the effect of syllable

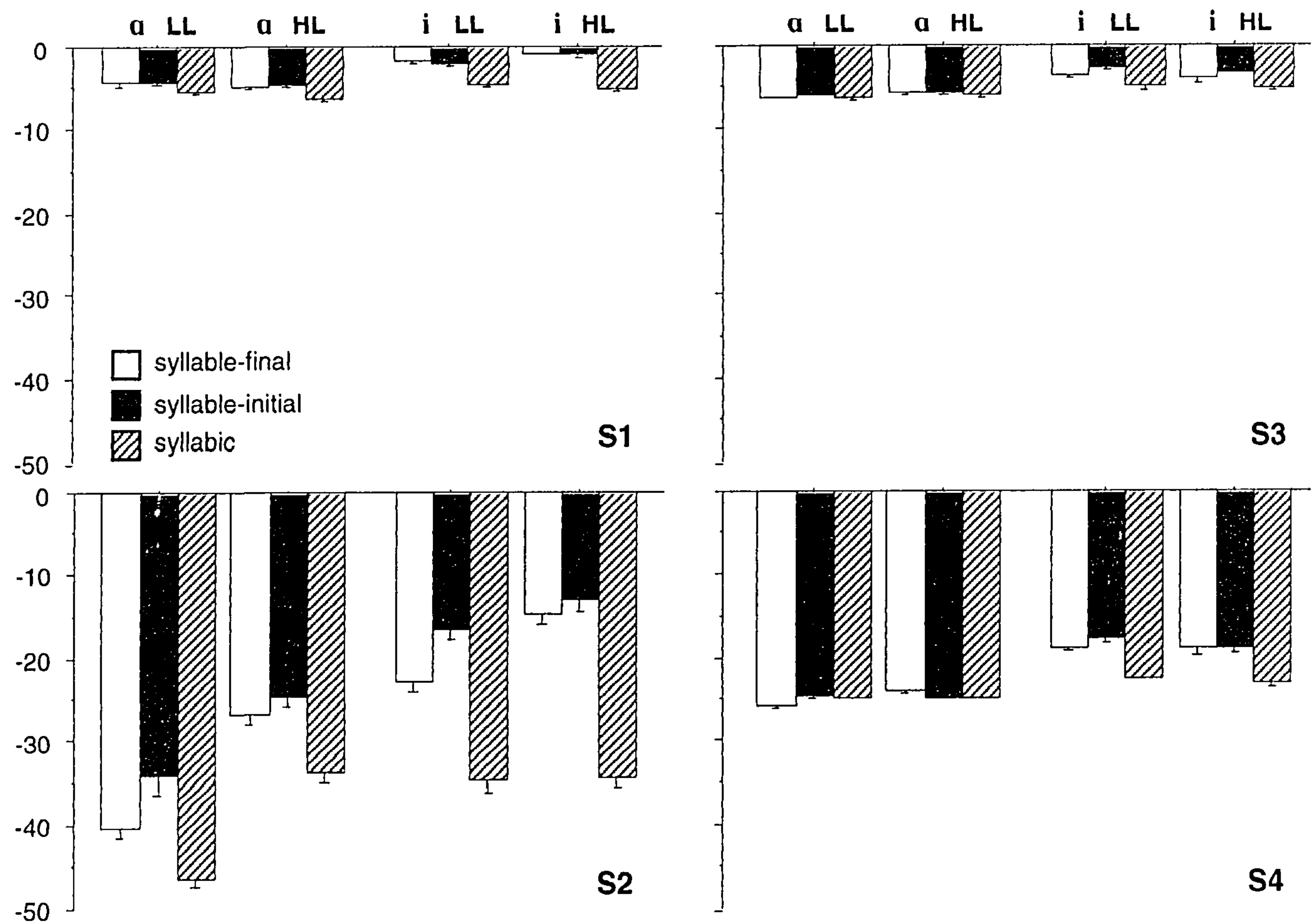

Figure 3.10 Positional minimum of the velum (in mm)
The horizontal bars indicate standard error.

position varied in the two vowel contexts. In /ɑ/ context, syllable-final nasals reached a slightly lower positional minimum, while in /i/ context, syllable-initial nasals did so.

The main effects of syllable position were significant. Pairwise comparisons were significant between syllabic nasals and syllable-final or syllable-initial nasals ($p<.0001$ for both comparisons), but syllable-final and syllable-initial nasals did not differ significantly from each other. There seemed to be an overall vowel effect, that is, a lower positional minimum was reached in the vowel /ɑ/ context. The main effect of vowel type was significant. The interaction between syllable position and vowel type was also significant. Tests of simple effect showed that the effect of syllable position was significant in both vowel contexts (for /ɑ/, $F[2,57]=9.091$, $p<.001$, and for /i/, $F[2,56]=62.98$, $p<.0001$). And further, in /ɑ/ context, pairwise comparisons were significant between syllabic and syllable-final or syllable-initial nasals (both $p<.001$), while in /i/ context, the same two comparisons were also highly significant (both $p<.0001$). The results also showed that significant effect of vowel type was found for every syllable position, with lower positional minima of the velum in /ɑ/ context: for syllable-final nasals, $F(1,38)=61.736$, $p<.0001$; for syllable-initial nasals, $F(1,38)=76.964$, $p<.0001$; and for syllabic nasals, $F(1,38)=13,393$, $p<.001$. No consistent tonal effect was observed and the main effect of tone was not significant. However, there were two significant interactions involving tone, one between syllable position and tone type, and the other between vowel type and tone type. For the interaction between syllable position and tone type, tests of simple effect revealed that while the effect of syllable position was significant for both tone conditions, ($F[2,57]=9.105$, $p<.001$ for the LL tone condition, and $F[2,57]=15.814$, $p<.0001$ for the HL tone condition), not all pairwise comparisons were significant. For the LL tone condition, two significant pairwise comparisons were found and they were between syllabic nasals and syllable-final or syllable-initial nasals (both $p<.001$). For the HL tone condition, the two significant pairwise comparisons were between syllabic and syllable-final or syllable-initial nasals (both $p<.0001$). As for the effect of tone type, it was significant only for syllabic nasals with a lower positional minimum of the velum achieved in the HL tone condition (F[1,37]=8.061, p=.0073). The significant interaction between vowel type and tone type was assessed by tests of simple effect. For both tone conditions, significantly lower positional minima of the velum were found in the vowel /ɑ/ context (for the LL tone condition, F[1,57]=23.685, p<.0001, and for the HL tone condition, F[1,58]=45.381, p<.0001). Significant tonal effect was found only in the vowel /ɑ/ context, with lower positional minima of the velum for the HL tone condition, (F[1,58]=5. 327, p<.05). No significant three-way interaction was found.

For S2, (Figure 3.10), similar to what was found for S1, syllabic nasals reached the lowest positional minimum of the velum when compared to syllable-final and syllable-initial nasals. Between syllable-final and syllable-initial nasals, syllable final nasals reached the lower positional minimum of the velum. Thus, the main effect of syllable position was significant. Further, pairwise comparisons were significant between syllable-final and syllable-initial nasals (p<.01), between syllable-final and syllabic nasals (p<.0001), and between syllable-initial and syllabic nasals (p<.0001). The positional minimum of the velum was affected by vowel context. The positional minimum of the velum was lower in the vowel /ɑ/ context. The main effect of vowel type was significant. The interaction between syllable position and vowel type was significant. Tests of simple effect showed that the effect of syllable position was significant in both vowel contexts (for /ɑ/, F[2,57]=8.118, p<.001; and for /i/, F[2,57]=63.99, p<.0001). And further, in /ɑ/ context, pairwise comparisons were significant between syllabic nasals and syllable-final or syllable-initial nasals (p<.05 and p<.0001, respectively), while in /i/ context, the same two comparisons were highly significant (both p<.0001). The comparison between syllable-final and syllable-initial nasals was not significant, but approaching the significance level (p=.0513). The results also showed that significant effect of vowel type was found for every syllable position with lower positional minima of the velum in /ɑ/ context: for syllable-final nasals, F(1,38)=44.184, p<.0001; for syllable-initial nasals, F(1,38)=43.298, p<.0001; and for syllabic nasals, F(1,38)=7.176, p<.05. As can be observed in Figure 3.10, the positional minimum of the velum was also affected by tone type, and was lower for the LL tone condition. Thus, the main effect of tone type was significant. There was a significant interaction between vowel type and tone type. The test of simple effect showed that the effect of vowel type was significant in both tone conditions, with lower positional minima of the velum in the vowel /ɑ/ context, (for the LL tone condition, F[1,58]=50.891, p<.0001; and for the HL tone, F[1,58]=13.337, p=.0006). The tests also showed that significant tonal effect was found in /ɑ/ context, with lower positional minimum of the velum for the HL tone (F[1,58]=42.444, p<.0001). No other significant interactions were found.

For S3 (Figure 3.10), the positional minimum of the velum also exhibited similar pattern as seen for S1 and S2. That is, syllabic nasals reached the lowest positional minima of the velum among the three types of nasals. Between syllable-final and syllable-initial nasals, the former reached relatively lower positional minima of the velum than syllable-initial nasals, especially in the vowel /i/ context. The main effect of syllable position was significant. Pairwise comparisons were significant between syllable-final and syllable-initial nasals, p<.0001; between syllable-final and syllabic nasals, p<.001; and between syllable-initial and syllabic nasals, p<.0001. As shown in Figure 3.10, positional minima of the velum were observed to be lower in the vowel /ɑ/ context than in the vowel /i/ context. Thus, the main effect of vowel type was significant. As expected from the pattern seen in the figure, there was a significant interaction between syllable position and vowel type. Tests of simple effect revealed that the effect of syllable position was significant only in /i/ context (F[2,57]=39.411, p<.0001). And further, in /i/ context, pairwise comparisons were significant between syllable-final and syllable-initial nasals (p<.001), and between syllabic nasals and syllable-final or syllable-initial nasals (both p<.0001). The results also showed that a significant vowel effect was found for nasals of all three syllable positions, with lower positional minima of the velum in the vowel /ɑ/ context, (for syllable-final nasals, $F[1,38]=154.032$, $p<.0001$; for syllable-initial nasals, $F[1,38]=196.033$, $p<.0001$, and for syllabic nasals, $F[1,38]=29.93$, $p<.0001$). Although the main effect of tone type was not significant, the interaction between vowel type and tone type was significant. Tests of simple effect were conducted to assess this significant interaction. The results showed that vowel effect was significant in both tone conditions with lower positional minimum in /ɑ/ context, (for the LL tone condition, $F[1,58]=95.283$, $p<.0001$; and for the HL tone, $F[1,58]=75.563$, $p<.0001$). The tests also showed that no significant tonal effect was found in either vowel context. No other significant interactions were found.

For S4 (Figure 3.10), the pattern of difference among nasals of different syllable positions was somewhat different from what was seen for other three subjects. The effect of syllable position varied in the two vowel contexts. In the vowel /i/ context, among the three types of nasals, syllabic nasals had the lowest positional minimum of the velum, while syllable-final nasals reached a relatively lower position than syllable-initial nasals. In the vowel /ɑ/ context, while syllabic nasals had lower positional minima of the velum than syllable-initial nasals, the difference between syllable-final and syllable-initial or syllabic nasals was less consistent. Also, as can be observed in Figure 3.10, the magnitude of difference among the three types of nasals was quite small in /ɑ/ context. The main effect of syllable position was significant. Pairwise comparisons were significant between syllabic nasals and syllable-final or syllable-initial nasals (both $p<.0001$). For nasals of all three syllable positions, lower positional minima of the velum were found in the vowel /ɑ/ context, and the main effect of vowel type was significant. There was also a significant interaction between syllable position and vowel type. Tests of simple effect showed that the effect of syllable position was significant only in the vowel /i/ context ($F[2,57]=43.011$, $p<.0001$). And further, in the vowel /i/ context, pairwise comparisons were significant between syllabic nasals and syllable-final or syllable-initial nasals (both $p<.0001$). The results also showed that a significant vowel effect was found for nasals of all three syllable positions with lower positional minimum of the velum in /ɑ/ context, (for syllable-final nasals, $F[1,38]=128.814$, $p<.0001$; for syllable-initial nasals, $F[1,38]=196.98$, $p<.0001$, and for syllabic nasals, $F[1,38]=55.654$, $p<.0001$). Although the main effect of tone type was not significant, the interaction between vowel type and tone type was significant. Tests of simple effect were conducted to assess this significant interaction. The results showed that vowel effect was significant in both tone conditions with lower positional minimum in /ɑ/ context (for the LL tone condition, $F[1,58]=112.055$, $p<.0001$; and for the HL tone, $F[1,58]=71.677$, $p<.0001$). The tests also showed that no significant tonal effect was found in either vowel contexts. No other significant interactions were found.

Table 3.16 summarizes the results presented on positional minimum of the velum for effect of syllable position.

TABLE 3.16 PAIRWISE COMPARISON FOR POSITIONAL MINIMUM OF THE VELUM

	Pairwise Comparisons			
Subject	vowel	Syl-final vs. Syl-initial	Syl-final vs. Syllabic	Syl-initial vs. Syllabic
S1	ɑ	lower	higher *	higher *
	i	higher	higher *	higher *
S2	ɑ	lower	higher *	higher *
	i	lower	higher *	higher *
S3	ɑ	lower	higher	higher
	i	lower *	higher *	higher *
S4	ɑ	lower	lower	higher
	i	lower	higher *	higher *

To summarize, the positional minimum of the velum exhibited a much clearer pattern for differences resulting from different factors. Overall, both effects of syllable position and vowel type were significant for all four subjects. More often than not, relatively lower positional minimum of the velum was reached by syllabic nasals than either syllable-final or syllable-initial nasals. In most cases, syllable-final nasals had relatively lower positional minima of the velum than syllable-initial nasals, however, the magnitude of the difference was not always statistically significant. Also, whenever there was a such difference in positional minimum of the velum between the two types of nasals, it was more prominent in the vowel /i/ context. Between the two vowel contexts, lower positional minimum of the velum was always found in /ɑ/ context. The main effect of tone type was found only for S2. There was an interaction between syllable position and tone type for S1; however, detailed analyses revealed that it was significant only for syllabic nasals.

- **Displacement amplitudes of velar raising**

The mean displacement amplitudes of velar raising are plotted in Figure 3.11 for all four subjects. The results of ANOVA analyses are presented in Table 3.17.

For S1 (Figure 3.11), the displacement amplitudes of velar raising differed inconsistently among nasals of different syllable positions. The main effect of syllable position was not significant.

TABLE 3.17 ANOVA RESULTS FOR DISPLACEMENT AMPLITUDE OF VELAR RAISING

	S1			S2		
	DF	F	P	DF	F	P
S	2,114	2.32	.1029	2,114	29.704	<.0001
V	1,114	12.237	<.0001	1,114	88.383	<.0001
S*V	2,114	12.832	<.0001	2,114	15.685	<.0001
	S3			S4		
	DF	F	P	DF	F	P
S	2,114	7.803	.0007	2,114	65.595	<.0001
V	1,114	131.142	<.0001	1,114	346.372	<.0001
S*V	2,114	7.323	.0010	2,114	58.307	<.0001

As for the effect of vowel type, the overall impression was that the displacement amplitude of velar raising was greater in the vowel /i/ context than in the vowel /ɑ/ context. The main effect of vowel type was significant. There was a significant interaction between syllable position and vowel type. Further analyses were conducted to assess the interaction. The results revealed that the effect of syllable position was significant in both vowel contexts (in /ɑ/ context, $F[2,57]=14.282$, $p<.0001$, and in /i/ context, $F[2,57]=4.3$, $p=.0182$). Pairwise comparisons were significant in /ɑ/ context between syllabic nasals and syllable-final or syllable-initial nasals (both $p<.001$), and significant between

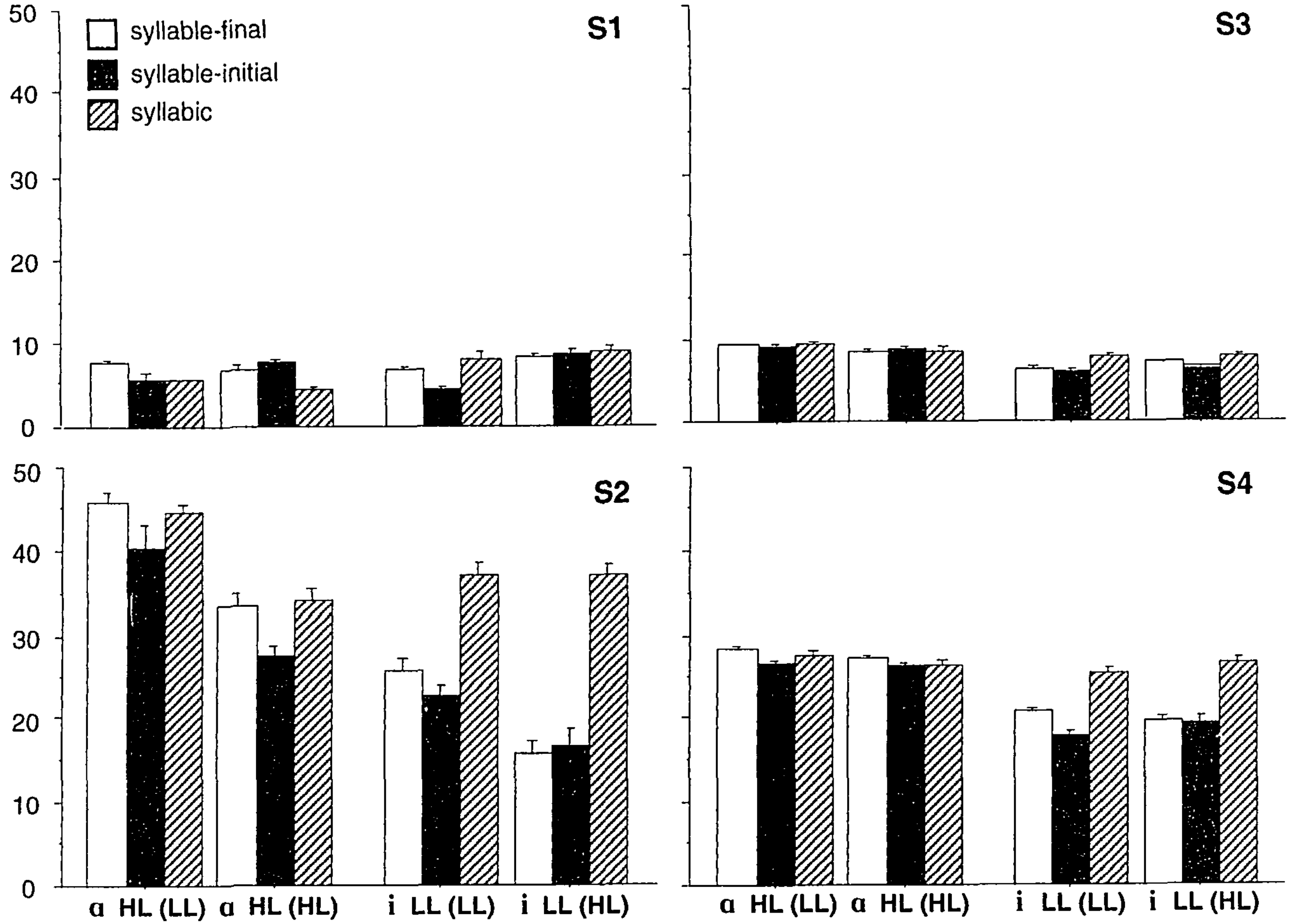

Figure 3.11 Displacement amplitude of velar raising (in mm)
The horizontal bars indicate standard error.

syllable-initial and syllabic nasals ($p<.01$) in /i/ context. The results also showed that the effect of vowel was not significant for either syllable-final nasals or syllable-initial nasals on this measure, however, it was significant for syllabic nasals ($F[1,38]=40.47$, $p<.0001$). Thus, the vowel effect did not affect syllable position consistently even though the main effect of vowel type was significant

For S2 (Figure 3.11), syllabic nasals had greater displacement amplitudes of velar raising than syllable-initial nasals. Syllable-final nasals had overall greater displacement amplitudes than syllable-initial nasals (with exception of one utterance in /i/ context). The pattern of difference between syllable-final and syllabic nasals varied in the two vowel contexts. In the vowel /ɑ/ context, they differed little from each other while in the vowel /i/ context, syllabic nasals clearly took the lead. The main effect of syllable position was significant. All three pairwise comparisons of displacement amplitudes of velar raising were significant: between syllable-final and syllable-initial nasals, $p<.05$, between syllable-final and syllabic nasals, $p<.0001$, and between syllable-initial and syllabic nasals, $p<.0001$. There was an observable vowel effect. The pattern of difference was that both syllable-final and syllable-initial nasals had greater displacement amplitudes in /ɑ/ context than in /i/ context. The main effect of vowel type was significant and the interaction between syllable position and vowel type was significant. Further testing of simple effect showed that the effect of syllable position was significant in both vowel contexts. In /ɑ/ context, the effect of syllable position was $F[2,57]=3.601$, $p=.0337$, with pairwise comparisons significant between syllable-final and syllable-initial nasals ($p<.05$), and between syllable-initial and syllabic nasals ($p<.05$); while in /i/ context, the effect of syllable position was highly significant ($F[2,57]=55.463$, $p<.0001$), and pairwise comparisons were also highly significant between syllabic and syllable-final or syllable-initial nasals (both $p<.0001$). However, the vowel effect was significant only for syllable-final nasals, $F[1,38]=71.90$, $p<.0001$, and syllable-initial nasals, $F[1,38]=33.38$, $p<.0001$, but not for syllabic nasals.

For S3 (Figure 3.11), relatively consistent effect of syllable position was observed. Except for one utterance, both syllable-final and syllabic nasals had greater displacement amplitudes than syllable-initial nasals. However, syllable-final nasals had greater displacement amplitudes than syllabic nasals in /ɑ/ context, while syllabic nasals had greater displacement amplitudes than syllable-final nasals in /i/ context. The main effect of syllable position was significant. Pairwise comparisons were significant only between syllabic nasals and syllable-final ($p<.05$) or syllable-initial nasals ($p<.0001$). As can be seen in Figure 3.11, the displacement amplitude was greater in the vowel /ɑ/ context than in the vowel /i/ context, and the main effect of vowel type was significant. There was a significant interaction of syllable position and vowel type, and further testing of simple effect showed that while no significant effect of syllable position was found in /ɑ/ context; a significant effect of syllable position was found in /i/ context ($F[2,57]=15.388$, $p<.0001$). The three pairwise comparisons between nasals of different syllable positions were significant, with syllable-final nasals having greater displacement amplitudes than syllable-initial nasals, ($p<.05$); syllabic nasals having greater displacement amplitudes than either syllable-final ($p<.001$) or syllable-initial nasals ($p<.0001$). The results also showed that the vowel effect was in fact statistically significant for nasals of all three syllable positions, (syllable-final, $F[1,38]=82.51$, $p<.0001$; syllable-initial, $F[1,38]=78.17$, $p<.0001$; and for syllabic, $F[1,38]=9.63$, $p<.01$).

For S4 (Figure 3.11), both syllable-final and syllabic nasals had consistently greater displacement amplitudes than syllable-initial nasals. However, there was a clear vowel interaction, for syllable-final nasals had greater displacement amplitudes than syllabic nasals in /ɑ/ context, but smaller displacement amplitudes in /i/ context. The main effect of syllable position was significant and all three pairwise comparisons among nasals of different syllable positions were highly significant (for all three comparisons, $p<.001$). A clear vowel effect can be observed in Figure 3.11, greater displacement amplitudes were seen for nasals of all three different syllable positions in /ɑ/ context than in /i/ context. The main effect of vowel type was significant. And the interaction between syllable position and vowel type was significant. Tests of simple effect revealed that the overall effect of syllable position was significant in both vowel contexts, (for /ɑ/, $F[2,57]=4.4$, $p=.0167$, and for /i/, $F[2,57]=88.863$, $p<.0001$). However, while the pairwise comparisons in /ɑ/ context were significant only between syllable-final and syllable-initial nasals, ($p<.01$), all three pairwise comparisons were significant in /i/ context, (between syllable-final and syllable-initial nasals, $p<.01$, and between syllabic and syllable-final or syllable-initial nasals, both $p<.0001$). For effect of vowel type, significantly greater displacement amplitudes were found for nasals of all three different syllable positions, (for syllable-final nasals, $F[1,38]=164.325$, $p<.0001$; for syllable-initial nasals, $F[1,38]=4.815$, $p=.0344$; and for syllabic nasals, $F[1,38]=290.502$, $p<.0001$).

Table 3.18 summarizes the results presented on displacement amplitude of velar raising for effect of syllable position.

TABLE 3.18 PAIRWISE COMPARISON FOR DISPLACEMENT AMPLITUDE OF VELAR RAISING

	Pairwise Comparisons						
Subject	vowel	Syl-final vs. Syl-initial		Syl-final vs. Syllabic		Syl-initial vs. Syllabic	
S1	ɑ	greater		greater		greater	*
	i	greater		smaller		smaller	*
S2	ɑ	greater	*	greater		smaller	*
	i	greater		smaller	*	smaller	*
S3	ɑ	greater		greater		smaller	
	i	greater		smaller	*	smaller	*
S4	ɑ	greater	*	greater		smaller	
	i	greater	*	smaller	*	smaller	*

To summarize the results on displacement amplitude of velar raising, for all four subjects, as can be seen in Table 3.18, the effect of syllable position was manifested in the patterns as follows. First, syllabic nasals in general had greater displacement amplitudes of velar raising than syllable-initial nasals; second, syllable-final nasals had greater displacement amplitudes than syllabic nasals; third, syllable-final nasals had greater displacement amplitude than syllabic nasals in the vowel /ɑ/ context, but smaller displacement amplitude than syllabic nasals in the vowel /i/ context. The displacement amplitudes were consistently greater in /ɑ/ context.

3.7.2 Labial Movement Patterns

The results of analyses of labial movement are presented separately for the temporal and the spatial measures.

Temporal Measurements

Temporal measurements included: durations of lower lip raising toward the bilabial nasal consonant, the high lower lip plateau, and lower lip lowering movements away from the bilabial nasal consonant.

- **Duration of lower lip raising**

The mean durations of lower lip raising for the bilabial nasal consonant are plotted in Figure 3.12 for all four subjects. ANOVA was conducted for each subject and the results are shown in Table 3.19.

TABLE 3.19 ANOVA RESULTS FOR DURATION OF LOWER LIP RAISING

	S1			S2		
	DF	F	P	DF	F	P
S	2,108	142.691	<.0001	2,108	157.122	<.0001
V	1,108	2.23	.1383	1,108	3.273	.0732
S*V	2,108	2.833	.0632	2,108	3.048	.0516
T	1,108	5.018	.0271	1,108	1.102	.2961
S*T	2,108	1.276	.2834	2,108	.583	.5602
V*T	1,108	7.063	.0091	1,108	5.436	.0216
S*V*T	2,108	4.48	.0135	2,108	.352	.7040
	S3			S4		
	DF	F	P	DF	F	P
S	2,108	87.731	<.0001	2,108	333.236	<.0001
V	1,108	31.002	<.0001	1,108	161.356	<.0001
S*V	2,108	15.377	<.0001	2,108	14.166	<.0001
T	1,108	.189	.6649	1,108	3.528	.0630
S*T	2,108	2.190	.1169	2,108	3.185	.0453
V*T	1,108	.382	.5378	1,108	3.441	.0663
S*V*T	2,108	.933	.3965	2,108	1.448	.2395

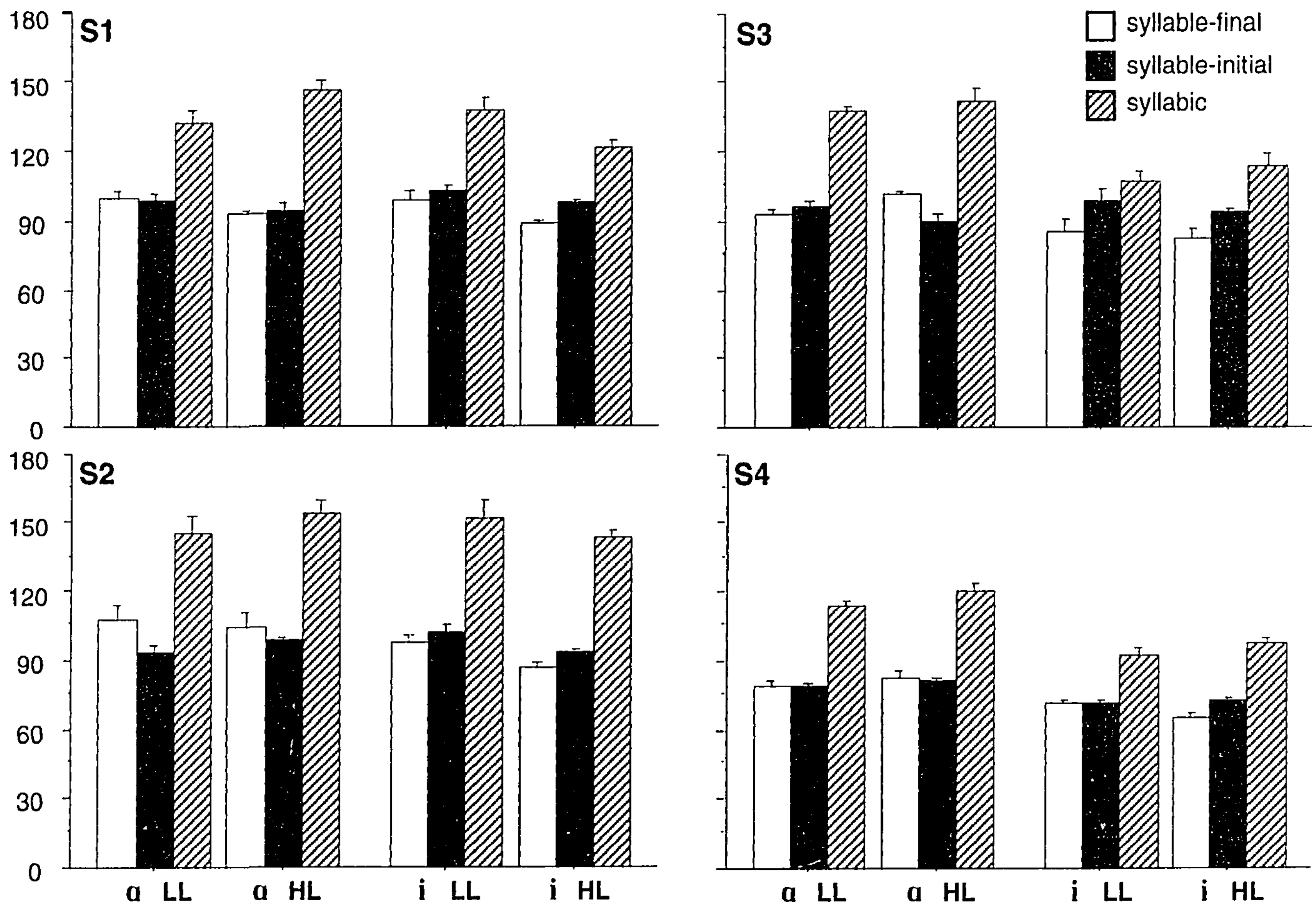

Figure 3.12 Duration of lower lip raising (in msec).
The horizontal bars indicate standard error.

For S1 (Figure 3.12), syllabic nasals had consistently longer durations of lower lip raising than syllable-final or syllable-initial nasals. Comparing syllable-final to syllable-initial nasals, the former had shorter durations of lower lip raising than the latter except for one utterance. The main effect of syllable position was significant. More detailed analyses revealed that the differences in duration of lower lip raising were significant between syllable-final and syllabic nasals ($p<.0001$) and between syllable-initial and syllabic nasals ($p<.0001$). The overall difference between /ɑ/ and /i/ contexts in duration of lower lip raising was small, and there was no main effect of vowel type. The interaction between syllable position and vowel type was not significant. Both syllable-final and syllable-initial nasals had relatively longer durations in the LL tone condition, but little tonal effect on syllabic nasals was observed. The main effect of tone was found significant, and so was the interaction between vowel type and tone type. Tests of simple effect indicated that no significant vowel effect was found in either tone condition, and the tonal effect was found significant only in the vowel /i/ context ($F[1,58]=4.052$, $p<.05$). There was a significant three-way interaction among the three main effects. The results of analyses of simple effect are summarized in Table 3.20.

TABLE 3.20 RESULTS OF ANALYSES OF SIMPLE EFFECT ON THE THREE-WAY INTERACTION (S1)

<table>
<tr><th>Effect</th><th colspan="6">Condition</th></tr>
<tr><td>Syllable position</td><td colspan="3">/ɑ/, LL, *</td><td colspan="3">/ɑ/, HL</td></tr>
<tr><td>Syllable position</td><td colspan="3">/i/, LL, *</td><td colspan="3">/i/, HL, *</td></tr>
<tr><td>vowel</td><td colspan="2">syllable-final, LL</td><td colspan="2">syllable-initial, LL</td><td colspan="2">syllabic, LL</td></tr>
<tr><td>vowel</td><td colspan="2">syllable-final, HL</td><td colspan="2">syllable-initial, HL</td><td colspan="2">syllabic, HL, *</td></tr>
<tr><td>tone</td><td colspan="2">syllable-final, /ɑ/</td><td colspan="2">syllable-initial, /ɑ/</td><td colspan="2">syllabic, /ɑ/</td></tr>
<tr><td>tone</td><td colspan="2">syllable-final, /i/, *</td><td colspan="2">syllable-initial, /i/</td><td colspan="2">syllabic, /ɑ/</td></tr>
</table>

As shown, the effect of syllable position on duration of lower lip raising was found significant much more often than the effect of vowel type or the effect of tone type.

For S2 (Figure 3.12), syllabic nasals had longer durations than syllable-final or syllable-initial nasals. The pattern of difference between syllable-final and syllable-initial nasals varied in the two vowel contexts; that is, syllable-final nasals had longer durations in /ɑ/ context, but not in /i/ context. The main effect of syllable position was significant. Tests of pairwise comparison revealed that the differences between syllabic nasals and syllable-final or syllable-initial nasals were significant (both $p<.0001$), but the difference between the latter two types of nasals was not. There was no observable effect of vowel and the main effect of vowel type was not significant. The interaction between syllable position and vowel type was not significant, but it was approaching the significance level. Thus, tests of simple effect were conducted. The results indicated that the effect of syllable position was significant in both vowel contexts (in /ɑ/ context, $F[2,57]=58.82$, $p<.0001$, and in /i/ context, $F[2,57]=108.787$, $p<.0001$). Pairwise comparisons were significant between syllabic nasals and syllable-final or syllable-initial nasals (both $p<.0001$) in /ɑ/ context, as well as in /i/ context (both $p<.0001$). The vowel effect was significant only for syllable-final nasals, $F(1,38)=9.222$, $p=.0043$. No observable tonal difference was found (Figure 3.12), and the ANOVA showed no main effect of tone type. Although a significant interaction between vowel type and tone type was found, tests of simple effect revealed that in fact no significant vowel effect was found in either tone conditions, nor was any tonal effect found in either of the two vowel contexts. It is possible that this significant interaction was due to the relatively longer durations found for syllable-final and syllable-initial nasals in /i/ context for the LL tone condition.

For S3 (Figure 3.12), as with both S1 and S2, the syllabic nasals had longer durations of lower lip raising than syllable-final or syllable-initial nasals. Syllable-initial nasals tended to have longer durations than syllable-final nasals in three of the four utterances. A significant main effect of syllable position was found. Pairwise comparisons were significant between syllabic nasals and syllable-final or syllable-initial nasals (both $p<.0001$), but the latter two types of nasals did not differ significantly from each other. For syllable-final and syllabic nasals, the durations of lower lip raising were longer in /ɑ/ context than in /i/ context, and the main effect of vowel was significant. There was a significant interaction between syllable position and vowel type. This was not surprising given that no clear difference between the two vowel contexts was seen for syllable-initial nasals. Analyses of simple effect revealed that in /ɑ/ context, the effect of syllable position was significant ($F[2,57]=97.928$, $p<.0001$), and so were the pairwise comparisons between syllabic nasals and syllable-final or syllable-initial nasals (both $p<.0001$). In /i/ context, again, the effect of syllable position was significant ($F[2,57]=18.356$, $p<.0001$), and the pairwise comparisons were also significant between syllabic nasals and syllable-final ($p<.0001$) or syllable-initial nasals ($p<.01$), and between syllable-final and syllable-initial nasals ($p<.01$). The vowel effect was significant only for syllable-final nasals ($F[1,38]=12.02$, $p=.0013$), and for syllabic nasals ($F[1,38]=32.03$, $p<.0001$), but not for syllable-initial nasals. No significant main effect of tone type was found, nor were any other significant interactions between factors.

For S4 (Figure 3.12), just as for other three subjects, syllabic nasals had longer durations of lower lip raising than syllable-final or syllable-initial nasals. Syllable-final nasals tended to have longer durations than syllable-initial nasals in three of the four utterances. The main effect of syllable position was statistically significant. Tests of pairwise comparison showed that while syllabic nasals were significantly different in duration from syllable-final or syllable initial nasals ($p<.0001$ for both comparisons), the latter two did not differ significantly from each other. It can be observed in Figure 3.12 that the duration of lower lip raising was longer in /ɑ/ context than in /i/ context. Thus, the main effect of vowel type was significant. There was a significant interaction between the main effect of syllable position and vowel type. Further testing of simple effect revealed that in /ɑ/ context, the overall effect of syllable position was significant ($F[2,57]=210.98$, $p<.0001$), but pairwise comparison were significant only between syllabic nasals and syllable-final or syllable-initial nasals ($p<.0001$ for both comparisons); while in /i/ context, not only was the overall effect of syllable position significant ($F[2,57]=104.52$, $p<.0001$), but also the three pairwise comparisons were significant at $p<.05$. The results also showed significant vowel effects for nasals of all three syllable positions (for syllable-final nasals:

F[1,38]=51.449, p<.0001, for syllable-initial nasals: F[1,38]=24.937, p<.0001, and for syllabic nasals: F[1,38]=72.963, p<.0001). The main effect of tone type was not significant, however, there was a significant interaction between syllable position and tone type. The tests of simple effect revealed significant effect of syllable position in both tone conditions (in LL tone conditions, F[2,57]=62.562, p<.0001, and in HL tone condition, F[2,57]=63.433, p<.0001). Pairwise comparisons among nasals of different syllable positions in each tone condition showed similar results, that is, comparisons were significant only between syllabic nasals and syllable-final or syllable-initial nasals (all p<.0001). However, no significant tonal effect was found for nasals in any of the three syllable positions. No other significant interactions were found among factors.

Table 3.21 summarizes the results presented on duration of lower lip raising for effect of syllable position.

TABLE 3.21 PAIRWISE COMPARISON FOR DURATION OF LOWER LIP RAISING

	Pairwise Comparisons			
Subject	vowel	Syl-final vs. Syl-initial	Syl-final vs. Syllabic	Syl-initial vs. Syllabic
S1	ɑ	shorter	shorter *	shorter *
	i	shorter	shorter *	shorter *
S2	ɑ	longer	shorter *	shorter *
	i	shorter	shorter *	shorter *
S3	ɑ	longer	shorter *	shorter *
	i	shorter *	shorter *	shorter *
S4	ɑ	longer	shorter *	shorter *
	i	shorter *	shorter *	shorter *

To summarize, for measures of duration of lower lip raising, significant main effects of syllable position were found for all four subjects. Further, syllabic nasals had consistently longer durations than syllable-final or syllable-initial nasals in both vowel contexts. For three of the four subjects, syllable-final nasals had longer durations of lower lip raising than syllable-initial nasals in /ɑ/ context, but shorter durations in /i/ context. The main effect of vowel was significant for S3 and S4. For both subjects, longer durations were found in /ɑ/ context. Only S1 had significant main effect of tone and only for syllable-final nasals in /i/ context.

- **Duration of high lower lip plateau**

The mean durations of lower lip high plateau are plotted in Figure 3.13 for all subjects. ANOVA results are presented in Table 3.22.

TABLE 3.22 ANOVA RESULTS FOR DURATION OF LOWER LIP LOW PLATEAU

	S1			S2		
	DF	F	P	DF	F	P
S	2,105	85.479	<.0001	2,107	80.219	<.0001
V	1,105	20.747	<.0001	1,107	.212	.6458
S*V	2,105	9.489	.0002	2,107	.714	.4919
T	1,105	1.105	.2955	1,107	2.415	.1231
S*T	2,105	.329	.7203	2,107	4.497	.0133
V*T	1,105	2.485	.1179	1,107	1.123	.2916
S*V*T	2,105	1.266	.2862	2,107	.209	.8119
	S3			S4		
	DF	F	P	DF	F	P
S	2,106	81.981	<.0001	2,106	75.263	<.0001
V	1,106	16.332	<.0001	1,106	30.458	<.0001
S*V	2,106	4.372	.0150	2,106	.806	.4494
T	1,106	.04	.8412	1,106	.487	.4867
S*T	2,106	.066	.9363	2,106	.125	.8830
V*T	1,106	.679	.4118	1,106	.496	.4828
S*V*T	2,106	.833	.4376	2,106	.313	.7321

For S1 (Figure 3.13), an effect of syllable position was observed. Syllabic nasals had longer durations of lower lip plateau than syllable-final or syllable-initial nasals, which differed in that syllable-final nasals had longer durations. Thus, the main effect of syllable position was significant. More detailed analyses showed that the differences were significant for all three pairwise comparisons: between syllabic and syllable-final nasals ($p<.0001$), between syllabic and syllable-initial nasals ($p<.0001$), and between syllable-final and syllable-initial nasals ($p<.05$). There was a clear effect of vowel type. All three types of nasals had longer durations in /i/ context than in /ɑ/ context. Thus, the main effect of vowel type was significant. The interaction between syllable position and vowel type was significant. As revealed by tests of simple effect, effect of syllable position was significant in both vowel contexts (in /ɑ/ context, $F[2,55]=46.238$, $p<.0001$; and in /i/ context, $F[2,56]=48.176$, $p<.0001$). However, in both vowel contexts, pairwise comparisons were significant only between syllabic nasals and syllable-final or

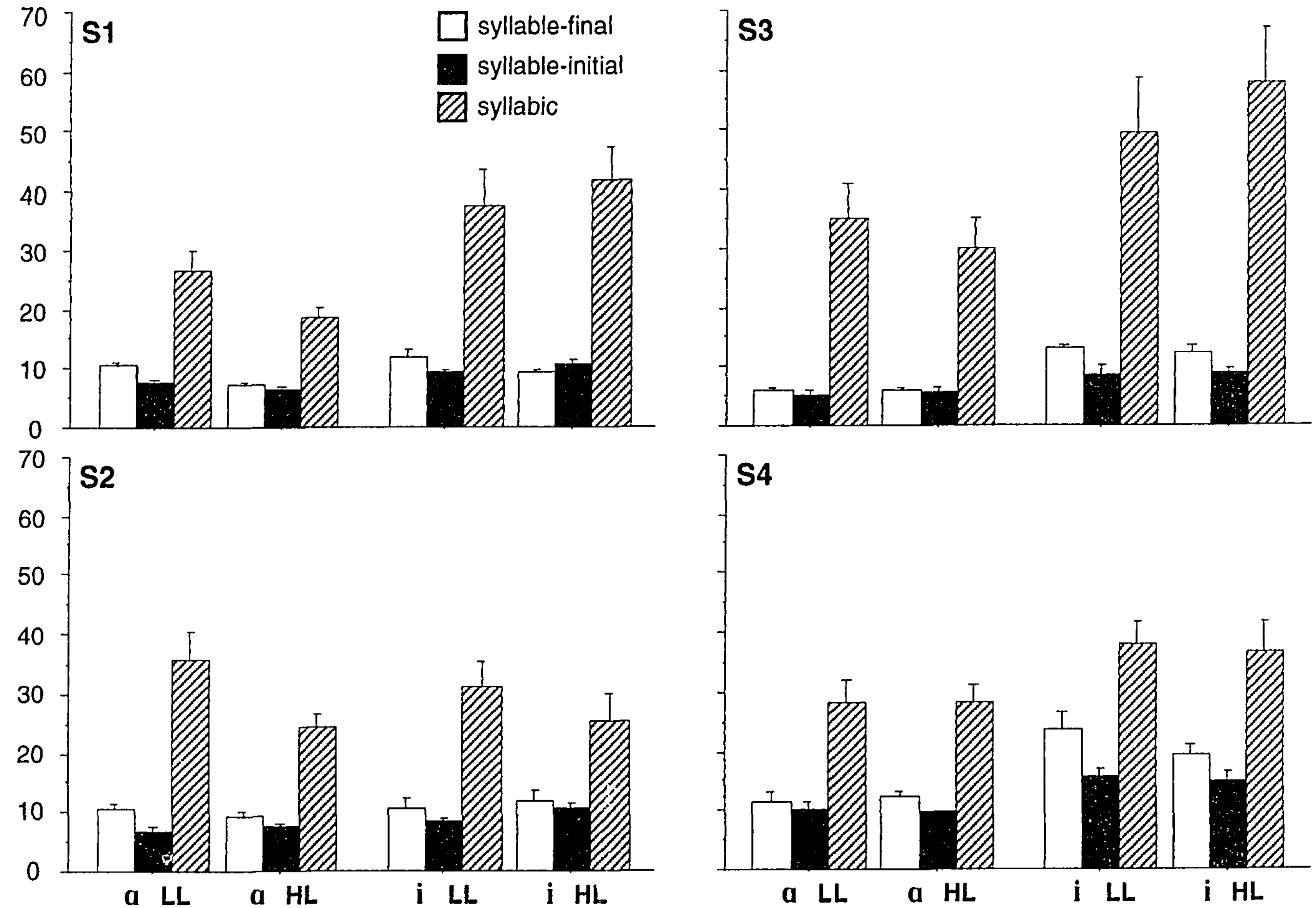

Figure 3.13 Duration of lower lip plateau (in msec).
The horizontal bars indicate standard error.

syllable-initial nasals (all significant at $p<.0001$), but not between syllable-final and syllable-initial nasals. The effect of vowel type was significant for nasals in all three syllable positions (for syllable-final nasals, $F[1,38]=5.62$, $p=.0230$; for syllable-initial nasals, $F[1,36]=27.76$, $p<.0001$; and for syllabic nasals, $F[1,37]=13.52$, $p=.0007$).

For S2 (Figure 3.13), a similar pattern was found. The effect of syllable position was evident: syllabic nasals had longer durations than either syllable-final or syllable-initial nasals, which also differed from each other, with syllable-final nasals having longer durations. The main effect of syllable position was significant. Further analyses showed that pairwise comparisons were significant between syllabic and syllable-final nasals ($p<.0001$), between syllabic and syllable-initial nasals ($p<.0001$), and between syllable-final and syllable-initial nasals ($p<.01$). No significant main effect of vowel type was found and no significant interaction was found between effect of syllable position and effect of vowel type. Although no significant tonal effect was found, there was a significant interaction between syllable position and tone type. Analyses of simple effect showed that the effect of syllable position was significant in both tone conditions (for the LL tone, $F[2,57]=49.541$, $p<.0001$; for the HL tone, $F[2,56]=33.46$, $p<.0001$). In both tone conditions, pairwise comparisons were significant between syllabic nasals and syllable-final or syllable-initial nasals (all $p<.0001$), but not significant between syllable-final and syllable-initial nasals. Only syllabic nasals was affected significantly by effect of tone type, with longer durations found in the LL tone condition. ($F[1,37]=4.272$, $p<.05$).

For S3 (Figure 3.12), as with S1 and S2, syllabic nasals had longer durations of high lower lip plateau than syllable-final or syllable-initial nasals, which differed from each other in that syllable-final nasals had longer durations. The main effect of syllable position was significant. Further analyses showed that pairwise comparisons were significant between syllabic and syllable-final nasals ($p<.0001$) or syllable-initial nasals ($p<.0001$), and between syllable-final and syllable-initial nasals ($p<.05$). As seen in Figure 3.13, durations were longer in /i/ context than in /ɑ/ context for all three types of nasals, and the

ANOVA showed a significant main effect of vowel type. There was a significant interaction between syllable position and vowel type. Tests of simple effect revealed that effect of syllable position was significant in both vowel contexts (in /ɑ/ context, $F[2,55]=49.417$, $p<.0001$; in /i/ context, $F[2,57]=44.291$, $p<.0001$). In both vowel contexts, pairwise comparisons were significant between syllabic nasals and syllable-final or syllable-initial nasals (all $p<.0001$), but not between syllable-final and syllable-initial nasals. A significant vowel effect was found for all three syllable positions (for syllable-final nasals, $F[1,38]=60.84$, $p<.0001$; for syllable-initial nasals, $F[1,37]=11.13$, $p=.0019$; and for syllabic nasals, $F[1,37]=7.68$, $p=.0087$). No significant main effect of tone type was found, nor were any other significant interactions.

For S4 (Figure 3.13), as with the other three subjects, an effect of syllable position was found. Syllabic nasals had longer durations than syllable-final or syllable-initial nasals, and syllable-final nasals had longer durations than syllable-initial nasals. The main effect of syllable position was significant. More detailed analyses revealed that all three pairwise comparisons between nasals of different syllable positions were significant at the level $p<.0001$. As can be observed in Figure 3.13, durations of high lower lip plateau were consistently longer in /i/ context than in /ɑ/ context and the main effect of vowel type was significant. Neither a significant main effect of tone type nor any significant interactions between factors were found.

Table 3.23 summarizes the results presented on duration of high lower lip plateau for effect of syllable position.

To summarize, for duration of lower lip plateau, the main effect of syllable position was significant for all subjects. And further, the patterns of difference in duration of lower lip plateau among nasals in three syllable positions were consistent within and across subject. That is, syllabic nasals had the longest durations, and syllable-initial nasals had the shortest durations. Three subjects had significant main effects of vowel type and the

Table 3.23 Pairwise comparison for duration of high lower lip plateau

	Pairwise Comparisons			
Subject	vowel	Syl-final vs. Syl-initial	Syl-final vs. Syllabic	Syl-initial vs. Syllabic
S1	ɑ	longer	shorter *	shorter *
	i	shorter	shorter *	shorter *
S2	ɑ	shorter	shorter *	shorter *
	i	shorter	shorter *	shorter *
S3	ɑ	longer *	shorter *	shorter *
	i	shorter	shorter *	shorter *
S4	ɑ	longer	shorter *	shorter *
	i	shorter	shorter *	shorter *

pattern of difference was consistent for the three subjects. That is, durations of high lower lip plateau were significantly longer in the vowel /i/ context than in the vowel /ɑ/ context. It is worth pointing out that , as shown in Table 3.23, this significant effect of vowel type on duration of lower lip plateau did not change the pattern of difference due to the effect of syllable position. No significant effect of tone type on duration of lower lip high plateau was found for any of the four subjects.

- **Duration of lower lip lowering**

The mean durations of lower-ip lowering from the bilabial nasal consonant are plotted in Figure 3.14 for all four subjects. A two-factor ANOVA (see 3.6.5) was conducted for each subject and the results are shown in Table 3.24.

TABLE 3.24 ANOVA RESULTS FOR DURATION OF LOWER LIP LOWERING

	S1			S2		
	DF	F	P	DF	F	P
S	2,114	67.208	<.0001	2,114	4.167	.0435
V	1,114	85.558	<.0001	1,114	122.149	<.0001
S*V	2,114	.84	.4343	2,114	1.355	.2620
	S3			S4		
	DF	F	P	DF	F	P
S	2,114	3.658	.0583	2,114	153.116	<.0001
V	1,114	26.168	<.0001	1,114	25.47	<.0001
S*V	2,114	3.272	.0415	2,114	4.439	.0139

For S1 (Figure 3.14), syllabic nasals had longer durations of lower lip lowering than syllable-final or syllable-initial nasals. Syllable-final nasals had longer durations than

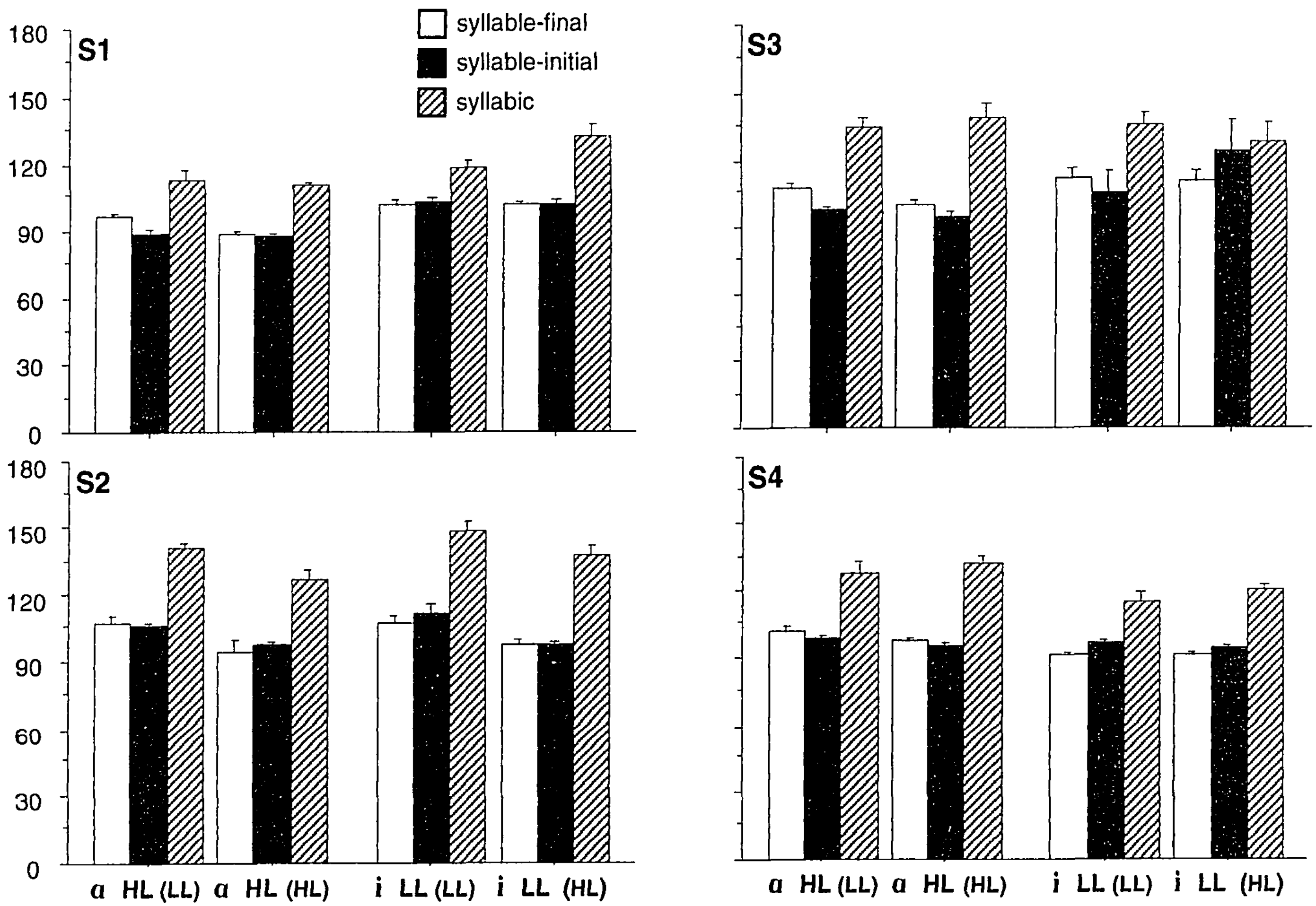

Figure 3.14 Duration of lower lip lowering (in msec).
The horizontal bars indicate standard error.

syllable-initial nasals in /ɑ/ context, but these two types of nasals differed inconsistently in /i/ context. The main effect of syllable position was significant. More detailed analyses revealed that while syllabic nasals had significantly longer durations than either syllable-final nasals ($p<.0001$) or syllable-initial nasals ($p<.0001$), the latter two types did not differ significantly from each other. The durations were also consistently longer in /i/ context than in /ɑ/ context. The main effect of vowel type was found significant. There was no significant interactions between the two main factors.

For S2 (Figure 3.14), similar to the pattern of difference seen for S1, in both vowel contexts, syllabic nasals had longer durations than syllable-final or syllable-initial nasals, which differed from each other inconsistently. The main effect of syllable position was significant. Pairwise comparisons were significant between syllabic nasals and syllable-final or syllable-initial nasals, but the latter two did not differ significantly from each other. As can be observed in Figure 3.14, similar to what was seen for S1, the durations were longer in /i/ context for syllable-final and syllabic nasals, and the main effect of vowel type was significant. Although there was no significant interaction between the main factors, since it was observed that the vowel effect was not present in all three types of nasals, a test of simple effect was conducted to see if the vowel effect was consistent in all syllable positions. The results indicated the vowel effect was significant only for syllabic nasals, $F(1,38)=4.448$, $p=.0416$.

For S3 (Figure 3.14), as seen for both S1 and S2, syllabic nasals were longer in durations than syllable-final or syllable-initial nasals. The pattern of difference between syllable-final and syllable-initial nasals for S3 is similar to that of S1. That is, syllable-final nasals had consistently longer durations than syllable-initial nasals in /ɑ/ context, but not in /i/ context. The ANOVA showed a significant main effect of syllable position. Further analyses indicated that the differences seen in durations between syllabic nasals and syllable-final or syllable-initial nasals were significant (both $p<.0001$), but there was no significant difference in duration between syllable-final and syllable-initial nasals.

Although no significant main effect of vowel type was found, there was a significant interaction between syllable position and vowel type. Analyses of simple effect revealed that the effect of syllable position was significant in both vowel contexts. In the vowel /ɑ/ context, not only was the main effect of syllable position significant ($F[2,57]=75.645$, $p<.0001$), but also the three pairwise comparisons (syllable-final and syllable-initial nasals, $p<.05$; syllabic and syllable-final or syllable-initial nasals, both $p<.0001$). In /i/ context, the effect of syllable position was significant ($F[2,57]=3.723$, $p<.05$), and so were the two pairwise comparisons between syllabic nasals and syllable-final or syllable-initial nasals (both $p<.05$). Durations of lower lip lowering were significantly longer in /i/ context than in /ɑ/ context for both syllable-final nasals, ($F[1,38]=4.51$, $p<.05$), and syllable-initial nasals, ($F[1,38]=4.51$, $p<.05$), but not for syllabic nasals. That is, the duration of lower lip lowering for syllabic nasals was not affected by vowel type.

For S4 (Figure 3.14), again, syllabic nasals had longer durations of lower lip lowering than syllable-final or syllable-initial nasals. The pattern of difference varied between syllable-final and syllable-initial nasals with the vowel context. That is, syllable-final nasals had longer durations of lower lip lowering than syllable-initial nasals in /ɑ/ context, but shorter ones in /i/ context. The main effect of syllable position was significant. More detailed analyses revealed that the difference between syllabic nasals and syllable-final nasals was significant ($p<.0001$), and so was the difference between syllabic and syllable-initial nasals ($p<.0001$). However, no significant difference was found between syllable-final and syllable-initial nasals. The overall duration was longer in /ɑ/ context and the main effect of vowel type was significant. There was a significant interaction between syllable position and vowel type. Tests of simple effect revealed that the effect of syllable position was significant in both vowel contexts (in /ɑ/ context, $F[2,57]=83.827$, $p<.0001$; and in /i/ context, $F[2,57]=71.518$, $p<.0001$). The pairwise comparisons in the vowel /ɑ/ context were significant only between syllabic nasals and syllable-final or syllable-initial nasals (both $p<.0001$). Results in /i/ context showed that pairwise comparisons were significant between syllable-final and syllable-initial nasals ($p<.01$), and between syllabic nasals and syllable-final or syllable-initial nasals (both $p<.0001$). It was also revealed that the effect of vowel type was significant for syllable-final nasals ($F[1,38]=20.16$, $p=.0001$), and for syllable-initial nasals ($F[1,38]=10.70$, $p<.01$), but not for syllabic nasals.

Table 3.25 summarizes the results presented on duration of lower lip lowering for effect of syllable position.

TABLE 3.25 PAIRWISE COMPARISON FOR DURATION OF LOWER LIP LOWERING

	Pairwise Comparisons						
Subject	vowel	Syl-final vs. Syl-initial		Syl-final vs. Syllabic		Syl-initial vs. Syllabic	
S1	ɑ	longer		shorter	*	shorter	*
	i	shorter		shorter	*	shorter	*
S2	ɑ	shorter		shorter	*	shorter	*
	i	shorter		shorter	*	shorter	*
S3	ɑ	longer	*	shorter	*	shorter	*
	i	shorter		shorter	*	shorter	*
S4	ɑ	longer		shorter	*	shorter	*
	i	shorter	*	shorter	*	shorter	*

To summarize, durations of lower lip raising were in general affected by both syllable position and vowel type. All subjects showed a significant main effect of syllable positions, but detailed analyses showed that only syllabic nasals had significantly longer durations than syllable-final or syllable-initial nasal, which did not differ significantly from each other except in two cases. It is worth pointing out that for three subjects (S1, S3, and S4), the pattern of difference indicated that syllable-final nasals tended to have longer durations of lower lip lowering than syllable-initial nasals in /ɑ/ context, but shorter durations in /i/ context, although the magnitude of this difference was not always statistically significant. Such interaction between syllable position and vowel type was also observed on duration of lower lip raising (S2, S3 and S4). For three subjects, significantly longer durations were found in the vowel /i/ context: for S1, for nasals of all three syllable positions; for S2, only for syllabic nasals; and for S3, only for syllable-final and syllable-initial nasals. For S4, a longer duration was found in the vowel /ɑ/ context for syllable-final and syllable-initial nasals but not for syllabic nasals.

Spatial Measurements

Spatial measurements included: displacement amplitude of lower lip raising, positional maximum of the lower lip, and displacement amplitude of lower lip lowering.

- **Displacement amplitude of lower lip raising**

Mean displacement amplitudes of lower lip raising for all utterances are plotted in Figure 3.15 for all subjects. Table 3.26 provides results of ANOVA conducted for each subject.

TABLE 3.26 ANOVA RESULTS FOR DISPLACEMENT AMPLITUDE OF LOWER LIP RAISING

	S1			S2		
	DF	F	P	DF	F	P
S	2,108	15.602	<.0001	2,108	7.534	.0009
V	1,108	622.628	<.0001	1,108	146.28	<.0001
S*V	2,108	4.499	.0133	2,108	1.815	.1678
T	1,108	7.367	.0077	1,108	1.127	.2909
S*T	2,108	15.356	<.0001	2,108	4.401	.0145
V*T	1,108	.484	.4881	1,108	3.094	.0814
S*V*T	2,108	3.512	.0333	2,108	.513	.5999
	S3			S4		
	DF	F	P	DF	F	P
S	2,108	15.114	<.0001	2,108	32.971	<.0001
V	1,108	164.125	<.0001	1,108	949.46	<.0001
S*V	2,108	13.036	<.0001	2,108	4.6	.0121
T	1,108	.439	.5088	1,108	13.596	.0004
S*T	2,108	.886	.4152	2,108	.075	.9282
V*T	1,108	.442	.5076	1,108	5.508	.0208
S*V*T	2,108	2.367	.0986	2,108	1.589	.2089

For S1 (Figure 3.15), for three of the four utterances, syllabic nasals had greater displacement amplitudes of lower lip raising than either syllable-final or syllable-initial nasals, and syllable-final nasals had greater displacement amplitudes of lower lip raising than syllable-initial nasals. The main effect of syllable position was significant. Further pairwise comparisons showed that while the displacement amplitudes were significantly greater for syllabic nasals than syllable-final ($p<.0001$) or syllable-initial nasals ($p<.0001$),

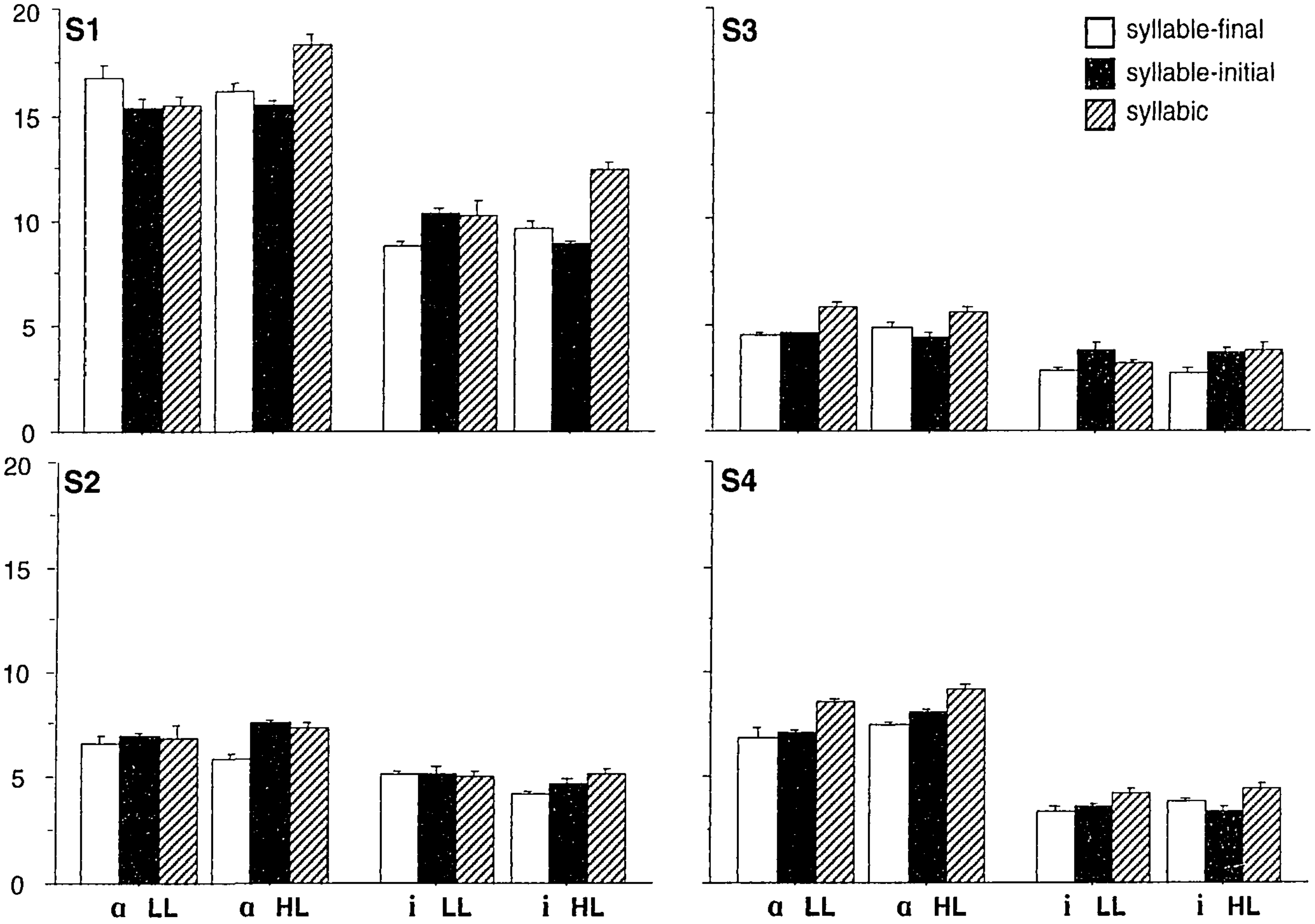

Figure 3.15 Displacement amplitude of lower lip raising (in mm).
The horizontal bars indicate standard error.

the difference in displacement amplitudes between syllable-final and syllable-initial nasals was not significant. As can be observed in Figure 3.15, the displacement amplitude of lower lip raising was greater in /ɑ/ context than in /i/ context for nasals of all three different syllable positions. Thus, the main effect of vowel type was significant. There was a significant interaction between syllable position and vowel type. The analyses of simple effect revealed the effect of syllable position was significant in both vowel contexts, (in /ɑ/ context, $F[2,57]=4.49$, $p=.0155$; and in /i/ context, $F[2,57]=11.53$, $p<.0001$). The pairwise comparisons in the vowel /ɑ/ context showed that syllable-final nasals had significantly greater displacement amplitudes than syllable-initial nasals ($p<.05$) and so were syllabic nasals when compared to syllable-initial nasals ($p<.01$). The pairwise comparisons in /i/ context showed that syllabic nasals had significantly greater displacement amplitudes than syllable-final or syllable-initial nasals (both $p<.001$). The vowel effect was also significant for nasals of all three syllable positions (for syllable-final nasals, $F[1,38]=324.913$, $p<.0001$; for syllable-initial nasals, $F[1,38]=277.513$, $p<.0001$; and for syllabic nasals, $F[1,38]=66.989$, $p<.0001$). The main effect of tone type was significant although except for syllabic nasals no such an effect could be directly observed in Figure 3.15. There was also a significant interaction between syllable position and tone type ($F[2,108]=15.356$, $p<.0001$). Tests of simple effect were conducted and the results showed that only syllabic nasals were affected by tone type ($F[1,38]=5.947$, $p<.05$), with greater displacement amplitudes in the HL tone condition. There was a significant three-

TABLE 3.27 RESULTS OF ANALYSES OF SIMPLE EFFECT ON THE THREE-WAY INTERACTION (S1)

<table>
<tr><th>Effect</th><th colspan="6">Condition</th></tr>
<tr><td>Syllable position</td><td colspan="3">/ɑ/, LL</td><td colspan="3">/ɑ/, HL, *</td></tr>
<tr><td>Syllable position</td><td colspan="3">/i/, LL</td><td colspan="3">/i/, HL, *</td></tr>
<tr><td>vowel</td><td colspan="2">syllable-final, LL, *</td><td colspan="2">syllable-initial, LL, *</td><td colspan="2">syllabic, LL, *</td></tr>
<tr><td>vowel</td><td colspan="2">syllable-final, HL, *</td><td colspan="2">syllable-initial, HL, *</td><td colspan="2">syllabic, HL, *</td></tr>
<tr><td>tone</td><td colspan="2">syllable-final, /ɑ/</td><td colspan="2">syllable-initial, /ɑ/</td><td colspan="2">syllabic, /ɑ/, *</td></tr>
<tr><td>tone</td><td colspan="2">syllable-final, /i/</td><td colspan="2">syllable-initial, /i/, *</td><td colspan="2">syllabic, /i/, *</td></tr>
</table>

way interaction among the three main effects. Analyses of simple effect were conducted and the results are summarized in Table 3.27. The analyses of the three-way interaction showed that effect of vowel type was found significant more often than either effect of syllable position or effect of tone type.

For S2 (Figure 3.15), the displacement amplitudes of both syllable-initial and syllabic nasals were greater than syllable-final nasals, and syllable-initial nasals had greater displacement amplitudes than syllabic nasals in three of the four utterances. The main effect of syllable position was significant. Pairwise comparisons in displacement amplitude of lower lip raising were significant between syllable-final and syllable-initial or syllabic nasals ($p<.01$ and $p<.001$, respectively), but no differences were found between the latter two types of nasals. The displacement amplitudes were greater in /ɑ/ context and the effect of vowel type was significant. No interaction between syllable position and vowel type was found. Although no significant tonal effect was found, there was a significant interaction between syllable position and tone type. Tests of simple effect revealed that the effect of syllable position was significant only in the HL tone condition ($F[2,57]=4.91$, $p<.05$), and pairwise comparisons in the HL tone condition were significant between syllable-final and syllable-initial or syllabic nasals ($p<.05$ and $p<.01$, respectively). Also revealed by the tests of simple effect was that the displacement amplitudes of lower lip raising were significantly greater in the LL tone condition than in the HL tone condition for syllable-final nasals ($F[1,38]=5.177$, $p<.05$).

For S3 (Figure 3.15), the general pattern was that syllabic nasals tended to have greater displacement amplitudes than either syllable-final or syllable-initial nasals (except for one utterance), and syllable-initial nasals tended to have greater displacement amplitudes than syllable-final nasals (except for one utterance). The main effect of syllable position was significant, and all three possible pairwise comparisons were significant ($p<.05$). As can be seen in Figure 3.15, there was a clear effect of vowel type, that is, greater displacement amplitudes were found in /ɑ/ context for nasals of all three different syllable positions. The main effect of vowel was significant and there was a significant interaction between syllable position and vowel type. Further analyses revealed that the effect of syllable position was significant in both vowel contexts (in /ɑ/ context, $F[2,57]=19.973$, $p<.0001$; and in /i/ context, $F[2,57]=9.142$, $p=.0004$). In /ɑ/ context, syllabic nasals had significantly greater displacement amplitudes than the other two types of nasals (for both comparisons, $p<.0001$). In /i/ context, both syllabic and syllable-initial nasals had significantly greater displacement amplitudes than syllable-final nasals ($p<.001$, and $p<.01$, respectively). No significant main effect of tone type nor other significant interaction was found.

For S4 (Figure 3.15), syllabic nasals had greater displacement amplitudes than syllable-final or syllable-initial nasals, and syllable-initial nasals tended to have greater displacement amplitudes than syllable-final nasals (except for one utterance). The main effect of syllable position was significant. However, only pairwise comparisons between syllabic nasals and syllable-final nasals or syllable-initial nasals were significant (both $p<.0001$). As can be observed in Figure 3.15, in /ɑ/ context, displacement amplitudes were significantly greater for nasals in all three syllable positions. The main effect of vowel type was significant. A significant interaction was found between syllable position and vowel type. Tests of simple effect showed that the effect of syllable position was significant in both vowel contexts (in /ɑ/ context, $F[2,57]=19.896$, $p<.0001$; and in /i/ context, $F[2,57]=9.797$, $p=.0002$). In /ɑ/ context, syllabic nasals had significantly greater displacement amplitudes than the other two types of nasals (for both comparisons, $p<.0001$). In /i/ context, syllabic nasals again had significantly greater displacement amplitudes than syllable-final or syllable-initial nasals ($p<.001$, and $p<.0001$, respectively). Effect of vowel type was found significant for all three types of nasals, (for syllable-final, $F[1,38]=163.643$, $p<.0001$; for syllable-initial, $F[1,38]=339.076$, $p<.0001$; and for syllabic, $F[1,38]=394.611$, $p<.0001$). There was an overall effect of tone type, with greater displacement amplitudes found in the HL tone condition. The main effect of tone type was significant. The direction of tonal effect varied with the vowel type. Thus, the interaction between vowel type and tone type was significant. As revealed by tests of simple effect, while a vowel effect was found in both tone conditions (in the LL tone condition, $F[1,58]=214.328$, $p<.0001$, and in the HL tone condition, $F[1,58]=415.004$, $p<.0001$), a significant tonal effect was found only in /ɑ/ context with greater displacement amplitudes in the HL tone condition ($F[1,58)=8.313$, $p=.0055$). No other significant interactions were found.

Table 3.28 summarizes the results presented on displacement amplitudes of lower lip raising for effect of syllable position.

TABLE 3.28 PAIRWISE COMPARISON FOR DISPLACEMENT AMPLITUDE OF LOWER LIP RAISING

	Pairwise Comparisons						
Subject	vowel	Syl-final vs. Syl-initial		Syl-final vs. Syllabic		Syl-initial vs. Syllabic	
S1	ɑ	greater	*	smaller		smaller	*
	i	smaller		smaller	*	smaller	*
S2	ɑ	smaller	*	smaller	*	greater	
	i	smaller		smaller		smaller	
S3	ɑ	greater		smaller	*	smaller	*
	i	smaller	*	smaller	*	greater	
S4	ɑ	smaller		smaller	*	smaller	*
	i	greater		smaller	*	smaller	*

To summarize, the results were generally in parallel to the findings on duration of lower lip raising. That is, significant main effects of both syllable position and vowel type were found. More often than not, significantly greater displacement amplitudes were found for syllabic nasals than syllable-final or syllable-initial nasals. Significantly greater displacement amplitudes were found in the vowel /ɑ/ context. Two subjects, S1 and S3, had similar pattern of difference when comparison was made between syllable-final and syllable-initial nasals. That is, syllable-final nasals tended to have greater displacement amplitudes than syllable-initial nasals in /ɑ/ context, but smaller displacement amplitudes in /i/ context. However, the opposite pattern was found for S4, and the pattern of difference in displacement amplitudes between the two vowel contexts was uniform for S2. Only two subjects exhibited a main effect of tone type. However, even that was not always present.

- **Positional maximum of the lower lip**

The average positional maxima of the lower lip are plotted in Figure 3.16. ANOVA was conducted for each subject and the results are shown in Table 3.29.

TABLE 3.29 ANOVA RESULTS FOR HIGH POSITIONAL MAXIMUM OF THE LOWER LIP

	S1			S2		
	DF	F	P	DF	F	P
S	2,108	15.472	<.0001	2,106	2.259	.1095
V	1,108	62.523	<.0001	1,106	2.248	.1368
S*V	2,108	.085	.9188	2,106	7.885	.0006
T	1,108	2.934	.0896	1,106	4.278	.0411
S*T	2,108	2.045	.1344	2,106	11.388	<.0001
V*T	1,108	.515	.4745	1,106	.979	.3248
S*V*T	2,108	4.592	.0122	2,106	.179	.8366
	S3			S4		
	DF	F	P	DF	F	P
S	2,107	101.14	<.0001	2,107	108.415	<.0001
V	1,107	12.005	.0008	1,107	85.229	<.0001
S*V	2,107	14.099	<.0001	2,107	21.176	<.0001
T	1,107	4.107	.0452	1,107	8.802	.0037
S*T	2,107	.286	.7515	2,107	2.684	.0729
V*T	1,107	.173	.6781	1,107	6.094	.0151
S*V*T	2,107	.381	.6840	2,107	4.239	.0169

For S1 (Figure 3.16), syllabic nasals reached relatively higher positional maxima compared to syllable-final or syllable-initial nasals, which differed from each other inconsistently. The main effect of syllable position was significant, but pairwise comparisons were significant only for differences between syllabic nasals and syllable-final or syllable-initial nasals (both $p<.0001$). As shown in Figure 3.16, a consistent vowel effect was observed: higher positional maxima were reached in /i/ context. The main effect of vowel type was significant. There was no significant interaction between syllable position and vowel type, and the main effect of tone type was not significant. However, a significant three-way interaction was found among the three main effects. Analyses of simple effect were conducted to assess it and the results are summarized in Table 3.30.

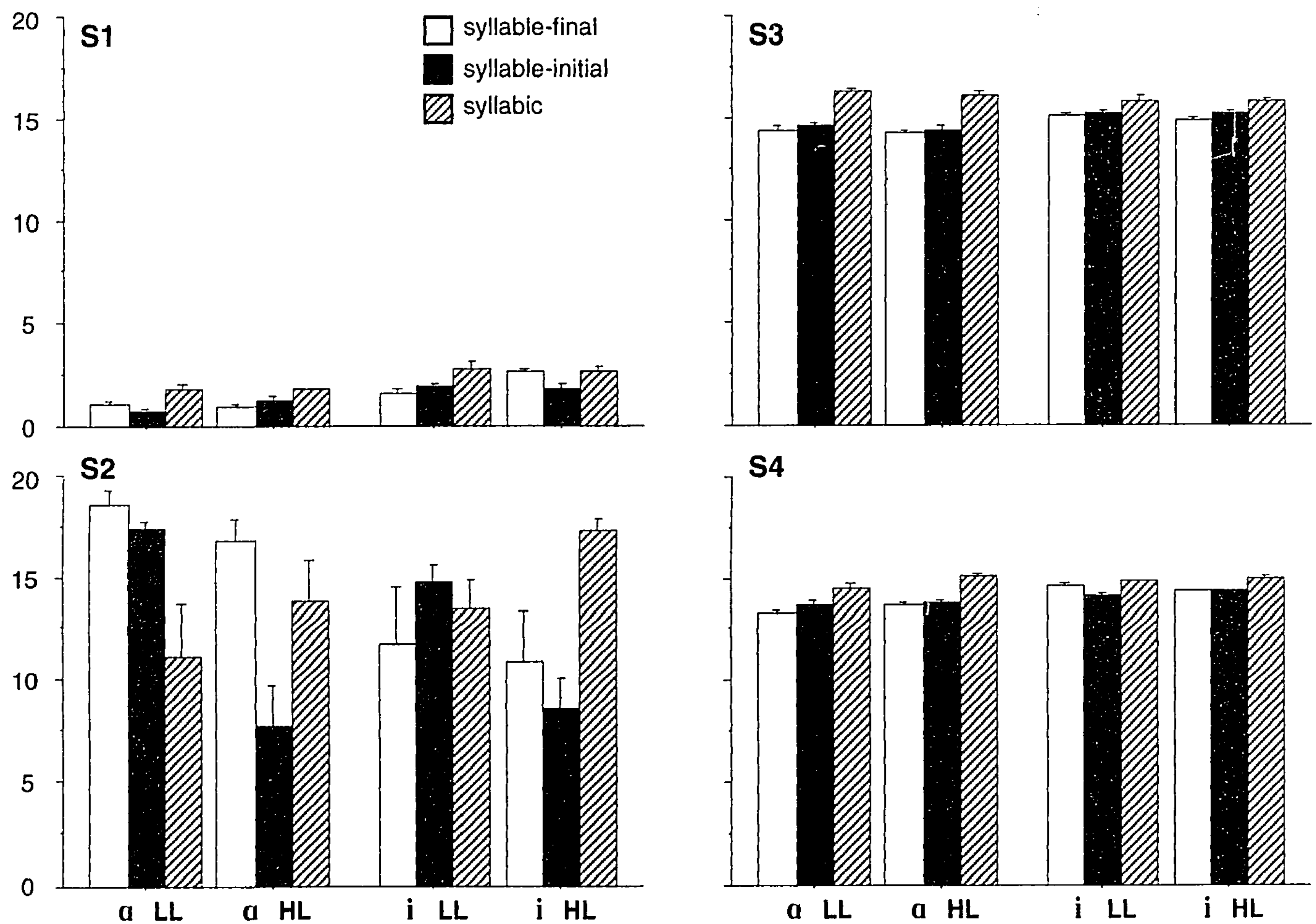

Figure 3.16 Positional maximum of the lower lip (in mm). The horizontal bars indicate standard error.

TABLE 3.30 RESULTS OF ANALYSES OF SIMPLE EFFECT ON THE THREE-WAY INTERACTION (S1)

Effect	Condition		
Syllable position	/ɑ/, LL, *	/ɑ/, HL	
Syllable position	/i/, LL, *	/i/, HL, *	
vowel	syllable-final, LL	syllable-initial, LL, *	syllabic, LL, *
vowel	syllable-final, HL, *	syllable-initial, HL	syllabic, HL, *
tone	syllable-final, /ɑ/	syllable-initial, /ɑ/	syllabic, /ɑ/
tone	syllable-final, /i/, *	syllable-initial, /i/	syllabic, /ɑ/

As shown, both effect of syllable position and effect of vowel type on the positional maximum were significant more often than the effect of tone type.

For S2 (Figure 3.16), the pattern of difference among nasals of different syllable position varied with vowel contexts. Compared to syllabic nasals, syllable-final nasals reached higher positional maxima in /ɑ/ context, but a lower positional maxima in /i/ context. Compared to syllable-initial nasals, syllable-final nasals reached higher positional maxima for three of the four utterances. Thus, no significant main effect of syllable position or vowel type was found. However, as expected, the interaction between syllable position and vowel type was significant. Tests of simple effect showed that the effect of syllable position was significant only in the vowel /ɑ/ context ($F[2,55]=5.4$, $p<.01$). In /ɑ/ context, pairwise comparisons were significant between syllable-final and syllable-initial nasals, $p<.01$, and between syllable-final and syllabic nasals ($p<.01$). In /i/ context, pairwise comparisons were significant between syllabic nasals and syllable-final or syllable-initial nasals (both $p<.05$). The results also indicated that the vowel effect was significant only for syllable-final nasals ($F[1,38]=11.386$, $p<.01$). Thus, it is clear that the effect of syllable position varied in the two vowel contexts so much that the main effect of syllable position failed to be detected. Although the main effect of tone was significant, the pattern differed among the three types of nasals. A significant interaction between syllable position and tone type prompted further analyses. No significant simple effect of syllable position was found in the LL tone condition, but this effect was significant in the HL tone condition ($F[2,56]=9.571$, $p<.0001$). Pairwise comparisons were significant between syllable-final and syllable-initial nasals, ($p<.01$), as well as between syllable-initial and syllabic nasals ($p<.0001$). A significant simple tonal effect was found only for syllable-initial nasals ($F[1,38]=37.612$, $p<.0001$), with higher positional maxima of the lower lip being reached in the LL tone condition.

For S3 (Figure 3.16), syllabic nasals consistently reached relatively higher positional maxima than syllable-final or syllable-initial nasals, between which syllable-initial nasals had higher maxima. ANOVA showed a significant main effect of syllable position. Pairwise comparisons revealed that the differences in positional maximum between syllabic and syllable-final nasals, and between syllabic and syllable-initial nasals were significant (both $p<.0001$). As shown in Figure 3.16, syllable-final and syllable-initial nasals reached relatively higher positional maxima in /i/ context than in /ɑ/ context. No such a difference was observed for syllabic nasals. Thus, the main effect of vowel type was significant. A significant interaction was found between syllable position and vowel type. Tests of simple effect revealed that the effect of syllable position was significant in both vowel contexts (in /ɑ/ context, $F[2,57]=105.629$, $p<.0001$; in /i/ context, $F[2,56]=18.706$, $p<.0001$). Pairwise comparisons in the two vowel contexts showed similar findings, that is, syllabic nasals reached higher positional maxima than syllable-final or syllable-initial nasals (all $p<.0001$), but no significant difference was found between the latter two types. As for the vowel effect, both syllable-final and syllable-initial nasals reached significantly higher positional maxima of the lower lip in the vowel /i/ context ($F[1,38]=14.554$, $p=.0005$, and $F[1,38]=26.053$, $p<.0001$, for syllable-final and syllable-initial nasals respectively). For syllabic nasals, the opposite was true, i.e., significantly higher positional maxima of the lower lip were found in the vowel /ɑ/ context ($F[1,37]=4.642$, $p=.0378$). A significant main effect of tone was demonstrated by ANOVA. But since this effect was not observable in Figure 3.16, tests of simple effect were conducted to assess it further. The results showed no significant tonal effect for any of the three types of nasals, nor in any of the vowel contexts.

For S4 (Figure 3.16), the pattern was similar to what was found for S3: syllabic nasals reached higher positional maxima than syllable-final or syllable-initial nasals. Compared to syllable-initial nasals, positional maxima of the lower lip for syllable-final nasals were relatively higher in /i/ context, but lower in /ɑ/ context. Thus, the main effect of syllable position was significant. The pairwise comparisons showed that syllabic nasals reached significantly higher positional maxima than either syllable-final or syllable-initial nasals (both $p<.0001$), which did not differ significantly from each other. As shown in Figure 3.16, higher positional maxima of the lower lip were found in the vowel /i/ context. The main effect of vowel was significant. There was a significant interaction between syllable position and vowel type. The main effect of syllable position was found significant in /ɑ/ context, ($F[2,56]=75.551$, $p<.0001$), as well as in /i/ context, ($F[2,57]=23.533$, $p<.0001$). Pairwise comparisons in /ɑ/ context were significant between syllabic and syllable-final or syllable-initial nasals (both $p<.0001$). Pairwise comparisons in /i/ context were significant between syllable-final and syllable-initial nasals, $p<.05$; and between syllabic and syllable-final or syllable-initial nasals, both $p<.0001$. As for the vowel effect, it was significant for syllable-final nasals ($F[1,38]=65.316$, $p<.0001$), and for syllable-initial nasals ($F[1,38]=34.361$, $p<.0001$), but not for syllabic nasals. Higher positional maxima were seen for syllabic nasals in the HL tone condition than the LL tone condition (Figure 3.16), and the main effect of tone was significant. There was also a significant interaction between vowel type and tone type. Further analyses revealed that the vowel effect was significant in both tone conditions (in the LL tone condition, $F[1,57]=26.479$, $p<.0001$; in the HL tone condition, $F[1,58]=6.015$, $p=.0172$), but the tonal effect was not significant in either vowel context. There was a significant three-way interaction among the three main effects. Analyses of simple effect were conducted to assess it and the results are summarized in Table 3.31. From the analyses of the three-way interaction, it seems that both the effect of syllable position and the effect of vowel type were found significant much more often than the effect of tone type. Recall also that both syllable-final and syllabic nasals in /ɑ/ context reached a higher positional maxima in the HL tone condition.

TABLE 3.31 RESULTS OF ANALYSES OF SIMPLE EFFECT ON THE THREE-WAY INTERACTION (S4)

Effect	Condition		
Syllable position	/ɑ/, LL, *		/ɑ/, HL, *
Syllable position	/i/, LL, *		/i/, HL, *
vowel	syllable-final, LL, *	syllable-initial, LL, *	syllabic, LL, *
vowel	syllable-final, HL, *	syllable-initial, HL, *	syllabic, HL
tone	syllable-final, /ɑ/, *	syllable-initial, /ɑ/	syllabic, /ɑ/, *
tone	syllable-final, /i/	syllable-initial, /i/	syllabic, /i/

Table 3.32 summarizes the results presented on high positional maximum of the lower lip for effect of syllable position.

TABLE 3.32 PAIRWISE COMPARISON FOR HIGH POSITIONAL MAXIMUM OF THE LOWER LIP

	Pairwise Comparisons			
Subject	vowel	Syl-final vs. Syl-initial	Syl-final vs. Syllabic	Syl-initial vs. Syllabic
S1	**ɑ**	higher	lower *	lower *
	i	higher	lower *	lower *
S2	**ɑ**	higher *	higher *	lower
	i	lower	lower *	lower *
S3	**ɑ**	lower	lower *	lower *
	i	lower	lower *	lower *
S4	**ɑ**	lower	lower *	lower *
	i	higher *	lower *	lower *

To summarize, for S1, S3, and S4, both main effects of syllable position and vowel type were found significant. Also, for the same three subjects, significantly higher positional maxima of the lower lip were found with nasals in syllabic position only. In most cases, the positional maxima of the lower lip did not differ significantly between syllable-final and syllable-initial nasals. When there was a significant vowel effect, higher positional maxima of the lower lip were always found in /i/ context than in /ɑ/ context. Interestingly, across subjects, vowel effect was not always significant for syllabic nasals, in contrast to syllable-final and syllable-initial nasals. The tonal effect was significant for three of the four subjects.

- **Displacement amplitude of lower lip lowering**

The mean displacement amplitudes of lower lip lowering are plotted in Figure 3.17 for all four subjects. ANOVA results are presented in Table 3.33.

TABLE 3.33 ANOVA RESULTS FOR DISPLACEMENT AMPLITUDE OF LOWER-LIP LOWERING

	S1			S2		
	DF	F	P	DF	F	P
S	2,114	10.527	<.0001	2,114	17.923	<.0001
V	1,114	21.547	<.0001	1,114	21.055	<.0001
S*V	2,114	1.954	.1464	2,114	11.771	<.0001
	S3			S4		
	DF	F	P	DF	F	P
S	2,114	33.714	<.0001	2,114	17.513	<.0001
V	1,114	110.908	<.0001	1,114	350.921	<.0001
S*V	2,114	10.663	<.0001	2,114	11.142	<.0001

For S1 (Figure 3.17), syllabic nasals had greater displacement amplitudes in both vowel contexts than syllable-final or syllable-initial nasals, which differed slightly and inconsistently from each other. For three utterance types, syllable-final nasals had greater displacement amplitudes than syllable-initial nasals. The main effect of syllable position was significant. Pairwise comparisons confirmed the observation: there was a significant difference in displacement amplitudes between syllabic nasals and syllable-final nasals (p<.01), or syllable-initial nasals (p<.0001), but not between syllable-final and syllable-initial nasals. Greater displacement amplitudes were seen in the vowel /ɑ/ context for all three syllable positions. The main effect of vowel type was significant. No significant interaction was found.

For S2 (Figure 3.17), syllable-initial nasals had greater displacement amplitudes than syllable-final or syllabic nasals, which did not differ from each other consistently. The main effect of syllable position was significant. Pairwise comparisons were significant between syllable-initial and syllable-final nasals (p<.0001), and between syllable-initial and syllabic nasals (p<.0001), but not significant between syllable-final and syllabic nasals, which confirmed the observation. As shown in Figure 3.17, syllable-initial nasals tended to have greater displacement amplitudes in /ɑ/ context. The main effect of vowel type was

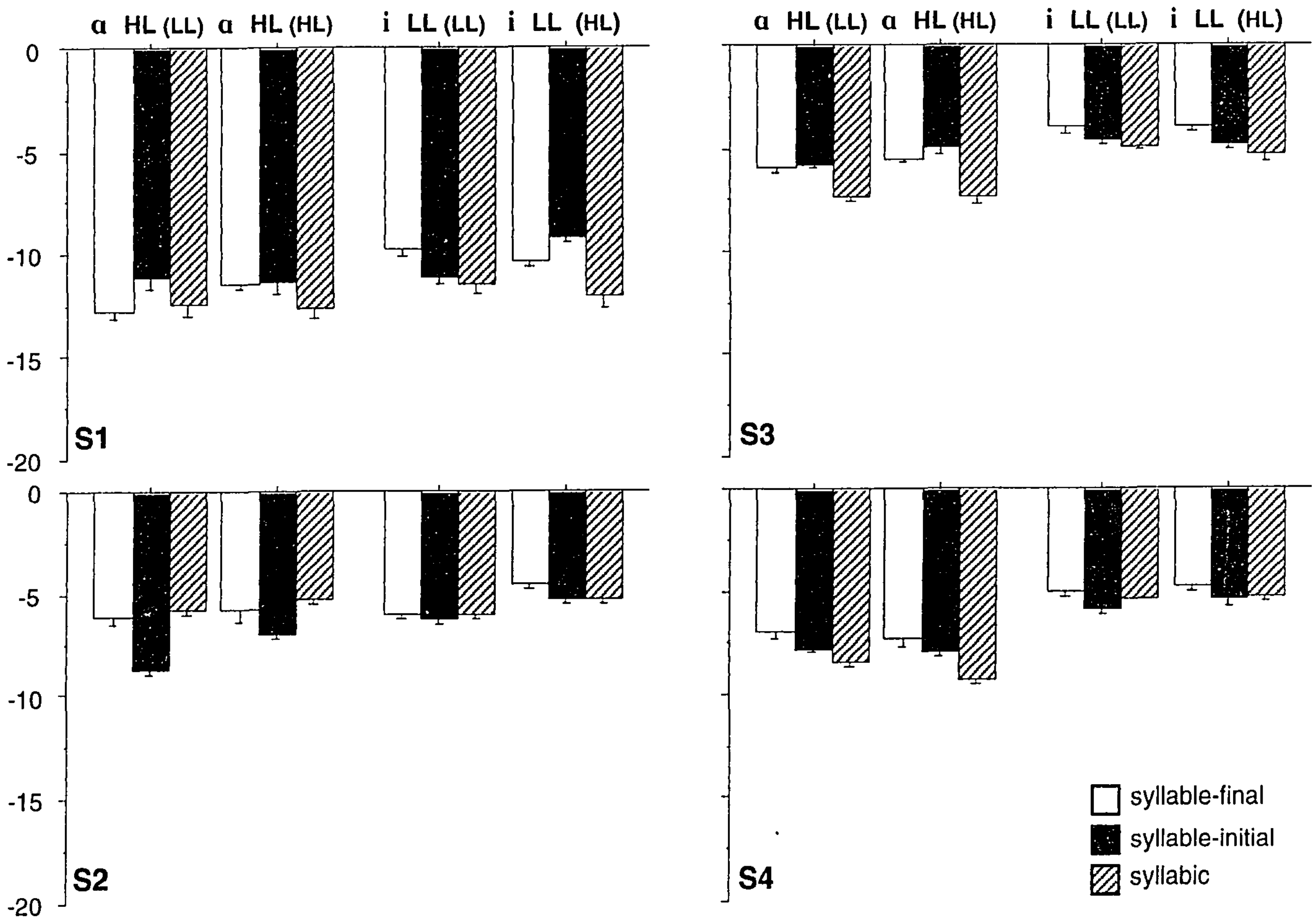

Figure 3.17 Displacement amplitude of lower lip lowering (in mm).
The horizontal bars indicate standard error.

significant. As expected, a significant interaction between syllable position and vowel type was found. Tests of simple effect showed that the effect of syllable position was significant only in /ɑ/ context ($F[2,57]=22.782$, $p<.0001$), and two significant pairwise comparisons were found between syllable-final and syllable-initial nasals ($p<.0001$), and between syllable-initial and syllabic nasals ($p<.0001$). The effect of vowel type was significant only for syllable-initial nasals, ($F[1,38]=51.081$, $p<.0001$).

For S3 (Figure 3.17), similar to the pattern seen for S1, syllabic nasals had greater displacement amplitudes than syllable-final or syllable-initial nasals, which differed from each other inconsistently in the two vowel contexts. In the vowel /ɑ/ context, syllable-final nasals had greater displacement amplitudes than syllable-initial nasals, while the opposite was true in the vowel /i/ context. The main effect of syllable position was significant. Pairwise comparisons were significant between syllabic nasals and syllable-final ($p<.0001$) or syllable-initial nasals ($p<.0001$). A vowel effect was clearly demonstrated (Figure 3.17). The displacement amplitudes of lower lip raising were greater in the vowel /ɑ/ context. Thus, the main effect of vowel type was significant. There was also a significant interaction between syllable position and vowel type. Tests of simple effect showed that in the vowel /ɑ/ context, effect of syllable position was significant, ($F[2,57]=41.296$, $p<.0001$), but pairwise comparisons were significant only between syllabic nasals and syllable-final or syllable-initial nasals (both $p<.0001$). In the vowel /i/ context, again, the overall effect of syllable position was significant, ($F[2,57]=8.313$, $p<.0001$), but only comparisons between syllable-final and syllable-initial or syllabic nasals were significant (both $p<.01$). The vowel effect was significant for all three syllable positions (for syllable-final nasals, $F[1,38]=53.321$, $p<.0001$; for syllable-initial nasals, $F[1,38]=7.799$, $p=.0081$; and for syllabic nasals, $F[1,38]=60.268$, $p<.0001$).

For S4 (Figure 3.17), both syllable-initial and syllabic nasals consistently had greater displacement amplitudes than syllable-final nasals. Syllable-initial nasals had greater displacement amplitudes than syllabic nasals in the vowel /i/ context, but smaller displacements in the vowel /ɑ/ context. The main effect of syllable position was significant. While the displacement amplitudes for syllable-final nasals were significantly smaller than for syllable-initial nasals or syllabic nasals, (both $p<.0001$), the difference in displacement amplitudes was not significant between syllable-initial and syllabic nasals. As shown in Figure 3.17, there was a consistent vowel effect. The displacement amplitudes were greater in /ɑ/ context for all three types of nasals. A significant main effect of vowel type was found. There was also a significant interaction between syllable position and vowel type. Further analyses of simple effect revealed that in /ɑ/ context, the effect of syllable position was significant ($F[2,57]=20.819$, $p<.0001$), and all three pairwise comparisons between nasals of different syllable positions were also significant (all $p<.01$). In /i/ context, the effect of syllable position was significant ($F[2,57]=20.819$, $p<.0001$), and pairwise comparisons were also significant between syllable-initial and syllable-final nasals ($p<.001$) or syllabic nasals ($p<.05$).

Table 3.34 summarizes the results presented on displacement amplitude of lower lip lowering for effect of syllable position.

TABLE 3.34 PAIRWISE COMPARISON FOR DISPLACEMENT AMPLITUDE OF LOWER LIP LOWERING

		Pairwise Comparisons		
Subject	vowel	Syl-final vs. Syl-initial	Syl-final vs. Syllabic	Syl-initial vs. Syllabic
S1	ɑ	greater	smaller	smaller *
	i	smaller	smaller *	smaller *
S2	ɑ	smaller *	greater	greater *
	i	smaller	smaller	greater
S3	ɑ	greater	smaller *	smaller *
	i	smaller *	smaller *	greater
S4	ɑ	smaller *	smaller *	smaller *
	i	smaller *	smaller	smaller *

To summarize, for all subjects, the effect of syllable position and effect of vowel type were highly significant. Interestingly, the pattern of difference shows that in many cases syllabic nasals had greater displacement amplitudes of lower lip lowering than syllable-final nasals. For two of the subjects (S1 and S3), the displacement amplitudes of lower lip lowering were found greater in /ɑ/ context, but smaller in /i/ context; while for other two subjects (S2 and S4), the displacement amplitudes of lower lip lowering were found greater in both vowel contexts. Significantly greater displacement amplitudes of lower lip lowering were always found in the vowel /ɑ/ context.

3.7.3 Coordination between Labial and Velar Gestures

In order to gain some insight of the inter-articulatory timing patterns of velum and lower lip during the production of bilabial nasal consonants affiliated with different syllable positions, mean durations of velar lowering, low velar plateau and velar raising are plotted in relation to the onset time of lower lip plateau (point zero in time), (which is generally considered as the point where complete lip closure has been achieved). In contrast to the velum movement were corresponding mean durations for lower lip raising, lower lip plateau, and lower lip lowering. Figures 3.18, 3.19, 3.20 and 3.21 are for S1, S2, S3 and S4, respectively. There are two graphs in each figure, the top one is for /ɑ/ conditext and the lower one for /i/ context. The articulators are indicated on the left side of the graph, and syllable position and tone type on the right side of the graph. Different shadings distinguish approaches (velar lowering, lower-lip raising), plateaus, and departures (velar raising, lower-lip lowering).

From these graphs, the following were observed: In general, the onset of velar lowering was earlier in relation to the onset of lower lip plateau for syllabic nasals than for syllable-final or syllable-initial nasals, regardless of vowel context. The offset of velar lowering was later in relation to the onset of lower lip raising for syllabic nasals than for syllable-final or syllable-initial nasals regardless of vowel context: no consistent pattern was seen between syllabic nasals and syllable-final or syllable-initial nasals for the offset of velar lowering relative to the onset of lower lip plateau, but it was mostly later for syllable-final nasals than for syllable-initial nasals. These observations of timing differences between velar and lower lip movement were assessed statistically and the results are discussed.

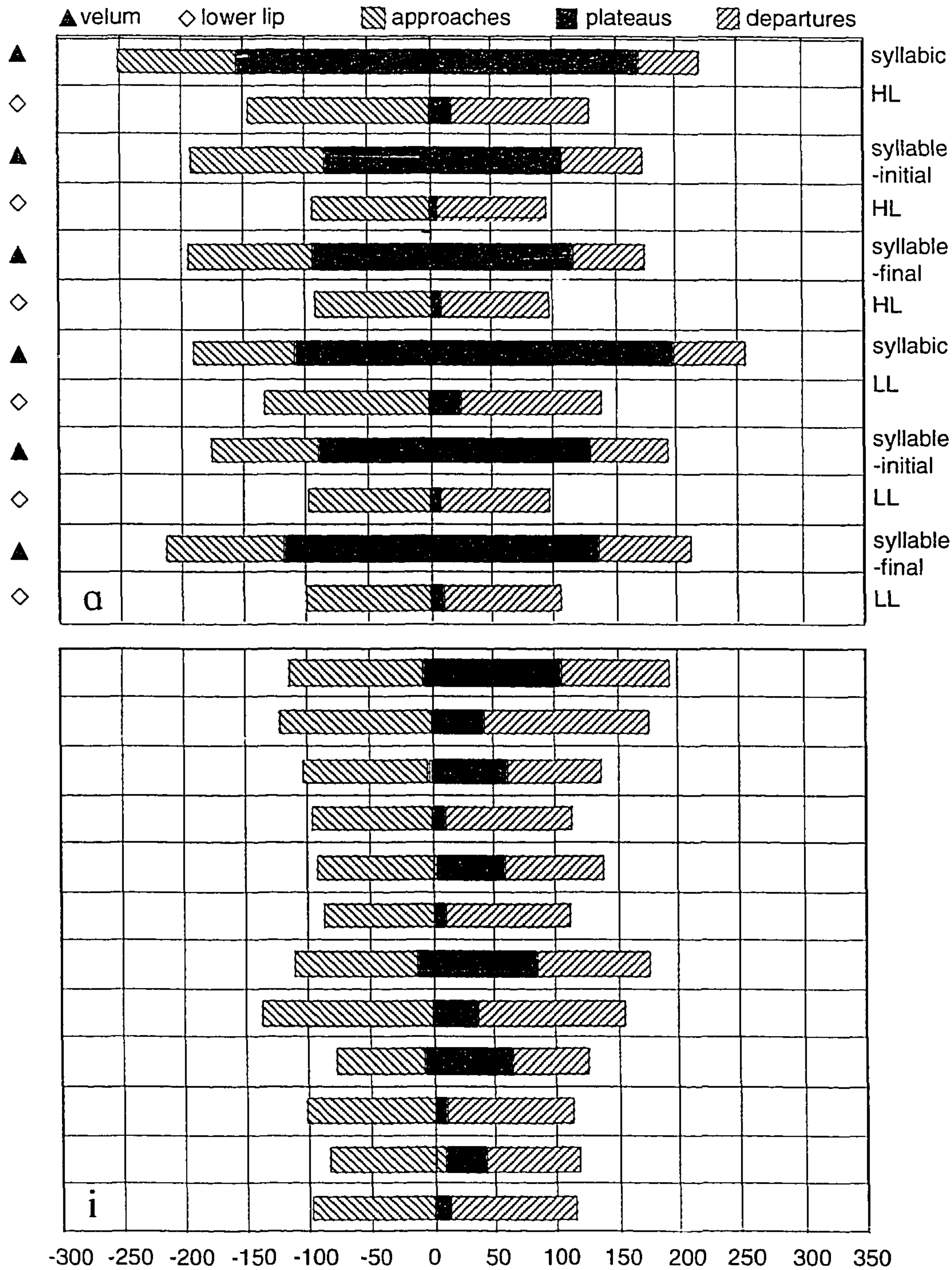

Figure 3.18 Comparison between movement pattern of the velum and the lower lip for S1.

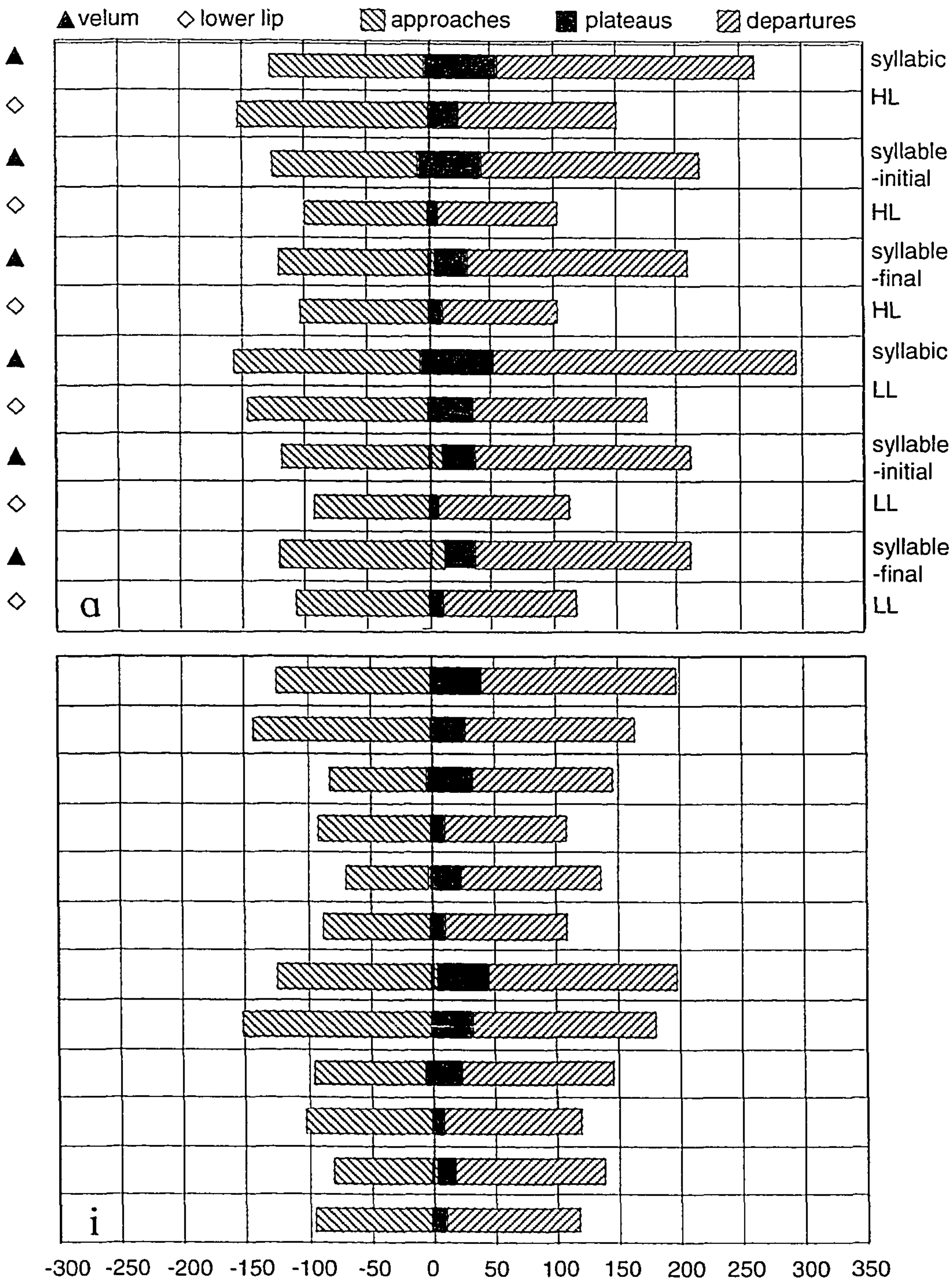

Figure 3.19 Comparison between movement pattern of the velum and the lower lip for S2.

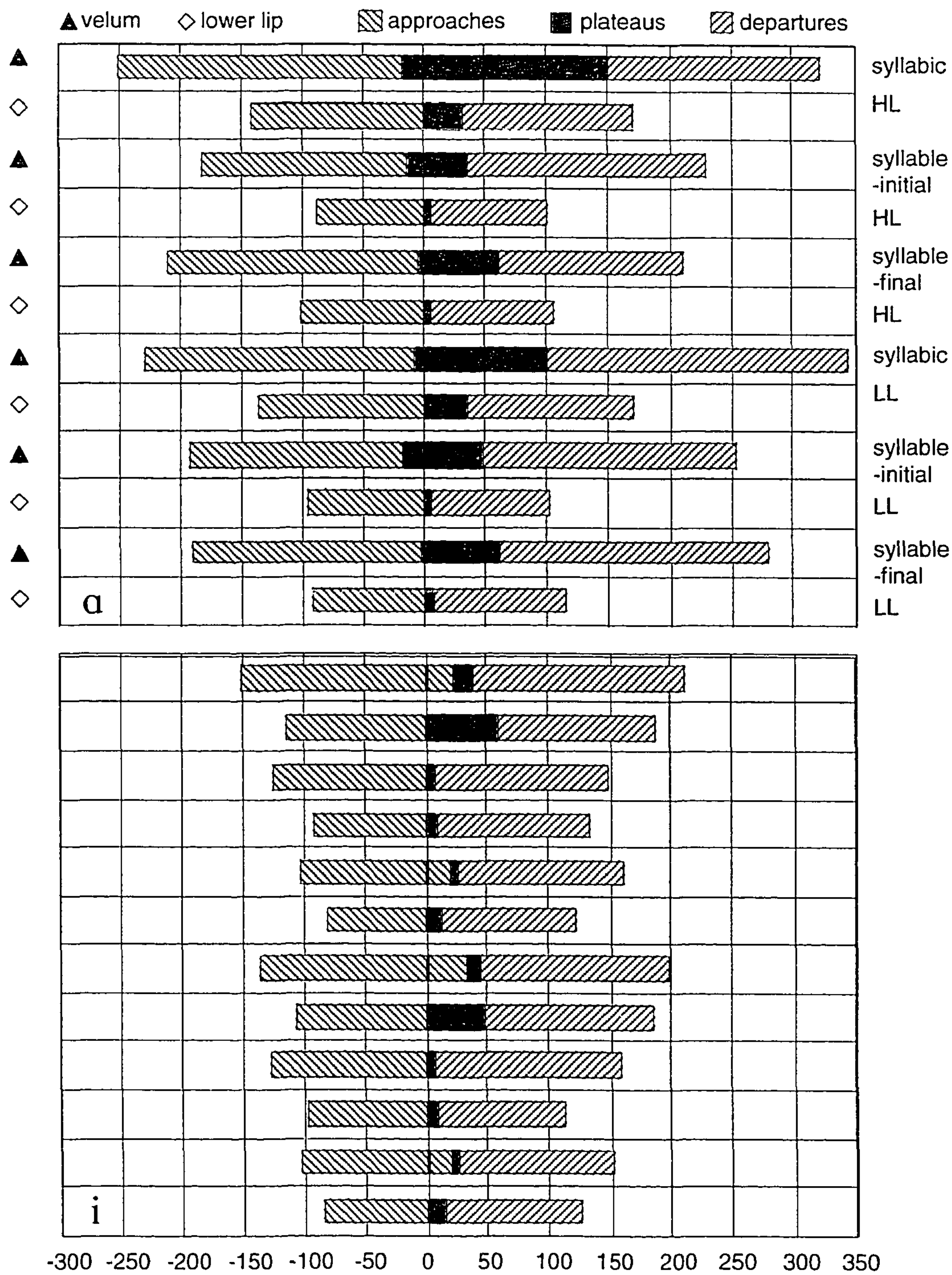

Figure 3.20 Comparison between movement pattern of the velum and the lower lip for S3.

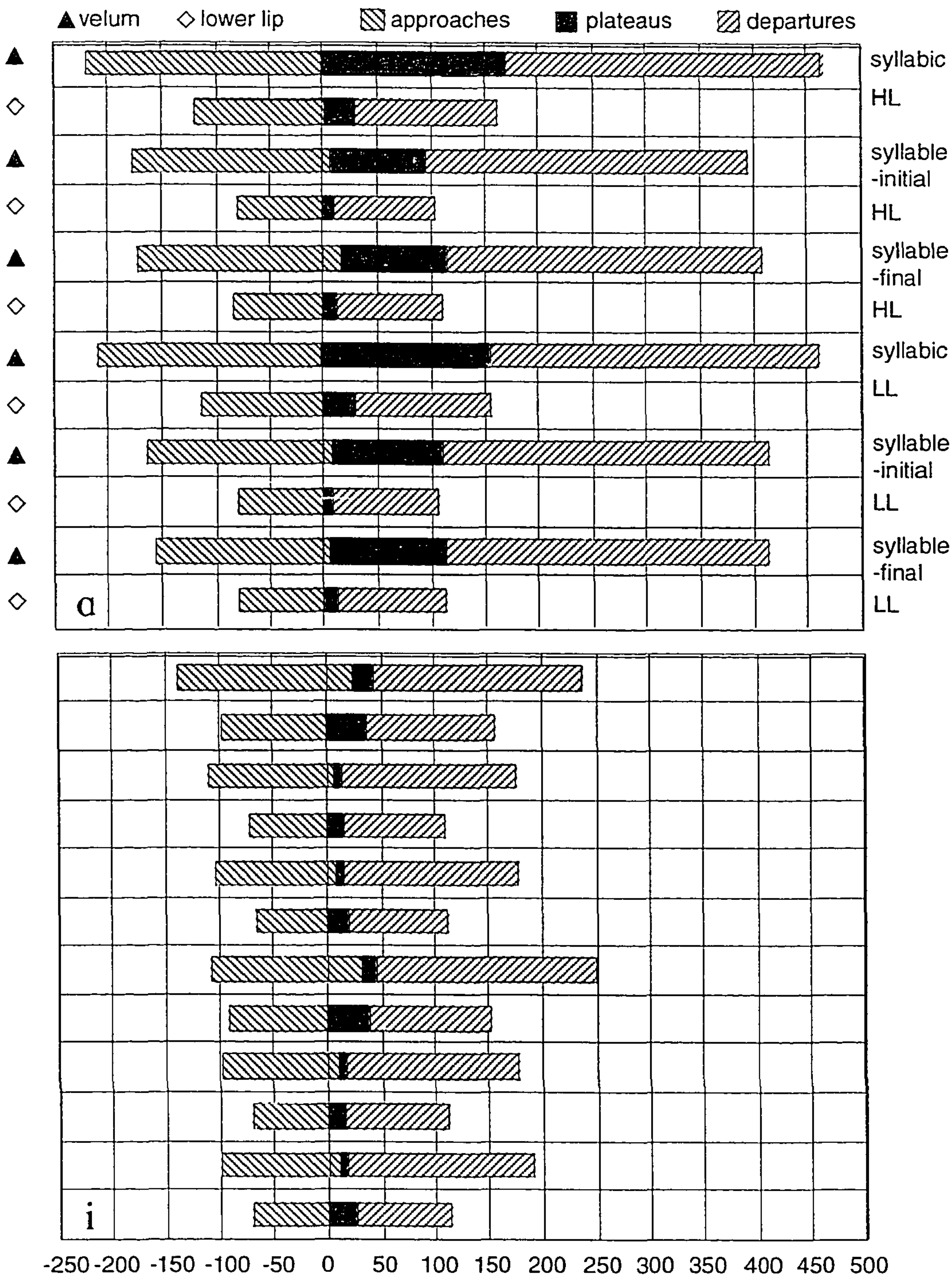

Figure 3.21 Comparison between movement pattern of the velum and the lower lip for S4.

Velar Lowering Onset Time in Relation to Lower lip Plateau Onset Time

The time intervals between the onset of velar lowering and the onset time of lower lip plateau provided information on how early the velar lowering started relative to the lip closure for different types of nasals. The means of this relative intervals are plotted in Figure 3.22 for all four subjects. ANOVA was conducted for each subject and the results are shown in Table 3.35.

TABLE 3.35 ANOVA RESULTS FOR RELATIVE TIMING OF VELAR LOWERING ONSET TO LOWER LIP PLATEAU ONSET

	S1			S2		
	DF	F	P	DF	F	P
S	2,108	38.424	<.0001	2,108	40.489	<.0001
V	1,108	1235.352	<.0001	1,108	101.384	<.0001
S*V	2,108	5.312	.0063	2,108	9.604	.0001
T	1,108	28.463	<.0001	1,108	6.502	.0122
S*T	2,108	10.618	<.0001	2,108	.630	.5347
V*T	1,108	1.267	.2628	1,108	.337	.5629
S*V*T	2,108	18.143	<.0001	2,108	5.800	.0040
	S3			S4		
	DF	F	P	DF	F	P
S	2,107	35.080	<.0001	2,107	145.956	<.0001
V	1,107	400.693	<.0001	1,107	1330.033	<.0001
S*V	2,107	7.474	.0009	2,107	29.195	<.0001
T	1,107	3.283	.0728	1,107	67.763	<.0001
S*T	2,107	2.093	.1283	2,107	6.046	.0033
V*T	1,107	1.503	.2229	1,107	.781	.3787
S*V*T	2,107	.828	.4398	2,107	1.366	.2596

For S1 (Figure 3.22), velar lowering always started before the lower lip plateau onset. The timing of velar lowering onset relative to the lower lip plateau onset was earlier for syllabic nasals than for either syllable-final or syllable-initial nasals, and earlier for syllable-final nasals than for syllable-initial nasals. The main effect of syllable position was significant. And all three possible pairwise comparisons between nasals of different syllable positions were also significant: syllable-final and syllable-initial nasals ($p<.05$); syllable-final and syllabic nasals ($p<.0001$); and syllable-initial and syllabic nasals ($p<.0001$). As shown in Figure 3.22, velar lowering onset was earlier relative to lower lip plateau onset in the vowel/ɑ/ context than in /i/ context. The main effect of vowel type

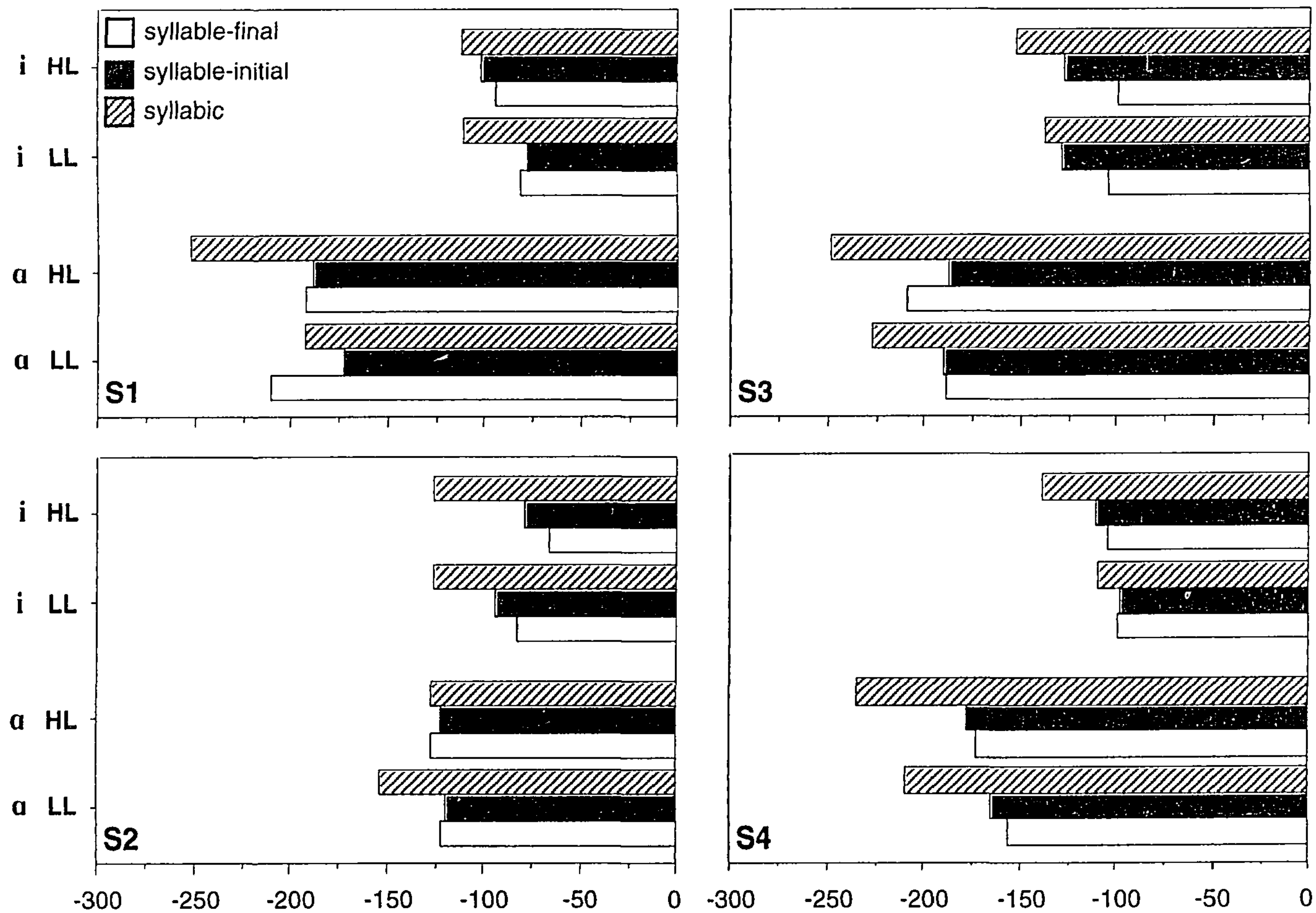

Figure 3.22 Mean relative timing difference between onset of velar lowering and onset of lower-lip plateau in msec (0=onset of lower-lip plateau).

was significant. There was a significant interaction between syllable position and vowel type. Further tests of simple effect revealed that in /ɑ/ context, the onset of velar lowering was earlier relative to the onset of lower lip plateau for syllabic nasals, and later for syllable-final nasals, and last for syllable-initial nasals. The effect of syllable position was significant, $F(2,57)=13.115$, $p<.0001$, and so were the three pairwise comparisons ($p<.05$ or $p<.01$). In /i/ context, the onset of velar lowering was again earlier relative to the onset of lower lip plateau for syllabic nasals, but inconsistent for syllable-final nasals and syllable-initial nasals. Therefore, although the effect of syllable position was significant, ($F[2,57]=111.984$, $p<.0001$), only comparisons between syllabic nasals and syllable-final or syllable-initial nasals were significant (both $p<.0001$). Velar lowering onset was significantly earlier in /ɑ/ context than in /i/ context for nasals in all three different syllable positions: for syllable-final nasals, $F(1,38)=533.073$, $p<.0001$; for syllable-initial nasals, $F(1,38)=250.126$, $p<.0001$; and for syllabic nasals, $F(1,38)=152.177$, $p<.0001$. The velar lowering onset was earlier relative to lower lip plateau onset in the HL tone condition than the LL tone condition. The main effect of tone type was significant. There was a significant interaction between syllable position and tone type. Interestingly, further tests of simple effect revealed that there was no significant tonal effect for nasals of all three syllable positions when pooled over vowel types, nor any significant effect of syllable position for either tones. There was a significant three-way interaction between syllable position, vowel type and tone, ($F[2,108]=18.143$, $p<.0001$). More detailed analyses revealed that there was significant tonal effect for syllable-initial nasals in both vowel contexts (both $p<.05$), and for syllabic nasals in the vowel /ɑ/ context only ($p<.0001$). In these cases, the onset velar lowering relative to the onset of lower lip plateau was earlier in the HL condition than in the LL condition; however, a tonal effect of opposite direction was significant for syllable-final nasals in the vowel /ɑ/ context ($p<.05$).

For S2 (Figure 3.22), velar lowering always started before the lower lip plateau onset. Among bilabial nasals of different syllable positions, velar lowering onset was earlier relative to the lower-lip plateau onset for syllabic nasals than either syllable-final or syllable-initial nasals, and earlier for syllable-final nasals than syllable-initial nasals in /ɑ/ context but later in /i/ context. The main effect of syllable position was significant. Pairwise comparisons were significant between syllabic nasals and syllable-final or syllable-initial nasals (both $p<.0001$), but the latter two types of nasals did not differ significantly from each other. As shown in Figure 3.22, the velar lowering onset was earlier relative to the onset of lower lip plateau for the /ɑ/ context than for the /i/ context. The main effect of vowel type was significant. The interaction between syllable position and vowel type was significant. Tests of simple effect revealed that there was a significant effect of syllable position in both /ɑ/ context, ($F[2,57]=3.92$, $p=.0254$), and /i/ context ($F[2,57]=73.469$, $p<.0001$). However, while in /ɑ/ context, the pairwise comparisons between syllabic nasals and syllable-final or syllable-initial nasals were significant (both $p<.05$); in /i/ context, all three pairwise comparisons were significant (all three $p\leq.01$). The vowel effect was significant for both syllable-initial nasals ($F[1,38]=123.779$, $p<.0001$), and syllable-initial nasals ($F[1,38]=64.608$, $p<.0001$), but not for syllabic nasals. There was a significant main effect of tone, although the pattern of this effect was unclear. There was a significant three-way interaction between syllable position, vowel type and tone, ($F[2,108]=5.8$, $p<.01$). Detailed analyses revealed that there was a significant tonal effect only for syllable-final and syllable-initial nasals in the vowel /i/ context, with the onset of velar lowering earlier in the LL tone condition in both cases (both $p<.01$).

For S3 (Figure 3.22), velar lowering always started before the lower lip plateau onset. Among bilabial nasals of different syllable positions, the relative timing of velar lowering onset to the lower lip plateau onset was earlier for syllabic nasals than either syllable-final or syllable-initial nasals, and earlier for syllable-final nasals than syllable-initial nasals in /ɑ/ context but later in /i/ context. The main effect of syllable position was significant. The pairwise comparisons were significant between syllabic nasals and syllable-final or syllable-initial nasals (both p<.0001), which did not differ from each other significantly. The onset of velar lowering was earlier relative to the onset of lower lip plateau in /ɑ/ context than in /i/ context. The main effect of vowel type was significant. There was a significant interaction between syllable position and vowel type. Tests of simple effect revealed that there was a significant effect of syllable position in both vowel contexts (in /ɑ/ context, F[2,56]=23.226, p<.0001); and in /i/ context, F[2,57]=17.83, p<.0001). In /ɑ/ context, pairwise comparisons were significant between syllabic nasals and syllable-final nasals or syllable-initial nasals (both p<.0001) as well as between syllable-final and syllable-initial nasals (p<.05); in /i/ context, all three pairwise comparisons were significant with p<.001. The vowel effect was significant for all three types of nasals: for syllable-final nasals, F(1,37)=213.774, p<.0001; for syllable-initial nasals, F(1,38)=181.179, p<.0001; and for syllabic nasals, F(1,38)=87.038, p<.0001. The main effect of tone was not significant, and no other significant interactions were found.

For S4 (Figure 3.22), velar lowering always started before the lower lip plateau onset began. Among bilabial nasals of different syllable positions, the relative timing of velar lowering onset to the lower lip plateau onset was earlier for syllabic nasals than either syllable-final or syllable-initial nasals, and earlier for syllable-initial nasals than syllable-final nasals. The main effect of syllable position was significant. Pairwise comparisons were significant between syllable-final and syllable-initial nasal (p<.05), as well as between syllabic nasals and syllable-final or syllable-initial nasals (both p<.0001). The onset of velar lowering was earlier relative to the onset of lower lip plateau in /ɑ/ context than in /i/ context. Thus, the main effect of vowel type was significant. There was a significant interaction between syllable position and vowel type. Tests of main effect revealed that there was a significant effect of syllable position in both /ɑ/ context, (F[2,56]=81.162, p<.0001), and /i/ context (F[2,57]=14.761, p<.0001). In /ɑ/ context, pairwise comparisons were significant between syllabic nasals and syllable-final nasals or syllable-initial nasals (both $p<.0001$); while in /i/ context , the two significant pairwise comparisons were between syllabic nasals and syllable-final or syllable-initial nasals (both $p<.0001$). The vowel effect was significant for all three types of nasals: for syllable-final nasals, $F(1,37)=341.763$, $p<.0001$; for syllable-initial nasals, $F(1,38)=204.541$, $p<.0001$; and for syllabic nasals, $F(1,38)=305.76$, $p<.0001$. As can be observed in Figure 3.22, the onset of velar lowering was earlier relative to the onset of the lower lip plateau in the HL tone condition than in the LL tone condition. Thus, the main effect of tone type was significant. The interaction between syllable position and tone type was significant. Tests of simple effect showed that the overall syllable position was significant in both tone conditions (in the LL tone condition, $F[2,56]=3.77$, $p<.05$; and in the HL tone condition, $F[2,57]=7.768$, $p<.001$), and in both tone conditions, pairwise comparisons were significant only between syllabic and syllable-final or syllable-initial nasals (in the LL tone condition, both $p<.05$, and in the HL tone condition, both $p<.01$). No significant tonal effect was found for any of the three types of nasals.

To summarize, the results of pairwise comparisons of the interval between velar lowering onset and the lower lip plateau onset are presented in Table 3.36. In the table, for each pairwise comparison, "earlier" or "later" refers to the timing of the onset of velar lowering relative to the onset of lower lip plateau of the first nasal in comparison to the second.

TABLE 3.36 PAIRWISE COMPARISONS OF RELATIVE TIMING BETWEEN ONSET OF VELAR LOWERING AND ONSET OF LOWER LIPPLATEAU AMONG NASALS OF DIFFERENT SYLLABLE POSITIONS

	Pairwise Comparisons						
Subject	vowel	Syl-final vs. Syl-initial		Syl-final vs. Syllabic		Syl-initial vs. Syllabic	
S1	ɑ	earlier	*	later	*	later	*
	i	later		later	*	later	*
S2	ɑ	earlier	*	later	*	later	*
	i	later	*	later	*	later	*
S3	ɑ	earlier	*	later	*	later	*
	i	later	*	later	*	later	*
S4	ɑ	later		later	*	later	*
	i	later		later	*	later	*

Thus, as can be seen from Table 3.36, overall, the onset times of velar lowering relative to the onset time of lower lip plateau differed significantly from one another among nasals of different syllable positions in both vowel contexts. For syllabic nasals, the onset of velar lowering was always earlier in comparison to syllable-final or syllable-initial nasals and the pattern was maintained across vowel contexts. Between syllable-final and syllable-initial nasals, the relative timing between the onset of velar lowering and the onset of lip closure varied with vowel context. For three subjects, velar lowering was earlier for syllable-final nasals in /ɑ/ context and later in /i/ context.

Velar Lowering Offset Time in Relation to Lower lip Raising Onset Time

The time interval between the offset of velar lowering in relation to the onset time of lower lip raising provided information on the pattern of coordination between the two articulators, velum and lower lip, with respect to the initiation of the labial gesture toward the bilabial nasal consonant. The means of this time interval are plotted in Figure 3.23 for all four subjects. ANOVA results are shown in Table 3.37.

TABLE 3.37 ANOVA RESULTS FOR RELATIVE TIMING
OF VELAR LOWERING OFFSET TO LOWER LIP RAISING ONSET

	S1			S2		
	DF	F	P	DF	F	P
S	2,106	19.382	<.0001	2,108	187.462	<.0001
V	1,106	1933.839	<.0001	1,108	9.782	.0023
S*V	2,106	14.373	<.0001	2,108	9.967	.0001
T	1,106	1.705	.1945	1,108	6.749	.0107
S*T	2,106	7.606	.0008	2,108	1.306	.2750
V*T	1,106	2.367	.1269	1,108	1.468	.2283
S*V*T	2,106	8.059	.0006	2,108	4.242	.0168
	S3			S4		
	DF	F	P	DF	F	P
S	2,107	61.489	<.0001	2,105	174.424	<.0001
V	1,107	13.448	.0004	1,105	5.974	.0162
S*V	2,107	.275	.7604	2,105	12.775	<.0001
T	1,107	.445	.5060	1,105	.759	.3857
S*T	2,107	.139	.8708	2,105	.597	.5523
V*T	1,107	.084	.7728	1,105	14.540	.0002
S*V*T	2,107	.081	.9224	2,105	2.589	.0799

For S1 (Figure 3.23), velar lowering ended later in relation to the beginning of lower lip raising for syllabic nasals than for syllable-final or syllable-initial nasals, between which, the offset of velar lowering was largely later in relation to the onset of lower lip raising for syllable-initial nasals. The main effect of syllable position was significant. Pairwise comparisons were significant between syllable-final and syllable-initial nasals ($p<.005$), and between syllabic and syllable-final ($p<.0001$), or syllable-initial nasals ($p<.001$). There was a significant effect of vowel type. Velar lowering ended earlier relative the beginning of lower lip raising for all three types of nasals in /ɑ/ context. The main effect of vowel type was significant. There was a significant interaction between syllable position and vowel type ($F[2,106]=14.373$, $p<.0001$). Tests of simple effect indicated that the differences in timing of velar lowering offset relative to lower lip raising onset observed among nasals of different syllable positions were significant in both vowel contexts; in /ɑ/ context, $F[2,55]=5.212$, $p<.01$; and in /i/ context, $F[2,57]=26.344$, $p<.0001$. Pairwise comparisons were significant between syllable-final and syllable-initial nasals ($p<.01$) in /ɑ/ context; and between syllabic and syllable-final or syllable-initial nasals (both $p<.0001$) in /i/ context. The velar lowering consistently ended earlier relative to the beginning of lower lip raising in the vowel /ɑ/ context than in the vowel /i/ context, for syllable-final nasals, $F(1,38)=548.61$, $p<.0001$; for syllable-initial nasals, $F(1,37)=548.256$, $p<.0001$; and for syllabic nasals, $F(1,37)=490.416$, $p<.0001$. No tonal effect was observed and the main effect of tone type was not significant. However, there was a significant interaction between syllable position and tone type and a significant three-way interaction. For the interaction between syllable position and tone type, the tests of simple effect indicated no overall effect of syllable position in either tone conditions, and no tonal effect was found for any of the three syllable positions. For the 3-way interaction, the effect of syllable position was significant in all combinations of vowel and tone; the vowel effect was significant in all combinations of syllable position and tone; but the tonal effect was significant only for syllable-final nasals in both vowel contexts as well as for

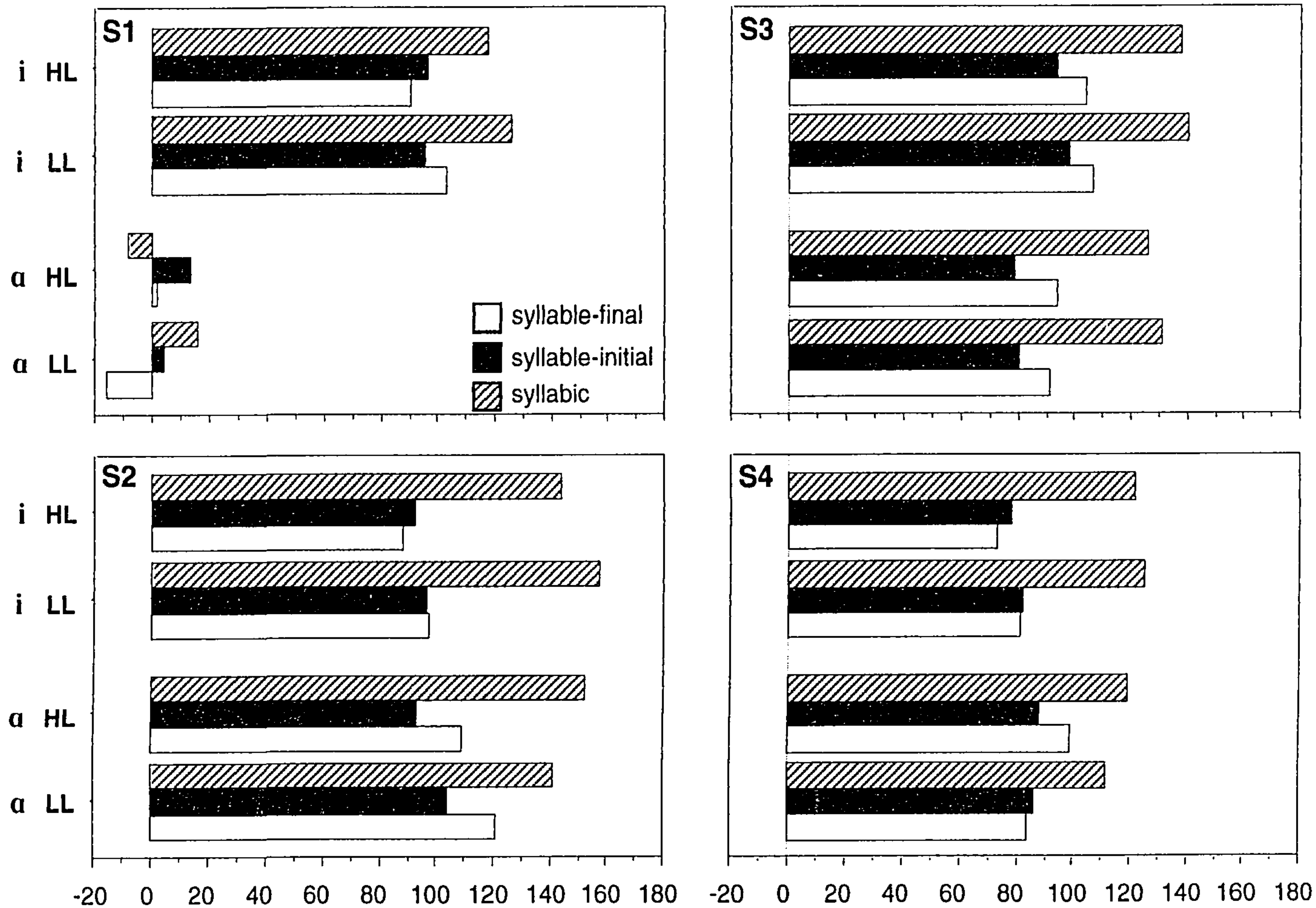

Figure 3.23 Mean relative timing difference between offset of velar lowering and onset of lower-lip raising in msec (0=onset of lower-lip raising).

syllabic nasals in /ɑ/ context. For syllable-final and syllabic nasals in /ɑ/ context, velar lowering offset was significantly earlier relative to the onset of lower lip raising in the LL tone condition, while for syllable-final in /i/ context, it was significantly earlier in the HL tone condition.

For S2 (Figure 3.23), the offset of velar lowering ended later relative to the onset of lower lip raising for syllabic nasals than for syllable-final or syllable-initial nasals, between which velar lowering ended later for syllable-final nasals. The main effect of syllable position was significant, and all three possible pairwise comparisons were significant (all $p<.01$). Overall, the velar lowering ended later relative to the beginning of lower lip raising in the vowel /ɑ/ context than in the vowel /i/ context. The main effect of vowel type was significant. The interaction between syllable position and vowel type was significant. Tests of simple effect revealed that the effect of syllable position was significant for vowel /ɑ/ context ($F[2,57]=52.722$, $p<.0001$), as well as for vowel /i/ context ($F[2,57]=142.296$, $p<.0001$). While all pairwise comparisons among nasals of different syllable positions were significant (all $p<.01$) in /ɑ/ context, only comparisons between syllabic nasals and syllable-final or syllable-initial nasals were significant in /i/ context (both $p<.0001$). The vowel effect was significant only for syllable-final nasals, ($F[1,38]=25.935$, $p<.0001$). As shown in Figure 3.23, overall, velar lowering ended later relative to the starting of lower lip raising for the LL tone condition and the main effect of tone type was significant. There was a significant 3-way interaction. Tests of simple effect revealed the following: the effect of syllable position was significant for all combinations of vowel and tone; the vowel effect was not significant for syllable-initial nasals in either tone conditions, nor for syllabic nasals in the HL tone condition; the tonal effect was significant only for syllable-final and syllabic nasals in /i/ context. For both types of nasals, the direction was that the velar lowering offset was later relative to the onset of lower lip raising in the LL tone condition.

For S3 (Figure 3.23), relative to the beginning of lower lip raising, velar lowering ended first for syllable-initial nasals and last for syllabic nasals. The main effect of syllable position was significant . All three possible pairwise comparisons among the three types of nasals were also significant ($p<.05$ or $p<.01$). For nasals of all three different syllable positions, velar lowering ended later relative to the beginning of lower lip raising in the vowel /i/ context. The main effect of vowel type was significant. No significant main effect of tone type was found nor were any interactions between factors.

For S4 (Figure 3.23), velar lowering ended later relative to the beginning of lower lip raising for syllabic nasals than for syllable-final or syllable-initial nasals, which differed little from each other. The main effect of syllable position was significant. However, only pairwise comparisons between syllabic nasal and syllable-final or syllable-initial nasals were significant. As can be observed from Figure 3.23, in /ɑ/ context, velar lowering ended later relative to the beginning of lower lip raising for syllable-final and syllable-initial nasals, but earlier for syllabic nasals. The main effect of vowel type was significant. The interaction between syllable position and vowel type was significant. Tests of simple effect revealed that in both /ɑ/ and /i/ contexts, the effect of syllable position was significant, (for /ɑ/, $F[2,54]=31.226$, $p<.0001$; and for /i/, $F[2,57]=175.429$, $p<.0001$). Pairwise comparisons between nasals in both vowel contexts were significant only between syllabic nasals and syllable-final or syllable-initial nasals ($p<.0001$ for all four comparisons). The vowel effect was significant for nasals in all three syllable positions. For both syllable-final and syllable-initial nasals, later velar lowering offset relative to the onset of lower lip plateau was seen in /ɑ/ context, but for syllabic nasals, in /i/ context. No significant main effect of tone type was found. Although the interaction between vowel type and tone type was significant, no significant effects of either factor were revealed by the tests of simple effect.

To summarize the timing difference exhibited by bilabial nasals of different syllable positions, the results of pairwise comparisons of the relative timing between velar lowering offset and the lower lip raising onset among these nasals of are presented in Table 3.38.

TABLE 3.38 PAIRWISE COMPARISONS OF RELATIVE TIMING BETWEEN OFFSET OF VELAR LOWERING AND ONSET OF LOWER LIP RAISING AMONG NASALS OF DIFFERENT SYLLABLE POSITIONS

	Pairwise Comparisons						
Subject	vowel	Syl-final vs. Syl-initial		Syl-final vs. Syllabic		Syl-initial vs. Syllabic	
S1	ɑ	earlier	*	earlier		earlier	
	i	later		earlier	*	earlier	*
S2	ɑ	later	*	earlier	*	earlier	*
	i	earlier		earlier	*	earlier	*
S3	ɑ	later	*	earlier	*	earlier	*
	i	later	*	earlier	*	earlier	*
S4	ɑ	later		earlier	*	earlier	*
	i	earlier		earlier	*	earlier	*

Thus, as summarized in Table 3.38, the offset time of velar lowering relative to the onset of lower lip raising was significantly later for syllabic nasals than for syllable-final or syllable-initial nasals. Between syllable-final and syllable-initial nasals, either the relative timing did not differ much, or velar lowering ended later relative to the beginning of lower lip raising for syllable-final nasals. Although significant vowel effect was found for all four subjects, the timing pattern found remained relatively stable across both vowel contexts.

Velar Lowering Offset Time in Relation to Lower lip Plateau Onset Time

The time interval between the offset of velar lowering, i.e., the onset of the low velar plateau, and the onset of lower lip plateau, i.e., the offset of lower lip raising, provided information on relative timing between the velum and lower lip when both of them reached their spatially maximum point: for velum, the positional minimum and for lower lip, the positional maximum. Means of this relative timing difference are plotted in Figure 3.24. ANOVA results are presented in Table 3.39.

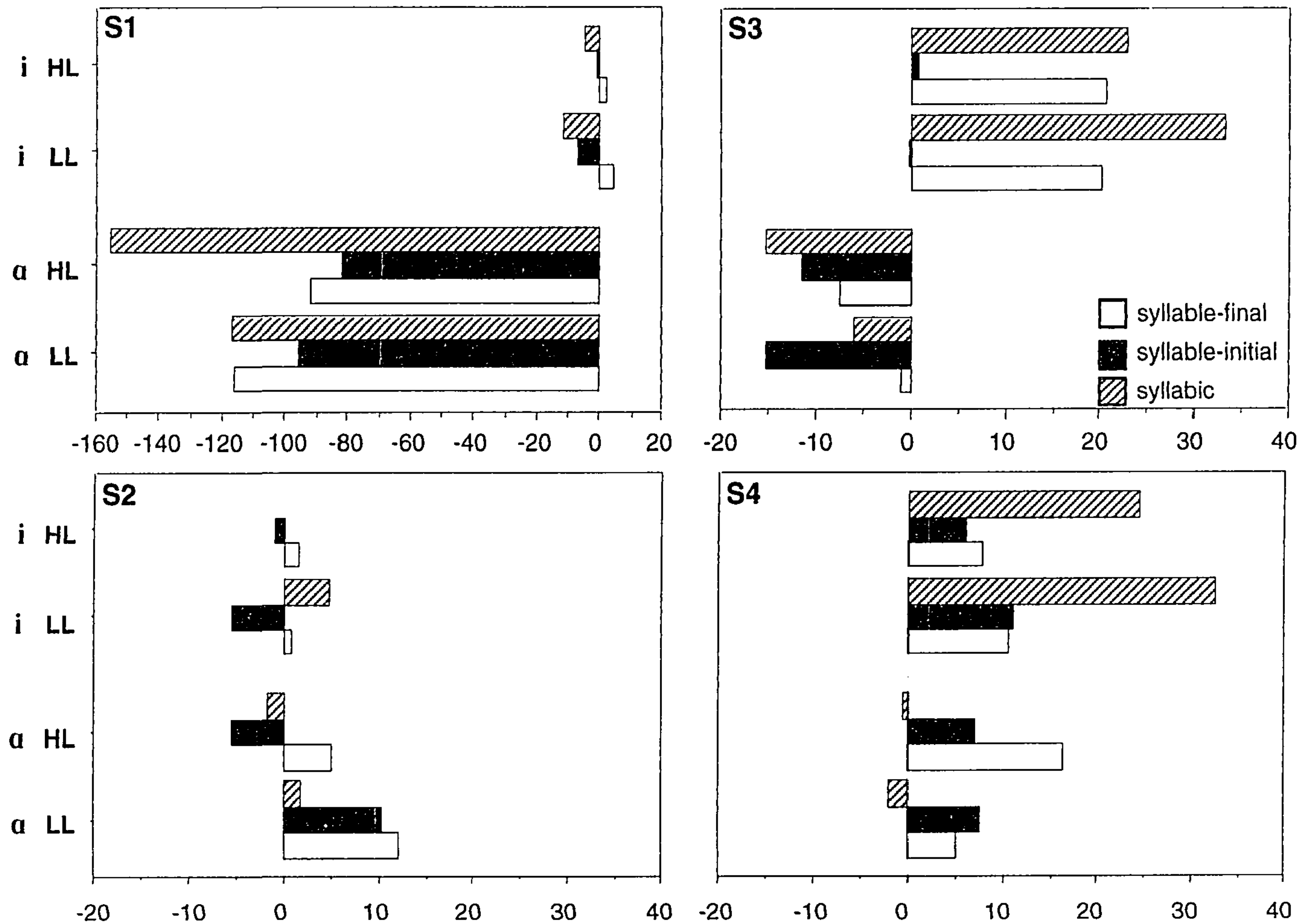

Figure 3.24 Mean relative timing difference between offset of velar lowering and onset of lower-lip plateau in msec (0=onset of lower-lip plateau).

TABLE 3.39 ANOVA RESULTS FOR RELATIVE TIMING OF VELAR LOWERING OFFSET TO LOWER-LIP PLATEAU ONSET

	S1			S2		
	DF	F	P	DF	F	P
S	2,106	30.415	<.0001	2,107	2.056	.1330
V	1,106	1370.410	<.0001	1,107	2.743	.1006
S*V	2,106	18.864	<.0001	2,107	1.891	.1560
T	1,106	.373	.5425	1,107	4.101	.0453
S*T	2,106	8.614	.0003	2,107	.109	.8968
V*T	1,106	.417	.5198	1,107	4.354	.0393
S*V*T	2,106	13.891	<.0001	2,107	2.147	.1218
	S3			S4		
	DF	F	P	DF	F	P
S	2,107	10.012	.0001	2,105	2.717	.0707
V	1,107	65.839	<.0001	1,105	23.515	<.0001
S*V	2,107	5.285	.0065	2,105	24.174	<.0001
T	1,107	1.200	.2757	1,105	.078	.7802
S*T	2,107	1.228	.2970	2,105	1.406	.2496
V*T	1,107	.024	.8759	1,105	5.433	.0217
S*V*T	2,107	.221	.8021	2,105	.514	.5995

For S1 (Figure 3.24), among bilabial nasals of different syllable positions, the relative timing of the offset of velar lowering to the onset of lower lip plateau was earlier for syllabic nasals than for syllable-final or syllable-initial nasals, between which, velar lowering offset was earlier for syllable-final nasals than syllable-final nasals in /ɑ/ context , but later in /i/ context . The main effect of syllable position was significant. And pairwise comparisons were significant only between syllabic nasals and syllable-final or syllable-initial nasals (both $p<.0001$). As shown in Figure 3.24, the relative timing of velar lowering offset was earlier in the vowel /ɑ/ context than in the /i/ context, and the main effect of vowel was significant. The interaction between syllable position and vowel type was significant. Further tests of simple effect revealed that the effect of syllable position was significant in the vowel /ɑ/ context, $F(2,55)=26.927$, $p<.0001$; but not significant in the vowel /i/ context. In /ɑ/ context , pairwise comparisons were significant between syllable-final and syllable-initial nasals ($p<.01$), as well as between syllabic nasals and syllable-final or syllable-initial nasals (both $p<.0001$). In /i/ context, although the overall effect of syllable position was not significant but only approaching significance, nonetheless, the pairwise comparison test was conducted to help understand the interaction. The results showed that there were two significant pairwise comparisons: between syllable-final and syllable-initial nasals ($p<.01$), and between syllable-final and syllabic nasals ($p<.05$). Therefore, the pairwise comparisons between nasals of different syllable positions were consistent with observations. All three types of nasals had significant earlier velar lowering offset relative to the onset of lower lip plateau in the vowel /ɑ/ context, for syllable-final nasals, $F(1,38)=627.195$, $p<.0001$; for syllable-initial nasals, $F(1,37)=402.59$, $p<.0001$; and for syllabic nasals, $F(1,37)=254.935$, $p<.0001$. Although the main effect of tone type was not significant, there was a significant interaction between syllable position and tone, and a significant 3-way interaction. Tests of simple effect revealed that for the interaction between syllable position and tone type, no effects either of syllable position nor of tone were significant. As for the 3-way interaction, effect of syllable position was found significant only in context for both tone conditions; effect of vowel was significant for all condition combinations of syllable position and tone type; and tonal effect was significant for syllable-final nasals and syllabic nasals, and the pattern of difference for syllable final-nasals was earlier offset of velar lowering offset relative to the onset of lower lip plateau in the LL tone condition.

For S2, the main effect of syllable position was not significant. The main effect of vowel type was not significant, either. The main effect of tone type was significant, so was the interaction between vowel type and tone type. Further tests of simple effect revealed that the velar lowering offset relative to the onset of lower lip plateau was significantly earlier in the LL tone condition in the vowel /ɑ/ context, ($F[1,57]=6.58$, $p<.05$), but was not in the vowel /i/ context. No other significant interactions were found.

For S3 (Figure 3.24), among nasals of different syllable positions, the relative timing of velar lowering offset to the lower lip plateau onset was earlier for syllable-initial nasals than either syllable-final or syllabic nasals, between which the relative timing of velar lowering offset was earlier for syllabic nasals than for syllable-final nasals in /ɑ/

context and later for syllabic nasals in /i/ context. The main effect of syllable position was significant. Pairwise comparisons were significant between syllable-final and syllable-initial nasals ($p<.001$) and between syllable-initial and syllabic nasals ($p<.0001$). The offset time of velar lowering in relation to the onset time of lower lip plateau was earlier in the vowel /ɑ/ context than in /i/ context, and the main effect of vowel type was significant. There was a significant interaction between syllable position and vowel type. Further tests of simple effect revealed that while the timing of velar lowering offset to the onset of lower lip plateau was significantly earlier in /ɑ/ context for syllable-final, syllable-initial and syllabic nasals, ($F[1,37]=36.48$, $p<.0001$; $F[1,38]=10.512$, $p<.01$; $F[1,38]=27.834$, $p<.0001$; respectively), the effect of syllable position was significant only in the vowel /i/ context ($F[2,57]=23.333$, $p<.0001$). Within /i/ context, pairwise comparisons were significant between syllable-final and syllable-initial nasals, and between syllable-initial and syllabic nasals (both $p<.0001$). The vowel effect was significant for syllable-final, syllable-initial, and syllabic nasals (for syllable-final nasals, $F[1,37]=36.48$, $p<.0001$; for syllable-initial nasals, $F[1,38]=10.512$, $p=.0025$; for syllabic nasals, $F[1,38]=27.834$, $p<.0001$), with later offset of velar lowering relative to the onset of lower lip plateau in /i/ context.

For S4 (Figure 3.24), the relative timing of velar lowering offset to the lower lip plateau onset did not differ consistently among bilabial nasals of different syllable positions, and the main effect of syllable position was not significant. As shown in Figure 3.24, the offset of velar lowering was earlier in relation to the onset of lower lip plateau in the vowel /ɑ/ context for syllabic nasals. For syllable-final and syllable-initial nasals, there did not seem to be a consistent vowel effect. The main effect of vowel was significant. There was a significant interaction between syllable position and vowel type. More detailed analyses of simple effect revealed that the effect of syllable position was significant in /ɑ/ context ($F[2,54]=5.605$, $p<.01$), as well as in /i/ context ($F[2,57]=25.988$, $p<.0001$). Pairwise comparisons between syllable-final and syllabic nasals, and between syllable-initial and syllabic nasals were significant both in the vowel /ɑ/ context ($p<.01$ and $p<.05$, respectively), and in the vowel /i/ context, (both $p<.0001$). The interaction between vowel type and tone type was also significant, $F(1,105)=5.433$, $p=.0217$. Tests of simple effect revealed that there was no tonal effect in either vowel context, further, the vowel effect was significant only in the LL tone condition ($F[1,57]=16.794$, $p<.0001$). No other interactions between factors were found.

To summarize the timing difference exhibited by bilabial nasals of different syllable positions, the results of pairwise comparisons of the relative timing between velar lowering offset and the lower lip plateau onset among these nasals of are presented in Table 3.40. In the table, for each pairwise comparison, “earlier” or “later” refers to the timing of the offset of velar lowering relative to the onset of lower lip plateau of the first nasal in comparison to the second one in a pair.

TABLE 3.40 PAIRWISE COMPARISONS OF RELATIVE TIMING BETWEEN OFFSET OF VELAR LOWERING AND ONSET OF LOWER LIP PLATEAU AMONG NASALS OF DIFFERENT SYLLABLE POSITIONS

	Pairwise Comparisons						
Subject	vowel	Syl-final vs. Syl-initial		Syl-final vs. Syllabic		Syl-initial vs. Syllabic	
S1	ɑ	earlier	*	later	*	later	*
	i	later	*	later	*	later	
S2	ɑ	later		later		later	
	i	later		earlier		earlier	
S3	ɑ	later		later		earlier	
	i	later	*	earlier		earlier	*
S4	ɑ	later		later	*	later	*
	i	later		earlier	*	earlier	*

To summarize, although not all pairwise comparisons were significantly different, the pattern was that velar lowering ended later in relation to the beginning of the lower lip plateau for syllable-final nasals than for syllable-initial nasals. The difference in relative timing was less consistent between syllable-final and syllabic nasals and between syllable-initial and syllabic nasals.

3.7.4 Acoustic Measurements

Acoustic measurements included duration of the vowel preceding the bilabial consonant, duration of the nasal murmur of the bilabial consonant, and duration of the vowel following the bilabial consonant. The F0 measures obtained are also included in this section.

Mean Duration of the Vowel Proceeding Bilabial Consonant

Mean acoustic durations of the vowel preceding bilabial consonants for each utterance are plotted in Figure 3.25 for all four subjects. ANOVA results are shown in Table 3.41.

TABLE 3.41 ANOVA RESULTS FOR MEAN DURATION OF THE VOWEL PRECEDING BILABIAL CONSONANT

	S1			S2		
	DF	F	P	DF	F	P
S	2,108	75.256	<.0001	2,108	245.285	<.0001
V	1,108	236.649	<.0001	1,108	281.138	<.0001
S*V	2,108	21.721	<.0001	2,108	31.250	<.0001
T	1,108	13.401	.0004	1,108	1.423	.2354
S*T	2,108	2.853	.0620	2,108	1.684	.1904
V*T	1,108	.927	.3377	1,108	5.550	.0203
S*V*T	2,108	1.925	.1508	2,108	.651	.5236
	S3			S4		
	DF	F	P	DF	F	P
S	2,108	143.178	<.0001	2,108	224.187	<.0001
V	1,108	783.469	<.0001	1,108	203.041	<.0001
S*V	2,108	18.536	<.0001	2,108	10.097	<.0001
T	1,108	1.235	.2689	1,108	19.091	<.0001
S*T	2,108	4.716	.0109	2,108	6.566	.0020
V*T	1,108	24.115	<.0001	1,108	2.399	.1243
S*V*T	2,108	.270	.7639	2,108	.234	.7914

For S1 (Figure 3.25), for both vowels, /ɑ/ and /i/, durations were longer before syllabic nasals than before either syllable-final or syllable-initial nasals. For three of the four utterances, vowel durations were longer before syllable-initial than before syllable-final nasals. Not surprisingly, the main effect of syllable position was significant, and the pairwise comparisons among these different types of nasals were also significant (all three

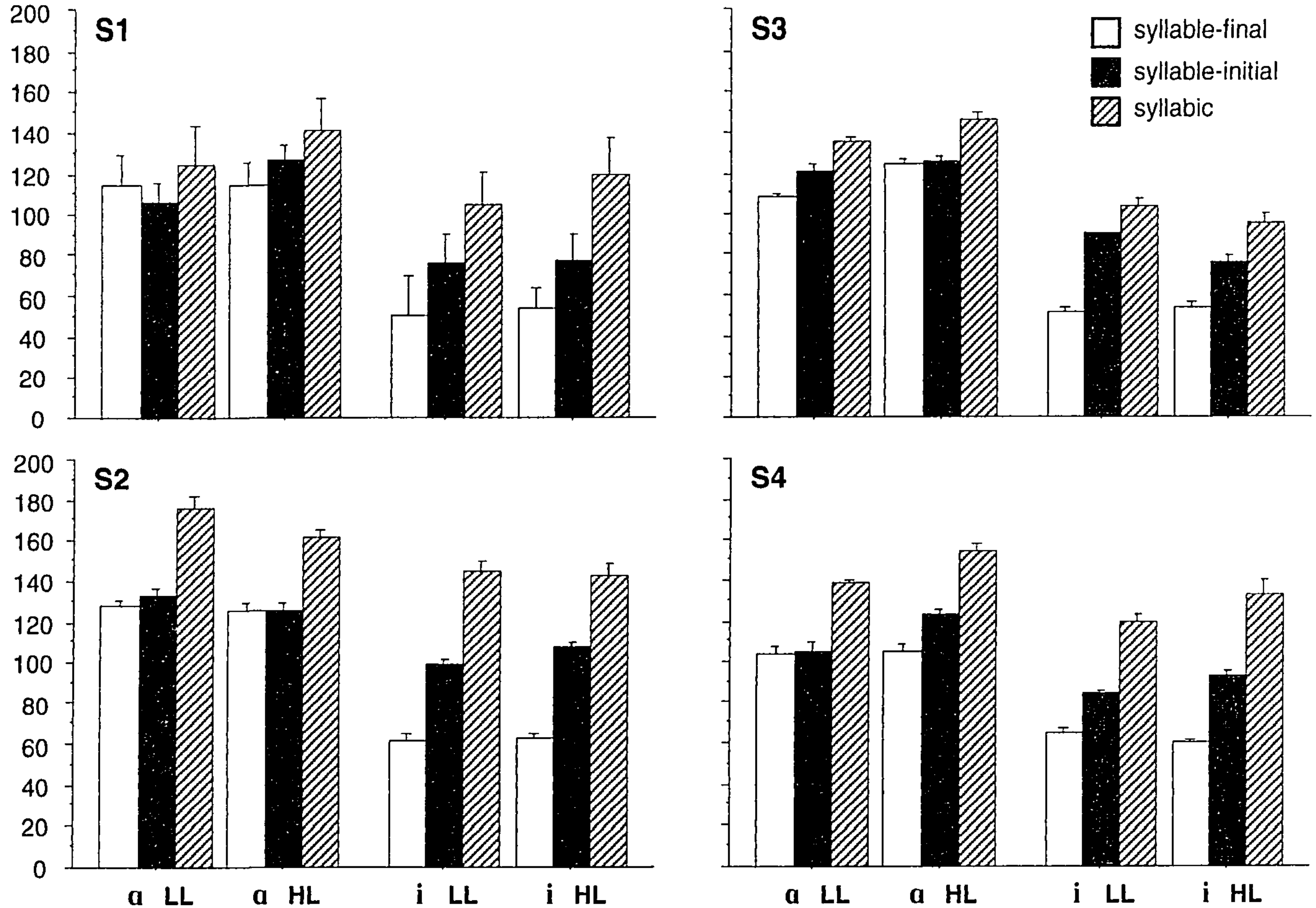

Figure 3.25 Mean duration of the vowel preceding bilabial nasal consonant (in msec).
The horizontal bars indicate standard error.

p<.0001). Vowel effects were also observed as expected. The vowel duration was longer for /ɑ/ than /i/ and the main effect of vowel type was significant. There was a significant interaction between syllable position and vowel type. More detailed testing revealed that the overall effect of syllable position was significant for both vowel contexts, (for /ɑ/, $F[2,57]=7.991$, $p<.001$; and for /i/, $F[2,57]=75.643$, $p<.0001$), and all pairwise comparisons, except the one between syllable-final and syllable-initial nasals in /ɑ/ context, were significant, with $p<.001$. Also, /ɑ/ had a significantly longer duration than /i/ regardless of the syllable position of the following nasals (for syllable-final nasals, $F[1,38]=205.53$, $p<.0001$; for syllable-initial nasals, $F[1,38]=91.092$, $p<.0001$; and for syllabic nasals, $F[1,38]=10.975$, $p<.01$). There was a tonal effect on the vowel duration for syllabic nasals (longer for the HL tone), but not evident for syllable-final or syllable-initial nasals (Figure 3.25). The main effect of tone type was significant. The interaction between syllable position and tone type was approaching but did not reach significance. Test of simple effect was conducted since the observation showed that only syllabic nasals were being affected. The result confirmed the observation: there was a significant tonal effect only before syllabic nasals ($F[1,38)=6.992$, $p<.05$). No other significant interaction was observed.

For S2 (Figure 3.25), similar to what was seen for S1, vowel durations (both /ɑ/ and /i/) were longer before syllabic nasals than before syllable-final or syllable-initial nasals. For /ɑ/, durations differed little whether before syllable-final or syllable-initial nasals, but for /i/, durations were shorter before syllable-final nasals than syllable-initial nasals. Thus, the main effect of syllable position was significant and the pairwise comparisons across vowel contexts were also significant with $p<.0001$. As evident in Figure 3.25, the duration was longer for /ɑ/ than for /i/ for all syllable positions. The main effect of vowel was significant. As discussed above, the effect of syllable position varied with the vowel type, thus, a significant interaction between syllable position and vowel type was found. Further tests of simple effect revealed that the overall effect of syllable position was significant for both vowel contexts, (for /ɑ/, F[2,57]=69.69, $p<.0001$; and for /i/, F[2,57]=187.812, $p<.0001$). Two of the three pairwise comparisons in the vowel /ɑ/ context (between syllabic and syllable-final or syllable-initial nasal), and all three pairwise comparisons in /i/ context were significant with $p<.0001$. Also, /ɑ/ had significantly longer duration than /i/ regardless of the syllable position of the following nasals (for syllable-final nasals, F[1,38]=434.205, $p<.0001$; for syllable-initial nasals, F[1,38]=63.397, $p<.0001$; and for syllabic nasals, F[1,38]=21.403, $p<.0001$). No tonal effect was found. The interaction between vowel type and tone type was significant. The tests of simple effect showed that while the vowel effect was significant in both tone conditions (in LL tone condition: F[1,58]=29.541, $p<.0001$, and in HL tone condition: F[1,58]=19.635, $p<.0001$), no significant tonal effect was found in either vowel context.

For S3 (Figure 3.25), effect of syllable position was evident: for both vowels, /ɑ/ or /i/, durations were longest when followed by syllabic nasals, shortest when followed by syllable-final nasals. Thus, the main effect of syllable position was significant, as were the three pairwise comparisons (for all three comparisons, $p<.0001$). These significant differences indicated consistent effects of syllable position on vowel durations. The vowel durations were longer for /ɑ/ than for /i/ regardless of the syllable positions of the following nasals. The main effect of vowel type was significant. The interaction between syllable position and vowel type was significant. Further tests of simple effect showed that the effect of syllable position was significant for durations of both vowels, (for /ɑ/, $F(2,57)=30.124$, $p<.0001$, and for /i/, $F(2,57)=96.709$, $p<.0001$), and the three pairwise comparisons of vowel durations among nasals of different syllable positions were also significant for both vowels (for /ɑ/, all three comparisons, $p<.05$, and for /i/, all three comparisons, $p<.0001$). The vowel effect was significant across the three syllable positions of the nasals (for syllable-final nasals: F[1,38]=410.607, $p<.0001$; for syllable-initial nasals: F[1,38]=184.625, $p<.0001$; for syllabic nasals: F[1,38]=113.358, $p<.0001$). Although no significant tonal effect was found, there was a significant interaction between syllable position and tone type, and between vowel type and tone type. The results of tests of simple effect indicated that while effect of syllable position was significant in both tone conditions, the tone effect was not significant for nasals of any syllable position. In the LL tone condition, the effect of syllable position was $F(2,57)=15.201$, $p<.0001$, and the three pairwise comparisons were also significant: between syllable-final and syllable-initial nasals ($p<.001$), between syllabic and syllable-final or syllable-initial nasal ($p<.0001$ and $p<.05$, respectively). In the HL tone condition, the effect of syllable position was $F(2,57)=5.449$, $p<.01$, and pairwise comparisons were significant between syllabic and syllable-final or syllable-initial nasal ($p<.01$ and $p<.05$, respectively). As for the interaction between vowel type and tone type, the findings from tests of simple effect indicated that while the vowel effect was significant in both tone conditions, (in the LL tone condition: $F[1,58]=63.709$, $p<.0001$, and in the HL tone condition: $F[1,58]=157.807$, $p<.0001$), the tonal effect was significant only in the vowel /ɑ/ context ($F[1,58]=8.393$, $p<.01$).

For S4 (Figure 3.25), the pattern of difference was similar to what was seen for S3. For both vowels, /ɑ/ or /i/, durations were longest when followed by syllabic nasals, shortest when followed by syllable-final nasals. Thus, the main effect of syllable position was significant, and the three pairwise comparisons among these nasal types were also significant (all three $p<.0001$), indicating consistent effects of syllable position on vowel durations. Longer vowel durations were observed for /ɑ/ than /i/. The main effect of vowel type was significant. The interaction between syllable position and vowel type was significant. Further tests of simple effect showed that the effect of syllable position on vowel duration was consistent across both vowel types: for /ɑ/, $F(2,57)=30.124$, $p<.0001$; and for /i/, $F(2,57)=96.709$, $p<.0001$. The three pairwise comparisons among nasals of different syllable positions were also significant for both vowels, but the significance level varied, for /ɑ/, all three comparisons were significant at the level of $p<.05$, while for /i/, all $p<.0001$. The effect of vowel type was consistent across nasals of all three syllable positions (all p<.001). A small in magnitude but relatively consistent tonal effect was observed with longer vowel durations for the HL tone condition. The main effect of tone was significant. There was a significant interaction between syllable position and tone type. The tests of simple effect revealed that while the effect of syllable position was significant in both tone conditions, the tone effect was significant only for two of the three types of nasals. In the LL tone condition, the effect of syllable position was F(2,57)=36.685, p<.0001 and pairwise comparisons were also significant between syllabic and syllable-final or syllable-initial nasal (both p<.0001). In the HL tone condition, the effect of syllable position was F(2,57)=41.073, p<.0001, and all three pairwise comparisons were significant, they were between syllable-final and syllable-initial nasals (p<.001) and between syllabic and syllable-final or syllable-initial nasal (both p<.0001). The tonal effect was significant for syllable-initial nasals (F[1,38]=6.226, p=.0170), and syllabic nasals (F[1,38]=7.883, p=.0078), just as observed in Figure 3.25. No other significant interactions were found.

Table 3.42 summarizes the results presented on duration of preceding vowel for the effect of syllable position and vowel.

TABLE 3.42 PAIRWISE COMPARISON FOR DURATION OF THE VOWEL PRECEDING BILABIAL CONSONANT

		Pairwise Comparisons					
Subject	vowel	Syl-final vs. Syl-initial		Syl-final vs. Syllabic		Syl-initial vs. Syllabic	
S1	ɑ	shorter		shorter	*	shorter	*
	i	shorter	*	shorter	*	shorter	*
S2	ɑ	shorter		shorter	*	shorter	*
	i	shorter	*	shorter	*	shorter	*
S3	ɑ	shorter	*	shorter	*	shorter	*
	i	shorter	*	shorter	*	shorter	*
S4	ɑ	shorter	*	shorter	*	shorter	*
	i	shorter	*	shorter	*	shorter	*

To summarize, for all four subjects, the syllable position of bilabial nasals had significant effect on the durations of the preceding vowels. For both vowels, (/ɑ/ and /i/), longer durations were always found before syllabic nasals than before either syllable-final or syllable-initial nasals. Further, the durations were in general shorter before syllable-final nasals than syllable-initial nasals. Not surprisingly, vowel durations were longer for /ɑ/ than for /i/ regardless of the syllable position of following nasals. Only two subjects, S1 and S4, showed significant tonal effect on vowel duration, however, as shown by detailed analysis, none had any when the following nasals were syllable-final.

Duration of Nasal Murmur of the Bilabial Consonant /m/

Mean acoustic durations of the nasal murmur of the bilabial nasal consonants are plotted in Figure 3.26 for all four subjects. ANOVA results are shown in Table 3.43.

TABLE 3.43 ANOVA RESULTS FOR MEAN DURATION OF NASAL MURMUR OF BILABIAL CONSONANT

	S1			S2		
	DF	F	P	DF	F	P
S	2,108	338.454	<.0001	2,108	184.846	<.0001
V	1,108	14.538	.0002	1,108	51.645	<.0001
S*V	2,108	2.878	.0606	2,108	.349	.7061
T	1,108	43.750	<.0001	1,108	4.111	.0451
S*T	2,108	1.860	.1606	2,108	8.757	.0003
V*T	1,108	7.477	.0073	1,108	.159	.6911
S*V*T	2,108	.793	.4551	2,108	13.702	<.0001
	S3			S4		
	DF	F	P	DF	F	P
S	2,108	567.788	<.0001	2,108	454.934	<.0001
V	1,108	26.470	<.0001	1,108	4.374	.0388
S*V	2,108	4.764	.0104	2,108	4.559	.0126
T	1,108	3.933	.0499	1,108	2.678	.1046
S*T	2,108	1.079	.3434	2,108	5.777	.0041
V*T	1,108	1.573	.2125	1,108	1.719	.1926
S*V*T	2,108	.596	.5528	2,108	.241	.7860

For S1 (Figure 3.26), nasal murmur durations were longer for syllabic nasals than syllable-final or syllable-initial nasals, which differed in that syllable-final nasals had longer durations than syllable-initial nasals. The main effect of syllable position was significant. And all pairwise comparisons were significant ($p<.005$), indicating that the observed differences in durations of nasal murmur for nasals of different syllable positions were very consistent. Also, the duration of nasal murmur was slightly longer in the vowel /i/ context, especially for syllable-initial nasals (Figure 3.26). The main effect of vowel type was significant. The interaction between syllable position and vowel type was not significant.

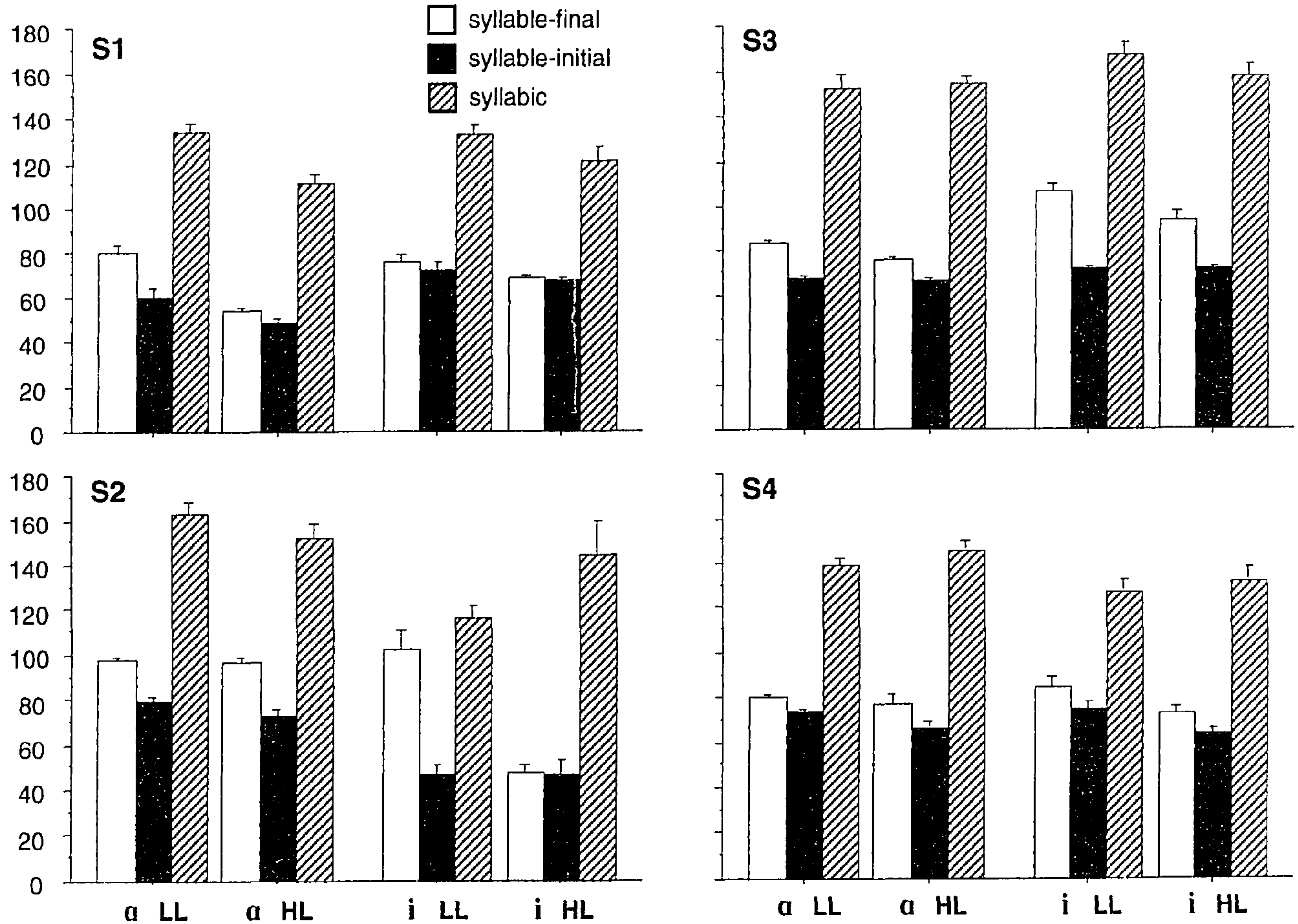

Figure 3.26 Mean duration of nasal murmur of bilabial nasal consonant (in msec).
The horizontal bars indicate standard error.

However, since it was approaching significance, tests of simple effect were conducted to further assess the interaction. The results confirmed the observation: only nasal murmur durations of syllable-initial nasals had a significant vowel effect ($F[1,38]=21.058$, $p<.0001$). Consistent effect of tone type was observed on the duration of nasal murmur for nasals of all three different syllable positions. The duration of nasal murmur appeared longer for the LL tone than for the HL tone. The main effect of tone type was significant. There was a significant interaction between vowel type and tone type. Further testing of simple effect revealed that although the vowel effect was not significant in either tone conditions, the tonal effect was significant in the vowel /ɑ/ context ($F[1,58]=5.847$, $p=.0188$) in the direction observed (longer duration in the LL tone condition).

For S2 (Figure 3.26), durations of nasal murmur were longer for syllabic nasals than syllable-final or syllable-initial nasals, which also differed from each other in that longer durations of nasal murmur were found for syllable-final nasals. Thus, the main effect of syllable position was significant, and all three pairwise comparisons were highly significant ($p<.0001$), indicating that the observed differences in durations of nasal murmur for nasals of different syllable positions were very consistent. As can be seen in Figure 3.26, durations of nasal murmurs were longer in /ɑ/ than /i/ context for all three types of nasals. The main effect of vowel was significant. There was no significant interaction between syllable position and vowel type. Nasal murmur durations of syllable-final nasals appeared to be longer in /i/ context in the LL tone condition. Although the main effect of tone type was not significant, the interaction between syllable position and tone type was significant, which prompted further analyses. The results confirmed the observation that tonal effect was limited to syllable-final nasals in /i/ context ($F[1,18]=37.415$, $p<.0001$). There was a significant three-way interaction among the three main effects. The results of analyses of simple effect are summarized in Table 3.44. From the analyses of the three-way interaction, it seemed that both effects of syllable-position and vowel type were found more often than the effect of tone, which was significant only in one sub-condition.

TABLE 3.44 RESULTS OF ANALYSES OF SIMPLE EFFECT ON THE THREE-WAY INTERACTION (S2)

Effect	Condition		
Syllable position	/ɑ/, LL, *	/ɑ/, HL, *	
Syllable position	/i/, LL, *	/i/, HL, *	
vowel	syllable-final, LL, *	syllable-initial, LL, *	syllabic, LL, *
vowel	syllable-final, HL, *	syllable-initial, HL, *	syllabic, HL
tone	syllable-final, /ɑ/	syllable-initial, /ɑ/	syllabic, /ɑ/
tone	syllable-final, /i/, *	syllable-initial, /i/	syllabic, /ɑ/

For S3 (Figure 3.26), similar to what was found for S2, comparison of nasal murmur durations across the three syllable positions revealed that the nasal murmur durations were longest for syllabic nasals, and shortest for syllable-initial nasals. The main effect of syllable position was significant, and pairwise comparisons of nasal murmur durations among nasals of different syllable positions were also significant (all p<.0001), indicating consistent effect of syllable position on nasal murmur durations. For all three syllable positions, the nasal murmur durations appeared longer in /ɑ/ context (Figure 3.26. The main effect of vowel type was significant. There was a significant interaction between syllable position and vowel type. Further testing revealed that effect of syllable position was significant in both vowel contexts, (in /ɑ/ context, F[2,57]=364.652, p<.0001, and in /i/ context, F[2,57]=225.665, p<.0001), and all six pairwise comparisons (three in each vowel context) were significant with p<.001. The tests also showed that the vowel effect was significant for syllable-final nasals (F[1,38]=42.732, p<.0001), and syllable initial-nasals (F[1,38]=6.245, p<.05), but not for syllabic nasals. In other words, the duration of nasal murmur of syllabic nasals did not differ significantly whether the preceding vowel was /ɑ/ or /i/. An observable effect of tone was seen only for syllable-final nasals (longer duration in LL tone condition), but not for syllable-initial or syllabic nasals. The main effect of tone type was found significant. No other significant interactions were found.

For S4 (Figure 3.26), just as for other subjects, durations of nasal murmur were longer for syllabic nasals than for syllable-final or syllable-initial nasals. And syllable-final nasals had longer nasal murmur durations than syllable-initial nasals. Thus, the main effect of syllable position was significant. All three pairwise comparisons were significant with p<.001. The nasal murmur durations were slightly longer in /ɑ/ context than in /i/ context for syllabic nasals. The main effect of vowel type was significant and so was the interaction between syllable position and vowel type. More detailed testing revealed that the effect of syllable position was significant in both vowel contexts, (in /ɑ/ context, F[2,57]=323.093, p<.0001; and in /i/ context, F[2,57]=138.554, p<.0001), and all six pairwise comparisons (three in each vowel context) were significant with p<.05. The tests of simple effect also confirmed the observation, that is, vowel effect was significant only for syllabic nasals (F[1,38]=8.013, p=.005). Although the main effect of tone type was not significant, the interaction between syllable position and tone type was. Tests of simple effect revealed that the effect of syllable position was significant in both tone conditions (in the LL tone condition, F[2,57]=175.254, p<.0001, in the HL tone condition, F[2,57]=245.285, p<.0001), and the six pairwise comparisons (three in each tone condition) were also significant (all p<.05). The tonal effect, on the other hand, was significant only for syllable-initial nasals (F[1,38]=19.133, p<.0001).

Table 3.45 summarizes the results presented on duration of velar lowering for effect of syllable position.

TABLE 3.45 PAIRWISE COMPARISON FOR DURATION OF NASAL MURMUR OF THE BILABIAL CONSONANT

	Pairwise Comparisons						
Subject	vowel	Syl-final vs. Syl-initial		Syl-final vs. Syllabic		Syl-initial vs. Syllabic	
S1	ɑ	longer	*	shorter	*	shorter	*
	i	longer		shorter	*	shorter	*
S2	ɑ	longer	*	shorter	*	shorter	*
	i	longer	*	shorter	*	shorter	*
S3	ɑ	longer	*	shorter	*	shorter	*
	i	longer	*	shorter	*	shorter	*
S4	ɑ	longer	*	shorter	*	shorter	*
	i	longer	*	shorter	*	shorter	*

To summarize, for all four subjects, the main effect of syllable position was significant. The acoustic duration of the nasal murmur was consistently longer for syllabic nasals than for syllable-final or syllable-initial nasals, and longer for syllable-final nasals than syllable-initial nasals. These differences were consistent across the two vowel contexts. Although for all four subjects, the main effect of vowel type was significant, the pattern of difference was not consistent across subjects. For S1, longer durations of the nasal murmur were seen in /i/ context, while for the rest three subjects, in /ɑ/ context. Also, it is worth pointing out that although for three subjects the main effect of tone type was significant, the effect was not stable across the three syllable positions.

Mean Duration of the Vowel Following the Bilabial Consonant

Mean acoustic durations of the vowel following the bilabial consonants are plotted in Figure 3.27 for all four subjects. A two-factor ANOVA was conducted for each subject with syllable position and vowel type as independent variables and the vowel duration the dependent variable (for reasons excluding tone factor from the analysis, see 3.6.5). The results are summarized in Table 3.46. Note that in the figure legend, the tone labels in parentheses were for the first CV sequence, and they was included here for reference purpose.

TABLE 3.46 ANOVA RESULTS FOR MEAN DURATION OF THE VOWEL FOLLOWING THE BILABIAL CONSONANT

	S1			S2		
	DF	F	P	DF	F	P
S	2,114	25.894	<.0001	2,114	67.749	<.0001
V	1,114	70.057	<.0001	1,114	52.516	<.0001
S*V	2,114	1.775	.1741	2,114	8.027	.0005
	S3			S4		
	DF	F	P	DF	F	P
S	2,114	100.086	<.0001	2,114	19.885	<.0001
V	1,114	477.085	<.0001	1,114	360.159	<.0001
S*V	2,114	13.738	<.0001	2,114	15.184	<.0001

For S1 (Figure 3.27), vowel duration was longer when preceded by syllabic nasals than syllable-final or syllable-initial nasals, and was slightly longer following syllable-final nasals than syllable-initial nasals. The main effect of syllable position was significant. Pairwise comparisons of vowel durations were significant between syllabic and syllable-final or syllable-initial contexts, (both p<.0001), but not between the latter two. As can be

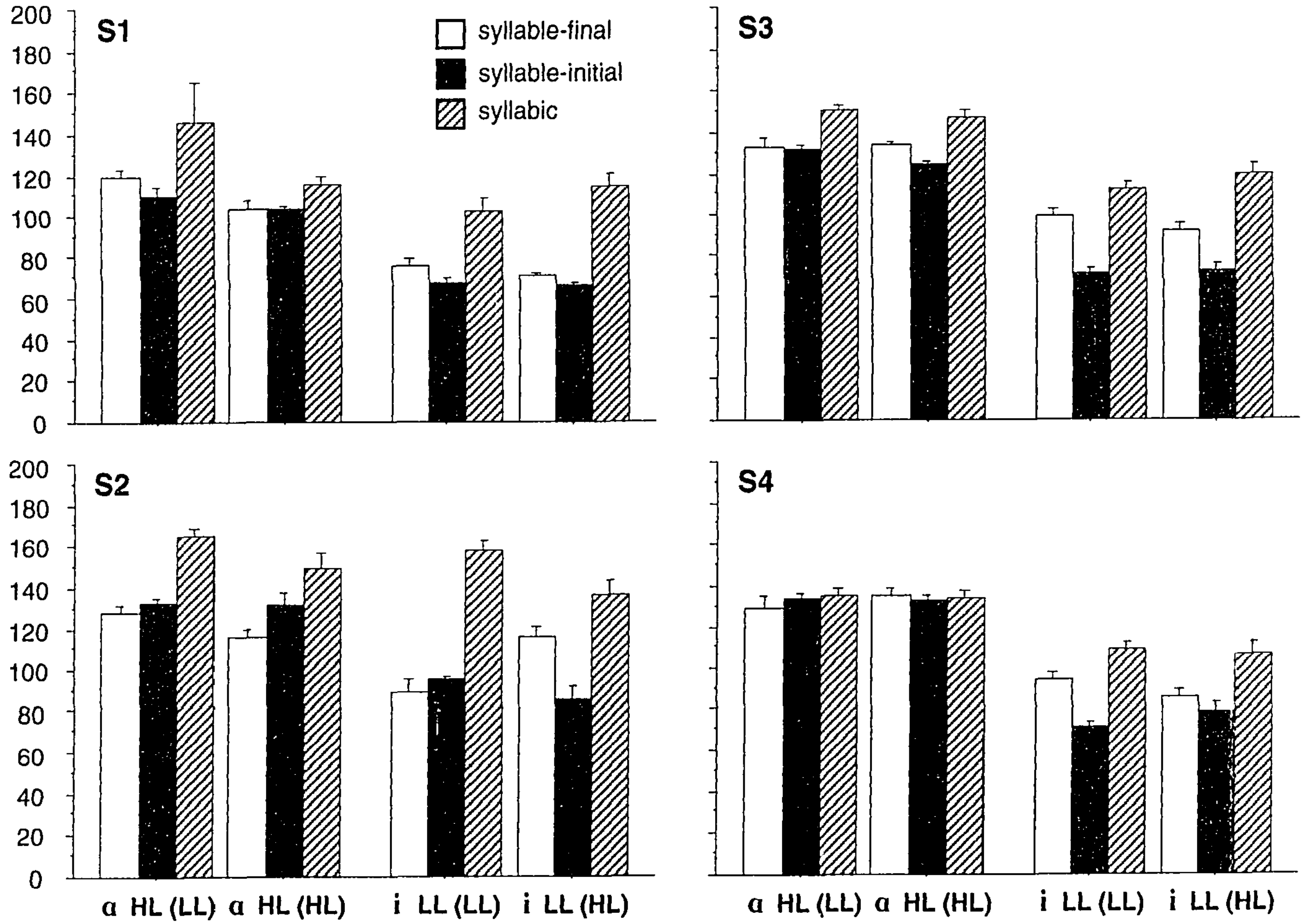

Figure 3.27 Mean duration of the vowel following bilabial nasal consonant (in msec). The horizontal bars indicate standard error.

observed from Figure 3.27, for nasals of all three different syllable positions, vowel duration was longer for /ɑ/ than for /i/. The main effect of vowel was significant. There was no significant interaction between the two main factors.

For S2 (Figure 3.27), durations of both vowels were longer when preceded by syllabic nasals. However, the vowel durations did not differ consistently when preceded by syllable-final and syllable-initial nasals. The main effect of syllable position was significant. When preceded by syllabic nasals, vowel durations were significantly longer than preceded by either syllable-final or syllable-initial nasals (both $p<.0001$), and no difference was found between vowel durations when preceded by syllable-final or syllable-initial nasals. As shown in Figure 3.27, the durations were longer for /ɑ/ than for /i/ and the main effect of vowel type was significant. There was a significant interaction between syllable position and vowel type ($F[2,114]=8.027$, $p<.001$). The results of simple effect tests indicated that the effect of syllable position was significant in both vowel contexts (in /ɑ/, $F[2,57]=27.694$, $p<.0001$, and in /i/, $F[2,57]=43.854$, $p<.0001$), but the pairwise comparisons in both vowel contexts were significant only between syllabic nasals and syllable-final or syllable-initial nasal (all $p<.0001$). The results also showed that vowel duration was affected significantly when preceded by syllable-final nasals ($F[1,38]=11.529$, $p<.005$), or syllable-initial nasals ($F[1,38]=84.28$, $p<.0001$), but not syllabic nasals.

For S3, the effect of syllable position on vowel duration was evident from Figure 3.27. Again, vowel durations were the longest when preceded by syllabic nasals, and shortest when preceded by syllable-initial nasals. The main effect of syllable position was significant, as well as the three pairwise comparisons among nasals of different syllable positions (all three $p<.0001$). For all three types of nasals, durations of the following vowel were longer when it was /ɑ/, shorter when it was /i/. The main effect of vowel was significant. The interaction between syllable position and vowel type was also significant. Further testing of simple effect revealed that the overall effect of syllable position was significant for both vowel contexts (for /ɑ/, $F[2,57]=26.219$, $p<.0001$; and for /i/, $F[2,57]=80.026$, $p<.0001$), and the effect of syllable position was significant in all pairwise comparisons conducted, except for the one between syllable-final and syllable-initial nasals when the vowel was /i/ (for all five significant comparisons, $p<.0001$). The results also showed that a consistent vowel effect was observed for nasals of all three syllable positions (for syllable-final, $F[1,38]=117.991$, $p<.0001$; for syllable-initial, $F[1,38]=462.911$, $p<.0001$; and for syllabic, $F[1,38]=72.523$, $p<.0001$).

For S4 (Figure 3.27), the vowel duration was longer when the preceding nasals were syllabic than syllable-final or syllable-initial. The vowel duration was generally longer when preceded by syllable-final than syllable-initial nasals and this was especially true for vowel /i/. The main effect of syllable position was significant, and so were the three pairwise comparisons of vowel durations preceded by nasals of three different syllable positions, (all three $p<.01$). As can be observed from Figure 3.27, for nasals of all three syllable positions, the vowel duration was always longer for /ɑ/ than for /i/. The main effect of vowel type was significant. There was also a significant interaction between syllable position and vowel type. Tests of simple effect were conducted to assess this significant interaction, and the results revealed that the effect of syllable position was not significant for vowel /ɑ/ context, but was for vowel /i/ context ($F[2,57]=390.333$, $p<.0001$). And further, all three pairwise comparisons of vowel /i/ durations were significant ($p<.001$) indicating a consistent effect of syllable position on vowel /i/. While for ?ɑ?, although the means were in the same order for /i/, longest for syllabic nasals, longer for syllable-final nasals and shortest for syllable-initial nasals, the difference was not significant statistically. As for the effect of vowel, the durations of /ɑ/ was significantly longer than that of /i/ regardless of the syllable position of the preceding nasals (all three $p<.0001$).

Table 3.47 summarizes the results presented on duration of velar lowering for effect of syllable position.

TABLE 3.47 PAIRWISE COMPARISON FOR DURATION OF THE VOWEL FOLLOWING BILABIAL CONSONANT

		Pairwise Comparisons		
Subject	vowel	Syl-final vs. Syl-initial	Syl-final vs. Syllabic	Syl-initial vs. Syllabic
S1	ɑ	longer	shorter *	shorter *
	i	longer *	shorter *	shorter *
S2	ɑ	shorter *	shorter *	shorter *
	i	longer *	shorter *	shorter *
S3	ɑ	longer	shorter	shorter
	i	longer *	shorter *	shorter *
S4	ɑ	shorter	shorter	shorter
	i	longer *	shorter *	shorter *

To summarize, for all subjects, the vowel duration following bilabial nasals was affected by the syllable status of the nasal consonant. Vowel duration was consistently longer when preceded by syllabic nasals, regardless of the vowel type, comparing to syllable-final or syllable-initial nasal; however, the vowel duration did not differ consistently when the preceding nasals were syllable-final or syllable-initial. And as expected, vowel durations were longer for /ɑ/ than for /i/ regardless of the syllable position of preceding nasals.

F0 Measures

Mean fundamental frequency values were obtained to provide tone values for the two tones, the LL tone and the HL tone, which were used as two different tone conditions for detecting tonal effect on velar and lower lip movement as well as on acoustic measures,

TABLE 3.48 F0 TABLE

		Tone Values (in Hz)	
Subject	vowel	the Low Level tone (LL)	the High Level tone (HL)
S1	ɑ	170	239
	i	182	246
S2	ɑ	192	241
	i	193	259
S3	ɑ	114	157
	i	117	171
S4	ɑ	100	146
	i	106	154

for detecting tonal effect on velar and lower lip movement as well as on acoustic measures, (see 3.6.3 &3.6.4 for procedures used for measuring F0). The results are presented in Table 3.48. The F0 values obtained are in agreement with those reported in literature (Kong, 1987).

3.8 Discussion

The primary purpose of this production study is to provide phonetic evidence for the syllable. At the beginning of this chapter, the following questions were raised:

- Are there any measurable differences in the velar movement of the stimuli that characterize the syllable position of the bilabial nasal consonants?
- Are there any measurable differences in the labial movement of the stimuli that characterize the syllable position of the bilabial nasal consonants?
- What are the coordination patterns between velar and lower lip gestures associated with the syllable structure?
- Are there any vowel effect on the velar and lip movements which are associated with syllable structure?
- Are there any tonal effect on the velar and lip movements which are associated with syllable structure?
- What is the correlation between the articulatory movements and the acoustic outcome?

3.8.1 Effect of Syllable Position

The first three questions raised at the beginning of this chapter (listed above) pertain to the primary question of the study: Is there any phonetic evidence for the syllable on the articulatory movement patterns of the velum and lower lip in Cantonese? The results (section 3.7) obtained in the current production study clearly demonstrated that the articulatory movement patterns of the velum and lower lip varied as the syllable position of the nasal consonant varied. Further, these manifestations of syllable structure on articulatory movement patterns are consistent across subjects.

Of the three bilabial nasal positons examined in this study, the effect of syllable position on velar movement was amplified consistently for nasals in syllabic position both temporally and spatially, especially during the time course when velum moved toward and remained in the low velar position. Either temporally or spatially, the velar movement of nasals in syllabic position patterned differently from those of syllable-final or syllable-initial nasals. The unique velar movement pattern of syllabic nasals was manifested in every phase throughout the entire velar movement that was being examined from high velar position to low velar position and back to high velar position. For velar lowering gesture towards the bilabial consonant, both duration and displacement amplitude were in general amplified in the syllabic position. That is, nasals in syllabic positions tended to start the movement toward the low velar position earlier (Table 3.36), travel a longer distance from the high to the low velar position (Table 3.6), and to arrive at a spatially lower position of the velum when compared to nasals in syllable-final or syllable-initial positions (Table 3.16). Once they reached the low position of the velum, they in general stayed at the low velar position much longer in time than nasals in either syllable-final or syllable-initial positions (Table 3.10). Because of the longer time spent at the spatially low position of the velum, the velar raising gestures of nasals in syllabic position usually began later when compared to nasals in syllable-final or syllable-initial positions. Again, nasals in syllabic position usually travel a longer distance back to the high velar position, thus, resulting in a longer duration as well as a greater displacement amplitude of velar raising than for either syllable-final and syllable-initial nasals, specially in the vowel /i/ context. It is worth noting that velar raising gestures of nasals in syllabic position were affected by vowel context to a certain extent, although this was somewhat inconsistent across subjects (see later discussion on the interaction between syllable position and vowel quality). Between nasals of syllable-final and syllable-initial positions, the effect of syllable position on velum movement was greater in the spatial domain than the temporal domain, that is, the displacement amplitudes of both velar lowering to, and raising away from, a low velum position were amplified in the syllable-final positions (see Table 3.14, Table 3.16, and Table 3.18). The temporal measures of velar movement were intertwined with vowel context, resulting in an inconsistent pattern of difference between nasals of these two syllable positions among subjects (Table 3.6, Table 3.10 and Table 3.12). Nasals in syllable-final positions tended to have shorter durations of velar lowering and low velar plateau than nasals in syllable-initial position in the vowel /i/ context. Interestingly, the shorter durations of nasals in syllable-final positions did not result in smaller displacement amplitudes. For nasals in syllabic positions, as discussed above, a greater displacement amplitude was always associated with a longer duration; while for nasals in syllable-final positions, the opposite was true in many cases. That is, greater displacement amplitudes were also found associated with shorter durations of velar lowering when compared to nasals in syllable-initial positions, indicating greater velocities of velar lowering for syllable-final nasals. This was evidenced in relatively greater peak velocity of velar lowering of nasals in syllable-final positions when compared to nasals in syllable-initial positions. Figure 3.28 provides an example of velar movement in ensemble averages, illustrating velar movement patterns of nasals in different syllable positions. The patterns

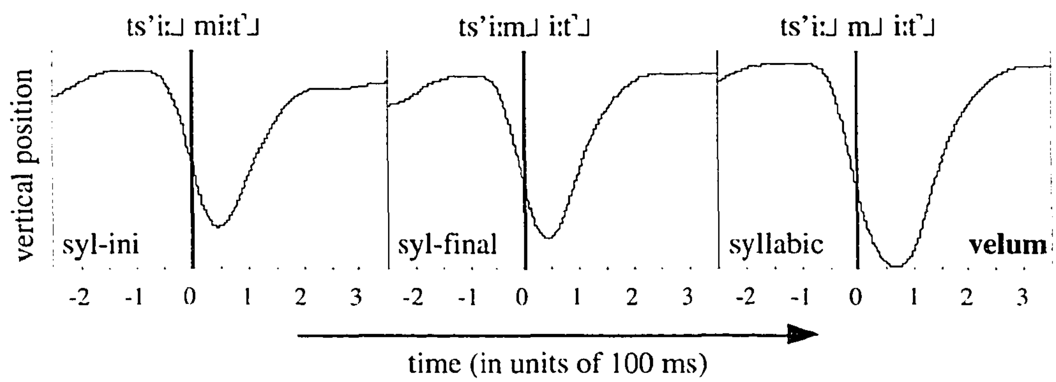

Figure 3.28 Velum movement for utterances with nasals in three different syllable positions (in the form of ensemble averages) in Cantonese (S4). The vertical line in each panel marks the onset of nasal murmur for /m/.

across syllable positions are synchronous both temporally and spatially. Note the temporally and spatially amplified velar gestures in syllabic position, and relatively lower position of the velum in syllable-final position compared to syllable-initial position. For lower lip movement, the effect of syllable position on the movement pattern was also clearly demonstrated. Labial gestures were amplified consistently for nasals in syllabic position, both temporally and spatially, compared to nasals in syllable-final or syllable-initial positions. This increase in magnitude on labial gestures for nasals in syllabic positions were observed for all subjects during the entire course of lower lip movement during the production of target utterances. For lower lip movement, when compared to nasals in syllable-final or syllable-initial positions, nasals in syllabic position always traveled further up, plateaued at a spatially higher lip position, and stayed longer at that higher position, thus resulting in longer durations of lower lip raising, high lower lip plateau and lower lip lowering, as well as greater displacement amplitudes and spatially higher positional maxima of the lower lip. These effects of syllable position on labial movement patterns of nasals of syllabic position were true regardless of the vowel context. The effects of syllable structure on labial movement were also evident from the differences observed on the movement patterns of nasals in syllable-final position when compared to nasals in syllable-initial position. In contrast to the velar movement, the effect of syllable structure on labial movement patterns of nasals in syllable-final position, when compared to nasals in syllable-initial position, were more consistently manifested in the temporal domain than in the spatial domain. That is, the durations of lower lip plateau were found consistently longer for nasals in syllable-final position than those in syllable-initial position. It is worth noting that for lower lip raising and lower lip lowering gestures, an interaction between syllable position and vowel quality were observed for all subjects. That is, the durations of lower lip raising and lowering gestures tended to be longer for nasals in syllable-final position than those in syllable-initial position in the vowel /ɑ/ context, but the opposite was found in the vowel /i/ context. However, such an interaction was not observed for nasals in syllabic position, for they had consistently longer gestures of lower lip raising and lowering when compared to nasals in syllable-final or syllable-initial positions, regardless of the vowel context. Nor was such an interaction was not observed on the durations of lower lip plateau. That is, the durations of lower lip plateau were consistently longest for nasals in syllabic position, shorter for those in syllable-final position and the shortest for those in syllable-initial position. Figure 3.29 provides an example of lower lip movement in ensemble averages, illustrating lower lip movement patterns of nasals in different syllable positions discussed. The patterns across syllable positions are synchronous both temporally and spatially. Note the temporally and spatially amplified gestures in syllabic position, and the relatively longer duration of high lower lip plateau in syllable-final position compared to syllable-initial position.

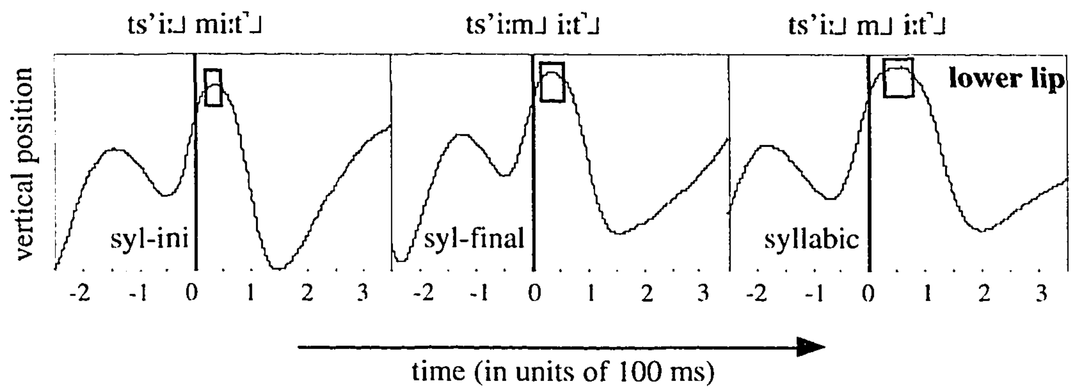

Figure 3.29 Lower lip movement for utterances with nasals in three different syllable positions (in the form of ensemble averages) in Cantonese (S4). The vertical line in each panel marks the onset of nasal murmur for /m/. The square in each panel indicates the lower lip plateau.

In short, the effect of syllable position was manifested on both velar and labial movement. For both velar and labial movement, the effect of syllable position was consistently observed on the movement patterns of nasals in syllabic position when compared to nasals in syllable-final or syllable-initial positions in the spatial domain as well as the temporal domain. The effect of syllable position was also consistently observed on the movement patterns of nasals in syllable-final position in the spatial domain for velar movement, and in the temporal domain for labial movement, when compared to both nasals of syllabic and syllable-initial positions.

To produce the bilabial nasal consonants, both articulators of velum and lower lip are required to work together. As shown by the results presented in section 3.7.3, for all subjects, the timing between velar and bilabial movement for nasals in syllabic position can be characterized as an earlier onset of velar lowering relative to the onset of lower lip plateau and a later offset of velar lowering relative to the lower lip raising onset when compared to nasals in syllable-final or syllable-initial positions. In other words, gestures of both velar lowering and lower lip raising started relatively early and finished relatively later compared to nasals in syllable-final or syllable-initial positions. This was not surprising since both velar lowering and lower lip raising were longer for nasals in syllabic position. This timing pattern set syllabic nasals apart from syllable-final and syllable-initial nasals. Between nasals in syllable-final and syllable-initial positions, there was a later offset of the velar lowering gesture relative to the onset of the lower lip plateau for syllable-final nasals compared to syllable-initial nasals. This timing pattern probably largely reflected the lower positional minimum of the velum reached by syllable-final nasals compared to syllable-initial nasals. That is, although the downward velar movement was initiated about the same time for both syllable-final and syllable-initial nasals, syllable-final nasals continued to move to reach a relatively lower velar position after initial nasals had stopped. When compared to syllable-initial nasals, the onset of velar lowering relative to the onset of lower lip plateau was earlier for syllable-final nasals in the vowel /ɑ/ context but later in the vowel /i/ context. One may argue that this timing difference was a direct result of the lower velar position required by /ɑ/. However, since the vowel context was kept constant across nasals of different syllable positions, one may only conclude that the timing difference may be attributed to the interaction between the effect of vowel context and syllable position. That is, the difference in interarticulatory timing pattern between syllable-final and syllable-initial nasals indicates that the relationship between the nasals and the preceding vowels are somewhat different (closer in one case?) because of their different syllable status. Figure 3.31 provides an example of the interarticulatory timing for nasals in three different syllable positions.

3.8.2 Effect of Vowel Type

Are there any vowel effects on the velar and lip movements which are associated with syllable structure?

To help answer this question, the overall effect of vowel type manifested on velar and labial gestures for nasals in the three different syllable positions are summarized in Table 3.49 based on the information presented in the result section (cf. section 3.7). In Table 3.49, the magnitude of each variable in /ɑ/ contest is in comparison to its counterpart in /i/ context for nasals in different syllable positions. '+' indicates a significantly longer duration, or greater displacement amplitude was found in the vowel /ɑ/ context, while '-' indicates that the opposite is true (i.e., in the vowel /i/ context). The blanks indicate that no significant vowel effect was found for that measure. 'S-F', 'S-I', and 'S', stand for syllable-final, syllable-initial and syllabic, respectively.

TABLE 3.49 VOWEL EFFECT ON DURATION AND AMPLITUDE MEASUREMENT BY SYLLABLE POSITION

VARIABLE	Pairwise Comparisons between /ɑ/ vs. /i/											
	S1			S2			S3			S4		
	S-F	S-I	S	S-F	S-I	S	S-F	S-I	S	S-F	S-I	S
duration of velar lowering			-	+	+		+	+	+	+	+	+
displ. amp. of velar lowering	+	+	-	+	+	+	+	+	+	+	+	-
duration of low velar plateau	+	+	+	+	+		+	+	+	+	+	+
positional min. of the velum	+	+	+	+	+	+	+	+	+	+	+	+
duration of velar raising	+		+	+	+	+	+	+	+	+	+	+
displ. amp. of velar raising			-	+	+		+	+	+	+	+	+
duration of lower lip raising				+			+		+	+	+	+
displ. amp. of lower lip raising	+	+	+	+	+	+	+	+	+	+	+	+
duration of high lower lip plateau	+	+	+	-	-		-	-	-	-	-	-
positional max. of the lower lip	-	-	-	-			-	-	+	-	-	
duration of lower lip lowering	-	-	-			-	-	-		+	+	
displ. amp. of lower lip lowering	+	+	+		+		+	+	+	+	+	+

In general, the effect of vowel type was observed on almost all measures for both velar and labial movements for all subjects. Further, the vowel effect was quite consistent across subjects whose data demonstrated the effect. The pattern of difference, as shown, is that for velar movement, the magnitude of the gesture, temporal or spatial, was usually significantly greater in the vowel /ɑ/ context. For labial movement, significantly longer durations and greater displacement amplitudes of lower lip raising, as well as greater displacement amplitudes of lower lip lowering, were usually seen in the vowel /ɑ/ context. For three subjects, longer durations of lower lip lowering and higher positional maxima of the lower lip were found in /i/ context, and for one subject, in /ɑ/ context. Also, for three subjects, longer durations of lower lip plateau were found in /i/ context, and for one subject, in /ɑ/ context. The vowel effect on velar movement found here is in agreement with the well-known fact that in English and in many other languages there is a direct relationship between velar position and vowel height, that is, low vowels tend to have lower velar position than high vowels (e.g., Bell-Berti, 1979; Henderson, 1984). Hence, the longer durations of velar lowering and raising gestures, the greater displacement amplitudes and the spatially lower positional minima of the velum are all direct results from the lower velar position required by /ɑ/. That is, the velum starts the downward movement earlier for /ɑ/; moreover, since /m/ requires an even lower velar position than /ɑ/, the velum has to continue to descend from the already low position for /ɑ/ compared to /i/. In other words, this is an integrated velar gesture for both /ɑ/ and /m/, or it is a continuation from the one for /ɑ/ into the other for /m/ (or from /m/ to /ɑ/ for velar raising). In fact, an interesting phenomenon observed here may illustrate the point. It was seen that for nasals in syllable-final and syllable-initial positions, there was an one step velar lowering gesture, i.e., an uninterrupted gesture, but for nasals in syllabic positions, the velar gesture sometimes showed a hesitation or 'interuption', that is, a downward or upward route with a small curve somewhere in the one thirds of the movement. This hesitation, may be an indication of changing of target for the velar gesture.

For the vowel effects on labial movement, the following is speculated. On the one hand, longer durations and greater displacement amplitudes of lower lip raising were found in /ɑ/ context because, compared to /i/, /ɑ/ has a relatively lower jaw/lower lip position to begin with. Therefore, it has to travel further up to reach the high position for achieving the labial closure required by the bilabial nasal consonant. On the other hand, the longer durations of high lower lip plateau and higher positional maximum for the lower lip seen in /i/ context may be due to the high jaw/lower lip position required by both the high vowel /i/ and the bilabial nasal consonant. As shown, among nasals of three different syllable positions, the vowel effect was the least consistent on nasals in syllabic position. Since a syllabic nasal constitutes a syllable by itself, this difference may be a direct manifestation of syllable structure.

Interaction between syllable position and vowel quality was found on both velar and labial movements, although the manifestation of the interaction was largely confined to certain syllable positions on certain part of the movement. For velar movement, the interaction between syllable position and vowel quality was found on the temporal measures between nasals in syllable-final and syllable-initial positions, as well as on spatial measure of displacement amplitudes of velar raising between nasals in syllable-final and syllabic positions. For labial movement, the interaction was found both on durations and displacement amplitudes of lower lip raising and lowering between nasals in syllable-final and syllable-initial positions. The pattern of difference for the interaction on temporal measures of velar movement was that, in general, syllable-final nasals tended to have longer durations compared to syllable-initial nasals in /ɑ/ context, but shorter durations in /i/ context. The interaction was seen in the velar lowering gesture for S2 and S3, and in the low velar plateau for S1 and S3. It is possible that because the relationship between the preceding vowel and the nasal consonant is a closer in the syllable-final case, the gesture overlapping is larger. As discussed before, since /ɑ/ requires a relatively lower velar position than /i/, the integrated velar gesture (of the vowel and the nasal) is manifested as longer durations in syllable-final nasals, and therefore, produces the interaction observed between syllable-final and syllable-initial nasals. However, the shorter durations in /i/ case are a different story. Since /i/ requires a high velar position, to fulfill the required velar height for /i/, the velum had to stay at the high position long enough not to distort the /i/. As a result, the onset of the lowering for the nasal was postponed. Because the relationship between the preceding vowel and the syllable-final nasal was, as assumed, a closer one, the distance between the vowel and the final nasal was shorter than the one between the vowel and the syllable-initial nasal. As a result, syllable-final nasals had less time to move to the required velar position for /m/, hence shorter durations and greater peak velocities were seen.

For the measure of displacement amplitudes of velar raising, all four subjects exhibited similar patterns. That is, syllable-final nasals had greater displacement amplitudes of velar raising compared to syllabic nasals. The explanation offered here is that because of the lower velum position required by vowel /ɑ/, the velar movement returning to the high velar position was being delayed. Since, as mentioned before, a two step velar movement was often seen for syllabic nasals, the point taken as the offset of velar raising was usually before the velum went back to the high velar position for the oral sound, which resulted in relatively smaller displacement amplitudes of velar raising.

The pattern of difference for the interaction on measures of lower lip movement was that, in general, when compared to syllable-initial nasals, syllable-final nasals tended to have longer durations and greater displacement amplitudes of both lower lip raising and lowering in /ɑ/ context, but shorter durations and smaller displacement amplitudes in /i/ context. What is the reason for the interaction to occur? It is speculated here that /ɑ/ tended to have a lower jaw/lower lip position when followed by a syllable-final nasal compared to syllable-initial nasal, resulting in a longer duration and greater displacement amplitudes of lower lip raising for the syllable-final nasals. What is the explanation for the longer and greater displacement amplitudes of lower lip lowering seen for syllable-final nasals when compared to syllable-initial nasals? It is speculated here that is because of the relatively closer relation between the nasal and the following vowel for syllable-initial nasals compared to syllable-final nasals. That is, to keep the lower lip at the high position required by /m/, the lowering gesture of the lower lip was delayed in the case of syllable-initial nasals, hence, resulting in shorter durations and smaller displacement amplitudes of lower lip lowering.

To summarize, the main effect of vowel type, as discussed, is relatively consistent within measures for all subjects, although the effect may not always reach the significance level. The pattern of difference seen between measures is believed to be a direct result of the different demands of the two vowels on the two articulators, velum and lower lip, due to the inherent qualities of these two vowels. The vowel effect is less consistent in syllabic context when compared to the other two syllable-based contexts. Although the interaction between syllable position and vowel type was responsible for some variations seen in the articulatory movement patterns, there are clear differences among articulatory movement patterns that are characteristics of syllable structure. In fact, all the aspects in temporal and spatial measures in both velar and lower lip movement that were enhanced by effect of syllable position, were quite consistent across vowel contexts. In other words, the effect of syllable position on the velar and bilabial movement patterns was over and above the effect of vowel type.

3.8.3 Effect of Tone Type

Are there any tonal effects on the velar and lip movements which are associated with syllable structure?

To help answer this question, tonal effects on duration and amplitude measurements of velar and labial movement were summarized based on the information presented in the result section. Table 3.50 provide an overall look at where the tonal effect was significant for each subject. Table 3.51 presents the tonal effect by syllable positions and Table 3.52 by vowel type. In all three tables, '+' indicates a significantly longer duration, or greater displacement, or lower minimum for the velum (or higher maximum for the lower lip) was found in for LL than for HL tone context; while '-' indicates that the opposite is true.

TABLE 3.50 MAIN TONAL EFFECT ON DURATION AND AMPLITUDE MEASUREMENT

VARIABLE	Pairwise Comparisons between LL Tone vs. HL Tone			
	S1	S2	S3	S4
duration of velar lowering	-	+		-
displ. amp. of velar lowering		+		
duration of low velar plateau		-		
positional min. of the velum		+		
duration of lower lip raising	+			
displ. amp. of lower lip raising	-			-
duration of high lower lip plateau				
positional max. of the lower lip		+	+	-

TABLE 3.51 TONAL EFFECT ON DURATION AND AMPLITUDE MEASUREMENT BY SYLLABLE POSITION

VARIABLE	Pairwise Comparisons between LL Tone vs. HL Tone											
	S1			S2			S3			S4		
	S-F	S-I	S	S-F	S-I	S	S-F	S-I	S	S-F	S-I	S
duration of velar lowering	-	-	-			+						
displ. amp. of velar lowering				+	+	+						
duration of low velar plateau					-							
positional min. of the velum				+	+	+						
duration of lower lip raising	+											
displ. amp. of lower lip raising			-									
duration of high lower lip plateau												
positional max. of the lower lip					+							-

TABLE 3.52 TONAL EFFECT ON DURATION AND AMPLITUDE MEASUREMENT BY VOWEL TYPE

VARIABLE	Pairwise Comparisons between LL Tone vs. HL Tone							
	S1		S2		S3		S4	
	ɑ	i	ɑ	i	ɑ	i	ɑ	i
duration of velar lowering	-	-	+	+			-	
displ. amp. of velar lowering			+	+				
duration of low velar plateau								
positional min. of the velum			+					
duration of lower lip raising		-						
displ. amp. of lower lip raising							-	
duration of high lower lip plateau								
positional max. of the lower lip			+					

As shown, tonal effect varied among subjects, among measures, and among nasals of different syllable positions, indicating the effect of tone type was a complicated one. Three of the four subjects (except for S3) exhibited a main effect of tone type in the temporal domain, but only one subject (S2) exhibited this effect in the spatial domain, indicating that the tonal effect varied greatly between the two domains. As shown (Table

3.51), for S1, significantly longer durations were found in the HL tone condition for nasals of all three different syllable positions; for S2, although only syllabic nasals had longer duration of velar lowering in the LL tone condition, significantly greater displacement amplitude was seen in nasals of all three syllable positions in the same tone condition, i.e., the LL tone condition; while for S4, no significant tonal effect was found for nasals of any of the three syllable positions on the velar lowering duration, although the main effect of tone type was significant. Therefore, the tonal effect was mainly manifested in the temporal domain for this part of the velar movement, and the direction of this effect varied among subjects.

Note that the main effect of tone type was significant for S2 for both low velar plateau duration (temporally) and positional minimum of the velum (spatially), which makes one wonder whether the tonal effect was manifested on the spatial measures because of effect of tone on the temporal measures. However, a further look at the data from S2 indicates that was not the case. Firstly, the tonal effect was significant for syllable-initial nasals only in the temporal measure of velar plateau duration, but it was significant for nasals of all three syllable positions in the spatial measure of positional minimum of the velum. Secondly, for syllable-initial nasals, the duration of low velar plateau was longer in the HL tone condition, while for nasals of all three syllable positions, the positional minimum of the velum was significantly lower in the LL condition. Therefore, this is one case where effect of tone on velar movement was being enhanced in different domains in different tonal conditions. It may be the case that although the tonal effect seemed to be consistent in this part of velar movement, the positional minimum of the velum was really independently affected by tone for different reasons.

Based on the findings, it seems that the effect of tone type, like the effect of vowel type, contributed to variations seen in the velar and labial movement patterns. However, it was a much weaker and inconsistent effect compared to the effect of syllable position. The effect of tone type varied among different measures between, and as well as within the two articulators, namely, velum and lower lip. It also differed tremendously among subjects. However, within each subject, the direction of the tonal effect was largely consistent across measurements as well as articulators, that is, either the LL tone was in favor or the HL tone was in favor. Nonetheless, it was found that for velar movement, tone affected the temporal measures more often, but for lower lip movement, it affected the spatial measures more often. It is worth noting that one subject (S2) had consistent tonal effects on both temporal and spatial measures of velar movement, but almost none on the measures of lower lip movement (except on positional maximum of the lower lip for syllable-initial nasals). Thus, no consistent tonal effect was found for any one particular syllable position. And the answer to the question raised, "Are there any tonal effects on the velar and lip movements which are associated with syllable structure?", is a negative one.

3.8.4 Acoustic Outcomes and Their Relations to Articulatory Movement

It is seen from the above discussion that segmentally defined identical sound sequences containing bilabial nasal consonants of different syllable positions exhibited different characteristics in the corresponding velar and bilabial movement patterns. If these significant differences seen in the velar and bilabial movement patterns reflected the syllable positions of the bilabial nasals, what are the resulting acoustic outcomes corresponding to these patterns? After all, speech is produced to be heard for communication purposes and it is believed that the perception and production of human speech are handled by the same specialized phonetic module (Liberman and Mattingly, 1985). The acoustic outcomes, as presented in section 3.7.4, were the results of these different articulatory patterns. As one will see, the effect of syllable position was captured in several aspects in the acoustic signals.

One obvious feature of nasal consonants is the nasal murmur, which is produced when the lips are closed and a relatively low position of the velum (or a sufficiently larger velar port opening) is achieved. In the utterances examined, for all four subjects, the acoustic duration of nasal murmur was consistently longer for syllabic nasals than for syllable-final or syllable-initial nasals. And syllable-final nasals had significantly longer nasal murmur than syllable-initial nasals. These differences were consistent across vowel contexts. As was discussed above, the vowel effect on nasal murmur was largely limited to the syllable-initial position, where longer nasal murmurs were found in the vowel /ɑ/ context.

The findings also indicated that the syllable positions of the nasal consonants had significant effects on the acoustic durations of the vowels preceding the bilabial nasals. Acoustic durations of both vowels, /ɑ/ and /i/, were always longer when followed by syllabic nasals compared to syllable-final or syllable-initial nasals, and generally shorter, (significantly so in the vowel /i/ context for all four subjects and in the vowel /ɑ/ context for two subjects), when followed by syllable-final nasals compared to syllable-initial or syllabic nasals. And further, this duration difference among nasals of different syllable positions, as noted above, remained consistent in the two vowel contexts examined. This difference observed in the vowel duration indicates that the nasals had a different overlapping relationship with the preceding vowel depending on their position in a syllable.

As for the vowel following the nasal consonants, again, the durations were usually longer when the preceding nasals were syllabic. Since the vowel begins the second syllable following both syllabic and syllable-final nasals, one would expect the vowel duration to be similar in the two cases. But the results indicated otherwise. For all four subjects, the duration of vowel /ɑ/ preceded by syllable-final did not differ significantly from its duration preceded by syllable-initial nasals, although all showed significant differences between the two for durations of /i/. Table 3.53 (also see Figure 3.27) provides mean durations of both vowels. Further, for all subjects, for both vowels, vowel durations following syllabic nasals were significantly longer than those following syllable-final nasals. Thus, the relationship between the vowels and the preceding nasals were apparently different for syllable-final and syllabic nasals.

TABLE 3.53 MEAN DURATIONS OF THE VOWEL FOLLOWING NASAL CONSONANTS

	/ɑ/			/i/		
Subject	syllable-final	syllable-initial	syllabic	syllable-final	syllable-initial	syllabic
S1	111.058	106.666	131.188	73.064	66.765	108.212
S2	122.179	131.904	157.457	102.601	90.213	147.199
S3	132.849	127.317	148.805	95.381	71.46	116.353
S4	132.444	132.820	134.946	89.775	74.768	102.323

The findings of tonal effect on acoustic durations were consistent with what has been documented in literature. That is, on the one hand, vowel duration varies between the LL tone and HL tone, on the other hand, the pattern of difference, i.e., whether the vowel duration is longer in the LL tone condition or in the HL tone condition, varies among speakers (Kong, 1987).

So far, the patterns of velar and lower lip movement have been examined, the timing patterns between the two articulatory movement have been examined, and the timing patterns between articulatory movement (lower lip) and the acoustic outcome have been examined. Is there any apparent relationship between the two domains, namely, articulatory and acoustic, which can be attributed to the effect of syllable position of the nasals? The answer is yes. For syllabic nasals, longer nasal murmurs (compared to syllable-final and syllable-initial nasals) seen in acoustics resulted mainly from longer durations of velar lowering and low velar plateau, greater displacement amplitudes and lower positional minimum of the velum, as well as the longer durations of lower lip raising and high lower lip plateau. Velar lowering started earlier relative to the onset of lower lip plateau. For the longer nasal murmurs in syllable-final nasals (compared to syllable-initial nasals), the story is different. They resulted from greater displacement amplitudes of velar lowering and relatively lower positional minimum of the velum, and longer durations of lower lip plateau. And to accomplish this, the offset of velar lowering relative to the onset of lower lip plateau was postponed in syllable-final nasals. Thus, taking together the evidence found in both articulatory and acoustic domains, it is clear that the articulatory movement patterns of the velum and the lower lip differ as a function of the syllable position of the bilabial nasal consonant. Hence, they provide physical evidence for the syllable in Cantonese, that is, syllable structure is physically real as well as psychologically real in Cantonese.

3.8.5 Individual Differences among Subjects

Individual differences are to be expected in any task, and this is true for speech production. Since characteristic articulatory patterns that are manifestations of syllable structure have been shown consistently across subjects in this study, and a lot of detailed information on individual differences has been discussed elsewhere in this chapter, here are just a few points that have not been said about individual differences among subjects.

It is speculated here, the effect of syllable structure may be described as an "invariant" in the sense that that it always dominates the overall planning of gestures of the two articulators, velum and lower lip, at different stages for the utterances examined. The effects of vowel quality and the effects of tone type are "variants" in the sense that they cooperate in the more general planning of syllable structure. In this more general planning, certain variations are allowed as long as they do not jeopardize the target intended by the speaker for communicative purposes.

Under this assumption, it is argued here that the individual differences seen in various aspects of velar and labial movements among subjects are just this sort of variants. To summarize, S1 had much longer durations of low velar plateau than other three subjects, specially in the vowel /ɑ/ context, although the overall durations of the stimuli were comparable to those for other subjects. Tonal effects were observed more often for S2 than for other three subjects. Compared to the other three subjects, the magnitudes of differences among factors were smaller for S4, but were just as consistent. S4 showed significant difference between the displacement amplitudes of syllable-final nasals and those of syllable-initial nasals in both vowel contexts while other three subjects did not. For both S3 and S4, in the vowel /i/ context, the durations of low velar plateau were shorter than those of lower lip plateau for the same utterances, but such an observation was not found for S1 and S2. It is important to point out here that all of the individual differences observed were limited to places where a significant interaction between syllable position and vowel quality was found, and these individual differences *did not* change the characteristics of syllable structure manifested on the articulatory organizations of velar and labial movements for utterances examined. Hence, this may be an indication that the individual differences observed are, as suggested, allowed by the more general planning of syllable level organization. Moreover, since these individual differences are "allowed variants", then it is up to the articulatory habit of, or functional strategies used by, each subject to resolve the conflict between the different articulatory requirements exerted by syllable structure and other linguistic factors such as vowel quality or stress, within the scope or planning determined by syllable structure.

3.8.6 Comparison of the Findings between Cantonese and American English

How do these observed syllable effects in Cantonese compare to those found for American English?

As was discussed in 3.8.1, in the current study in Cantonese, while effects of syllable position were found for labial and velar gestures both temporally and spatially, they were manifested in different domains for different articulators. Thus, the effects of syllable position were enhanced spatially for velar movement but temporally for lip movement. Although no gestures were enhanced in syllable-initial position, the significantly longer duration and greater displacement amplitude in syllabic and syllable-final positions resulted in qualitatively different movement patterns among the three syllable positions (e.g., Figure 3.28 & 3.30). The information about these structural differences carried by these different articulatory movement patterns is readily available to speakers of Cantonese, as demonstrated in the perception study in Chapter Two.

Recall the Krakow (1989) study of syllable level organization described in Chapter One. In that study, kinematic analysis was carried out on gestures of two independent articulators, velum and lip, and their inter-articulatory coordinations. Pairs of disyllabic stimuli, each containing a bilabial nasal consonant contrasting only in syllable position, (e.g., *seem E*, syllable-final /m/, versus *see me*, syllable-initial /m/), were produced by two American English speakers.

In American English, /m/ can occur in two different syllable positions, syllable-final and syllable-initial, while in Cantonese, /m/ can occur in three different syllable positions, syllabic, syllable-final and syllable-initial. Effects of syllable structure on labial and velar articulatory movement patterns were observed in both languages. For American English (Krakow, 1989), although effects of syllable structure on labial and velar articulatory movement patterns were found both spatially and temporally, the pattern of effects was different from those found in Cantonese. For velum, greater displacement amplitudes of velar lowering and raising, a lower spatial minimum as well as a longer duration of the low velar plateau were found for syllable-final nasals than for syllable-initial nasals; while for the lower lip, effects of syllable position were not statistically significant for one of her subjects, and mostly on the syllable-initial nasals for the other subject. That is, longer duration and greater displacement amplitude of lip raising gesture, as well as spatially higher maximum of the lower lip were found for syllable-initial nasals compared to syllable-final nasals. Thus, the information carried by these different articulatory movement patterns should be available to speakers of American English to distinguish otherwise identical sound sequences such as *seem E* or *see me*.

Moreover, the differences found between the two languages in terms of their syllable level organization are particular striking in the inter-articulator timing patterns. As can be seen in Figure 3.30 (Krakow, 1989), it is clear that for American English, the end of velar lowering was closely timed to the onset of lower lip raising for the word-final (syllable-final) nasals, but the end of velar lowering was closely timed to the end of lower lip raising for word-initial (syllable-initial) nasals. As a rusult, vowels before syllable-final nasals were more heavily nasalized than those before syllable initial nasals.

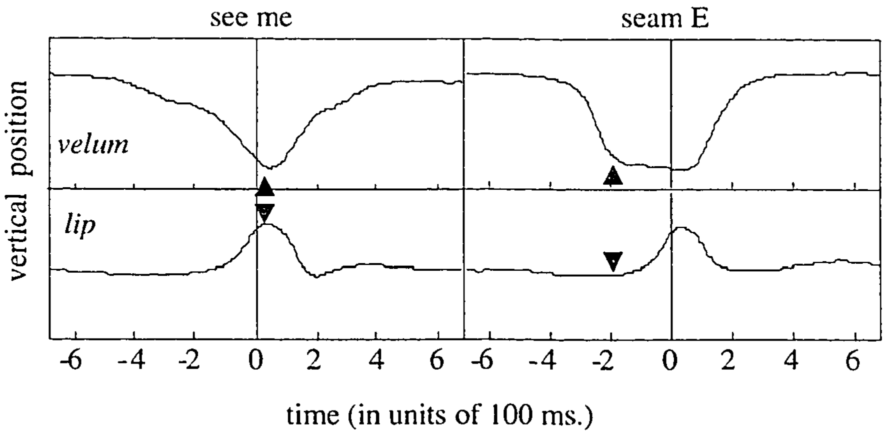

Figure 3.30 Sample inter-articulator timing for utterances with nasals in two different syllable positions (in the form of ensemble averages) in American English (S2). The vertical line in each panel marks the onset of bilabial contact for /m/. The triangles in the panels mark velum lowering offset and the coordinated event in the lower-lip movement.

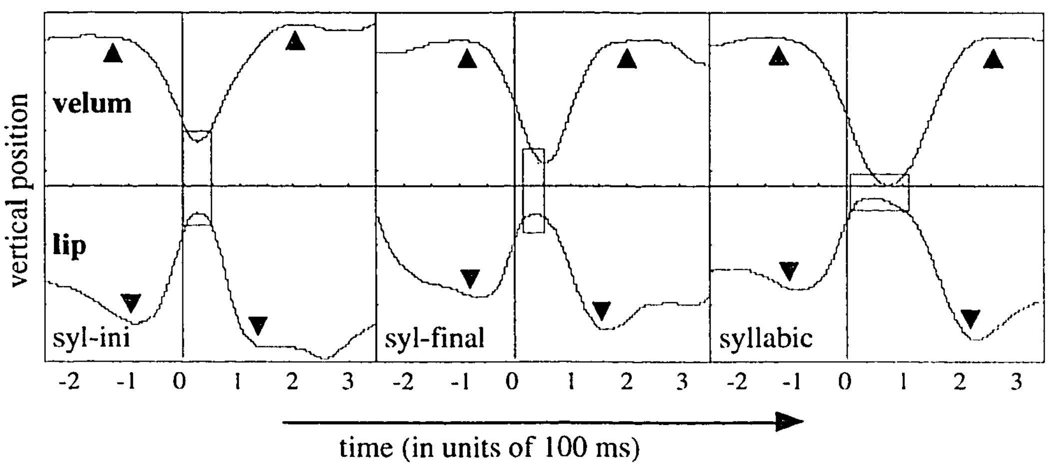

Figure 3.31 Sample inter-articulator timing for utterances with nasals in three different syllable positions (in the form of ensemble averages) in Cantonese (S3). The vertical line in each panel marks the onset of nasal murmur for /m/. The unfilled squares mark the the lower-lip plateau and coordinated event in the velar movement. The triangles mark velar lowering onset, velar raising offset, lower-lip raising onset and lower-lip lowering offset.

In Cantonese, as shown in Figure 3.31, the inter-articulator timing is quite different from American English. For syllable-final nasals, the end of velar lowering was later in relation to the end of lower-lip raising than for syllable-initial nasals. That is, although the downward velar movement began at about the same time for both syllable-final and syllable-initial nasals, the syllable-final nasals continued to move to reach a relatively lower velar position even after the initial nasals had ended the downward movement. This can be immediately observed from Figure 4.2, since both the timing and vertical position are synchronized.

Apparently, the temporal patterning of velar and lower lip movement for nasals of different syllable positions seems to be different between these two studies. In fact, to a certain extent, the inter-articulatory timing patterns of all three syllable positions in the present study seem to be parallel to that of syllable-initial position in Krakow's study. Two possible explanations are attempted here to account for the differences. One possibility is that since these two languages have different phonological structures (1.2.1), it is not unreasonable to find, based on what is already known about variations in coarticulation across different languages (Clumeck, 1976; Henderson, 1984), that the temporal relationship between the velum and the lower lip for different syllable structures differs in these two languages.

Another possibility may lie in speaking rate used by the speakers in these two experiments. In the current study, the subjects were told to use a self-defined conversational speaking rate, while in the Krakow study (1989), the subjects were told to produce the stimuli at a speaking rate slower than that used in a running speech to guarantee detectable differences at the word-boundary to listeners. Although a statistical comparison of speaking rate between the two studies was not possible, an observation from the velar movement of comparable stimuli did indicate that the speaking rate was relatively faster in the Cantonese study. Also, when compared to the vowel durations produced in citation forms reported in the literature for Cantonese (Kao, 1971; Lee, 1983), the vowel (or vocalic segment) durations in the current study were found relatively shorter for both vowel /ɑ/ and /i/.

Therefore, speaking rate could have been a contributing factor for the different temporal patterns seen in Cantonese and American English. That is, in the current study, perhaps there just wasn't time for a larger syllable-final velum-lowering movement to finish before the lip plateau started, as in the data of American English (Krakow, 1989). If this is true, it may suggest that temporal coordination patterns in Cantonese might turn out to be fundamentally similar to English when rate is controlled. It may also suggest that the size of the gesture is what matters, the relative timing of the velum and the lip varying with rate. However, since the speakers of both production and perceptual studies in Cantonese were instructed the same way to use a self-defined conversation speaking rate, and it has shown (see Chapter Two) that the native speakers of Cantonese were able to identify the stimuli reliably, there is no reason to believe that the stimuli produced in the production study were less intelligible than those in the perceptual study. Therefore, independent study with rate manipulation is needed to assess the second possibility.

A third possibility is that in the present study, the lower minima for syllable-final position may have compensated for the late offset of velar lowering, so that there was, in fact greater nasalization of vowels before syllable-final nasals than before syllable-initial nasals, as in Krakow's study. To test this possbility, the absolute values of velar height in the mid point of the vowel preceding the nasal consonant were measured. An ANOVA was conducted with syllable position, vowel type and tone type as the dependent variables and mid-vowel velar height as the independent variable. The result indicates that, for three of the four subjects, there was no consistent pattern of the effect of syllable position; this effect was not statistically significant, either. However, significant effect of syllable position was found for S4. The pattern of difference was that velar position was lower for syllable-final nasals than for syllable-initial nasals. This pattern indicates that for this subject only nasalization was stronger in the vowels preceding syllable-final than syllable-initial nasals.

CHAPTER FOUR

GENERAL DISCUSSION

4.1 Introduction

This study was designed to provide phonetic evidence for the reality of the syllable by investigating movement patterns of the velum and the lower lip during the production of Cantonese bilabial nasal /m/. In this chapter, attempts will be made, based on the current findings, to address the questions raised in the introduction, and to show that characteristic organizations of articulatory movement patterns found in Cantonese are in fact manifestations of syllable structure. Based on the present findings in Cantonese and previous findings in American English, it is suggested that the abstract notion of syllable has in fact phonetic reality universally, hence, syllable level organization is a general phenomenon of human articulatory organization, and syllables are units of speech motor organization. A model is proposed for computing the number of possible articulatory movement patterns based on the degree of freedom of a given articulator for a given sound, to account for the different articulatory movement patterns found in the current study of Cantonese and in a previous study of American English (Krakow, 1989).

4.2 Syllable as the Unit of Speech Motor Organization

4.2.1 Syllable Level Organization in Cantonese

The question, "Are there any articulatory characteristics of velar and lip gestures and their coordination patterns that are associated with the syllable structure in Cantonese?", was raised at the beginning of the thesis. Based on the findings of this study, the answer to this question is YES.

Effects of syllable structure were observed for both the velum and lower lip, spatially and temporally. For syllabic nasals, both lower lip and velar movement were amplified compared to syllable-final and syllable-initial nasals. For the velum, durations of velar lowering and low velar plateau were longer, displacement amplitudes of velar lowering were greater, and the positional minimum of the velum was lower; while for the lower lip, durations of lower-lip raising and high lower-lip plateau were longer. As a result, the acoustic duration of nasal murmur was much longer. Effects of syllable structure were also observed in syllable-final nasals compared to syllable-initial nasals. Greater displacement amplitude of velar lowering, relatively lower positional minima of the velum and longer durations of lower-lip plateau were found for syllable-final nasals. As a result, the acoustic duration of nasal murmur was significantly longer. Effects of syllable structure were also found on the coordination patterns between the velar and lower lip movement. For the syllabic nasals, when compared to syllable-final or syllable-initial nasals, downward velar movement began earlier relative to the onset of the lower lip plateau, and finished later relative to the onset of the lower lip raising. Such a timing relationship was not found for syllable-final or syllable-initial nasals. For syllable-final nasals, compared to syllable-initial nasals, the onset of the low velar plateau was postponed relative to the onset of lower-lip plateau.

4.2.2 Relation of Vowel and Tone to Syllable Level Organization

The effect of vowel quality on velar position has been found in both non-nasal and nasal environments in many studies in various languages (e.g., Bell-Berti et al., 1979; Henderson, 1984). The general finding is that there is a direct relationship between vowel height and velar height. The velar position is lower for low vowels than for high vowels in both nasal and oral environments (Henderson, 1984). Although the primary goal for this thesis was to investigate syllable structure effects on velar and labial movement patterns, a low vowel and a high vowel were chosen to allow observations of possible vowel effects on syllable structure. For velar movement, the current findings in Cantonese were consistent with what has been found in other languages. The results (see Table 3.49) indicated overall longer durations of low velar plateau and lower positional minimum of the velum in vowel /ɑ/ context regardless of the syllable position of the following nasal, i.e., whether it was syllable-final, syllable-initial or syllabic. For velar lowering and raising, a significantly vowel effect was found in most cases, but the direction of the effect was not as consistent for syllabic nasals when compared to syllable-final or syllable-initial nasals. This is interesting, since based on the phonologically described structures, one would expect a similar vowel effect on syllable-initial and syllabic nasals for velar lowering movement, and a similar vowel effect on syllable-final and syllabic nasals for the velar raising movement. The results indicated that this was not the case. The slightly unstable vowel effect on syllabic positions indicated a possibly looser relationship between syllabic nasals and the preceding and following vowels.

For labial movement, the most consistent vowel effect was observed in the spatial domain, with greater displacement amplitudes for lower-lip raising and lower-lip lowering in vowel /ɑ/ context, and greater positional maxima of the lower-lip in vowel /i/ context. Again, these effects were consistent across syllable positions. The results were consistent with the intrinsic characteristics of both vowel /ɑ/ and /i/, for /ɑ/ has a relatively lower jaw/lower-lip position, thus the jaw and lip have a longer distance to travel to reach the position for /m/; while /i/ has a higher jaw/lower-lip position, thus, a higher positional maximum is found for /m/ in its context. Comparing the findings on effect of syllable structure to the effect of vowel type, it is clear that the effect of syllable structure on the velar and bilabial movement patterns was orthogonal to the effect of vowel type. Although interactions between syllable position and vowel effect were found in certain measures, they were limited to certain parts of the movements as was discussed in 3.8.2.

The effect of tone type, as summarized in Table 3.50, 3.51 and 3.52, was much weaker and less consistent than the effect of syllable position or effect of vowel type, since it not only varied a great deal among measures, but the pattern of difference between the two tones also varied among subjects when it was significant, although one explanation for such variation may be that it is inherent in the nature of the two tones chosen for this study. For all four subjects, a significant effect of syllable position and effect of vowel type were found much more often, with a much more consistent pattern of difference than the effect of tone type. Since the tone was necessarily controlled in this study, this may be an indication that the tone was largely under control. However, tentative conclusions can still be made based on what is seen in the findings. Tonal effects, as demonstrated in this study, did not seem to affect any one syllable position in particular. Based on the information obtained in this study, a tonal effect was found more often in vowel /ɑ/ context than in /i/ context. Across subjects, the overall tonal effect was found more often on the temporal measures for the velar movement, but more often on the spatial measures for the lower lip movement (Table 3.50). The tonal effect differed greatly among subjects, e.g., S2 had significant tonal effect on all measurements of the velar movement while S3 had almost none. However, it is worth pointing out that the direction of the tonal effect was found consistent within each subject (that is, if a greater effect was seen in the LL tone condition for the velum, then a greater effect was also seen in the LL tone condition for the lower-lip, and both domains, temporal and spatial). Thus, based on the current findings, the answer is 'NO' to the question: "Are there consistent interactions between syllable position and tonal effect?".

What explanation can we offer for the results found in this study? A recent study on Mandarin tone by Löfqvist, Koenig, & McGowan (1994) showed that for their two subjects, while the fundamental frequency contours for each tone were similar in shape, the voice quality changes were not. The authors suggested that their subjects used different laryngeal strategies in obtaining the same fundamental frequency contour. If tone is a complex matter, involving more than just fundamental frequency contour, as suggested by Löfqvist et al, then it is not surprising that our subjects used different strategies. The observation that the overall tonal effect was found more often on the temporal measures for the velar movement but more often on the spatial measures for lower lip movement, may also suggest that variable coordination patterns between larynx and velum, and between larynx and lower lip may be involved in achieving the same tonal contour. The observation in the current study that the direction of tonal effect was uniform within each subject was consistent with the suggestion that individuals may use different laryngeal strategies; and it was also consistent with the finding that vowel duration varied between these two tones in different directions among speakers (Kong, 1987).

4.2.3 Syllables as Units of Speech Motor Organization

As was discussed in 3.8.6, effects of syllable structure on velar and labial movements were observed in both Cantonese and American English. In the current study in Cantonese, for velar movement, longer durations and greater displacement amplitudes were found in all parts of the velar movement for syllabic nasals, when compared to either syllable-final or syllable-initial nasals. For both velar lowering and velar raising gestures for syllable-final nasals than syllable-initial nasals, and for three of the four subjects, the positional minimum of the velum was spatially lower for the syllable-final nasals than for syllable initial nasals. For labial movement, again, gestures were amplified both temporally and spatially in syllabic position. Relatively longer duration of high lower lip plateau was found in syllable-final position, when compared to syllable-initial position. Thus, in general, the effects of syllable position were enhanced spatially for velar movement but temporally for lip movement.

For American English (Krakow, 1989), for the velum, greater displacement amplitudes of velar lowering and raising, a lower spatial minimum as well as a longer duration of the low velar plateau were found for syllable-final nasals than for syllable-initial nasals; while for the lower lip, a longer duration and a greater displacement amplitude of lip raising gesture, as well as a spatially higher maximum of the lower lip were found for syllable-initial nasals compared to syllable-final nasals.

Differences were also found between the two languages in the syllable level organization in the inter-articulatory timing patterns (see 3.8.6 for discussion).

Based on the findings presented in this thesis for Cantonese and those found in American English (Krakow, 1989), it is clear that both languages demonstrated syllable-level articulatory organization, although the specific articulatory movement patterns of syllable level organization for the bilabial nasal consonant /m/ were quite different in the two languages. The following discussion will show that while different languages may choose different articulatory movement patterns for different syllable structures, nonetheless, they provide physical evidence for the syllable in each language, suggesting that the syllables are units of speech motor organization, and hence, for the universality of syllable structure.

The existence of the syllable in various languages has been discussed in detail at the beginning of this thesis from several points of view, including phonological, psychological, acoustic phonetic and articulatory phonetic. It is clear that the syllables have a function in languages, that is, to distinguish among otherwise identical sound sequences or phoneme strings. In other words, gestures of different articulators are organized into functional units according to the nature of the tasks required by the language (Mattingly, 1990). For any given sound in a given language, the number of syllable positions in which the sound occurs is synchronically stable and usually is identifiable from its phonological structure. It is proposed here that for any articulator involved in producing any given sound in human languages, the possible combinations of articulatory movement patterns for producing required contrasts of the sound in different syllable positions are finite and can be predicted, because the number of ways an articulator can vary (i.e., degree of freedom) is limited by human physiology (for example, the lower lip can be lowered only as far as the jaw can go). For the sake of simplicity, consonant clusters are not considered here, although consonant clusters can contrast between syllable-initial and syllable-final position in languages such as English (e.g., *be <u>st</u>eel* versus *bea<u>st</u> eel*). Assuming that for any given sound, the number of possible syllable positions where it can occur is r, the degree of freedom of the articulator involved producing the sound is N, then C, the number of possible articulatory movement pattern combinations of this articulator reflecting different syllable structures, can be obtained by the following formula:

$$C_r^N = \frac{N!}{r\,!\,(N - r)!} \qquad \text{(Spence et al, 1983)}$$

Since the maximum number of possible syllable positions[1] a sound can occur in any human language is 3, that is, syllable-initial, syllable-final and syllabic, the formula can be further simplified to:

$$C_3^N = \frac{N!}{3!\,(N - 3)!}$$

However, it is worth pointing out that based on what is known about phonological patterns of syllable structure in languages of the world, it is conceivable that not all possible articulatory movement pattern combinations are equally applicable to all syllable positions.

For example, for the bilabial consonant /m/, for which the velum is involved in producing the needed nasal coupling, the degree of freedom (N) for velum is 4 (to make things simple, spatial velar height control is assumed to be binary, high or low, multiplied by the temporal control, also binary, short or long, therefore, 2x2=4), using the formula proposed above (from here on, the Syllable Structure Patterning Model or SSP model), the possible articulatory movement pattern combination C is therefore 4!/3!(4-3)! or (4x3x2x1)/(3x2)(4-3). The result is 4, that is, the number of possible articulatory movement patterns that can distinguish nasals of three possible syllable positions is four for any language. For the lower lip, using the SSP model, the number of possible articulatory movement patterns is also four, since for the lower lip, like the velum, both the spatial

[1]Note that so-called ambisyllabicity in English will not count as a particular syllable position, as it is the case with syllable-initial, syllable-final or syllabic, since it does not serve a unique linguistic function as syllable-initial, syllable-final or syllabic position will, that is, to distinguish otherwise identical sound sequences. It was shown that in fact, in American English, the articulatory movement patterns of sounds in ambisyllabic positions would either represent those in syllable-initial positions or those in syllable-final positions depending on the suprasegmental factors such as stress (e.g., Turk, 1994).

control of lip height and the temporal control of duration are binary. For both velum and lower lip, the four possible articulatory movement patterns can be illustrated in Figure 4.1, where 1=default state, 2=enhanced state, S=spatial domain, and T=temporal domain. It is assumed that the default state is meaningful only within each language, and it is the initial state or the state which has the minimal value in that domain, whatever that may be. It is also assumed that the enhanced state always has a greater value than that of the initial state.

S1T1	S2T2
S2T1	S1T2

Figure 4.1 Possible articulatory movement pattern combinations for velum and lower lip for /m/.

It was shown that in American English (Krakow, 1989), the effect of syllable structure resulted in different articulatory movement patterns. For the velar movement, the gestures were spatially and temporally amplified in syllable-final position, and for the lower lip movement, the gestures were spatially and temporally amplified in syllable-initial position. In Cantonese, gestures were spatially and temporally amplified in syllabic position for both velum and lower lip, gestures were amplified in syllable-final position spatially for the velum and temporally for the lower lip. Using the model proposed above, the observed articulatory movement patterns in American English can be classified for the velum as S1T1 in syllable-initial position and S2T2 in syllable-final position, and as S2T2 for the lower lip in syllable-initial position and S1T1 in syllable-final position. For Cantonese, the observed articulatory movement patterns can be classified for the velum as S1T1 in syllable-initial position, S2T1 in syllable-final position and S2T2 in syllabic position; while for the lower lip, S1T1 in the syllable-initial position, S1T2 in the syllable-final position and S2T2 for the syllabic position. Therefore, as demonstrated, both American English and Cantonese employed different articulatory movement patterns for different syllable structures, as required by each language, from a pool of possible articulatory movement pattern combinations that contrast different syllable positions for any human language. Hence, both languages, American English and Cantonese, demonstrate that different languages can and will have different articulatory movement patterns that are manifestations of different syllable structures meaningful in that language. However, they are all drawn from a finite set of articulatory movement patterns that are characteristic of different syllable structures delimited only by the physiology of the articulator involved. Therefore, the syllable level organizations of articulatory movement patterns observed in both American English and Cantonese are no doubt phonetic evidence for the syllable structure.

It is worth noting that in both Cantonese and American English, the effect of syllable structure was consistently enhanced in syllabic position in Cantonese (also spatially in syllable-final position), and syllable-final position in English. However, it was not so for the lower lip, for which the enhanced position was syllable-initial in American English but syllabically and syllable-finally in Cantonese. It may be speculated that the difference seen in different syllable positions may be due to a hierarchical ranking of syllable positions as the phonological observations have suggested (Hooper, 1976). If, as claimed, syllable-initial position is 'stronger' than syllable-final position (Hooper, 1976), the greater displacement of velar gestures or lower velar position in both languages syllable-finally may be taken as evidence of the reduced effort to maintain relatively elevated velar height in syllable-final position (Krakow, 1989). However, that leaves one to wonder why syllabic position shows a similar syllable structure effect, e.g., the lower velar position, in Cantonese. For the lower lip, if greater raising gestures in syllable-initial position in American English are evidence of greater effort syllable-initially because syllable-initial is a 'stronger position', one would wonder why syllabic positions have greater raising gestures in Cantonese. It is speculated here that while for each language, the articulatory movement patterns are drawn from a finite set of possible articulatory movement patterns for each articulator to maintain the contrast between/among different syllable structures, articulators must be actively controlled higher up to have compatible patterns so as to produce such a results with the least effort of the system. Thus, the choice of different patterns for a given articulator for different syllable structures may lie in the functional organization among articulators required by the nature of the tasks in a particular language (Mattingly, 1990). It is also worth pointing out that based on the observations for Cantonese and American English, it is unlikely that all the articulatory possible patterns are equally likely for all syllable positions. For example, in both Cantonese and American English, the initial state was chosen by the syllable-initial position. This may indicate some other independent constraints apply that warrant for further investigation.

4.3 Conclusion and Future Research

We have argued in this thesis that different articulatory movement patterns are characteristic of syllable level organization. By comparing the findings for syllable structure in American English and current findings in Cantonese, we have shown that the seemingly different articulatory movement patterns for the velum and lower lip found in these two languages were drawn from the same finite set of possible articulatory movement patterns characteristic of syllable structures and delimited only by human physiological mechanics. Therefore, they provide phonetic evidence for the syllable in the articulatory domain. Further, the definition of universality of syllable structure is not that every language should have identical articulatory movement patterns for a given syllable position, but rather, that syllable level organization is maintained via possibly different articulatory movement patterns. Based on the current findings in Cantonese and previous findings in American English (Krakow, 1989), we conclude that there is a phonetic basis for the syllable and that the syllables are units of speech motor organization.

Since for different syllable structures, different timing patterns are observed in both American English and Cantonese, it would be interesting to test the clinically defined dysarthric or apraxic speech to see if a major breakdown in timing patterns can be observed comparing to the normal speakers for syllable level organization. It would also be interesting to test how the proposed SSP model in this thesis works for the same articulator(s) or a different articulator(s) for sounds other than nasals. Although, to simplify the task, the model was described as if each articulator were an independent system, further modifications are needed to combine different articulatory subsystems to further our understanding of the coordination between different articulators requiring for achieving the same communicative tasks.

REFERENCES

Abramson, A. S. (1962). *The vowels and tones of standard Thai: acoustical measurements and experiments*. Bloomington: Indiana University.

Bell-Berti, F. (1979). The extent of a vowel's influence: Evidence from a study of velar function. Paper presented at the 97th Meeting of the Acoustical Society of America, Cambridge, MA.

Bell-Berti, F., & Harris, K. S. (1974). More on the motor organization of speech gestures. *Haskins Laboratories Status Report on Speech Research, SR37/38*, 73-77.

Bell-Berti, F. , Baer, T., Harris, K. S., & Niimi, S. (1979). Coarticulatory effects of vowel quality on velar function. *Phonetica, 96*, 187-193.

Bell, A., & Hooper, J. B. (1978). Issues and evidence in syllabic phonology. In A. Bell & J. B. Hooper (Eds.), *Syllables and segments* (pp. 3-22).\ Amsterdam: North-Holland Publishing Company.

Blumstein, S. E. (1978). Segment structure and the syllable in aphasia. In A. Bell & J. B. Hooper (Eds.), *Syllables and segments.*(pp. 189-200). Amsterdam: North-Holland Publishing Company.

Browman, C. P., & Goldstein, L. (1988). Some notes on syllable structure in articulatory phonology. *Phonetica 45,* 140-155.

Browman, C. P., & Goldstein, L. (1992). Articulatory phonology: An overview. *Phonetica, 49,* 155-180.

Browman, C. P., & Goldstein, L. (1995). Gestural syllable position effects in American English. In F. Bell-Berti & L. J. Raphael (Eds.), *Producing speech: Contemporary issues. For Katherine Safford Harris.* (AIP series in modern acoustics and signal processing, pp. 19-34). Woodbury, NY: American Institute of Physics.

Byrd, D. (1994). Articulatory timing in English consonant sequences. Doctoral dissertation. *UCLA Working Papers in Phonetics,* 86.

Chao, Y. R. (1947). *Cantonese primer.* Cambridge, MA: Harvard University Press.

Clements, G. N., & Keyser, S. J. (1983). CV phonology: A generativetheory of the syllable. *Linguistic Inquiry Monograph 9.* Cambridge: The MIT Press.

Clumeck, H. (1976). Patterns of soft palate movements in six languages. *Journal of Phonetics, 4,* 337-351.

Daniloff, R. C. (1967). *A cinefluorographic study of selected aspects of coarticulation of speech sounds.* Unpublished doctoral dissertation, University of Iowa.

Donegan, P. J., & Stampe, D. (1978). The syllable in phonological and prosodic structure. In A. Bell & J. B. Hooper (Eds.), *Syllables and segments.*(pp. 25-34). Amsterdam: North-Holland Publishing Company.

Fowler, C. A., Treiman, R., & Gross, J. 1993). The structure of English syllables and polysyllables. *Journal of Memory and Language, 32,* 115-140.

Fromkin, V. A. (1973). *Speech errors as linguistic evidence.* The Hague: Mouton.

Fujimura, O., & Lovins, J. B. (1978). Syllables as concatenative phonetic units. In A. Bell & J. B. Hooper (Eds.), *Syllables and segments* (pp. 107-120). Amsterdam: North-Holland Publishing Company.

Fujimura, O., Miller, J. E., & Kiritani, S. (1977). A computer-controlled X-ray microbeam study of articulatory characteristics of nasal consonants in English and Japanese. Paper Presented at the 9th International Congress on Acoustics, Madrid, Spain.

Gay, T. (1978). Articulatory units: segments or syllables? In A. Bell & J. B. Hooper (Eds.), *Syllables and segments* (pp. 121-131). Amsterdam: North-Holland Publishing Company.

Gracco, V. L., & Abbs, J. H. (1988). *Central patterning of speech movements. Experimental Brain Research, 71,* 515-526.

Harris, K. S., & Bell-Berti, F. (1984). On consonants and syllable boundaries. In L. Raphael, C. Raphael, & R. R. Valdovinos (Eds.), *Language and Cognition* (pp. 89-95). New York: Plenum Publishing.

Haruko, K. (1982). *An acoustical basis for universal constraints on sound sequences.* Unpublished doctoral dissertation, University of California, Berkeley.

Hashimoto, O-K. Y. (1972). *Studies in Yue dialects 1: Phonology of Cantonese.* London: Cambridge University Press.

Henderson, J. B. (1984). *Velopharyngeal function in oral and nasal vowels: A cross-language study.* Unpublished doctoral dissertation, University of Connecticut, Storrs.

Hooper, J. (1976). *An introduction to natural generative phonology.* New York: Academic Press.

Horiguchi, S., & Bell-Berti, F. (1987). The Velotrace: A device for monitoring velar position. *Cleft Palate Journal, 24,* 104-11.

Kao, D. (1971). *Structure of the syllable in Cantonese.* The Hague: Mouton & Co. N.V., Publishers.

Kay, B. A., Munhall, K. G., Vatikiotis-Bateson, E., & Kelso, J. A. S. (1985). A note on processing kinematic data: Sampling, filtering, and differentiation. *Haskins Laboratories Status Report on Speech Research, 81,* 291-303.

Kent, R. D., Carney, P. J., & Severeid, L. R. (1974). Velar movement and timing: Evaluation of a model for binary control. *Journal of Speech and Hearing Research, 17,* 470-488.

Keppel, G. (1982). *Design and analysis: A researcher's handbook.* New Jersey: Prentice-Hall, Inc.

Kong, Q. M. (1987). Influence of tone upon vowel duration in Cantonese. *Language and Speech, 30,* 387-399.

Kozhevnikov, R. V., & Chistovich, L. (1965). *Speech: Articulation and perception.* (Translated from Russian) Report 30, 543. Washinton, DC: Joint Publications Research Service.

Krakow, R. A. (1989). *The articulatory organization of syllables: A kinematic analysis of labial and velar gestures.* Unpublished doctoral dissertation, Yale University, New Haven.

Ladefoged, P. (1967). *Three areas of experimental phonetics.* Oxford: Oxford University Press.

Ladefoged. P., Draper, M. H., & Whitteridge, D. (1958). Syllables and stress. *Misellanea Phonetica, 3,* 1-14.

Lehiste, I. (1964). *Acoustical characteristics of selected English consonants.* Bloomington: Indiana University.

Lee, T. (1983). The vowel system in two varieties of Cantonese. *UCLA Working Papers in Phonetics, 57,* 97-113.

Liberman, A. M., & Mattingly, I. G. (1985). The motor theory of speech perception revised. *Cognition, 21,* 1-36.

Light, T. (1976). *The Chinese syllabic final: xphonological relativity and constituent analysis.* New York: The Cornell East Asia Papers.

Löfqvist, A., Koenig, L. L., & McGowan, R. S. (1994). Voice source variations in running speech: A study of Mandarin Chinese tones. In O. Fujimura & M. Hirano (Eds.), *Vocal fold physiology: Voice quality control* (pp. 3-22). San Diego: Singular Publishing Group, Inc.

Macchi, M. (1988). Labial articulation patterns associated with segmental features and syllable structure in English. *Phonetica, 45,* 109-121.

MacKay, D. G. (1978). Speech errors inside the syllable. In A. Bell & J. B. Hooper (Eds.), *Syllables and segments* (pp. 201-212).. Amsterdam: North-Holland Publishing Company.

Maddieson, I. (1985). Phonetic cues to syllabification. In V. A., Fromkin (Ed.), *Phonetics linguistics: Essays in honor of Peter Ladefoged* (pp. 203-221). New York: Academic Press.

Malmberg, B. (1955). The phonetic basis for syllable division. *Studia Linguistica IX,* Lund.

Malmberg, B. (1963). *Phonetics.* New York: Dover.

Mattingly, I. G. (1981). Phonetic representation and speech synthesis by rule. In T. Myers, J. Laver, & J. Anderson (Eds.), *The cognitive representation of speech* (pp. 415-420). North-Holland Publishing Company.

Mattingly, I. G. (1990). The global character of phonetic gestures. *Journal of Phonetics, 18,* 445-452.

McClean. M. (1973). Forward Coarticulation of velar movement at marked junctural boundaries. *Journal of Speech and Hearing Research, 16,* 286-296.

Moll, K. L., & Daniloff, R. G. (1971). Investigation of the timing of velar movements during speech. *Journal of Acoustic Society of America, 50(2),* 678-684.

Rubin, P. E., & Löfqvist, A. (in preparation). The Haskins Analysis Display and Experiment System (HADES). Paper in preparation for the *Haskins Laboratories Status Report on Speech Research.*

Saib, J. (1978). Segment organization and the syllable in Tamazight Berber. In A. Bell & J. B. Hooper (Eds.), *Syllables and segments* (pp. 93-104). Amsterdam: North-Holland Publishing Company.

So, L. K., & Dodd, B. J. (1994). Phonologically disordered Cantonese-speaking children. *Clinical Linguistics and Phonetics. Vol. 8* (3), 235-255.

Sproat, R., & Fujimura, O. (1993). Allophonic variation in English /l/ and its implications for phonetic implementation. *Journal of Phonetics, 21,* 291-311.

Stetson, R. H. (1951). *Motor phonetics: A study of speech movements in action* (2nd ed.). Amsterdam: North Holland.

Studdert-Kennedy, M. (1977). Universals in phonetic structure and their role in linguistic communication. In T. H. Bullock (Ed.), *Recognition of complex acoustic signals* (pp. 37-48). Berlin: Dahlem Konferenzen.

Turk, A. (1994). Articulatory phonetic clues to syllable affiliation: gestural characteristics of bilabial stops. In P. A. Keating (Ed.), *Phonological structure and phonetic form: Papers in laboratory phonology III,* (pp. 107-135). London: Cambridge University Press.

Ushijima, T., & Hirose, H. (1974). Electromyographic study of the velum during speech. *Journal of Phonetics, 2,* 315-326.

Vance, T. J. (1976). An experimental investigation of tone and intonation in Cantonese. *Phonetica, 33,* 368-392.

Whalen, D. H., Wiley, E. R., Rubin, P. E., & Cooper, F. S. (1990). The Haskins Laboratories' pulse code modulation (PCM) system. *Behavior Research Methods, Instruments and Computers, 22,* 550-559.

Wijnen, F. (1988). Spontaneous word fragmentations in children: evidence for the syllable as a unit in speech production. *Journal of Phonetics, 16,* 187-202.

Yip, M. (1990). *The tonal phonology of Chinese.* New York: Garland Publishing, Inc.

APPENDIX

MEANS TABLES

Means Table for Figure 3.6 (in msec)

			S1				S2			
			Count	Mean	Std. Dev.	Std. Err.	Count	Mean	Std. Dev.	Std. Err.
syl-f	a	LL	10	94.080	11.409	3.608	10	134.240	6.008	1.900
syl-ini	a	LL	10	85.040	16.164	5.111	10	129.840	18.118	5.729
syllabic	a	LL	9	79.644	6.041	2.014	10	148.880	20.815	6.582
syl-f	a	HL	10	101.280	10.912	3.451	9	126.578	14.728	4.909
syl-ini	a	HL	10	107.280	8.620	2.726	10	116.720	9.233	2.920
syllabic	a	HL	10	96.400	10.708	3.386	10	124.640	11.052	3.495
syl-f	i	LL	10	86.564	15.108	4.777	10	83.760	6.533	2.066
syl-ini	i	LL	10	71.040	5.972	1.889	10	88.480	8.958	2.833
syllabic	i	LL	9	102.844	6.389	2.130	10	130.000	8.152	2.578
syl-f	i	HL	10	96.160	9.190	2.906	10	68.640	5.852	1.851
syl-ini	i	HL	10	100.160	15.820	5.003	10	77.920	12.890	4.076
syllabic	i	HL	10	108.480	8.910	2.818	10	125.440	11.871	3.754
			S3				S4			
			Count	Mean	Std. Dev.	Std. Err.	Count	Mean	Std. Dev.	Std. Err.
syl-f	a	LL	10	188.240	24.825	7.850	10	160.400	15.325	4.846
syl-ini	a	LL	10	174.640	14.867	4.701	10	172.080	18.021	5.699
syllabic	a	LL	10	220.480	53.010	16.763	10	207.120	10.024	3.170
syl-f	a	HL	10	205.680	27.796	8.790	10	189.280	12.256	3.876
syl-ini	a	HL	9	169.333	20.715	6.905	10	185.440	13.695	4.331
syllabic	a	HL	10	232.480	23.726	7.503	10	219.120	30.006	9.489
syl-f	i	LL	10	124.480	10.794	3.413	10	110.000	7.592	2.401
syl-ini	i	LL	10	128.160	13.396	4.236	10	109.040	8.559	2.707
syllabic	i	LL	10	170.560	25.401	8.033	10	141.600	9.019	2.852
syl-f	i	HL	9	125.867	16.307	5.436	10	111.680	8.485	2.683
syl-ini	i	HL	10	126.560	20.496	6.481	10	116.320	10.036	3.174
syllabic	i	HL	10	174.720	23.309	7.371	10	162.720	14.968	4.733

Means Table for Figure 3.7 (in msec)

			S1				S2			
			Count	Mean	Std. Dev.	Std. Err.	Count	Mean	Std. Dev.	Std. Err.
syl-f	a	LL	10	253.520	21.881	6.919	10	21.680	8.579	2.713
syl-ini	a	LL	10	216.080	47.770	15.106	10	26.000	18.364	5.807
syllabic	a	LL	10	304.733	39.096	12.363	10	58.480	23.105	7.306
syl-f	a	HL	10	206.560	25.460	8.051	10	25.760	11.462	3.625
syl-ini	a	HL	10	189.680	19.157	6.058	10	47.840	12.687	4.012
syllabic	a	HL	10	325.760	29.060	9.190	10	56.480	21.576	6.823
syl-f	i	LL	9	32.978	8.633	2.878	10	16.080	2.705	.855
syl-ini	i	LL	10	70.800	10.163	3.214	10	28.880	4.687	1.482
syllabic	i	LL	10	95.920	36.566	11.563	10	39.600	12.163	3.846
syl-f	i	HL	10	56.160	6.776	2.143	10	19.120	7.019	2.220
syl-ini	i	HL	10	61.600	11.513	3.641	9	31.911	8.104	2.701
syllabic	i	HL	10	107.680	20.971	6.632	10	38.720	10.931	3.457

			S3				S4			
			Count	Mean	Std. Dev.	Std. Err.	Count	Mean	Std. Dev.	Std. Err.
syl-f	a	LL	10	61.280	10.661	3.371	10	106.160	26.329	8.326
syl-ini	a	LL	10	63.200	22.539	7.128	10	101.680	16.535	5.229
syllabic	a	LL	10	104.991	49.543	15.667	10	157.440	14.478	4.578
syl-f	a	HL	9	63.022	25.285	8.428	10	95.920	35.774	11.313
syl-ini	a	HL	9	44.978	14.482	4.827	10	86.160	18.137	5.736
syllabic	a	HL	10	164.000	48.211	15.246	10	169.440	37.774	11.945
syl-f	i	LL	10	4.720	1.331	.421	10	5.200	.864	.273
syl-ini	i	LL	10	6.080	4.417	1.397	9	5.422	.777	.259
syllabic	i	LL	9	11.200	4.400	1.467	10	11.760	5.032	1.591
syl-f	i	HL	10	4.560	1.309	.414	10	6.480	1.096	.347
syl-ini	i	HL	10	7.200	3.133	.991	10	6.240	2.024	.640
syllabic	i	HL	10	15.200	2.872	.908	9	17.600	11.285	3.762

Means Table for Figure 3.8 (in msec)

			S1				S2			
			Count	Mean	Std. Dev.	Std. Err.	Count	Mean	Std. Dev.	Std. Err.
syl-f	a	LL	10	74.320	9.226	2.917	10	183.280	10.536	3.332
syl-ini	a	LL	10	63.600	21.622	6.838	10	175.200	21.092	6.670
syllabic	a	LL	10	58.180	17.343	5.484	10	242.480	19.932	6.303
syl-f	a	HL	10	59.280	10.643	3.366	10	178.160	14.256	4.508
syl-ini	a	HL	10	64.400	6.632	2.097	10	176.960	13.633	4.311
syllabic	a	HL	10	47.040	6.342	2.006	10	207.680	20.456	6.469
syl-f	i	LL	10	75.892	18.056	5.710	10	118.160	11.980	3.788
syl-ini	i	LL	10	61.840	8.534	2.699	10	122.640	11.092	3.508
syllabic	i	LL	10	90.720	26.483	8.375	10	153.920	32.802	10.373
syl-f	i	HL	10	80.720	9.499	3.004	10	114.320	13.400	4.237
syl-ini	i	HL	10	76.240	11.563	3.656	10	114.640	17.701	5.598
syllabic	i	HL	10	89.120	18.024	5.700	10	157.920	29.154	9.219

			S3				S4			
			Count	Mean	Std. Dev.	Std. Err.	Count	Mean	Std. Dev.	Std. Err.
syl-f	a	LL	10	218.800	49.869	15.770	10	302.480	32.578	10.302
syl-ini	a	LL	10	205.600	53.361	16.874	10	303.680	39.257	12.414
syllabic	a	LL	10	245.070	70.342	22.244	10	304.640	39.257	12.414
syl-f	a	HL	10	151.120	23.426	7.408	10	294.560	33.496	10.592
syl-ini	a	HL	10	195.119	57.405	18.153	10	301.120	40.128	12.690
syllabic	a	HL	10	172.480	54.579	17.259	10	294.000	48.368	15.295
syl-f	i	LL	10	127.920	17.496	5.533	10	173.920	10.853	3.432
syl-ini	i	LL	10	153.440	12.932	4.089	10	162.480	9.684	3.062
syllabic	i	LL	10	153.520	17.077	5.400	10	204.160	19.233	6.082
syl-f	i	HL	10	135.200	17.179	5.432	10	164.080	10.542	3.334
syl-ini	i	HL	10	140.080	15.697	4.964	10	162.960	14.684	4.643
syllabic	i	HL	10	172.640	26.781	8.469	10	195.600	16.976	5.368

Means Table for Figure 3.9 (in mm)

			S1				S2			
			Count	Mean	Std. Dev.	Std. Err.	Count	Mean	Std. Dev.	Std. Err.
syl-f	a	LL	10	-11.666	1.005	.318	10	-46.407	4.460	1.410
syl-ini	a	LL	10	-9.956	.696	.220	10	-41.459	8.124	2.569
syllabic	a	LL	10	-9.160	1.016	.321	10	-44.103	2.542	.804
syl-f	a	HL	10	-10.549	1.121	.354	10	-32.971	4.661	1.474
syl-ini	a	HL	10	-10.657	.514	.162	10	-27.387	3.008	.951
syllabic	a	HL	10	-9.419	.830	.263	10	-35.315	5.248	1.660
syl-f	i	LL	9	-9.016	2.572	.857	10	-24.806	3.497	1.106
syl-ini	i	LL	10	-6.428	.682	.216	10	-23.185	4.073	1.288
syllabic	i	LL	9	-11.075	1.241	.414	10	-36.208	3.552	1.123
syl-f	i	HL	10	-7.721	1.675	.530	10	-15.479	4.544	1.437
syl-ini	i	HL	10	-7.724	1.485	.470	10	-17.253	6.595	2.086
syllabic	i	HL	10	-11.025	1.677	.530	10	-34.725	4.713	1.491

			S3				S4			
			Count	Mean	Std. Dev.	Std. Err.	Count	Mean	Std. Dev.	Std. Err.
syl-f	a	LL	10	-8.060	.585	.185	10	-24.284	1.027	.325
syl-ini	a	LL	10	-8.169	.542	.171	10	-24.164	1.387	.438
syllabic	a	LL	9	-9.235	1.255	.418	10	-25.018	1.037	.328
syl-f	a	HL	10	-8.404	.796	.252	10	-24.280	.729	.230
syl-ini	a	HL	10	-7.769	.633	.200	10	-24.207	1.399	.442
syllabic	a	HL	10	-8.556	.478	.151	10	-24.912	1.173	.371
syl-f	i	LL	10	-6.360	.494	.156	10	-20.585	1.404	.444
syl-ini	i	LL	10	-5.352	1.024	.324	10	-19.929	1.850	.585
syllabic	i	LL	10	-7.762	1.323	.418	10	-25.749	1.163	.368
syl-f	i	HL	9	-6.967	.781	.260	10	-20.651	1.954	.618
syl-ini	i	HL	10	-6.182	1.158	.366	10	-21.253	2.665	.843
syllabic	i	HL	10	-7.775	.792	.251	10	-27.030	1.267	.401

Means Table for Figure 3.10 (in mm)

			S1				S2			
			Count	Mean	Std. Dev.	Std. Err.	Count	Mean	Std. Dev.	Std. Err.
syl-f	a	LL	10	-4.165	1.918	.607	10	-40.404	4.704	1.488
syl-ini	a	LL	10	-4.219	1.188	.376	10	-33.875	9.436	2.984
syllabic	a	LL	10	-5.280	.636	.201	10	-45.617	3.151	.996
syl-f	a	HL	10	-4.863	.636	.201	10	-27.272	4.294	1.358
syl-ini	a	HL	10	-4.689	.475	.150	10	-25.212	3.483	1.101
syllabic	a	HL	10	-6.259	.799	.253	10	-33.475	4.666	1.475
syl-f	i	LL	10	-1.630	1.423	.450	10	-22.734	4.906	1.551
syl-ini	i	LL	10	-2.165	.428	.135	10	-16.991	4.899	1.549
syllabic	i	LL	9	-4.404	.982	.327	10	-34.290	5.071	1.604
syl-f	i	HL	10	-.780	.843	.267	10	-14.232	4.969	1.571
syl-ini	i	HL	10	-.936	1.357	.429	10	-12.730	5.795	1.833
syllabic	i	HL	10	-5.106	.526	.166	10	-34.155	5.237	1.656

			S3				S4			
			Count	Mean	Std. Dev.	Std. Err.	Count	Mean	Std. Dev.	Std. Err.
syl-f	a	LL	10	-6.168	.274	.087	10	-25.779	1.840	.582
syl-ini	a	LL	10	-5.956	.492	.156	10	-24.635	.650	.206
syllabic	a	LL	10	-6.200	.659	.208	10	-24.927	.556	.176
syl-f	a	HL	10	-5.803	.388	.123	10	-24.155	.629	.199
syl-ini	a	HL	10	-5.820	.459	.145	10	-24.837	.590	.187
syllabic	a	HL	10	-6.079	.339	.107	10	-24.841	.472	.149
syl-f	i	LL	10	-3.729	.357	.113	10	-18.914	1.557	.492
syl-ini	i	LL	10	-2.579	.821	.260	10	-17.804	1.830	.579
syllabic	i	LL	10	-4.915	1.030	.326	10	-22.520	.822	.260
syl-f	i	HL	10	-3.978	.886	.280	10	-19.054	2.012	.636
syl-ini	i	HL	10	-3.188	.775	.245	10	-18.853	2.079	.658
syllabic	i	HL	10	-5.121	.395	.125	10	-23.144	1.330	.421

Means Table for Figure 3.11 (in mm)

			S1				S2			
			Count	Mean	Std. Dev.	Std. Err.	Count	Mean	Std. Dev.	Std. Err.
syl-f	a	LL	10	7.811	.717	.227	10	45.887	3.945	1.248
syl-ini	a	LL	10	5.819	2.214	.700	10	40.449	7.932	2.508
syllabic	a	LL	10	5.495	1.253	.396	10	44.667	3.315	1.048
syl-f	a	HL	10	6.982	1.231	.389	10	33.600	4.260	1.347
syl-ini	a	HL	10	7.813	.585	.185	10	27.271	3.738	1.182
syllabic	a	HL	10	4.449	1.476	.467	10	34.164	4.616	1.460
syl-f	i	LL	10	6.704	1.942	.614	10	25.715	4.457	1.409
syl-ini	i	LL	10	4.521	.731	.231	10	22.527	4.184	1.323
syllabic	i	LL	10	8.227	1.869	.591	10	37.277	4.337	1.371
syl-f	i	HL	10	8.495	.891	.282	10	15.733	4.430	1.401
syl-ini	i	HL	10	8.620	1.957	.619	10	16.305	7.175	2.269
syllabic	i	HL	10	8.889	2.307	.730	10	37.099	4.457	1.410

			S3				S4			
			Count	Mean	Std. Dev.	Std. Err.	Count	Mean	Std. Dev.	Std. Err.
syl-f	a	LL	10	4.507	.604	.191	10	28.204	1.303	.412
syl-ini	a	LL	10	4.646	.336	.106	10	26.537	1.206	.382
syllabic	a	LL	10	5.854	.824	.261	10	27.551	1.238	.392
syl-f	a	HL	10	4.927	.469	.148	10	26.943	.816	.258
syl-ini	a	HL	10	4.445	.498	.157	10	26.215	1.453	.460
syllabic	a	HL	10	5.634	.944	.299	10	26.390	1.079	.341
syl-f	i	LL	10	2.873	.517	.163	10	20.675	1.258	.398
syl-ini	i	LL	10	3.871	.973	.308	10	17.720	1.982	.627
syllabic	i	LL	10	3.189	.471	.149	10	25.412	1.254	.396
syl-f	i	HL	10	2.829	.440	.139	10	19.544	1.599	.506
syl-ini	i	HL	10	3.767	.559	.177	10	19.319	2.624	.830
syllabic	i	HL	10	3.837	1.100	.348	10	26.568	1.635	.517

Means Table for Figure 3.12 (in msec)

			S1 Count	S1 Mean	S1 Std. Dev.	S1 Std. Err.	S2 Count	S2 Mean	S2 Std. Dev.	S2 Std. Err.
syl-f	a	LL	10	100.240	11.245	3.556	10	108.160	17.510	5.537
syl-ini	a	LL	10	98.960	8.748	2.766	10	93.200	11.607	3.670
syllabic	a	LL	10	132.080	17.255	5.457	10	145.440	23.961	7.577
syl-f	a	HL	10	92.640	4.943	1.563	10	104.480	19.429	6.144
syl-ini	a	HL	10	95.200	6.081	1.923	10	98.800	5.035	1.592
syllabic	a	HL	10	146.080	13.109	4.145	10	153.920	16.243	5.137
syl-f	i	LL	10	98.480	14.118	4.464	10	97.200	11.533	3.647
syl-ini	i	LL	10	102.960	8.009	2.533	10	101.680	11.385	3.600
syllabic	i	LL	10	137.200	20.487	6.479	10	152.160	22.567	7.136
syl-f	i	HL	10	88.560	4.542	1.436	10	87.120	6.074	1.921
syl-ini	i	HL	10	96.960	7.909	2.501	10	92.960	5.949	1.881
syllabic	i	HL	10	122.160	9.899	3.130	10	143.520	10.377	3.282

			S3 Count	S3 Mean	S3 Std. Dev.	S3 Std. Err.	S4 Count	S4 Mean	S4 Std. Dev.	S4 Std. Err.
syl-f	a	LL	10	92.720	8.119	2.567	10	79.040	4.797	1.517
syl-ini	a	LL	10	96.400	9.193	2.907	10	78.720	5.228	1.653
syllabic	a	LL	10	137.040	10.197	3.224	10	114.160	6.683	2.113
syl-f	a	HL	10	101.360	7.775	2.459	10	82.800	6.770	2.141
syl-ini	a	HL	10	90.560	7.503	2.373	10	81.040	5.116	1.618
syllabic	a	HL	10	141.520	19.921	6.300	10	120.800	8.542	2.701
syl-f	i	LL	10	85.920	15.800	4.996	10	70.880	3.292	1.041
syl-ini	i	LL	10	98.880	16.222	5.130	10	71.600	4.935	1.561
syllabic	i	LL	10	107.120	13.261	4.193	10	92.480	9.084	2.873
syl-f	i	HL	10	82.888	11.768	3.721	10	64.960	5.629	1.780
syl-ini	i	HL	10	93.520	6.989	2.210	10	72.480	4.773	1.509
syllabic	i	HL	10	114.240	16.433	5.197	10	97.600	7.225	2.285

Means Table for Figure 3.13 (in msec)

			S1 Count	S1 Mean	S1 Std. Dev.	S1 Std. Err.	S2 Count	S2 Mean	S2 Std. Dev.	S2 Std. Err.
syl-f	a	LL	10	10.400	1.809	.572	10	10.320	4.035	1.276
syl-ini	a	LL	9	7.467	1.649	.550	10	6.640	2.067	.654
syllabic	a	LL	9	26.578	10.657	3.552	10	35.680	15.764	4.985
syl-f	a	HL	10	6.960	1.135	.359	10	9.280	2.827	.894
syl-ini	a	HL	10	6.480	1.219	.386	10	7.520	1.777	.562
syllabic	a	HL	10	18.480	5.286	1.672	10	24.320	7.858	2.485
syl-f	i	LL	10	11.840	2.740	.867	10	10.640	5.130	1.622
syl-ini	i	LL	10	9.280	1.317	.417	10	8.320	1.652	.523
syllabic	i	LL	10	37.520	19.364	6.123	10	31.040	14.165	4.479
syl-f	i	HL	10	9.213	1.776	.562	10	11.920	4.732	1.496
syl-ini	i	HL	9	10.400	2.227	.742	10	10.480	3.445	1.089
syllabic	i	HL	10	41.530	18.178	5.748	9	25.422	13.283	4.428

			S3				S4			
			Count	Mean	Std. Dev.	Std. Err.	Count	Mean	Std. Dev.	Std. Err.
syl-f	a	LL	10	5.840	1.309	.414	10	11.520	3.718	1.176
syl-ini	a	LL	9	5.067	1.649	.550	9	10.133	2.993	.998
syllabic	a	LL	10	35.052	18.942	5.990	10	28.560	11.764	3.720
syl-f	a	HL	10	5.680	1.434	.453	10	12.080	1.940	.613
syl-ini	a	HL	10	5.520	2.783	.880	10	9.600	1.067	.337
syllabic	a	HL	9	29.956	14.763	4.921	10	28.560	7.683	2.430
syl-f	i	LL	10	12.960	2.160	.683	10	23.680	9.139	2.890
syl-ini	i	LL	10	8.560	4.604	1.456	10	15.440	4.217	1.334
syllabic	i	LL	10	49.234	28.864	9.128	10	37.760	11.702	3.700
syl-f	i	HL	10	12.013	4.738	1.498	10	19.120	5.860	1.853
syl-ini	i	HL	10	8.880	3.232	1.022	10	15.040	3.691	1.167
syllabic	i	HL	10	57.760	28.832	9.117	9	36.711	14.905	4.968

Means Table for Figure 3.14 (in msec)

			S1				S2			
			Count	Mean	Std. Dev.	Std. Err.	Count	Mean	Std. Dev.	Std. Err.
syl-f	a	LL	10	96.720	5.872	1.857	10	108.08	6.655	2.105
syl-ini	a	LL	10	89.760	3.805	1.203	10	106.32	6.11	1.932
syllabic	a	LL	10	112.960	14.473	4.577	10	140.72	8.976	2.838
syl-f	a	HL	10	88.560	5.517	1.745	10	94.72	15.523	4.909
syl-ini	a	HL	10	87.680	4.433	1.402	10	97.52	4.732	1.496
syllabic	a	HL	10	110.240	6.398	2.023	10	126.96	14.035	4.438
syl-f	i	LL	10	102.960	3.111	.984	10	107.92	7.366	2.329
syl-ini	i	LL	10	103.680	6.048	1.913	10	111.36	12.871	4.07
syllabic	i	LL	10	118.320	10.749	3.399	10	148.72	13.479	4.262
syl-f	i	HL	10	102.403	3.655	1.156	10	97.68	6.74	2.132
syl-ini	i	HL	10	102.960	4.741	1.499	10	97.36	4.635	1.466
syllabic	i	HL	10	133.087	15.194	4.805	10	137.84	14.689	4.645

			S3				S4			
			Count	Mean	Std. Dev.	Std. Err.	Count	Mean	Std. Dev.	Std. Err.
syl-f	a	LL	10	108.000	5.744	1.816	10	101.680	9.499	3.004
syl-ini	a	LL	10	97.600	5.927	1.874	10	98.560	4.459	1.410
syllabic	a	LL	10	135.165	13.641	4.314	10	127.680	15.709	4.968
syl-f	a	HL	10	99.840	8.252	2.610	10	97.440	3.767	1.191
syl-ini	a	HL	10	94.960	6.105	1.931	10	95.440	4.495	1.421
syllabic	a	HL	10	139.280	19.590	6.195	10	132.480	9.609	3.039
syl-f	i	LL	10	112.080	13.725	4.340	10	91.040	4.871	1.540
syl-ini	i	LL	10	105.541	27.935	8.834	10	96.720	2.757	.872
syllabic	i	LL	10	135.930	15.922	5.035	10	115.040	12.948	4.095
syl-f	i	HL	10	110.664	13.858	4.382	10	91.040	3.730	1.179
syl-ini	i	HL	10	123.920	46.249	14.625	10	93.840	5.240	1.657
syllabic	i	HL	10	129.120	25.081	7.931	10	119.840	9.912	3.134

Means Table for Figure 3.15 (in mm)

			S1				S2			
			Count	Mean	Std. Dev.	Std. Err.	Count	Mean	Std. Dev.	Std. Err.
syl-f	a	LL	10	16.817	1.890	.598	10	6.557	1.205	.381
syl-ini	a	LL	10	15.243	1.537	.486	10	6.940	.813	.257
syllabic	a	LL	10	15.411	1.809	.572	10	6.890	1.589	.502
syl-f	a	HL	10	16.175	1.077	.340	10	5.855	1.062	.336
syl-ini	a	HL	10	15.451	.640	.202	10	7.527	.626	.198
syllabic	a	HL	10	18.392	1.543	.488	10	7.341	.624	.197
syl-f	i	LL	10	8.829	.848	.268	10	5.158	.576	.182
syl-ini	i	LL	10	10.323	.900	.284	10	5.179	.899	.284
syllabic	i	LL	10	10.202	2.302	.728	10	5.067	.680	.215
syl-f	i	HL	10	9.634	.904	.286	10	4.185	.415	.131
syl-ini	i	HL	10	8.841	.482	.152	10	4.746	.504	.159
syllabic	i	HL	10	12.386	1.130	.357	10	5.114	.850	.269

			S3				S4			
			Count	Mean	Std. Dev.	Std. Err.	Count	Mean	Std. Dev.	Std. Err.
syl-f	a	LL	10	9.331	.563	.178	10	6.839	1.468	.464
syl-ini	a	LL	10	8.899	1.155	.365	10	7.024	.649	.205
syllabic	a	LL	10	9.189	1.197	.378	10	8.514	.554	.175
syl-f	a	HL	10	8.552	.706	.223	10	7.485	.521	.165
syl-ini	a	HL	10	8.688	.729	.231	10	8.093	.480	.152
syllabic	a	HL	[illegible]	8.501	1.023	.324	10	9.186	.676	.214
syl-f	i	LL	10	6.363	.633	.200	10	3.364	.537	.170
syl-ini	i	LL	10	6.066	.990	.313	10	3.575	.607	.192
syllabic	i	LL	10	7.753	1.436	.454	10	4.172	.746	.236
syl-f	i	HL	10	7.080	.827	.261	10	3.829	.461	.146
syl-ini	i	HL	10	6.263	.917	.290	10	3.373	.631	.200
syllabic	i	HL	10	7.795	.473	.150	10	4.439	.774	.245

Means Table for Figure 3.16 (in mm)

			S1				S2			
			Count	Mean	Std. Dev.	Std. Err.	Count	Mean	Std. Dev.	Std. Err.
syl-f	a	LL	10	1.052	.432	.137	10	18.773	1.997	.632
syl-ini	a	LL	10	.688	.710	.224	10	17.448	1.398	.442
syllabic	a	LL	10	1.739	.791	.250	9	11.213	7.399	2.466
syl-f	a	HL	10	.962	.385	.122	9	16.874	3.314	1.105
syl-ini	a	HL	10	1.185	.953	.301	10	7.795	6.072	1.920
syllabic	a	HL	10	1.707	.477	.151	10	13.925	6.322	1.999
syl-f	i	LL	10	1.502	.778	.246	10	11.824	8.717	2.757
syl-ini	i	LL	10	1.911	.476	.150	10	14.866	2.531	.800
syllabic	i	LL	10	2.769	.877	.277	10	13.549	4.387	1.387
syl-f	i	HL	10	2.638	.636	.201	10	10.954	7.475	2.364
syl-ini	i	HL	10	1.854	.544	.172	10	8.740	4.520	1.429
syllabic	i	HL	10	2.604	.867	.274	10	17.425	1.752	.554

			S3 Count	S3 Mean	S3 Std. Dev.	S3 Std. Err.	S4 Count	S4 Mean	S4 Std. Dev.	S4 Std. Err.
syl-f	a	LL	10	14.430	.486	.154	10	13.275	.344	.109
syl-ini	a	LL	10	14.599	.301	.095	10	13.666	.346	.109
syllabic	a	LL	10	16.286	.561	.177	9	14.538	.315	.105
syl-f	a	HL	10	14.233	.254	.080	10	13.629	.399	.126
syl-ini	a	HL	10	14.377	.531	.168	10	13.678	.317	.100
syllabic	a	HL	10	16.076	.447	.141	10	15.120	.244	.077
syl-f	i	LL	10	15.070	.369	.117	10	14.564	.386	.122
syl-ini	i	LL	10	15.145	.382	.121	10	14.134	.292	.092
syllabic	i	LL	9	15.883	.365	.122	10	14.820	.222	.070
syl-f	i	HL	10	14.746	.668	.211	10	14.317	.320	.101
syl-ini	i	HL	10	15.156	.407	.129	10	14.326	.238	.075
syllabic	i	HL	10	15.783	.630	.199	10	14.961	.322	.102

Means Table for Figure 3.17 (in mm)

			S1 Count	S1 Mean	S1 Std. Dev.	S1 Std. Err.	S2 Count	S2 Mean	S2 Std. Dev.	S2 Std. Err.
syl-f	a	LL	10	-12.707	1.279	.405	10	-6.220	1.025	.324
syl-ini	a	LL	10	-11.119	1.757	.556	10	-8.657	.779	.246
syllabic	a	LL	10	-12.327	2.020	.639	10	-5.762	1.073	.339
syl-f	a	HL	10	-11.419	.740	.234	10	-5.801	1.738	.550
syl-ini	a	HL	10	-11.263	1.876	.593	10	-7.066	.552	.175
syllabic	a	HL	10	-12.641	1.725	.545	10	-5.280	.842	.266
syl-f	i	LL	10	-9.762	1.092	.345	10	-6.046	.767	.243
syl-ini	i	LL	10	-11.109	.802	.254	10	-6.275	.675	.213
syllabic	i	LL	10	-11.425	1.536	.486	10	-6.022	.850	.269
syl-f	i	HL	10	-10.386	.831	.263	10	-4.607	.682	.216
syl-ini	i	HL	10	-9.101	.833	.264	10	-5.317	.492	.156
syllabic	i	HL	10	-12.125	1.707	.540	10	-5.327	.796	.252

			S3 Count	S3 Mean	S3 Std. Dev.	S3 Std. Err.	S4 Count	S4 Mean	S4 Std. Dev.	S4 Std. Err.
syl-f	a	LL	10	-5.939	.678	.214	10	-7.009	1.237	.391
syl-ini	a	LL	10	-5.774	.559	.177	10	-7.831	.611	.193
syllabic	a	LL	10	-7.378	.678	.215	10	-8.550	.575	.182
syl-f	a	HL	10	-5.584	.484	.153	10	-7.484	.655	.207
syl-ini	a	HL	10	-5.041	.713	.225	10	-7.977	.615	.194
syllabic	a	HL	10	-7.430	1.066	.337	10	-9.298	.927	.293
syl-f	i	LL	10	-3.982	1.103	.349	10	-5.086	.577	.182
syl-ini	i	LL	10	-4.665	.674	.213	10	-6.025	.465	.147
syllabic	i	LL	10	-4.908	.764	.242	10	-5.302	.605	.191
syl-f	i	HL	10	-4.064	.639	.202	10	-4.862	.934	.295
syl-ini	i	HL	10	-4.864	.801	.253	10	-5.525	.734	.232
syllabic	i	HL	10	-5.337	1.167	.369	10	-5.296	.955	.302

Means Table for Figure 3.22 (in msec)

			S1				S2			
			Count	Mean	Std. Dev.	Std. Err.	Count	Mean	Std. Dev.	Std. Err.
syl-f	a	LL	10	-210.080	13.551	4.285	10	-121.920	11.576	3.661
syl-ini	a	LL	10	-172.640	18.285	5.782	10	-119.280	15.279	4.832
syllabic	a	LL	10	-192.640	24.769	7.833	10	-153.520	41.650	13.171
syl-f	a	HL	10	-192.800	14.766	4.669	10	-127.040	18.874	5.969
syl-ini	a	HL	10	-189.360	11.495	3.635	10	-122.160	12.621	3.991
syllabic	a	HL	10	-251.280	18.380	5.812	10	-126.240	16.729	5.290
syl-f	i	LL	10	-81.760	18.066	5.713	10	-82.880	10.715	3.388
syl-ini	i	LL	10	-77.920	11.182	3.536	10	-93.840	6.965	2.202
syllabic	i	LL	10	-109.840	20.684	6.541	10	-125.120	11.879	3.756
syl-f	i	HL	10	-94.000	6.653	2.104	10	-67.040	8.802	2.784
syl-ini	i	HL	10	-100.880	19.408	6.137	10	-78.720	14.222	4.497
syllabic	i	HL	10	-112.480	10.621	3.359	10	-125.440	18.731	5.923

			S3				S4			
			Count	Mean	Std. Dev.	Std. Err.	Count	Mean	Std. Dev.	Std. Err.
syl-f	a	LL	10	-189.280	15.773	4.988	9	-155.111	11.359	3.786
syl-ini	a	LL	10	-189.920	9.045	2.860	10	-164.400	15.063	4.763
syllabic	a	LL	10	-226.400	42.238	13.357	10	-209.040	10.349	3.273
syl-f	a	HL	9	-209.511	16.883	5.628	10	-172.720	4.777	1.511
syl-ini	a	HL	10	-186.480	11.651	3.684	10	-178.240	14.305	4.524
syllabic	a	HL	10	-247.760	23.424	7.407	10	-234.560	13.439	4.250
syl-f	i	LL	10	-104.080	13.709	4.335	10	-99.200	5.927	1.874
syl-ini	i	LL	10	-128.320	13.334	4.217	10	-98.000	12.951	4.095
syllabic	i	LL	10	-137.200	26.792	8.472	10	-108.960	8.689	2.748
syl-f	i	HL	10	-99.440	29.144	9.216	10	-103.840	10.738	3.396
syl-ini	i	HL	10	-125.840	21.569	6.821	10	-110.160	12.062	3.814
syllabic	i	HL	10	-151.680	27.253	8.618	10	-138.080	11.735	3.711

Means Table for Figure 3.23 (in msec)

			S1				S2			
			Count	Mean	Std. Dev.	Std. Err.	Count	Mean	Std. Dev.	Std. Err.
syl-f	a	LL	10	-15.760	11.327	3.582	10	120.480	17.344	5.485
syl-ini	a	LL	9	4.000	16.570	5.523	10	103.760	16.992	5.373
syllabic	a	LL	9	15.556	8.382	2.794	10	140.800	16.912	5.348
syl-f	a	HL	10	1.120	13.827	4.372	10	109.520	13.256	4.192
syl-ini	a	HL	10	13.120	10.748	3.399	10	93.360	8.788	2.779
syllabic	a	HL	10	-8.800	16.273	5.146	10	152.320	10.029	3.171
syl-f	i	LL	10	103.284	14.267	4.512	10	98.080	11.118	3.516
syl-ini	i	LL	10	96.080	5.561	1.759	10	96.320	11.594	3.666
syllabic	i	LL	10	125.840	20.382	6.445	10	157.040	15.713	4.969
syl-f	i	HL	10	90.720	8.281	2.619	10	88.720	6.634	2.098
syl-ini	i	HL	10	96.240	11.105	3.512	10	92.160	10.785	3.410
syllabic	i	HL	10	118.160	8.608	2.722	10	143.520	10.996	3.477

			S3 Count	S3 Mean	S3 Std. Dev.	S3 Std. Err.	S4 Count	S4 Mean	S4 Std. Dev.	S4 Std. Err.
syl-f	a	LL	10	91.680	14.157	4.477	9	83.467	17.504	5.835
syl-ini	a	LL	10	81.120	15.124	4.782	10	86.400	8.141	2.574
syllabic	a	LL	10	131.039	28.916	9.144	10	112.240	9.137	2.889
syl-f	a	HL	9	94.578	25.421	8.474	10	99.360	8.859	2.801
syl-ini	a	HL	10	79.040	19.783	6.256	10	88.240	10.231	3.235
syllabic	a	HL	10	126.240	28.777	9.100	8	119.600	8.147	2.880
syl-f	i	LL	10	106.320	12.913	4.083	10	81.680	5.259	1.663
syl-ini	i	LL	10	98.720	13.687	4.328	10	82.640	5.074	1.605
syllabic	i	LL	10	140.480	19.319	6.109	10	125.120	7.740	2.448
syl-f	i	HL	10	103.920	15.940	5.041	10	72.800	6.093	1.927
syl-ini	i	HL	10	94.240	10.857	3.433	10	78.640	8.228	2.602
syllabic	i	HL	10	137.280	14.107	4.461	10	122.240	14.434	4.564

Means Table for Figure 3.24 (in msec)

			S1 Count	S1 Mean	S1 Std. Dev.	S1 Std. Err.	S2 Count	S2 Mean	S2 Std. Dev.	S2 Std. Err.
syl-f	a	LL	10	-116.000	9.114	2.882	10	12.320	11.974	3.787
syl-ini	a	LL	9	-95.022	18.884	6.295	10	10.560	14.846	4.695
syllabic	a	LL	9	-117.156	20.927	6.976	9	1.867	16.795	5.598
syl-f	a	HL	10	-91.520	16.067	5.081	10	5.040	16.076	5.084
syl-ini	a	HL	10	-82.080	13.098	4.142	10	-5.440	6.786	2.146
syllabic	a	HL	10	-154.880	17.163	5.427	10	-1.600	11.751	3.716
syl-f	i	LL	10	4.804	7.413	2.344	10	.880	8.856	2.801
syl-ini	i	LL	10	-6.880	6.369	2.014	10	-5.360	6.862	2.170
syllabic	i	LL	10	-11.360	32.188	10.179	10	4.880	13.001	4.111
syl-f	i	HL	10	2.160	6.423	2.031	10	1.600	6.322	1.999
syl-ini	i	HL	10	-.720	8.403	2.657	10	-.800	6.618	2.093
syllabic	i	HL	10	-4.000	11.364	3.594	10	.000	15.038	4.755

			S3 Count	S3 Mean	S3 Std. Dev.	S3 Std. Err.	S4 Count	S4 Mean	S4 Std. Dev.	S4 Std. Err.
syl-f	a	LL	10	-1.040	10.969	3.469	9	5.156	17.219	5.740
syl-ini	a	LL	10	-15.280	12.436	3.933	10	7.680	7.324	2.316
syllabic	a	LL	10	-6.001	25.669	8.117	10	-1.920	13.990	4.424
syl-f	a	HL	9	-7.467	20.124	6.708	10	16.560	12.086	3.822
syl-ini	a	HL	10	-11.520	18.842	5.958	10	7.200	10.600	3.352
syllabic	a	HL	10	-15.280	29.206	9.236	8	-.400	7.369	2.605
syl-f	i	LL	10	20.400	9.763	3.087	10	10.800	7.158	2.264
syl-ini	i	LL	10	-.160	9.672	3.059	10	11.040	6.880	2.176
syllabic	i	LL	10	33.360	17.681	5.591	10	32.640	12.860	4.067
syl-f	i	HL	10	20.880	8.587	2.715	10	7.840	9.282	2.935
syl-ini	i	HL	10	.720	11.839	3.744	10	6.160	5.466	1.728
syllabic	i	HL	10	23.040	18.893	5.975	10	24.640	14.009	4.430

Means Table for Figure 3.25 (in msec)

			S1				S2			
			Count	Mean	Std. Dev.	Std. Err.	Count	Mean	Std. Dev.	Std. Err.
syl-f	a	LL	10	115.068	13.023	4.118	10	127.386	8.267	2.614
syl-ini	a	LL	10	105.821	10.366	3.278	10	132.845	9.325	2.949
syllabic	a	LL	10	123.611	20.095	6.355	10	176.033	16.487	5.214
syl-f	a	HL	10	113.927	11.444	3.619	10	125.221	10.168	3.215
syl-ini	a	HL	10	126.329	7.144	2.259	10	125.314	11.232	3.552
syllabic	a	HL	10	140.801	16.156	5.109	10	161.074	14.142	4.472
syl-f	i	LL	10	50.032	19.784	6.256	10	60.768	12.602	3.985
syl-ini	i	LL	10	76.348	13.089	4.139	10	98.156	10.459	3.308
syllabic	i	LL	10	104.107	16.509	5.221	10	144.491	15.304	4.839
syl-f	i	HL	10	53.969	10.053	3.179	10	62.420	8.517	2.693
syl-ini	i	HL	10	77.584	12.027	3.803	10	107.118	8.186	2.589
syllabic	i	HL	10	120.263	17.192	5.437	10	141.955	20.781	6.571

			S3				S4			
			Count	Mean	Std. Dev.	Std. Err.	Count	Mean	Std. Dev.	Std. Err.
syl-f	a	LL	10	108.032	6.115	1.934	10	103.304	11.727	3.708
syl-ini	a	LL	10	120.695	8.677	2.744	10	105.046	12.231	3.868
syllabic	a	LL	10	134.836	7.376	2.332	10	137.691	7.726	2.443
syl-f	a	HL	10	123.298	10.142	3.207	10	105.624	8.438	2.668
syl-ini	a	HL	10	125.127	8.543	2.701	10	122.702	8.846	2.797
syllabic	a	HL	10	146.186	11.473	3.628	10	154.235	10.448	3.304
syl-f	i	LL	10	51.886	8.255	2.610	10	65.123	6.698	2.118
syl-ini	i	LL	10	89.453	5.778	1.827	10	83.809	7.585	2.398
syllabic	i	LL	10	103.229	12.237	3.870	10	118.739	11.045	3.493
syl-f	i	HL	10	53.677	8.184	2.588	10	59.845	7.702	2.436
syl-ini	i	HL	10	76.242	8.806	2.785	10	92.423	11.165	3.531
syllabic	i	HL	10	95.060	13.891	4.393	10	132.807	22.568	7.137

Means Table for Figure 3.26 (in msec)

			S1				S2			
			Count	Mean	Std. Dev.	Std. Err.	Count	Mean	Std. Dev.	Std. Err.
syl-f	a	LL	10	80.373	8.873	2.806	10	97.386	6.271	1.983
syl-ini	a	LL	10	59.742	14.273	4.514	10	79.163	6.446	2.038
syllabic	a	LL	10	133.689	14.251	4.507	10	162.252	21.156	6.690
syl-f	a	HL	10	53.877	5.249	1.660	10	96.261	7.652	2.420
syl-ini	a	HL	10	48.744	7.427	2.349	10	73.210	6.786	2.146
syllabic	a	HL	10	111.335	9.605	3.037	10	151.791	19.979	6.318
syl-f	i	LL	10	76.535	7.441	2.353	10	101.739	26.417	8.354
syl-ini	i	LL	10	72.349	9.974	3.154	10	47.312	12.770	4.038
syllabic	i	LL	10	131.825	18.590	5.879	10	116.673	15.735	4.976
syl-f	i	HL	10	68.565	4.481	1.417	10	48.169	8.317	2.630
syl-ini	i	HL	10	66.750	5.175	1.636	10	46.759	19.575	6.190
syllabic	i	HL	10	120.555	20.772	6.569	10	144.678	45.199	14.293

			S3				S4			
			Count	Mean	Std. Dev.	Std. Err.	Count	Mean	Std. Dev.	Std. Err.
syl-f	ɑ	LL	10	81.834	7.231	2.287	10	79.697	7.491	2.369
syl-ini	ɑ	LL	10	66.865	6.550	2.071	10	73.705	3.604	1.140
syllabic	ɑ	LL	10	152.444	21.934	6.936	10	138.815	12.740	4.029
syl-f	ɑ	HL	10	76.167	3.284	1.039	10	77.567	12.218	3.864
syl-ini	ɑ	HL	10	65.964	5.608	1.773	10	66.860	7.847	2.481
syllabic	ɑ	HL	10	154.075	11.259	3.561	10	145.895	10.518	3.326
syl-f	i	LL	10	106.010	11.246	3.556	10	84.179	13.130	4.152
syl-ini	i	LL	10	71.252	4.704	1.487	10	75.977	7.472	2.363
syllabic	i	LL	10	167.196	18.937	5.988	10	127.517	13.689	4.329
syl-f	i	HL	10	94.260	12.540	3.966	10	73.410	6.282	1.987
syl-ini	i	HL	10	70.927	7.128	2.254	10	64.602	6.859	2.169
syllabic	i	HL	10	157.357	19.294	6.101	10	132.493	17.370	5.493

Means Table for Figure 3.27 (in msec)

			S1				S2			
			Count	Mean	Std. Dev.	Std. Err.	count	Mean	Std. Dev.	Std. Err.
syl-f	ɑ	LL	10	119.033	11.788	3.728	10	127.968	12.054	3.812
syl-ini	ɑ	LL	10	109.696	17.608	5.568	10	132.227	9.822	3.106
syllabic	ɑ	LL	10	146.110	60.537	19.144	10	165.129	11.284	3.568
syl-f	ɑ	HL	10	103.082	12.355	3.907	10	116.390	11.935	3.774
syl-ini	ɑ	HL	10	103.637	3.725	1.178	10	131.582	17.611	5.569
syllabic	ɑ	HL	10	116.266	10.436	3.300	10	149.785	22.167	7.010
syl-f	i	LL	10	75.696	9.912	3.135	10	89.244	20.619	6.520
syl-ini	i	LL	10	67.409	5.707	1.805	10	94.414	7.591	2.400
syllabic	i	LL	10	102.782	15.759	4.983	10	158.486	16.125	5.099
syl-f	i	HL	10	70.432	6.625	2.095	10	115.958	14.829	4.689
syl-ini	i	HL	10	66.122	4.120	1.303	10	86.012	19.160	6.059
syllabic	i	HL	10	113.641	23.764	7.515	10	135.913	23.370	7.390

			S3				S4			
			Count	Mean	Std. Dev.	Std. Err.	count	Mean	Std. Dev.	Std. Err.
syl-f	ɑ	LL	10	132.357	14.417	4.559	10	129.563	16.678	5.274
syl-ini	ɑ	LL	10	131.272	7.044	2.227	10	133.004	10.825	3.423
syllabic	ɑ	LL	10	150.273	10.065	3.183	10	135.173	9.760	3.087
syl-f	ɑ	HL	10	133.340	6.035	1.909	10	135.325	12.375	3.913
syl-ini	ɑ	HL	10	123.362	7.321	2.315	10	132.636	9.438	2.984
syllabic	ɑ	HL	10	147.337	10.609	3.355	10	134.720	8.421	2.663
syl-f	i	LL	10	98.551	12.099	3.826	10	93.927	11.380	3.599
syl-ini	i	LL	10	70.665	8.709	2.754	10	70.814	7.320	2.315
syllabic	i	LL	10	112.543	12.210	3.861	10	108.012	12.644	3.998
syl-f	i	HL	10	92.211	9.425	2.980	10	85.623	10.598	3.351
syl-ini	i	HL	10	72.254	8.329	2.634	10	78.722	15.129	4.784
syllabic	i	HL	10	120.162	14.600	4.617	10	106.635	18.720	5.920