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The timing of vowel and consonant gestures

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The Timing of Vowel and Consonant Gestures

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ABSTRACT

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Cross-language differences in the temporal organization of articulatory gestures for vowels and consonants may relate to the overall rhythmic structure of a language. Two models of these differences are compared. In one, successive vowels are timed in relation to each other; in the other, intervening consonants are also taken into account.

The two models of timing were compared using Articulatory Phonology (Browman and Goldstein 1986), in which articulatory gestures are the basis of phonological representation. Movements of the tongue and lips in Japanese and Italian utterances with single and geminate consonants were recorded using the NIH X-ray microbeam facility at the University of Wisconsin, Madison, and the timing of the articulatory gestures was investigated by relating the abstract gestures to measurements of these movements. Virtually every measured interval in the Japanese utterances was longer when the intervocalic consonant was a geminate, suggesting that the coordination between gestures is affected by the length of the consonant, as predicted by the combined vowel-and-consonant timing model. The Italian speakers showed a tendency to maintain a constant interval between the times at which the two vowels reached their target positions, supporting the hypothesis that a change in consonant length does not affect the relative timing of the vowels, as in the vowel-to-vowel timing model.

Temporal patterns of the two languages were modeled by specifying the coordination among gestures in terms of stiffness and phasing relations. These models, when used to predict the durations of the measured intervals, showed that the observed

patterns of durational differences between utterances with single and geminate consonants could be produced using an organization based on combined vowel-and-consonant timing for Japanese, and an organization based on vowel-to-vowel timing for Italian.

Finally, some suggestions are made as to how the difference in the timing organization of Japanese and Italian relates to other prosodic characteristics of these languages, particularly the traditional descriptions of Italian as syllable-based and Japanese as mora-based.

PREFACE

This dissertation, perhaps more than most, required the assistance of a great many people. I will attempt to recognize those who made direct contributions, and I apologize to those not named here who were also important to me.

Starting with the most tangible contribution, I would like to thank the National Science Foundation for providing me with the Graduate Fellowship that initially enabled me to come to Yale. NSF also provided grant BNS 8820099 to Haskins Laboratories, which funded this dissertation, along with NIH grant DC 00121. I am deeply grateful for having been permitted to work at Haskins as a research assistant for quite a number of years; I could not have produced this dissertation without the prior experience I had accumulated.

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Of course the most substantive contribution to this work was made by my advisor, Louis Goldstein. Louis has contributed to every aspect of this dissertation, from his original, helpful(?) suggestion to use the microbeam, to organizing my writing into something more than random walks through the data. The training I received as a research assistant with Cathe Browman was also essential to my accomplishment of this dissertation. I would especially like to thank Louis and Cathe for sharing their

excitement in their work, as well as the work, with me over the years I have been at Haskins. I hope that they feel this dissertation is a worthy expansion to the realm of Articulatory Phonology.

Ignatius Mattingly has been friend, counselor and editor *par excellence*. Never at a loss for a word of wisdom or encouragement, Ignatius has helped me all along the way. I would also like to thank Draga Zec for helpful discussion and for serving as a reader.

Many other people at Haskins have helped me. It has been my good fortune to have assistance from unusually cooperative programmers. In particular, Mark Tiede developed several programs that I used in processing microbeam data, and was always willing to entertain questions and suggestions. Marian MacEachron and Bill Scully also listened to my queries and comments about their programs and were very responsive to my needs. I would also like to thank the rest of the Haskins technical staff – Mike DiAngelo, Vin Gulisano, Donald Hailey, Yvonne Manning and Ed Wiley – for helping me many times.

Many of my fellow students and colleagues at Haskins have contributed in various ways to my work, and to making the basement of 270 Crown Street as fun a place to work as a windowless basement could be. For various forms of assistance during the course of my dissertation preparation, thanks to Anders Löfqvist, Phil Rubin, Elliot Saltzman and Doug Whalen. I am grateful for friends near and far who cheered me on, especially during the last few weeks of non-stop work. Special thanks go to Betty Kollia, Rena Krakow, Mark Tiede and Lisa Zsiga, who provided bright ideas, kind words, lunch, dinner, and much friendship and encouragement.

For last-minute assistance, a very big thank you to Lisa Zsiga and Melanie Campbell, who were generous with their time in helping me to prepare this document.

And, last but not least, I would like to thank Stonyfield Farm for their cappuccino yoghurt, which sustained me through countless evenings and solved the mystery of how much weight is added by geminating an intervocalic /p/ (5 calories).

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Chapter I

INTRODUCTION

In work on the phonological representation of vowels and consonants, two questions in particular have received special attention: the conditions for separating vowel and consonant melodic features onto distinct tiers or planes (e.g., McCarthy 1981, 1982, 1986, 1989; Prince 1987; Archangeli 1985; Cole 1987; Steriade 1986), and the possibility of separating vowel and consonant features in the feature tree (Clements 1985, 1989, 1991; McCarthy 1988; Sagey 1986). Both of these questions concern the degree to which vowels and consonants are specified independently of one another. Most frameworks take the distinction between these two classes as a fundamental given of phonological structure, usually represented by the root node of a feature tree being specified as + or - consonantal (C or V). (Those systems that do not use CV-slots organize the feature trees by means of higher-level structures within the syllable, but the distinction between vowels (syllable nuclei) and consonants (syllable margins) is still necessary.) Representing vowels and consonants on separate tiers or planes gives them considerable autonomy phonologically. Many analyses have taken advantage of this separation to explain processes in which locality conditions are superficially violated, for example, when vowels sometimes behave as if an intervocalic consonant were absent or consonants as if a vowel were not there (e.g. Archangeli 1985; Keating 1985a; McCarthy 1981, 1982, 1989; McCarthy & Prince 1986).

That vowels and consonants may be autonomous to some degree has also been concluded from analyses of articulatory and acoustic data of consonant-vowel sequences: it has been hypothesized that the production of vowels is continuous, with the consonants added as local, individual events (Joos 1948; Öhman 1966, 1967; Fowler 1980, 1981, 1983). This phenomenon has been called "coproduction" (Fowler 1980), because the assumption is that there are distinct vowels and consonants, identifiable as such, but produced at least partially simultaneously, with the consequence that their articulatory and acoustic consequences influence each other.

The convergence of these two forms of evidence, both suggesting, as will be discussed below, that the relation between consonants and vowels may be more complex than just a linear ordering, was taken as the starting point for this study. It is proposed here that languages may choose from a number of alternative ways of specifying the coordination among consonants and vowels, and that these alternatives underlie differing prosodic properties that languages may demonstrate. The approach taken here to this question involves defining consonants and vowels in terms of articulatory gestures. This provides a phonological description that also explicitly specifies how consonants and vowels behave in speech production. As will be discussed below, this specificity makes it possible to predict how differences in articulatory coordination could result in different prosodic characteristics, such as the timing patterns traditionally described as stress-, syllable- or mora-timing.

1. Goals of this study

This dissertation is about how cross-language differences in the patterns of coordination of vowel and consonant gestures could be responsible for the perceived differences in rhythmic structure among languages. The problem of relating articulatory timing patterns to traditional timing categories can be broken down into: (a) what the observed articulatory timing indicates about the relations between consonant and vowel gestures, (b) how such relations can be modeled, and (c) how different consonant-vowel relations can capture the contrasts between traditional categories of timing patterns. To begin to answer these questions I will first consider the possible types of organization between consonants and vowels that can be hypothesized to occur in languages.

2. Gestural models of consonant-vowel relations

Consonants and vowels can be distinguished along a number of different dimensions, including function, phonological patterning, and articulatory properties. To take "consonant" and "vowel" as phonological primitives requires determining the frame of reference in which these terms are being used. In terms of function, a vowel can be defined as the peak of a syllable, a consonant as an element of the margin of the syllable (e.g. Clements & Keyser 1983). Abercrombie (1967), following Pike (1943), combines two dimensions ("form" and "function") that have been used to define vowels and consonants, and contrasts four categories, instead of just two: more open positions of the vocal tract that may or may not occupy a syllable peak and more closed positions of the vocal tract that can also occupy syllable peaks or margins.

The contrast between vowels and consonants has also been made in more articulatory terms. Results from studies of the production and perception of rhythm and coarticulation, as well as physiological evidence (e.g. Perkell 1980), led Fowler (1977, 1983) to propose that vowel and consonant production are separate, and that vowels are produced in a continuous cycle whose parameters vary, while consonants are more localized, discrete deformations of the vocal tract. The two categories are distinguished, in part, by their different dynamic characteristics. A distinction between vowels and consonants in terms of dynamic differences is also made in the model of Browman and Goldstein (1989), in which vowels are those tongue gestures for which the constriction is more open than that which would result in frication but which lack the increased (dynamic) stiffness, leading to more rapid movement, characteristic of approximant consonants. Gestures with tighter constrictions or increased stiffness are consonants.

For the questions posed here regarding temporal interactions, defining consonants and vowels in terms of articulatory gestures offers some significant advantages. As used here, a gesture is both a primitive of phonological representation and an abstract, dynamic unit of action, which controls the coordinated movement of one or more articulators towards a constriction goal (Browman & Goldstein 1986, 1990a,b, in press).

Steriade (1990) noted that probably the most salient difference between a gestural specification and a feature-based specification is that gestures are units that have their own intrinsic temporal extent. Treating consonants and vowels as gestures having intrinsic duration means that a description of the timing relations between them could be more principled because time does not have to be explicitly imposed to combine non-temporal units, as would be necessary in a system without intrinsic timing (Fowler, Rubin, Remez & Turvey 1980). Since the gestures are defined as having spatial and temporal extent, all that has to be specified is how they are arranged in time and space. The overlapping among multiple gestures is then a natural and automatic consequence of the specification of the individual gestures and their arrangement. In addition, the correspondence between articulatory data and the specification of the underlying units can be more direct when these units are gestures than in a feature-based system (Browman & Goldstein 1990a,b). In Articulatory Phonology, a gesture is a coordinative structure (Turvey 1977) that characterizes the task-oriented movements of a set of coordinated articulators. Each gesture is defined in spatial terms by tract variables (Saltzman 1986; Saltzman & Kelso 1987; Saltzman & Munhall 1989), whose characteristics are specified by categorical descriptors of the tasks that make up the gesture, a task typically being the formation of a constriction in some part of the vocal tract. Temporally, the gesture is specified by a small set of parameters that determine the time course of the movements associated with that gesture (Browman & Goldstein 1986, 1990 a,b, in press; Saltzman 1986; Saltzman & Kelso 1987; Saltzman & Munhall 1989). Because Articulatory Phonology provides an explicit connection between phonological representation (in terms of categorial gestural units) and resulting articulatory movement, the phonological implications of different models of timing can be compared without introducing many additional assumptions.

Viewing consonants and vowels as defined by articulatory gestures, two models of consonant-vowel relations will be compared here that make explicit predictions about how the two types of gestures interact. Both models were originally proposed to account for the temporal organization of gestures in English; this study suggests that each may best account for languages, other than English, belonging to different categories of linguistic rhythm.

2.1. Two models of consonant-vowel relations

Previous research has suggested that consonants and vowels may combine in a not strictly linear fashion, but as separate layers with some temporal independence (Joos 1948). Öhman's (1967) analysis of vowel-to-vowel coarticulation proposed that the production of individual consonants is superimposed on a continuous vowel production. Fowler (1983) summarized a variety of experimental and phonological evidence suggesting that, at least for a sequence of stressed monosyllables, vowels are produced continuously and consonants are coordinated with them. That is, the consonants are produced separately from vowels but organized temporally with respect to them; since the production of vowels is continuous, consonants will overlap them (Fowler 1983). In this kind of model, consonants are essentially irrelevant to the temporal organization of the vowels, which is dependent on the foot structure (patterning of the stressed and unstressed units). The production of vowels should not be affected by the number of consonants or by any other property of them, such as inherent temporal differences among types of consonants.

A different possible model is one in which consonants and vowels are mutually coordinated (e.g. Browman & Goldstein 1990a): vowels can be coordinated with respect to consonants, and vice versa, rather than being exclusively coordinated with other vowels. This would mean that the temporal properties of the consonants could affect the vowels, either as a result of the properties of individual consonants or as a function of the number of consonants. How such an effect would come about depends on exactly how the consonants and vowels are coordinated. For example, in a VCV sequence suppose one stage of the consonant's production (e.g. the achievement of closure) is coordinated with the preceding vowel and that the following vowel is coordinated with respect to a later stage in the consonant (e.g. its release). If the duration of the consonant were to increase, the time between the two stages of the consonant, and hence between the vowels, might be expected to increase. This contrasts with the prediction of Fowler's model that the vowels would not be affected by differences in the consonant(s).

The behavior of these models could be distinguisbed by comparing the behavior of vowels in the contexts of different "amounts" of consonant. Such a comparison could be made by examining vowels in pairs of utterances that differed only in the number or length of the intervocalic consonant. In a general sense, if the timing relation between the vowels is the same with different numbers or lengths of consonant, then Fowler's model is supported, but if the relation between the vowels is different, then the model that coordinates vowels and consonants together is supported.

2.1.1. Vowel-to-vowel timing model

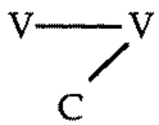
Fowler's model predicts that timing relations between vowels would be relatively independent of any changes in the consonants, since the vowels are organized rhythmically among themselves. Originally developed for English, this model was framed in terms of unstressed vowels overlapping the continuous production of stressed vowels, but could equally well apply to languages in which stress alternation is not an important organizing principle. If every vowel has equal status, as in a syllable-timed language, then all vowels would be produced in a single continuous cycle, and consonants would be overlaid on them.

One problem in comparing the model suggested by Fowler with a model of combined coordination of vowels and consonants is that the models are based on somewhat different concepts of vowel production. If the vowels and consonants are both defined in terms of discrete articulatory gestures, as in Articulatory Phonology, then the production of vowels is not a strictly continuous cycle as it is in Fowler's model. A similar model could be conceived that retains the independence of vowels from consonants that characterizes Fowler's model, but treats each vowel as a discrete gesture that must be coordinated with other vowel gestures. This will be referred to as a vowel-to-vowel timing model.

In order to examine the models' predictions more closely, it is necessary to consider just how the coordination between consonants and vowels might be described, or modeled. If they are treated as discrete gestures, then the temporal relations among them may differ depending on what points of the gestures' time courses are coordinated. Identifiable stages in a gesture will be termed "events": these include the onset of the gesture and the time at which its constriction task is achieved. Relations among events in different gestures can be described in terms of phasing relations between them (Kelso & Tuller 1987; Kelso, Saltzman & Tuller 1986; Nittrouer et al. 1988). When the gestures are specified by dynamical control regimes, each gesture can be envisioned as consisting of a virtual 360° cycle. Two gestures are phased with one another if a point in the cycle of one gesture is crucially coincident in time with a particular point in the other gesture (Browman & Goldstein 1990a,b). So, for instance, the onset of the cycle of the vowel gesture might occur at the same time as the onset of the cycle of a consonant gesture. This approach enables explicit statement of the temporal relations between two gestures whose acoustic output is not necessarily temporally adjacent.

In a model in which both vowels and consonants are specified as discrete gestures, the timing of vowel gestures independent of the consonants can be stated explicitly in terms of phasing relations. Each vowel gesture can be phased with respect to another vowel gesture, and the consonant(s) can be phased with respect to individual vowels. This structure can be represented as in (1) where lines indicate specified phasing relations:

(1)

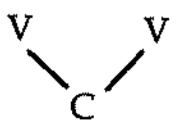


where the consonant is shown to be phased with the second vowel. Differences in number or length of consonants will not affect the phasing between the vowels, but depending on exactly how the consonant(s) is phased with the vowels, a difference in consonant length may imply a difference in the temporal relations between some subset of consonant events and the two vowel gestures.

2.1.2. Combined vowel-and-consonant model

In the model described in Browman and Goldstein (1988, 1990a,b, 1991), vowels and consonants are coordinated interdependently. Instead of an utterance being structured around (stressed) vowel relations, as in the vowel-to-vowel timing model, in this model neither vowel nor consonant gestures take precedence. Both types of gestures, specified by tract variables for constrictions of the oral part of the vocal tract, are phased with other oral gestures (although, as Browman and Goldstein note, the dynamical properties of the different gesture types result in patterns of articulatory movements compatible with Fowler's description: vowel production is nearly continuous with consonant gestures overlapping). In the simplest case, vowel and consonant gestures are coordinated sequentially, a vowel gesture phased with the preceding consonant gesture, and a consonant gesture with the preceding vowel gesture, except where there is evidence that a special organization may apply to a particular structure. An example of a more complex structure would be that the vowel after an initial consonant cluster may be coordinated with respect to a global metric for the cluster as a whole, not just the consonant that immediately precedes the vowel (Browman & Goldstein 1988). The general model will be referred to as the combined vowel-and-consonant model, and can be represented as in (2).

(2)



2.1.3. Comparing the two models

In both gesture-based models, the temporal relations between vowels and consonants can be fully specified in terms of phasing. However, because of differences in which gestures are phased with which, they make different kinds of predictions about the timing of articulatory movements in utterances for which differences (whether in duration or number) in the consonants create temporal contrasts.

In this way the models' predictions can be compared by looking at pairs of utterances identical except for a difference of duration or number in the intervocalic consonant, for example utterances with single and geminate consonants. Changing consonantal length means that only the timing is changed, as far as contrastive properties between classes of consonants are defined. (There may be other differences between single and geminate consonants, but the contrast is usually defined in terms of a difference in duration.)

What predictions do the two models make for the timing of the vowels in the context of different lengths of consonant? The top of Figure 1.1 shows a simple schematic view of the vowel-to-vowel timing model and illustrates its predictions, showing the movement of the tongue associated with the vowel gestures and movement of the lips associated with a consonant gesture (the example shows an utterance like [ipɑ]). The black lines show an utterance with a short consonant. The gray lines (slightly offset vertically) show the corresponding utterance with a geminate consonant in one possible configuration relative to the utterance with the short consonant. This model predicts that a change in the consonant(s)' duration will not affect the movements due to vowel gestures, as shown in the figure. However, the model makes no specific predictions about how the consonant will be coordinated with the vowels: in the figure, the midpoint of the consonant gesture is in the same relation to the vowel gestures in both utterances, but it could be that a different point in the consonant gesture maintains a constant relation with respect to the vowels. If the consonant gestures are coordinated with the vowel gestures exactly as shown in the figure, the acoustic consequence of the longer consonant would be to shorten the acoustic segments for both vowels, if the rest of the utterance remains the same. Different patterns of coordination of the articulatory gestures would have different consequences for the

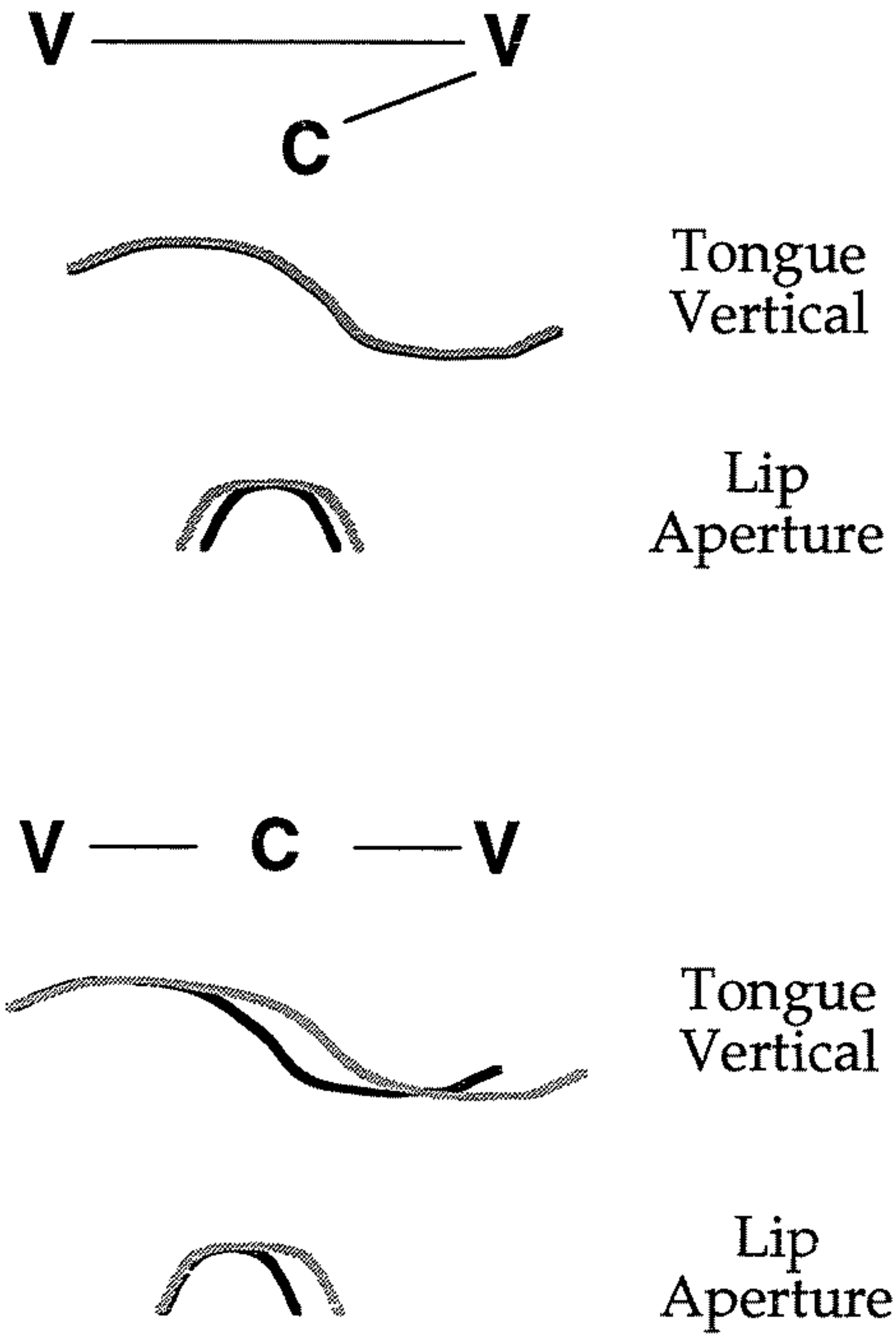


Figure 1.1. Sketch of two models of timing, (a) vowel-to-vowel, and (b) combined vowel-and-consonant.

acoustic durations, but in any case, the prediction of the model is that the movement from one vowel to the next will not be affected by changes in the consonant.

The combined vowel-and-consonant model predicts that the second vowel could occur later relative to the first when the consonant lengthens. This could result from a difference in the intrinsic duration of the consonant gesture, greater for a longer consonant, the effect of which would be to delay in absolute time all phases of the consonant relative to its onset. If either the consonant or the second vowel is phased to a point after the onset of the preceding gesture, a change in the interval from first to second vowel is possible. One form of this prediction is illustrated in Figure 1.1. Suppose that the onset of the consonant is phased to some event in the first vowel, and that the second vowel is phased to the consonant, such that the point at which the vowel constriction is achieved is coordinated with the release of the consonant gesture. The figure shows what is predicted by this form of organization when the consonant lengthens: the second vowel occurs later relative to the first vowel, following a longer consonant, and the movement from the first to the second vowel is delayed when the consonant is longer. This illustration of the model does not predict any acoustic change in the first vowel, since the consonant gesture starts at the same time relative to the start of the gesture for the first vowel; the second vowel could also maintain its same acoustic duration if the delay in the movement between vowels is equal to the increased duration of the consonant gesture. This figure illustrates one form of the model, but the vowel and consonant gestures might be phased in a different way while still conforming to this basic scheme, so specific predictions about the pattern of intergestural coordination cannot necessarily be expected to hold. A model of this general form would be indicated, however, by data showing that the consonant crucially affects the temporal relation between the vowels.

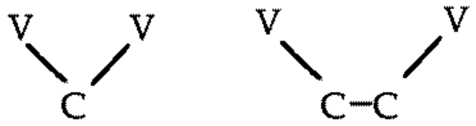
These two models are, at the very least, different logical possibilities for coordinating consonant and vowel events. It is possible, then, to ask which of these possibilities is employed by languages. It is hypothesized here that both are, in fact, employed, but by languages with different prosodic structures, with the vowel-to-vowel model of organization underlying languages that have been described as "syllable-timed", and the consonant-vowel model underlying languages that have been described as "mora-timed".

An ideal syllable-timed language would be one in which all syllables have approximately equal duration. The time from one vowel to the next would thus be close to constant, since each syllable must contain a vowel. In this type of language the interval from vowel to vowel forms the basis for the organization of the language's timing, which is what is instantiated by the vowel-to-vowel model.

Mora-timing is defined similarly to syllable-timing, except that it is the duration of each mora that is constant. (Here the term mora is being used in the traditional durational sense for Japanese, not as a unit of metrical weight.) The canonical shape of a mora in, for example, Japanese is a consonant-vowel sequence, but a vowel alone can be a mora, as can a syllable-final nasal. A CV sequence of which the consonant is a geminate consists of two moras, so an oral stop can be a mora by itself if it is part of a geminate. Thus both consonants and vowels must be taken into account in determining duration, suggesting that mora-timing would be found with a timing organization that attributes equal importance to vowels and consonants, such as the combined vowel-and-consonant model sketched above.

In this study, the hypothesis that the vowel-to-vowel and combined vowel-and-consonant models underlie syllable-timing and mora-timing will be tested by taking one language of each timing category and examining how its articulatory gestures are organized. Italian and Japanese were chosen as representatives of the two timing categories. Evidence is presented in the next section in support of choosing Italian and Japanese as examples of syllable- or vowel-based timing and mora-based timing, respectively.

It is simpler to compare the models' predictions for single versus longer consonants by comparing utterances with singles and geminates rather than single consonants and clusters, as the single/geminate contrast does not introduce additional, irrelevant variation that would be found with clusters. Both Italian and Japanese have geminate consonants at similar places of articulation, an additional reason for choosing these particular languages to compare. In terms of gestures, different analyses of geminates are possible, for example as one gesture that is longer than a single consonant or as two gestures. The crucial difference in the behavior of the two models is predicted, regardless of the analysis of geminates, which this study will not attempt to decide on. Specifically, the vowel-to-vowel model will never predict differences in the timing between vowels as the consonant changes from single to geminate, regardless of how the geminates are treated, while for the combined vowel-and-consonant model such differences can be predicted under either interpretation of geminate. The discussion above showed the effect of lengthening a single gesture. If instead, geminates are considered to be two gestures, vowel-to-vowel differences would be predicted if vowels are assumed to be phased to the immediately adjacent consonant, as in (3). The time between vowel 1 and vowel 2 is predicted to be longer in the geminate case because the events to which they are phased are further apart in time.

(3) 

2.2. Comparing timing organization across languages

In a previous study investigating the dynamic characteristics of production in different languages, Vatikiotis-Bateson (1988) found that articulatory movements had different temporal characteristics in English, French, and Japanese, languages exemplifying respectively stress-, syllable-, and mora-timing. In reiterant syllables (replacing the actual sounds with /ba/ or /ma/), Japanese and French speakers produced jaw opening and closing movements with much less variability in duration than did English speakers, suggesting that there is a stronger tendency to isochrony in these movements in Japanese and French than in English. This finding supports the hypothesis that in these languages there is a single prosodic unit (the mora or the syllable), whereas English is based on the alternation of stressed and unstressed syllables. Further, the Japanese speakers varied in their interpretation of the reiterant task when producing 2-mora, 1-syllable sequences, sometimes producing each mora with a separate CV syllable and sometimes combining the tautosyllabic moras into one larger movement with different dynamic characteristics, suggesting that at least for Japanese, mora and syllable can be distinguished. Bateson's results suggest that differences that might be associated with the categories of stress-, syllable- and mora-timing can show up as differences in the dynamics (temporal patterns) of individual movements.

In the current study, the timing patterns of sequences of gestures were investigated by comparing two languages hypothesized to represent the two models of timing proposed above. By comparing these models of timing in languages that have been described as syllable- and mora-based, this study, like Bateson's, contributes to understanding possible articulatory bases for the traditional categories of timing.

2.2.1. Evidence for classifying Japanese as a mora-timed language

The combined vowel-and-consonant model is hypothesized to underlie mora-timing, which depends on the "count" of both vowels and consonants. Japanese being the classic example of mora-timing, the question becomes what evidence exists that moras are truly the relevant prosodic unit. As Beckman (1982) and others have pointed out, it is not enough that moras exist in the minds of speakers or in the orthography, they must be shown to be better predictors of duration/rhythm than other units. Evidence for the 'reality' of the mora has been gathered in many domains. Researcbers concentrating on duration have found for the most part good support for the mora as a timing unit: Port, Dalby and O'Dell (1987) showed that there was a tight correlation between number of moras in an utterance and duration, within sets of similar utterances, but that on the other hand neither number of acoustic segments nor number of syllables were reliably correlated. Campbell and Sagisaka (1991) also found acoustic durations that were compensatory for moras but not syllables. For example, the duration of a vowel in the same mora as an intrinsically long consonant (such as /s/) would tend to be shorter than the same vowel in a mora with a shorter consonant, thus tending to equalize the durations of the moras. The same tendency was not found for syllables. The results that did not support the mora as having constant duration, found by Beckman (1982), can be attributed to her criteria being too stringent an interpretation of mora-timing. She examined very short utterances and found that moras did not keep a truly constant duration. But while there is much local variability in moraic duration, over a longer span of speech total acoustic duration varies linearly with the number of moras, as Port et al (1987) have shown. Despite the variability in short utterances, the mora is the most accurate predictor of duration for Japanese.

Evidence for the psychological reality of moras comes from a number of domains. As is well-known, Japanese verse forms such as the haiku require a specified number of moras in a line. (However, the fact that mora-counting applies in versification does not necessarily imply that it plays any role in the metrical organization of ordinary speech.) In the "babibu" language game, bV is inserted after each mora, with the vowel a copy of the vowel in the preceding mora or /u/ if the preceding mora has no vowel (Haraguchi 1982 cited in Davis 1988), showing that utterances can bo divided at mora boundaries. Similarly, in the setting of words to music, words can be divided at syllable boundaries or at mora boundaries that do not coincide with syllable boundaries, suggesting that speakers have access to both moras and syllables (Vance 1987). Speech errors also seem to occur in both mora- and syllable-sized units (Kubozono 1989), with neither one being more common than expected. Errors in which two words are blended occur at mora boundaries that are also syllable boundaries no more often than proportionate to the frequency of occurrence of such boundaries (which account for about 75% of all mora boundaries). That is, syllable boundaries are not especially favored as the location for splitting a word.

Also, rules of accent placement that need to be stated in terms of both moras and syllables also supply evidence that both units are synchronically relevant (Poser 1984; Pierrehumbert & Beckman 1986; Vance 1987). Indeed, Shibatani (1990) claims that in a few remote dialects the rhythmic unit is the syllable, not the mora, although he provides no evidence for this claim. These various types of evidence strongly support the 'psychological reality' of both the mora and the syllable, as well as their relevance to synchronic phonology.

A prosodic unit that may be evidenced in the phonology and morphology is the bimoraic foot (Poser 1984, 1990). Poser provides a number of examples of processes that refer to bimoraic units, although many of them are marginal (formation of certain types of hypocoristics). The existence of such units also supports the existence of the mora independent of the syllable, since Poser (1990:103) notes that the boundaries of the bimoraic feet "need not coincide with syllable boundaries", but of course necessarily do coincide with mora boundaries. This suggests that the prosodic organization of Japanese may incorporate two kinds of feet, as the metrical feet proposed to account for pitch accent are quite different from the bimoraic feet proposed for the morphological processes discussed by Poser (1990). However, neither kind of foot appears to affect the temporal regularity found at the level of the mora.

One further question is whether both moras and syllables are primitives in Japanese, or whether the dominant role of the mora in Japanese prosody eliminates any potential role for the syllable. As mentioned above, there is evidence that rules of accent placement, for example, refer to both moras and syllables. However, since the mora is clearly a sub-unit of the syllable, possibly the syllable is a derived unit constructed from 1, 2 or 3 moras. There does not seem to be any evidence one way or another on this: because all syllable boundaries are also mora boundaries, there is no reason that the relevant definition of a syllable could not be just as a combination of moras (with a single vowel or vowel sequence). This interpretation might make sense in light of the arguments for bimoraic feet. If so, the only primitive timing unit in Japanese is the mora, though different morphophonological processes are sensitive to particular sequences of moras, which resemble syllables or feet in other languages.

The necessity of describing the rhythm of Japanese in terms of moras, which take both vowels and consonants into account, coincides with the predictions of the combined vowel-and-consonant model that gives equal precedence to both types of gestures, that was expected to apply to Japanese.

2.2.2. Evidence for classifying Italian as syllable-based language

In contrast to Japanese, in which the mora is clearly the most important unit for timing purposes, Italian seems to be based on the syllable. In addition to being the relevant domain for phonological rules (Vogel 1977), the syllable may also be the span over which regular timing rhythm is maintained (Bertinetto 1977, 1983, Bertinetto & Vivalda 1978). There is considerable debate over whether Italian should be viewed as stress or syllable-timed; perhaps the most sensible response to this question is given by Dauer (1983), who suggests that there is not a categorical distinction between these two rhythmic patterns. Rather, languages vary along a continuum in the extent to which they approach having regular intervals from syllable to syllable or foot to foot, and Italian may be closer to the syllable-based regularity.

Several other researchers, however, have attempted to use temporal measurements to determine the prosodic unit over which Italian is organized, whether principally in syllables, words or (stress) feet. Den Os (1985) found that variation in vowel length was much less pronounced in Italian than in Dutch (a stress-timed language), suggesting that Italian is primarily syllable-timed. Further evidence for constant-duration intervals between syllables, which could give the impression of regular syllable-timed rhythm, was found by Farnetani and Kori (1986), who observed that the interval from vowel onset to vowel onset is the interval whose duration is most nearly constant, regardless of vowel and consonant quality and length differences. However, they also found word-level effects, suggesting that the syllable and the word may both be domains of temporal organization in Italian.

Vayra, Avesani and Fowler (1984) found no evidence for either the syllable or the foot as a regularly recurring rhythmic unit, as stressed vowels showed little shortening within either syllables or feet in the context of additional unstressed syllables. Investigating word-level effects led Vayra, Fowler and Avesani (1987) to conclude that the foot is not a relevant unit of metrical structure in Italian as Fowler (1981) had suggested it is for English: Italian speakers, unlike English speakers, did not show a correlation between vowel-to-vowel coarticulation and shortening of vowel durations with the addition of unstressed syllables within a foot, which was the strongest evidence that the English speakers were producing speech in a foot-based rhythm. Vayra, Fowler and Avesani (1987) suggest that either the connection between coarticulation and shortening found in English is accidental, or it is a correlate of stress-timing, which would imply that its absence in Italian suggests that Italian is not stress-timed. Their experiments do not provide any real support for Italian as being syllable-timed, either, but it seems reasonably clear that stress feet are not the unit over which rhythm is based in Italian.

There seems to be still some doubt as to how Italian is organized rhythmically. However, it is clear that syllables play an important role in creating the impression of a regular rhythm. As far back as Josselyn (1900), acoustic measurements have shown that the shortening of vowels before geminate consonants and consonant clusters tends to result in open and closed syllables having approximately the same duration (see Maddieson 1985 for comparison with other languages). Thus even if other units (most likely word-level) are also involved, so far it seems that the greatest regularity has been observed in acoustic durations of syllables. Since in Italian each syllable contains one full vowel, the syllable-based regularity could be interpreted as reflecting regularity from one vowel to the next (which would be consistent with Farnetani and Kori's (1986) observation of the relative invariance of vowel onset to vowel onset intervals). In interpreting this rhythmic regularity in terms of regularities that might be found in articulatory timing, the vowel-based regularity that seems to be found in Italian is in keeping with the vowel-to-vowel timing model that predicts timing patterns structured around the vowels.

2.2.3. Acoustic evidence for different durational patterns in Japanese and Italian

The hypothesis that a mora-based language such as Japanese could be modeled by the combined vowel-and-consonant model, and a syllable-based language such as Italian by the vowel-to-vowel model, can be tested by comparing the timing of the vowels in these languages in the context of temporally varying intervocalic consonant(s), as outlined above. If Italian does behave according to the vowel-to-vowel model, then it would be expected that the vowels would not differ in their timing in the contexts of different numbers or durations of consonant. If Japanese behaves according to the combined vowel-and-consonant model, it is possible that there would be differences in the vowels, depending on exactly how the vowels and consonants are coordinated. These predictions could be tested by comparing the contexts of single and geminate consonants in the two languages.

A preliminary comparison using acoustic data (Smith 1988) was consistent with the predictions. It was hypothesized that in the context of single vs. geminate consonants, different timing organization among vowel and consonant gestures would result in differences in the durations of the acoustic segments and the magnitude of context effects shown by one vowel on the other's formants (traditionally referred to as vowel-to-vowel "coarticulation"). Both models being compared can account for vowel-to-vowel context effects as the overlap of vowel gestures extending through an intervocalic consonant. If the vowel gestures overlap each other more, then greater context effects would result. The magnitude of this context effect that is apparent in the acoustic segments for the vowels would depend on how much overlap there was between vowel gestures. If the intervocalic consonant does not affect the coordination of the vowels, as predicted for Italian, then the amount of acoustic context effect (measured at the extreme positions for both vowels) should not be affected by consonant length, but the durations of the acoustic vowel segments might vary depending on how the consonant is phased to the vowels. For

Japanese, the prediction was that a difference in the amount of vowel-to-vowel coarticulation would be found, but somewhat smaller differences in acoustic vowel duration were expected in the context of different consonant lengths than were found in Italian.

In the experiment designed to test these general differences between the two languages' ways of organizing vowel and consonant timing, speakers produced disyllabic nonsense words with single or geminate intervocalic consonants. Measurements of the acoustic waveforms showed strikingly different durations in the two languages. In Italian, as expected, vowels were shorter before geminates and the total durations of two-syllable words were approximately the same regardless of the length of the intervocalic consonant (cf. Farnetani & Kori 1986). This pattern suggests that the number of syllables is an important determiner of the length of the word, consistent with the hypothesis that the timing of Italian depends on the syllable as the basic unit (Bertinetto 1977, 1983; Bertinetto & Vivalda 1978). In contrast, in Japanese the length of the words containing geminate consonants was substantially greater than the length of words containing single consonants. This is consistent with a moraic analysis of Japanese in that geminating the consonant adds a mora to the word, but the number of syllables remains the same. This simple measurement of acoustic word durations can be interpreted as supporting the traditional descriptions of the durational patterns of Italian and Japanese.

However, the acoustic durations do not show how the consonants and vowels are coordinated in these words. In Italian the shortening of the preconsonantal vowel is approximately equal to the additional duration of the geminate consonant, suggesting some kind of compensatory relation. Duration measurements of the acoustic waveform alone cannot show whether the vowel gesture is actually shorter or whether the vowel gesture keeps the same duration but the constriction for the consonant blocks the looser constriction of the vowel. In the acoustic experiment, an attempt was made at distinguishing these two possibilities by comparing the formant values of the two vowels in the context of different transconsonantal vowels. The magnitude of the effect of one vowel on the other was assumed to be a measure of the extent of overlap between the gestures producing the two vowels. In Japanese, the magnitude of the vowel-to-vowel context effect was reduced across geminate consonants, which can be accounted for by hypothesizing that the vowel gestures are overlapping less when separated by a geminate. This change in relations between the vowels is, in turn, consistent with the combined vowel-and-consonant timing model. The results were less clear in Italian, but to a first approximation, the magnitude of the vowel-to-vowel context effect was little affected by the length of the intervocalic consonant, suggesting that the vowel gestures retained approximately the same relation to each other.

The inferences that can be made from acoustic data about gestures and their overlap are necessarily indirect. In this study, gestural organization will be investigated using articulatory movement data. By examining consonant–vowel combinations in which the consonants are produced using articulators not critically involved in vowel production (e.g. the lips for bilabial consonants), the relation between the movements involved in the production of the consonants and those involved in the production of vowels can be differentiated, and the temporal extent and organization of consonants and vowels can be estimated.

Chapter II

METHODS

1. Data collection

This experiment used data collected at the NIH X-ray microbeam facility at the University of Wisconsin, Madison (Abbs and Nadler 1987; Nadler, Abbs and Fujimura 1987; Westbury 1991). The microbeam tracks the movement of vocal tract articulators, to which small gold pellets bave been affixed, by means of microscopic, localized X-rays. Microbeam data consist of trajectories of the pellets over time that show the movements of the articulators, making it possible to identify periods in the movement that can be related to particular gestures.

1.1. Stimuli

This experiment was designed to make it possible to compare the timing of vowels in the context of consonants of different lengths, especially geminate consonants as compared to singletons. In choosing the stimulus words, the choice of the X-ray microbeam as the method of data collection introduced certain limitations. For each speaker, data collection time on the microbeam is limited to 15 minutes. This meant that the carrier phrases had to be kept short and that only a limited number of repetitions could be collected. Since data were being collected from speakers of Italian and Japanese, stimuli and carrier phrases were designed to be as similar as possible across the two languages. The vowels chosen for this experiment were [ɑ] and [i], which were expected to show constrictions formed in maximally separated parts of the vocal tract. The consonants chosen were bilabials and alveolars. Since bilabial consonants are not specified for movement of the tongue, they are especially suited to the goal of separately measuring articulations relating to vowels and consonants. Alveolar consonants, produced with movement of the tongue tip, should be more independent of the vowel-related movement than velar consonants would be. Nonetheless, the physiology of the tongue dictates that movement associated with the alveolars should be more apparent in the pellets representing tongue movement than is the case with the bilabials (MacNeilage and DeClerk 1969). Japanese and Italian both have bilabial and alveolar single and geminate voiceless stops and nasals. Japanese does not have geminate voiced stops except in a few unassimilated loan words, so these were not included in the stimulus set. Japanese permits consonant clusters only in the case of homorganic nasal + stop clusters; Italian permits these and certain other clusters.

These considerations led to the choice of the following stimuli, where V represents either [ɑ] or [i], all combinations of which were collected, with one exception. In Japanese, because /t/ palatalizes to [tʃ] before /i/, no utterances were collected with the sequences /ti/ or /tti/.

$mV_1p(p)V_2$	$mV_1t(t)V_2$
$mV_1m(m)V_2$	$mV_1n(n)V_2$

mV_1mpV_2 (collected for 1 Italian speaker and all Japanese speakers)

Carrier phrases: "Dica ______ molto." (Italian)
Say ______ again.

"Boku wa ______ mo aru." (Japanese)
I topic-particle ______ also have.

The carrier phrases were chosen to have approximately the same phonological context for the target phrase in both languages. Additional productions were collected at the same time but not analyzed here (see Appendix 1).

The stimuli were organized into blocks of 4 to 7 for presentation to the speakers. Each block was repeated multiple times during the experiment with the order of the stimuli "rotated" each time (i.e., the first item in the current list was moved to the end of the new list, and so on). The order of the blocks was randomized. Each block of stimulus words consisted of words in which the intervocalic consonants had the same length. For the Italian speakers, the vowel pattern within a block was constant (either a-a, a-i, i-a, or i-i), but in all blocks for Japanese the vowel pattern was varied within a block. Since the utterances with different vowels in the two syllables were of primary interest, the experiment was constructed so that speakers produced these utterances more often than utterances with the same vowel in the two syllables. The organization of utterances into blocks and the number of repetitions of each block are shown in Appendix 1. Two Italian speakers (I2 and I3) were recorded using the same stimulus presentation material, although the number of presentations was reduced for speaker I3. The other Italian speaker (I1) was recorded using a slightly different set of materials, in which /mp/ clusters were included and the time allotted for each record was slightly longer than for the other speakers. The Japanese stimuli were presented to speaker J2 in romaji, and to speakers J1 and J3 in hiragana in a different order.

1.2. Speakers

Speakers were members of the university community at the University of Wisconsin, Madison, where recordings were made over a period of several months. Of the three Japanese speakers, J3 was female and J1 and J2 male; of the three Italian speakers, I1 and I3 were female and I2 male. All speakers had a university education and claimed to speak the "standard" dialect of their language (Tokyo dialect or standard Italian which has contrastive consonant length). This was verified by consultation with a Japanese member of the microbeam staff and Italian listeners recruited later. The Japanese listener believed that all the speakers were using Tokyo dialect. Although the Italian listeners could give broad identifications of the dialectal regions for two of the speakers, they did not believe that any of the speakers had unusual regional characteristics. Speakers visited the microbeam before the recording session to have an X-ray scan performed to check whether their dental work that would make it difficult to track the pellets. Normally, a person with any metal fillings is not used as a speaker in a microbeam experiment; however, because of the difficulty of locating suitable speakers of Japanese and Italian in Wisconsin, all the speakers used in this experiment with the exception of Italian speaker I1 did have some fillings. This sometimes necessitated compromises in the placement of pellets, which cannot be placed too close to metal dental fillings.

1.3. Experimental set-up

1.3.1. Pellet placement

The experimental set-up was shown in advance to the speaker, who was also given an opportunity to practice the material to be read. After the speaker had practiced producing the utterances, a dental impression was made of the speaker's teeth to enable measurements to be made later that could locate the pellets precisely relative to the occlusal plane. An otolaryngologist then attached the pellets at various positions in the vocal tract. The gold pellets were generally of diameter 2.5 mm (3 mm pellets were used in some instances) and each one was attached to a string. Pellets attached to the bridge of the nose and the upper incisor provided reference for head movement, which was corrected for in pre-processing of the data. Pellets were attached to the vermilion border of the upper and lower lips and to the lower incisor, to measure jaw movement. (For Japanese speaker J1 it was not possible to have a pellet attached to the upper lip.) Four pellets, or fewer if it was not possible to attach four to a particular speaker, were fixed to the midline of the tongue using a dental adhesive, and then the string for each pellet was taped to the cheek so that if the pellet detached from the tongue it would not be swallowed or aspirated. The frontmost pellet was positioned approximately 10 mm back from the very tip of the tongue. The rearmost pellet was generally placed as far back as the speaker was willing to tolerate, and the others were spaced approximately equidistantly between these two. Crude measurements of the distance back from the tongue tip were made using a small wooden stick laid against the stretched tongue, which give an approximate notion of how the pellets were placed on the different speakers. These positions reflect different parts of the tongue depending on the overall size of the vocal tract of that individual. Table 2.1 shows the locations of the pellets for the various speakers, in mm from the tongue tip. The abbreviations used for the pellet names are as follows: the frontmost tongue pellet was named Tongue Tip (TT), the next-rearmost Tongue Body 1 (TB1), next was Tongue Body 2 (TB2), and finally Tongue Dorsum (TD). The names are roughly descriptive but do not imply anything about the location of the pellet relative to particular parts of the tongue. In particular, the TT pellet was always substantially behind the tip of the tongue, since it was not possible to adhere a pellet to the actual tip.

		Pellet names			
Language	Speaker	TT	TB1	TB2	TD
Italian	I1	10	30	50	70
	I2	8	26	40	60
	I3	9	28		
Japanese	J1	8	35	50	70
	J2		29	44	64
	J3	10	35	50	65

Table 2.1. Pellet locations, in mm from tip of tongue

Italian speaker I3 could not tolerate pellets on the rear part of the tongue body, so it was only possible to attach 2 to her tongue. Japanese speaker J2 had a large filling on a mandibular tooth near the front of the mouth which interfered with tracking of any pellet near the tongue tip; therefore, only three pellets could be attached to his tongue.

!.3.2. Experimental procedure

After the pellets were attached, the speaker was seated in a dental chair positioned a fixed distance from the pinhole from which the microbeam radiates. Figure 2.1 shows the experimental set-up. The speaker had to be seated comfortably enough that the posture could be maintained for fairly long periods of time during the experiment. A small laser beam focused on a paper dot attached to the speaker's forehead shone from in front of and above the speaker. By looking in the mirror placed in front of her, the speaker could get

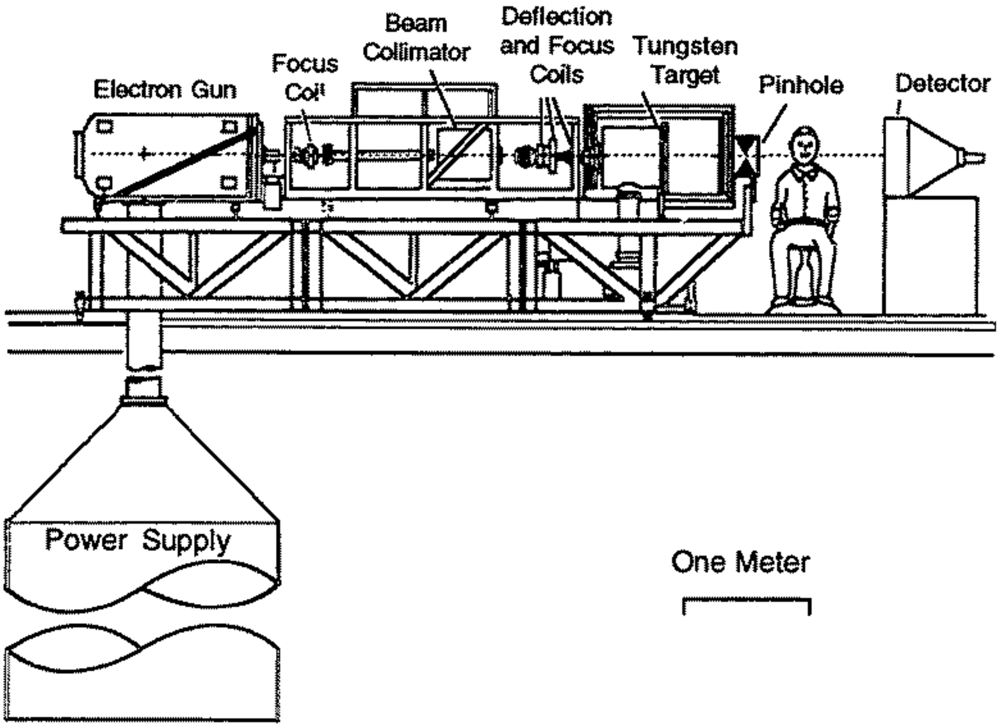


Figure 2.1. Experimental set-up for X-ray microbeam.
Adapted from Abbs and Nadler (1987).

feedback as to whether she was maintaining her position. A CRT monitor was also positioned in front of the speaker at a comfortable distance for reading. The carrier phrase along with the block of stimulus words to be produced in that record were presented on this screen.

The speaker was given some time to prepare before reading each set of utterances, and was instructed to begin speaking as soon as an audible signal was heard. At this time recording began and terminated automatically a pre-determined amount of time afterwards. The speakers were instructed to keep talking as long as recording was going on by recycling through the list of stimuli. As a result, the number of tokens actually produced by the speakers varied greatly. The Japanese speakers almost invariably produced more than one repetition of the stimulus set. For the Italian speakers, the amount of time allotted was in some cases insufficient to allow even one repetition of each of the presented utterances.

Before recording, a full-head scan of the speaker was made to locate all the pellets. During recording, the detector software looked in turn for each pellet within a small area whose location was predicted on the basis of immediately previous locations of this pellet. The pellet's location was then recorded and stored. The sampling rate used to track a particular pellet depended on the expected speed of the articulator. The Tongue Tip was tracked at approximately 180 samples per second, the other tongue pellets and the lower lip at approximately 90 samples per second, and the jaw and upper lip at approximately 45. The speaker's productions were monitored by the experimenter, and in case of error, the block was repeated. The tracking of the pellets could also be checked on a display, and the recording was repeated in case of serious mistracking. Mistracking occurred for a variety of reasons, most often because of the pellet-tracking algorithm mistaking something else (e.g. a dental filling) for a pellet.

Pre-processing done by the staff at the Microbeam facility corrected for head movement and for the time lag between sampling the pellet positions that results from their being tracked in a sweep from the front to the back of the mouth. The sampled data files consist of time series of the horizontal and vertical positions of the pellets in millimeters relative to the speaker's occlusal plane. The origin is set at the tip of the upper incisor, and the x-axis is midsagittal on the occlusal plane with the y-axis perpendicular to that. Thus pellet locations towards the rear of the tongue have negative x-values, and pellets on the lips have positive x-values, and similarly, pellets above the occlusal plane have positive y-values and those below have negative y-values. Based on careful measurements of the effects of speakers' head movements in 3 dimensions in introducing measurement error during the course of microbeam experiments, Westbury (1991) concluded that such data are accurate to within ±5%.

1.4. Preparing the data for analysis

All further processing was done at Haskins Laboratories. The first step in preparing the data for analysis was to convert it from the 16-bit format used at the Microbeam facility to the 12-bit Haskins PCM format. This process created sets of data files for each record, one each for the x and y dimensions of each pellet, and one for the speech waveform. For speakers for whom 4 tongue pellets were used, this resulted in 15 data files, with correspondingly fewer for speakers I3 and J2. Each of the pellet files was then smoothed, using a triangular window. The size of the smoothing window was varied depending on the sampling rate of the pellets. The Tongue Tip pellet was smoothed with a window of 5 samples, and the other pellets with a window of 3. The smoothed data were used in all further analyses.

1.4.1. Reasons for which tokens were excluded from analysis

The pellet trajectories and speech waveform for all the utterances were then displayed using software that provides both the usual position versus time display of the x and y traces and a display of pellet position in x-y space at a given time. Each token was checked to see that it was a fluent production of the correct utterance, and that all the pellets which were to be measured for that utterance had been tracked properly. If either of these two conditions was not met, the token was not measured. However, utterances in which the intervocalic consonant of the stimulus word was a bilabial were not excluded from measurement if there was a mistracking in the Tongue Tip pellet. Utterances in which the intervocalic consonant was an alveolar were not measured if a mistracking occurred in either of the lip pellets because these pellets were used to measure the initial /m/. If a mistracking occurred only during the carrier phrase, the token was retained. Other tokens that were excluded were any in which for any reason there was not data available for all channels being measured. In most records, recording of the acoustics ended before recording of the movements of the pellets. Tokens were not measured in which the speech waveform was truncated before the end of the stimulus word, but were measured if the waveform ended before the end of the carrier phrase.

For the Italian speakers, especially I2, there were some tokens for which the consonant length seemed ambiguous. Since this distinction is crucial for this experiment, a listening test was devised to determine which tokens should be retained. All 89 Italian tokens for which the relative durations of the consonant and the preceding vowel fell within the range found to be potentially ambiguous by Bertinetto and Vivalda (1978) were included in the listening test, as were one unambiguous token of each utterance for which any ambiguous tokens had been identified (except 2 utterances for which there were no unambiguous tokens). Three repetitions of each of these tokens were presented in random order (separated by speaker) to two Italian listeners, who marked on an answer sheet whether they heard the intervocalic consonants as single or geminate. Of the ambiguous tokens, the listeners consistently identified 19 as having consonant length other than what had been presented as the stimulus. All these tokens had been produced by speaker I2, and were excluded from all further analysis. (This suggested that speaker I2 may be speaking a dialect in which the consonant length contrast is not robust, as is the case for some northern Italian dialects.) For 5 additional tokens (3 for speaker I2 and 2 for speaker I1), one or the other listener responded once per token that its consonant length was different from what had been presented as the stimulus. These tokens were included in the measurements. The other 91 tokens that were presented to the listeners were unambiguously identified as having the consonant length corresponding to the presented stimulus.

2. Data Analysis

2.1. Using microbeam data as evidence of gestural timing

In Articulatory Phonology gestures are abstract entities that model goal-directed movements defined not in terms of individual articulators but rather in terms of task-space tract variables (Browman & Goldstein 1986; Saltzman & Munhall 1989). In order to measure the temporal properties of the gestures, therefore, the tract variables have to be related to something that can be measured: the movements of the articulators that appear to form constrictions in the part of the vocal tract under the control of that particular tract variable. Then the problem becomes deciding which articulators should be measured for each tract variable; in many cases more than one articulator influences a single tract variable. For example, the jaw, and lower and upper lips all contribute to the formation of constrictions by the Lip Aperture tract variable. In the model of Browman and Goldstein (1986, 1990a), there are several tract variables that control constrictions formed with the tongue. A particular constriction is defined in terms of two tract variables, one controlling the location and one the degree of constriction: for example, gestures involving the body of the tongue are specified by Tongue Body Constriction Location and Tongue Body Constriction Degree, for which the controlled articulators are the tongue body and the jaw. The vowel /i/ can be specified as having a tongue body constriction with a location of palatal and degree narrow. Alveolar consonants are specified in terms of the Tongue Tip Constriction Location and Degree tract variables, with location of alveolar and degree equal to closure, or complete constriction.

In this experiment, the gestures to be measured are those associated with the production of two vowels, /a/ and /i/, and bilabial and alveolar oral and nasal stops. For the consonants, the choice of pellet trajectories to measure is relatively simple.

Constrictions for bilabial consonants are defined in terms of Lip Aperture tract variable, the vertical distance between the lips. Therefore, the vertical difference between the positions of the pellets on the two lips can be considered as representing the Lip Aperture tract variable. The dental or alveolar consonants, formed by a closure of the tongue tip or blade against the teeth or alveolar ridge, are defined in terms of the Tongue Tip tract variables. In order to estimate the time at which the tongue tip approached its target position (closure with the fixed surface of the vocal tract) for these consonants, the trajectory of the vertical position of the Tongue Tip pellet was measured, as an approximation to the Constriction Degree tract variable.

For vowels, the problem of associating pellet locations on the tongue with tract variables is more complex. The microbeam tracks the horizontal and vertical movements of a limited number of points on the tongue (up to 4 in this experiment). These movements are recorded in dimensions calculated with respect to the occlusal plane, but the Tongue Body Constriction Degree and Location tract variables in terms of which vowels are defined are not orthogonal to this plane. For a simple approximation to the dimension of Constriction Degree for the vowels /i/ and /a/ in English, Browman and Goldstein (1990a) used the horizontal movement of the rearmost pellet, in analyzing data collected at the Tokyo X-ray microbeam. Other analyses of X-ray microbeam data have used combinations of the horizontal and vertical pellet dimensions to calculate dimensions more closely indicative of vocalic movements. For example, Kiritani, Sekimoto and Imagawa (1977) and Kiritani, Itoh, Hirose, and Sawashima (1977) derived three parameters from the movements of pellets attached to the tongue and jaw in the production of Japanese vowels. All three were required to approximate the trajectories of pellet movements, including one parameter primarily associated with vertical movement of the tongue and one primarily with horizontal. For English vowels, a canonical discriminant analysis of the movements of pellets on the tongue, jaw and lips showed components involved in vowel production that incorporated both horizontal and vertical dimensions (Johnson 1991). The space defined by the first two of these components resembled the layout of a traditional vowel chart and shows [i] and [ɑ] having extreme and almost opposite values for the components.

For the present experiment, two approaches were used to the problem of estimating the movements associated with the Tongue Body tract variables. The rearmost pellet (Tongue Dorsum), which is closest to the pharyngeal constriction for [ɑ], and the next rearmost, which is closest to the region of the palatal constriction for [i], were chosen for measurement. Since the locations of these Tongue Body constrictions differ in both the height and front-back dimensions, when translated into the two-dimensional pellet space, it seemed desirable to measure both horizontal and vertical dimensions of pellet movement. Since the frontmost Tongue Tip pellet showed the most movement for the alveolar consonants and the pellets further back showed decreasing effects of the consonant, it was expected that the rearmost pellet would be the most typical of the vowels. However, for most speakers there was almost no vertical movement in the rearmost pellet, so only its horizontal movements were measured (a similar situation was noted by Kiritani, Sekimoto and Imagawa (1977)). Vertical movement was measured in the next rearmost pellet, Tongue Body 2 (TB2).

The other approach used to estimate the time of constrictions controlled by the Tongue Body tract variable was a factor analysis of the pellet positions in an effort to find a limited number of degrees of freedom that could characterize the movement of all the pellets on the tongue. The details will be explained below, but briefly, a principal components analysis was run on the files of data containing the horizontal and vertical positions of all the pellets during a block of productions. Two factors were derived for most speakers. These factors represent correlated patterns of movement of the tongue pellets, and therefore reflect changes in the positioning of the tongue body as a whole. They should also be more comparable across speakers, since they are not tied to the precise locations of the pellets. In general, for each speaker one factor was predominantly representative of horizontal movement and one of vertical movement. Thus these factors could be considered as showing basically the same kind of movement for all the speakers for whom comparable factors were derived. Time functions were created from the factor scores that were similar to those for the individual dimensions of the pellets, and these factors were also measured to index the gestures for the vowels /i/ and /a/.

2.2. Trajectories chosen for measurement

The only dimensions of pellet movement measured were those that could be associated with a particular gesture: for the vowels, these were the horizontal dimension of the rearmost pellet (Tongue Dorsum) and the vertical dimension of the next-to-rearmost (Tongue Body 2), for all speakers except I3. For speaker I3 the horizontal and vertical dimensions of the Tongue Body pellet were measured. For speaker I2, the horizontal dimension of the Tongue Dorsum pellet showed almost no movement in the a-initial utterances; therefore, it was measured only in i-initial utterances. To measure the bilabial consonants, Lip Aperture (LA) was calculated by taking the difference between the vertical positions of the upper and lower lips, except for speaker J1, for whom the upper lip pellet was missing. Figure 2.2 illustrates the different dimensions in a sample token of Italian speaker I1 producing the utterance /mipa/, and Table 2.2 shows which pellet dimensions were measured for which speakers. The abbreviation LLy refers to the vertical dimension of the lower lip trajectory. This trajectory was substituted for Lip Aperture for speaker J1.

Speaker	no. of tongue pellets	TDx	TB2y	TBx	TBy	bilabials	alveolars: TTy
J1	4	✔	✔			LLy	✔
J2	3	✔	✔			LA	
J3	4	✔	✔			LA	✔
I1	4	✔	✔			LA	✔
I2	4	i-initial only	✔			LA	✔
I3	2			✔	✔	LA	✔

Table 2.2. Pellet dimensions measured for different speakers

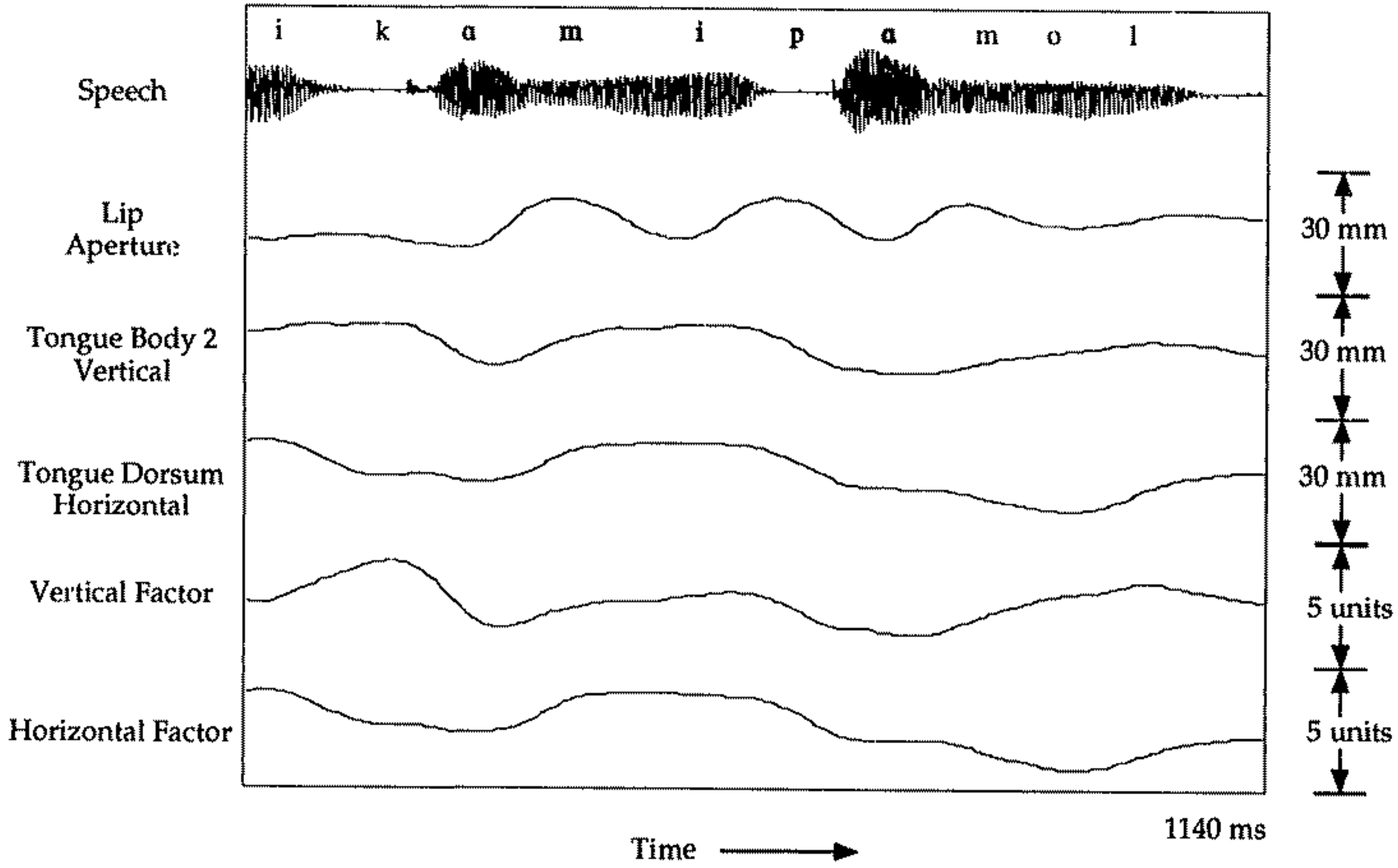


Figure 2.2. Production of /mipa/ by Italian speaker I1, showing the pellet dimensions and factors measured for this speaker.

In addition, velocity time functions for all pellets were created in a similar way, by differentiating the displacement trajectories of the pellets that had been chosen for measurement.

2.3. Factor analysis

Factor analysis, a statistical technique for expressing the co-variation among a large number of data variables in terms of a smaller number of components (Green and Carroll 1976), was applied to these data as a way of abstracting away from the specific pellet locations for the individual speakers, and combining the pellet movements into a minimal number of dimensions that capture the redundancies among the correlated movements. Each factor extracted from the data corresponds to an independent degree of freedom of correlated movement in the pellets. Ideally, it was hoped that it would be possible to associate one factor with movement for /a/ and a different factor with movement for /i/, which would make it possible to detect any overlap between the two vowels that could be attributed to coproduction of movements associated with the two vocalic gestures. However, this did not prove possible.

2.3.1. Procedure

The factor analysis was done separately for each speaker on a subset of the smoothed data. For each speaker, one example of each stimulus block type was analyzed (see Appendix 1). A total of 12 block types were used for each of the Italian speakers and 5 for the Japanese speakers. These block types were chosen to include at least one token of every utterance produced by the speakers. (For the Japanese speakers, block types that included duplicate utterances from other types were not included in the subset that was analyzed.) The block types that were used are listed below. These included utterances that were not measured in this study, such as those with the same vowel in both syllables or Italian utterances with intervocalic clusters.

Italian		Japanese
aCa	iCa	
aCCa	iCCa	aCV
aGa	iGa	aGV
aCi	iCi	iCV
aCCi	iCCi	iGV
aGi	iGi	VmpV

Table 2.3. Utterance classes included in the subset of data submitted to the factor analysis. C represents a single consonant, CC a cluster, G a geminate consonant, and V either /i/ or /a/.

Data for factor analysis included the carrier phrases as well as the stimulus words for all utterances. The pellet positions were interpolated to a uniform sampling rate of 200 Hz, so there was a value for each pellet dimension at every 5 ms frame. Thus the input data for a given speaker consists of *m* pellet dimensions (discussed below) at approximately 20,000 time frames.

The data for each speaker were submitted to a factor analysis. The BMDP program 4M was used to perform a principal components analysis, with the default VARIMAX rotation. This extracts orthogonal (uncorrelated) factors, in contrast to the more numerous pellet dimensions, which are highly correlated. The program calculates factor loadings for each pellet dimension, which for orthogonal factors are equal to the correlation of the pellet dimension with the factors. The size of the loading gives the extent to which a given pellet dimension is represented by that factor. In this experiment, the value of each pellet dimension varies over time from one frame of data to the next. Thus the contribution of each factor to predicting the set of pellet positions will also vary between samples. This contribution is known as the factor score. The product of the matrix of factor loadings times the factor scores for all the factors at a given sample yields the predicted standard scores for the pellet dimensions at that sample. Since due to space limitations the factor analysis was performed on only a subset of the speaker's data, a separate program was written to calculate the factor scores for all samples in all the data files, using the factor loadings calculated on the basis of the subset of the data.

Two analyses were tested: one including all tongue pellets in the factor analysis, and one excluding the Tongue Tip pellet. Inclusion of the Tongue Tip pellet was often found to result in factors that reflected the movement of the tongue towards the alveolar consonants and made it difficult to distinguish the movements most closely associated with the two vowels in the target words. However, in some cases (speaker J3, for example) the contrast between the vowels was more apparent, so factors derived from the analysis including the Tongue Tip were used. For analyses in which the Tongue Tip was included, there were 8 variables (4 tongue pellets X 2 dimensions) in the data that were factor analyzed, and for analyses excluding the Tongue Tip, there were 6 variables. Note that for speaker J2, for whom the Tongue Tip pellet could not be tracked, only one analysis was performed, with 6 variables, and likewise for speaker I3 only the analysis including the Tongue Tip was performed (4 variables).

2.3.2. Factors and interpretation

Table 2.4 shows the eigenvalues and cumulative percent of variance accounted for by different numbers of factors. There was generally a substantial decrease in the proportion of variance accounted for by those factors that had eigenvalues less than 1; this was used as the criterion for choosing the number of factors to retain in each case. The retained factors are indicated by a † in Table 2.4.

ITALIAN

I1 (excluding TT)				I2 (excluding TT)			
# of Factors	Eigenvalues	Cumulative proportion of variance in data space		# of Factors	Eigenvalues	Cumulative proportion of variance in data space	
1	4.0289	.672	†	1	4.6899	.782	†
2	1.2001	.872	†	2	0.9273	.936	
3	0.5608	.965		3	0.2558	.979	
4	0.1340	.987		4	0.0741	.991	
5	0.0575	.997		5	0.0447	.999	
6	0.0187	1.000		6	0.0083	1.000	

I3 (including TT)			
1	3.1668	.792	†
2	0.4848	.913	
3	0.3089	.990	
4	0.0395	1.000	

JAPANESE

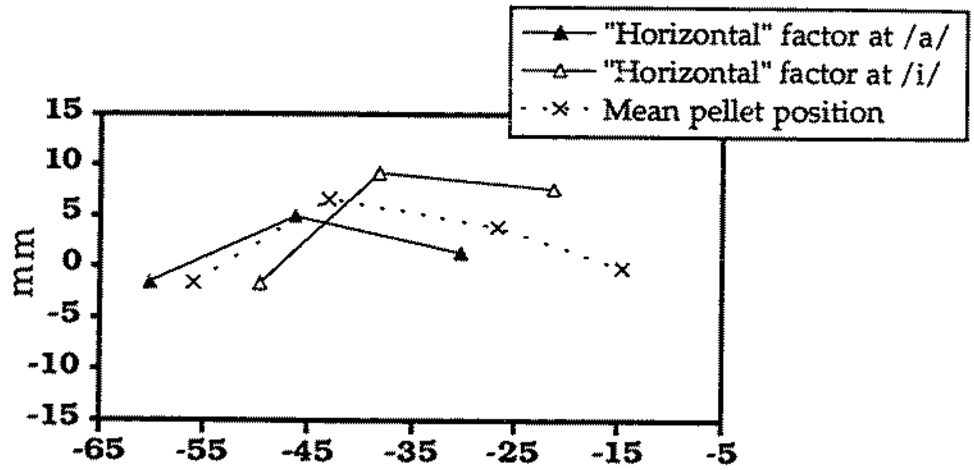
J1 (excluding TT)				J2 (excluding TT)			
# of Factors	Eigenvalues	Cumulative proportion of variance in data space		# of Factors	Eigenvalues	Cumulative proportion of variance in data space	
1	4.3659	.728	†	1	4.2823	.714	†
2	1.0391	.901	†	2	1.1389	.904	†
3	0.5206	.988		3	0.5080	.988	
4	0.0425	.995		4	0.0371	.994	
5	0.0255	.999		5	0.0235	.998	
6	0.0064	1.000		6	0.0101	1.000	

J3 (excluding TT)				J3 (including TT)			
1	3.7460	.624	†	1	4.7523	.594	†
2	1.4764	.970	†	2	1.6478	.800	†
3	0.6008	.971		3	1.1600	.945	†
4	0.1186	.990		4	0.2465	.976	
5	0.0520	.999		5	0.1061	.989	
6	0.0062	1.000		6	0.0591	.997	
				7	0.0224	.999	
				8	0.0058	1.000	

Table 2.4. Proportion of variance accounted for by retained factors

The plots in Figures 2.3-2.9 illustrate how the factors for each speaker contribute to the pellet positions for two vowels /a/ and /i/. They show the mean pellet positions for that speaker, and how that pattern is displaced by the factors during one frame corresponding to /i/ and another one corresponding to /a/. These plots were produced using the following procedure. For each speaker, within a token of the utterance /mipə/, the samples of data at which Lip Aperture was maximal were identified in each of the two vowels. These samples were taken as being representative positious for that speaker of the tongue pellets for the two vowels. Multiplying the matrix of factor loadings by the matrix of factor scores at each of these two selected samples gives the standard scores as predicted by the factors for all the pellet dimensions at the two samples. The standard scores for each pellet dimension at each of these samples were then multiplied by the standard deviation for that dimension over the entire data set, and added to the mean value for that dimension to convert the standard score values back to "pellet space" for the plots. Thus the positions plotted as "i" and "a" represent the positions of the pellets as predicted by each factor for particular data samples during the production of these vowels.

Overall, the factors show a great deal of similarity across speakers and languages. For speakers for whom 2 factors were extracted, one tended to correspond primarily to horizontal movement with some vertical component, and one primarily to vertical, and they are labeled accordingly in the figures. For speakers I2 and I3, only one factor was extracted, which corresponds most closely to the horizontal factor of the other speakers. For speaker J3, factors from two analyses were used for measurement. In the interests of comparability with other speakers, the horizontal factor from the analysis excluding the Tongue Tip was used; however, the vertical factor from this analysis did not show clearly the contrast between /a/ and /i/, so it was not measured (see Figure 2.8). To provide additional data for this speaker, the analysis including the Tongue Tip pellet was also used: the horizontal factor was very similar to the horizontal factor from the other analysis, and



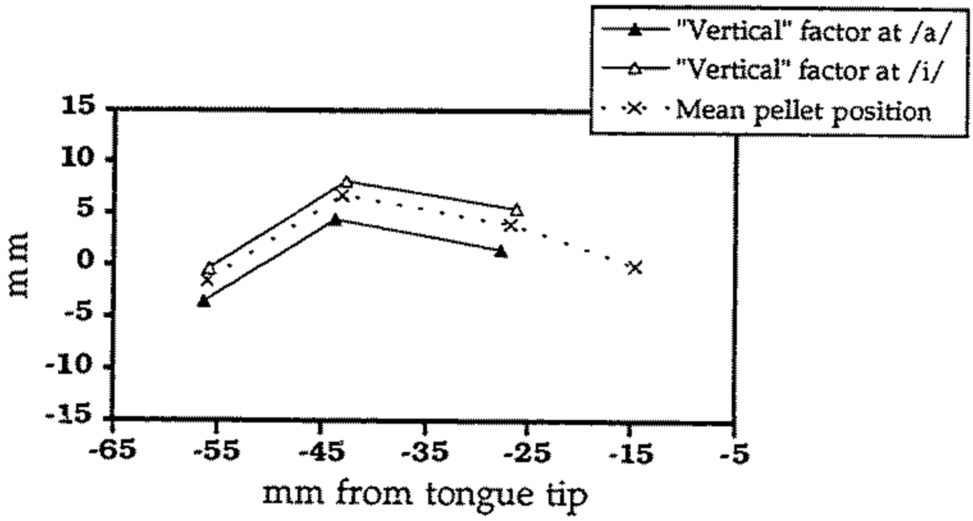


Figure 2.3. Contribution of 2 factors (analysis excluding Tongue Tip pellet) to pellet positions for /a/ and /i/ for Italian speaker I1.

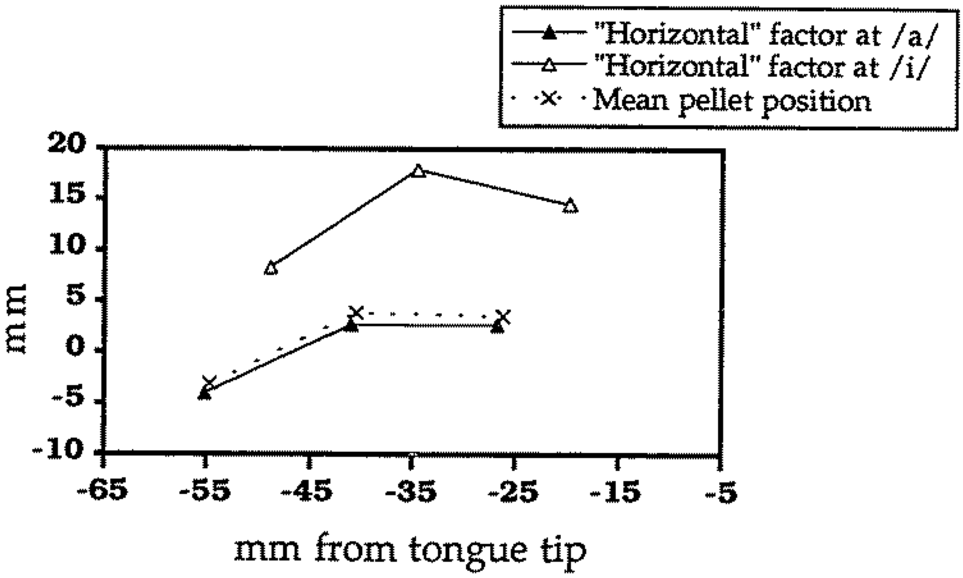


Figure 2.4. Contribution of 1 factor (analysis excluding Tongue Tip pellet) to pellet positions for /a/ and /i/ for Italian speaker I2.

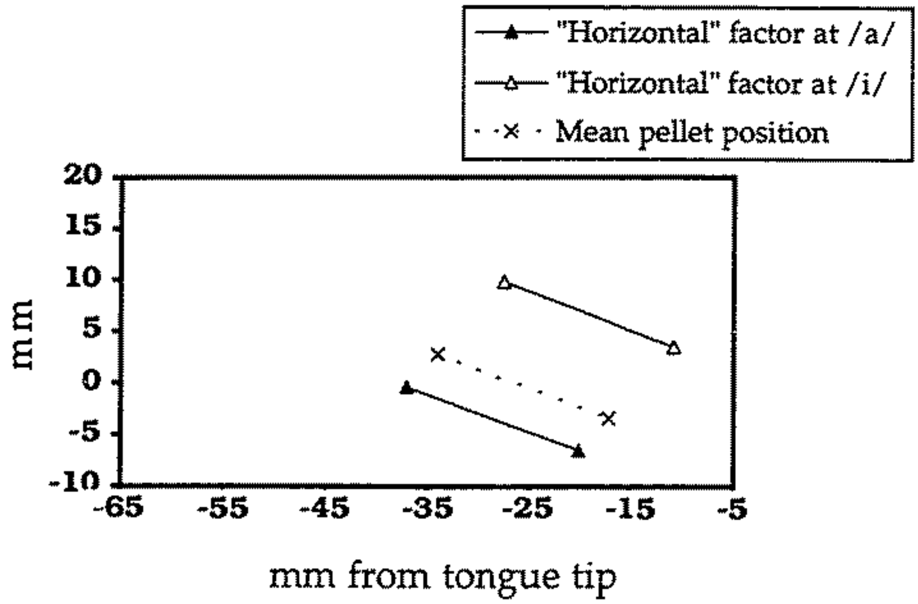


Figure 2.5. Contribution of 1 factor (analysis including Tongue Tip pellet) to pellet positions for /a/ and /i/ for Italian speaker I3.

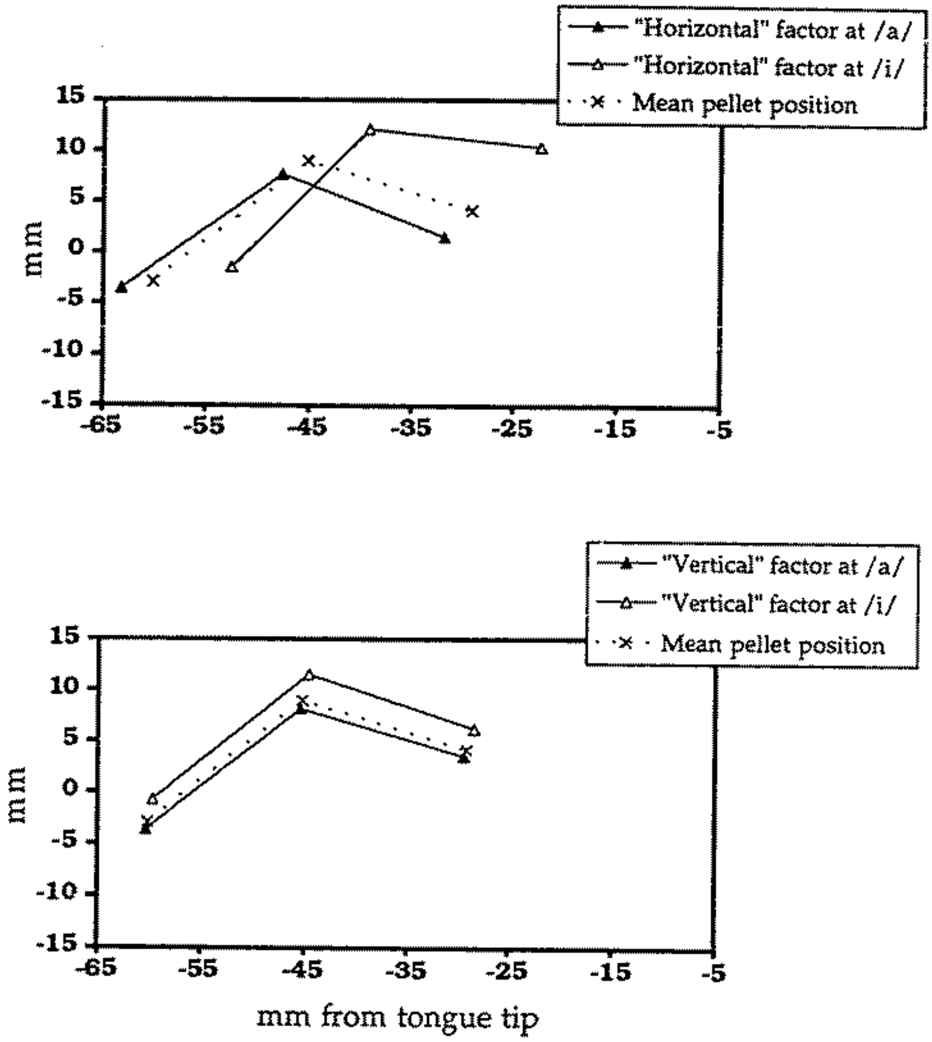


Figure 2.6. Contribution of 2 factors (analysis excluding Tongue Tip pellet) to pellet positions for /a/ and /i/ for Japanese speaker J1.

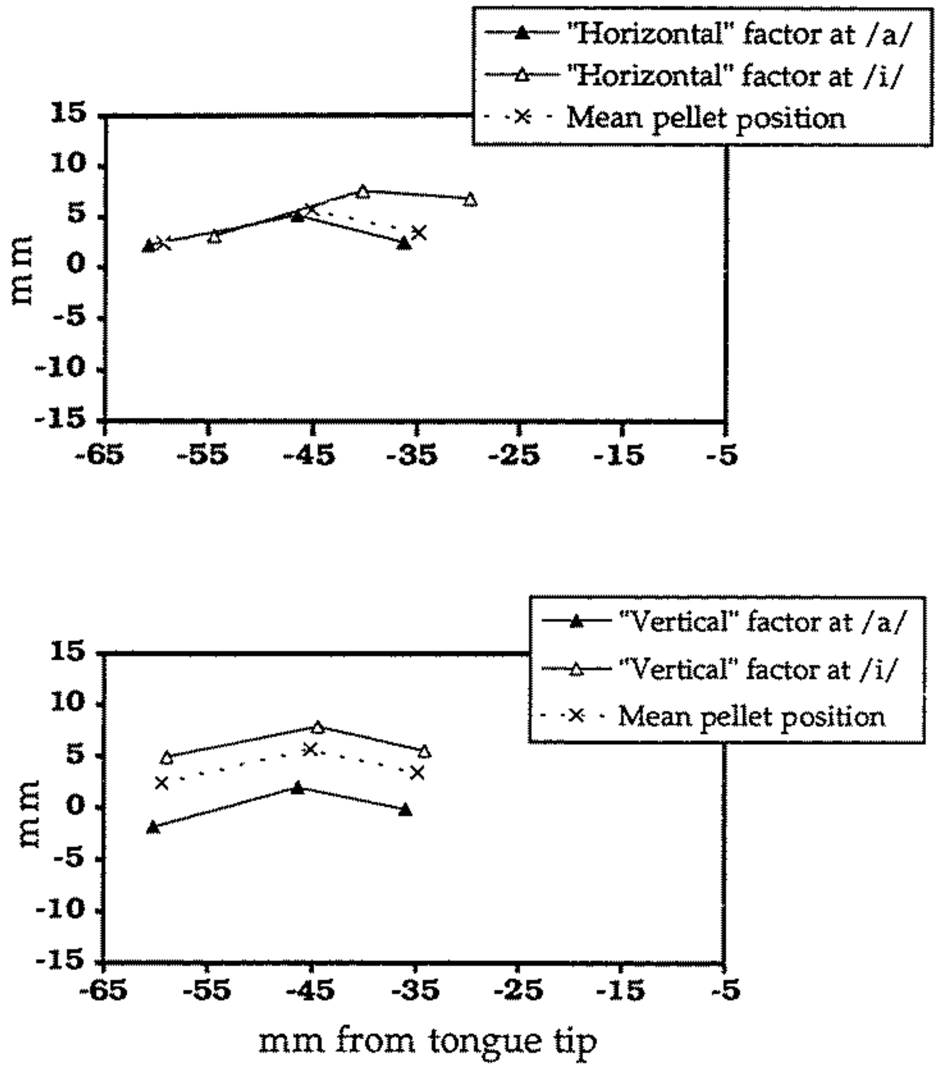
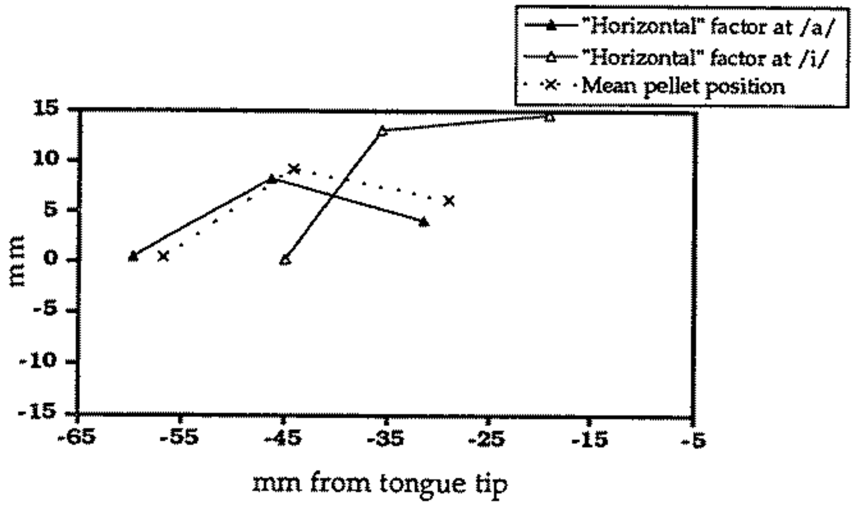


Figure 2.7. Contribution of 2 factors (analysis excluding Tongue Tip pellet) to pellet positions for /a/ and /i/ for Japanese speaker J2.



The "Vertical" factor was not measured.

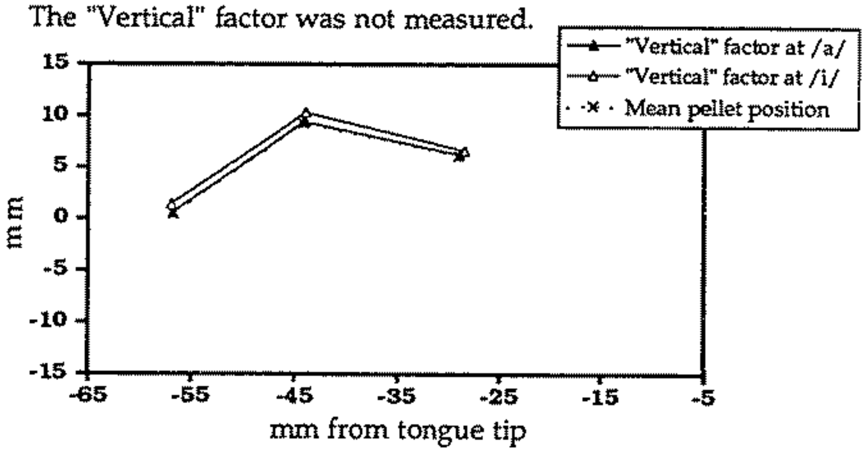
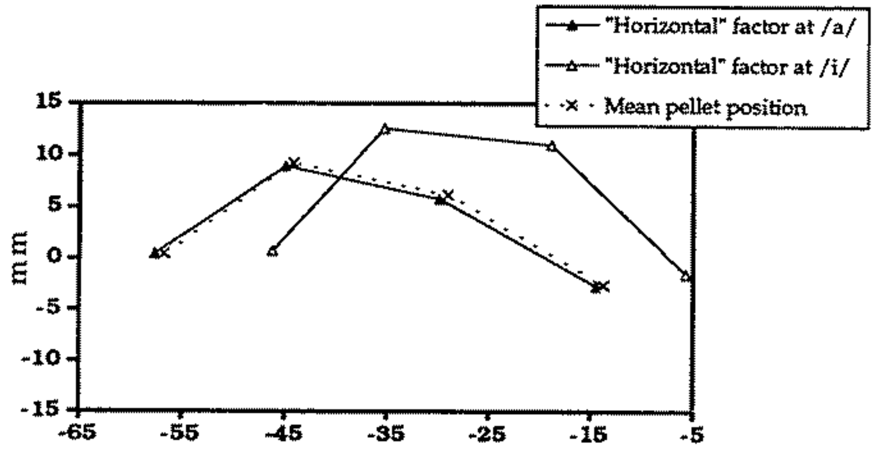
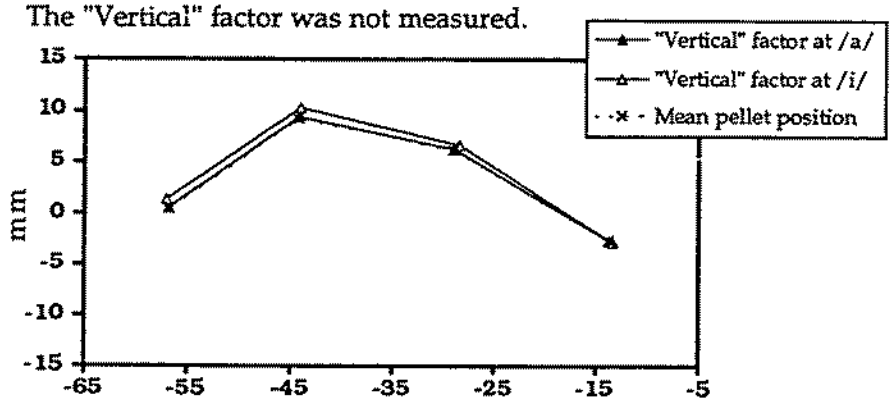


Figure 2.8. Contribution of 2 factors (analysis excluding Tongue Tip pellet) to pellet positions for /a/ and /i/ for Japanese speaker J3.



The "Vertical" factor was not measured.



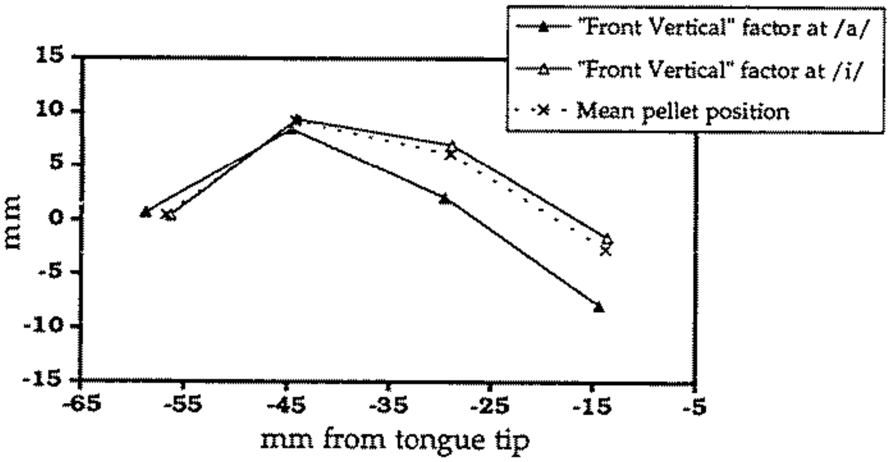


Figure 2.9. Contribution of 3 factors (analysis including Tongue Tip pellet) to pellet positions for /a/ and /i/ for Japanese speaker J3.

the "front vertical" factor showed vertical movement that, although heavily influenced by Tongue Tip movement, seemed more like the vertical factor for some of the other speakers than did the vertical factor from the analysis excluding the Tongue Tip. In all, three factors were measured for J3, of which two closely resembled each other (the two horizontal factors).

Table 2.5 shows which pellets were used for the factor analysis for different speakers, and which factors were chosen for measurement.

Speaker	no. of tongue pellets	no. of factors extracted	used for measurement	analysis
JAPANESE				
J1	4	2	Horizontal, Vertical	excluding TT
J2	3	2	Horizontal, Vertical	excluding TT
J3	4	3	Horizontal, Front Vertical	including TT
		2	Horizontal	excluding TT
ITALIAN				
I1	4	2	Horizontal, Vertical	excluding TT
I2	4	1	Horizontal	excluding TT
I3	2	1	Horizontal	including TT

Table 2.5. Factors measured for different speakers

For each of the factors chosen for measurement, factor scores were calculated in order to produce factor score time functions similar in form to the pellet time functions, with sampling rates of 200 Hz (since the data files used to perform the factor analysis had been converted to 200 Hz). They were smoothed over a 5-sample triangular window. The factor score time functions for a given record were not measured if any of the tongue pellets had mistracked in that record, since this could result in spurious values for the factor scores. Thus there were a very few records for which the pellets were measurable but the factors were not, if mistracking had occurred in the TB1 pellet which was not measured directly but was included in the factor analysis. Generally, the factor score trajectories closely resembled measured pellet trajectories: for many speakers, the first factor was similar to the horizontal dimension of the TD pellet, and the second factor was similar to the vertical dimension of the TB2 pellet.

2.4. Identifying events

2.4.1. Segmenting the acoustic waveform

Duration measures were made of the acoustic waveform for comparison with the durations of the articulatory measures. The onset of the first vowel (chosen at a point of abrupt increase in amplitude after the initial /m/), the offset of the first vowel (chosen where the intervocalic consonant closure occurred), the release of the intervocalic consonant, and the offset of the second vowel (also at the change in amplitude for the following /m/) were labeled by hand in the acoustic waveform. Although both Italian and Japanese voiceless stops are described as unaspirated, in a few tokens there was a noticeable interval between release of the consonant and the onset of voicing for the second vowel. In these tokens an additional label was inserted at the onset of voicing. Since the acoustic data were synchronized in the display program to the articulatory data, which had been converted to a sampling rate of 200 Hz, the labelling in the acoustic waveform was also accurate to only a 5 ms resolution. The acoustic signal was not used directly in identifying events in the articulatory data, but in some tokens it was used to suggest which portion of an articulatory trajectory might correspond to the production of a vowel.

2.4.2. Identifying events in the movement trajectories

To determine the timing of different events in the gestures that made up the different utterances, gestures were associated with movements shown in the pellet and factor score trajectories as described above: the initial /m/ and bilabial intervocalic consonants were identified in Lip Aperture (Lower Lip vertical for speaker J1), alveolar intervocalic consonants in Tongue Tip vertical, and vowels in the selected factors and in Tongue Dorsum horizontal and Tongue Body 2 vertical time functions. The following five events were marked in the time functions associated with vowel gestures: onset of movement towards the first vowel, time at which a plateau was reached for the first vowel (corresponding to the point at which movement towards vowel 1 ended), end of the first vowel plateau and beginning of movement towards the second vowel, time at which a plateau was reached for the second vowel, and end of the plateau for the second vowel. Figure 2.10 shows these events in a sample token of the Tongue Body 2 vertical dimension for Italian speaker I1's production of /mipa/. Recall that the carrier phrase began "Dica ...", with an /a/ immediately preceding the stimulus word. Figure 2.11 shows the same speaker's production of /mapi/. It is apparent that there was little or no movement in the tongue during the initial /m/ of /mapi/, so that there is no clear boundary between the /a/ in "dica" and the /a/ in /mapi/. A similar problem occurred in Japanese, because the particle "wa" immediately preceded the stimulus words. Because of this problem, the first two events listed above were not marked in stimulus words in which /a/ was the initial vowel.

2.4.3. Criteria for identifying events in trajectories

Two methods of identifying the events were considered: locating them on the basis of when the movement trajectory reached or left a region containing a displacement extremum, or locating them on the basis of when the velocity of the movement approached zero, which indicates a relatively steady-state portion of the displacement. This velocity-based method of identifying events was chosen as it permits the identification of plateau regions in the displacement that do not contain an actual extremum. This ability seemed desirable given that some parts of the trajectories that appeared to be associated with vowels did not include displacement extrema; see for example the second vowel in Figure 2.12, which is visible as an inflection point in the tongue position but not a peak or valley. To select regions where the velocity approaches zero, the software employed allowed automatic identification of portions of a time function during whicb the value is arbitrarily close to 0; that is, the user specifies a numerical "noise value", and any portion of the

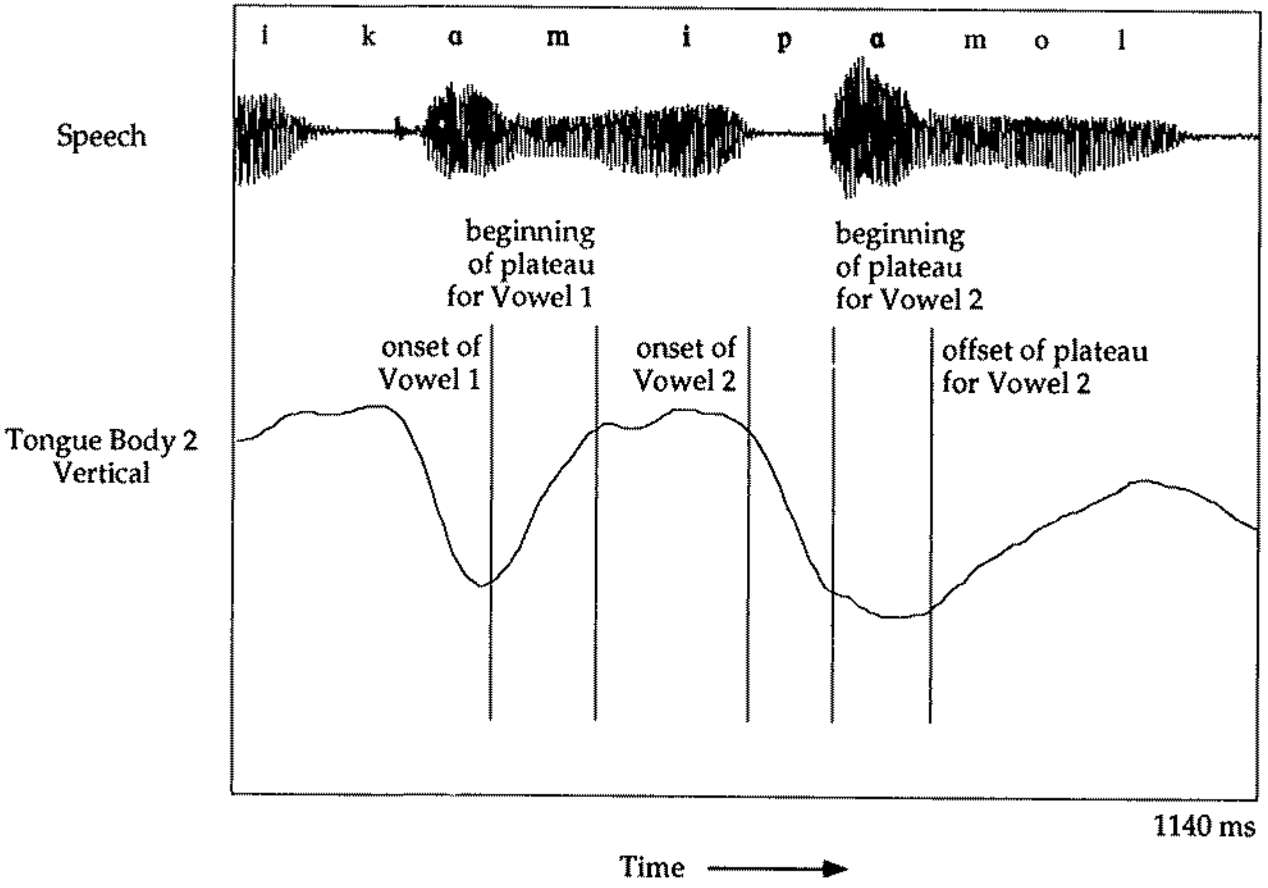


Figure 2.10. Events marked in time functions associated with vowel gestures, shown in a production of /mipa/ by Italian speaker I1.

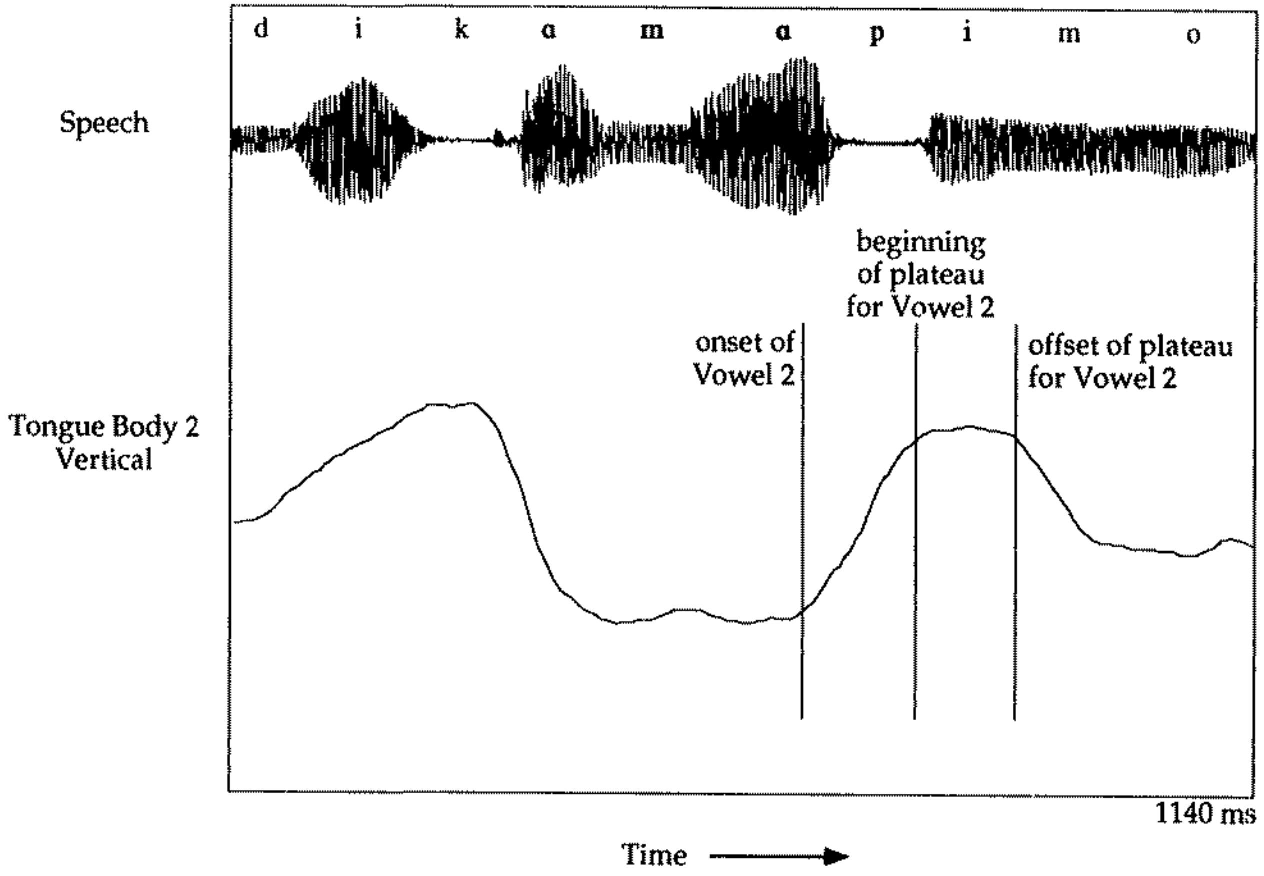


Figure 2.11. Events that could be marked in utterances with initial /a/, shown in a production of /mapi/ by Italian speaker I1.

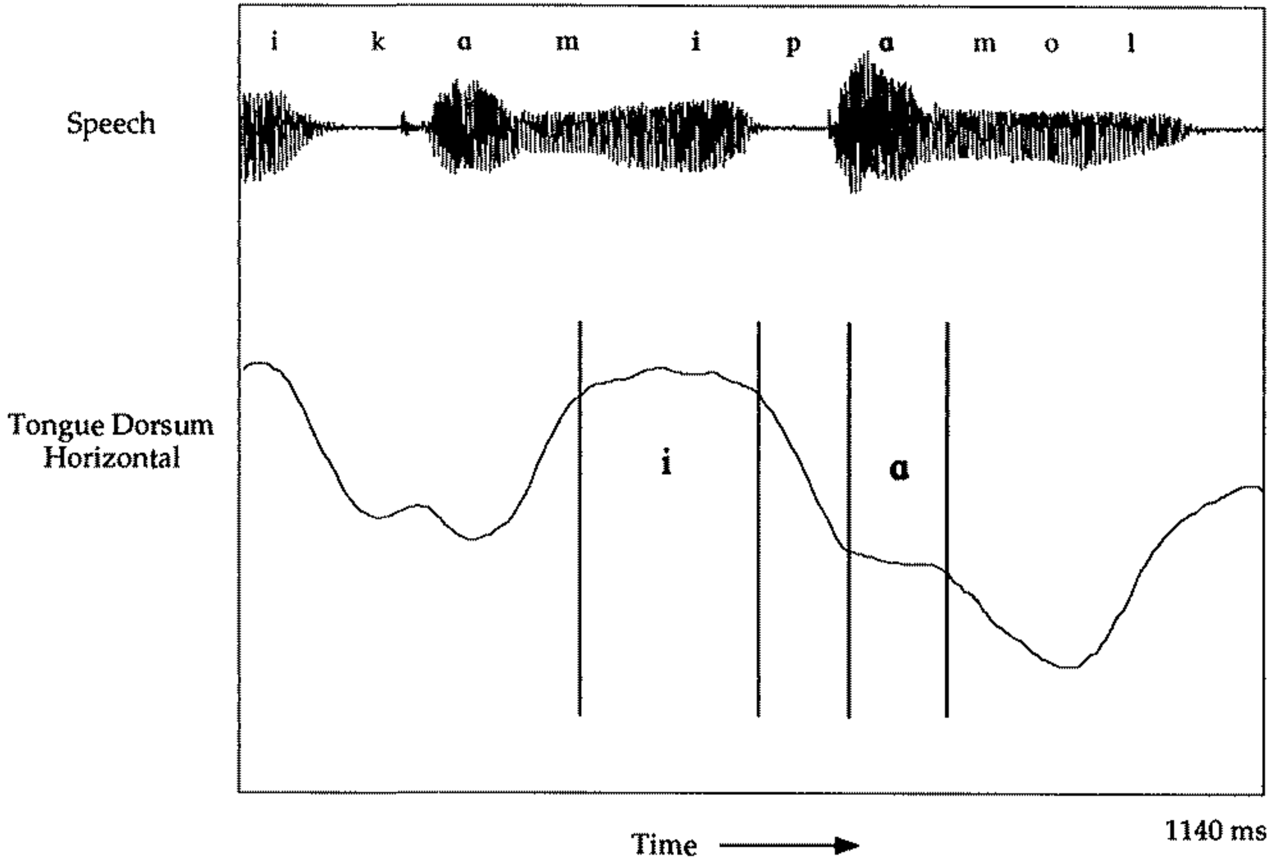


Figure 2.12. Events marked in a production of /mipa/ by Italian speaker I1, showing that the region associated with the second vowel could be identified as an inflection in the tongue movement.

trajectory for which the value is less than this noise is marked by the program as being equivalent to "zero". This technique is illustrated in Figure 2.13.

In order to select the portions of the trajectories that would be associated with specific gestures, "noise value" criteria had to be determined for each channel. The criterion level for the vowel-related movements were chosen to be 10% of the total range of velocities for that channel for that speaker. That is, the absolute values of the most extreme positive and most extreme negative velocities of a given pellet dimension or factor produced by an individual speaker were summed together and divided by 10. This value became the "noise value". At any time that the absolute value of the amplitude of the velocity for that trajectory became smaller than this value, the program identified that sample as being in a zero region. The only exceptions made to this method of determining the noise value were for certain speakers for whom very high velocity movements occurred during the carrier phrase (particularly in /r/ which occurred in the carrier phrases for both languages). In these cases, the noise value was calculated on the basis of the most extreme velocities that occurred during productions of the stimulus words. Table 2.6 shows the velocities found in the various channels and the noise values used.

A different technique was used for determining the noise values for consonant-related movements. It seemed desirable to use the same noise value for both bilabial and alveolar related movements, to provide some comparability in the measures across the two places of articulation. While the bilabial closing movements appeared as smooth, curved humps in the Lip Aperture trajectory, the alveolar closures tended to appear in the Tongue Tip vertical trajectory as humps with sharper corners at the edges of relatively flat plateau regions. (See Figure 2.14, which shows Italian speaker I1 saying /mita/.) Therefore, an appropriate location for the edge of a Tongue Tip closure could usually be determined by inspection. For each speaker, a number of tokens of different utterances were examined, and suitable locations for the beginning and end of the Tongue Tip closures were marked in the Tongue Tip displacement. The velocities were then examined at these locations, and a

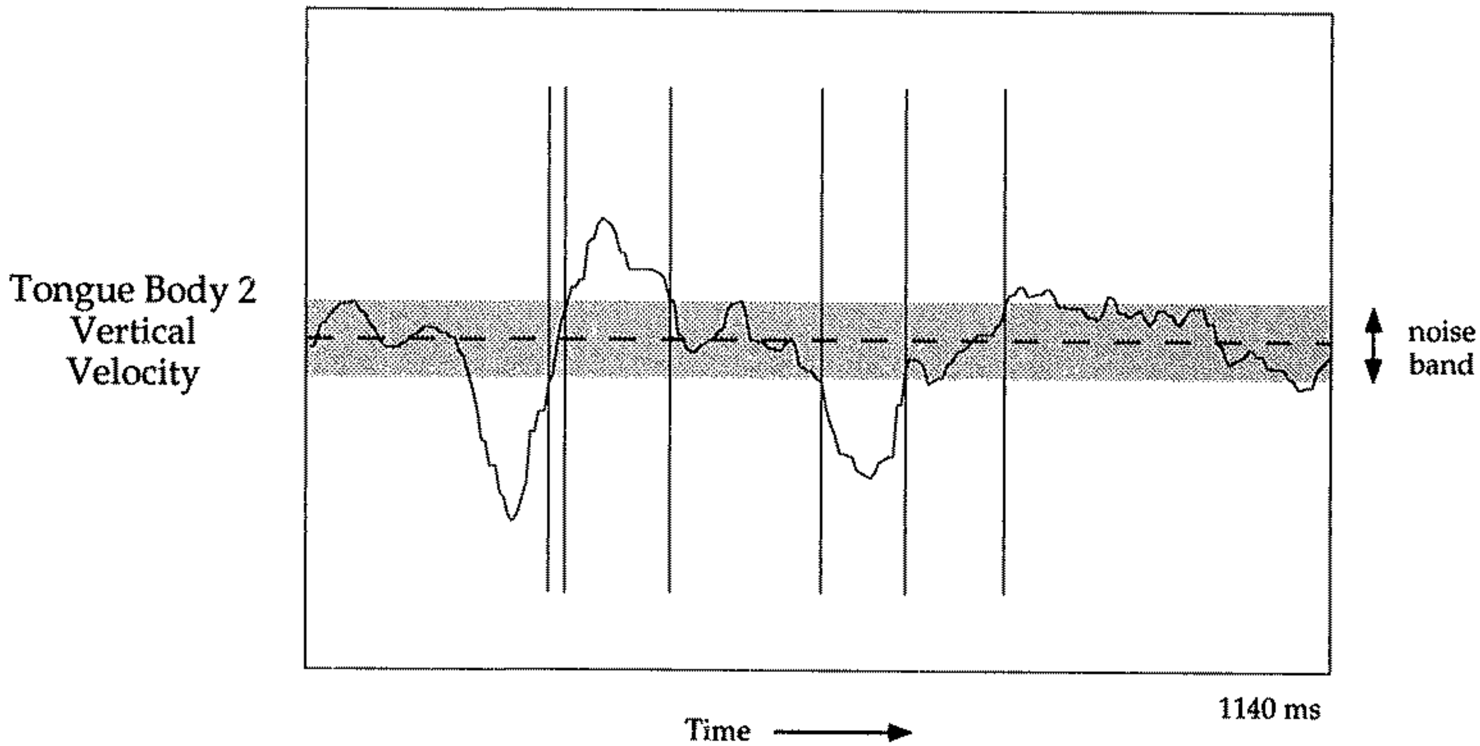


Figure 2.13. Velocity for TB2y in a production of /mipa/ by Italian speaker I1, showing the noise band used in marking events to identify regions where the velocity approached zero.

	ITALIAN	MAX velocity (overall) in cm/s	MAX velocity (after exclusions) in cm/s	Exceptional values that were excluded	MIN velocity (overall) in cm/s	MIN velocity (after exclusions) in cm/s	Final choice of noise criterion in cm/s
I1	LLy	**26.6**			21.7		(LA) 3.2
	TTy	**44.6**	32.0	/r/ (in some stimuli)	28.7		3.2
	TB2y	17.0			**21.4**		4.0
	TDx	**25.6**			22.8		4.8
	Horiz. Factor (no TT)	47.2 units/sec			**51.2** units/sec		10 units/sec
	Vert. Factor (no TT)	36.0 units/sec			**62.0** units/sec		10 units/sec
I2	LLy	**20.0**			17.3		(LA) 3.8
	TTy	**46.7**	39.8	/r/ (in some stimuli)	35.1		3.8
	TB2y	19.5	18.2	/r/ (in some stimuli)	**20.1**		3.8
	TDx	17.0			**18.7**		3.6
	Horiz. Factor (no TT)	45.8 units/sec			41.2 units/sec		8 units/sec
I3	LLy	26.8			**30.2**		(LA) 2.8
	TTy	**37.9**			36.7		2.8
	TBy	**20.4**			19.4		4.0
	TBx	24.6	17.4	/r/ (in some stimuli)	**25.3**		4.2
	Horiz. Factor (incl. TT)	36.8 units/sec		files with any mistracks	33.4 units/sec		7 units/sec

JAPANESE

J1	LLy	**26.4**			24.6		3.2
	TTy	**55.0**	(22.0)	/r/ (in carrier phrase)	37.6	(15.0)	3.2
	TB2y	**20.3**			18.5		3.8
	TDx	23.4			**25.0**		4.8
	Horiz. Factor (no TT)	58.6 units/sec			**62.6** units/sec		12 units/sec
	Vert. Factor (no TT)	**52.2** units/sec			35.4 units/sec		8 units/sec
J2	LLy	**27.2**			26.3		(LA) 3.8
	TB1y	**25.5**			(16.0)		
	TB2y	**18.3**			(16.4)		3.4
	TDx	**17.0**		estimate because of mistrackings	(16.2)		3.4
	Horiz. Factor (no TT)	49.6 units/sec			**54.2** units/sec		10 units/sec
	Vert. Factor (no TT)	(46.0) units/sec		estimate because of mistrackings	**50.8** units/sec		10 units/sec
J3	LLy	23.7			**24.8**		(LA) 3.4
	TTy	**43.0**	23.4	/r/ (in carrier phrase)	23.6		3.4
	TB2y	**17.9**			13.7		3.0
	TDx	23.0			**28.3**		5.2
	Horiz. Factor (no TT)	49.8 units/sec			**54.4** units/sec		10 units/sec
	Horiz. Factor (incl. TT)	49.8 units/sec			**58.4** units/sec		10 units/sec
	Front Vert. Factor (incl. TT)	**62.2** units/sec	52.8 units/sec	/r/ (in carrier phrase)	36.4 units/sec		9 units/sec

Table 2.6. Maximum and minimum velocity, and noise criterion used in identifying events, for all pellets and factors. For each pellet or factor, its peak velocity is in **bold**. () means the value was estimated from a sample of data files. The reasons for having to estimate were mistrackings, strange movements at beginning or end of data files, or if no files could be found without high-velocity /r/.

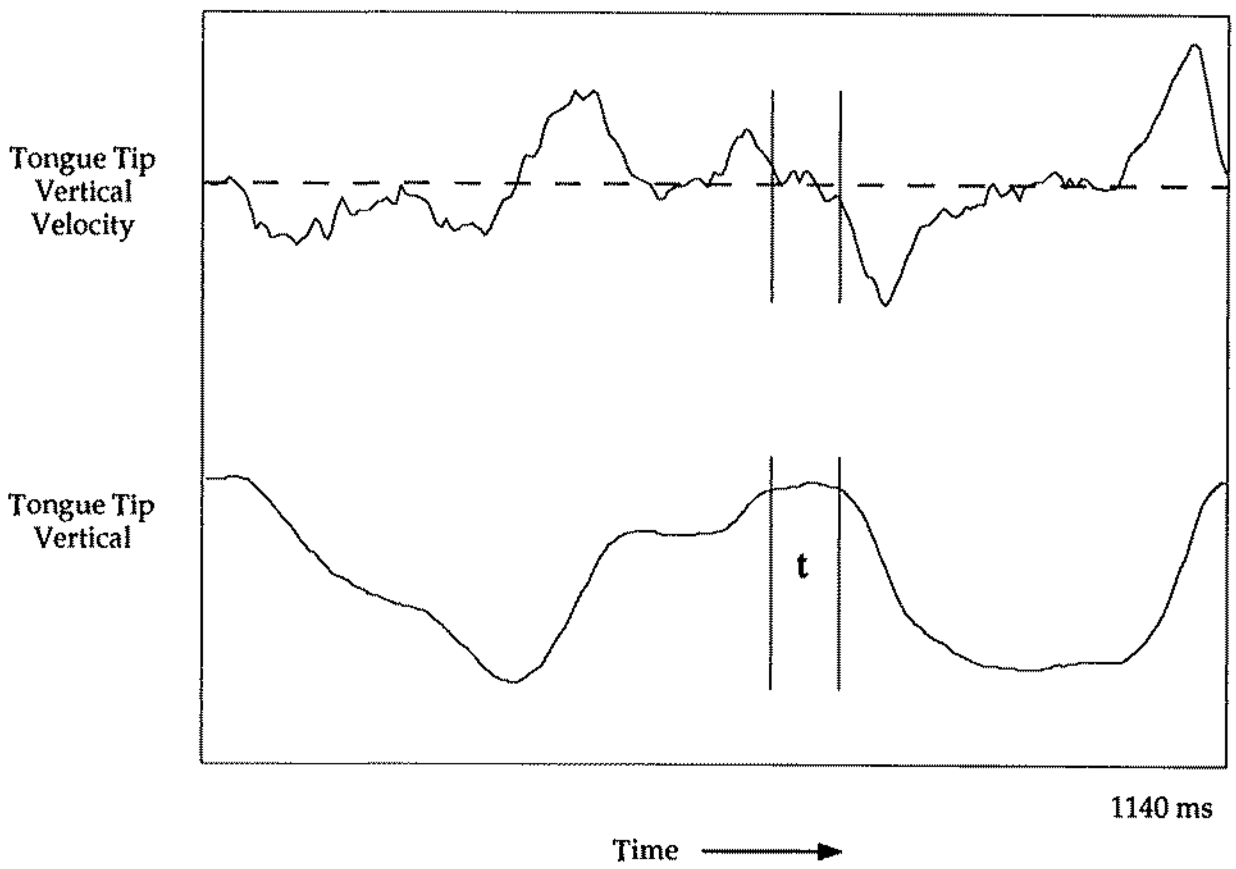


Figure 2.14. Production of /mita/ by Italian speaker I1, showing the shape of the Tongue Tip trajectory for an alveolar consonant.

value chosen that was between the largest velocities during the plateau region and the smallest velocities outside the plateau region. This value was used as the noise value for the Tongue Tip and Lip Aperture (or Lower Lip) trajectories. This procedure meant that both Tongue Tip and Lip Aperture were demarcated at locations that were comparable, at least in terms of how much the movements had slowed down.

The procedure for identifying the significant events was to display a displacement time function and its velocity with the regions of zero velocity detected automatically, and verify that the edges of these regions correspond to one of the events named above. Since more regions of zero velocity were chosen in a given section than the number of events being identified, some of these regions were eliminated by hand. Figure 2.15 shows an example of the utterance /mami/ produced by Italian speaker II, with zero regions identified automatically in the velocity signal, and on the displacement signal, those events that were retained after hand-editing. Around the onset of movement towards /i/, the edge that was used was right edge of the region in which the velocity changed sign; during this portion of the trajectory, any regions in which the velocity approached zero but did not change sign were disregarded. Sometimes the velocity exceeded the noise value for a brief portion of the time between two zero regions that appeared to be part of the same vowel plateau; in these instances marked edges were deleted so that the two zero regions were combined into one. An example of this is shown in Figure 2.16, which is again Italian speaker I1. Utterances in which the intervocalic consonant was an alveolar were particularly problematic to segment, as the tongue raising associated with the alveolar closure overlapped the tongue raising associated with the high vowel, even for pellets towards the rear of the mouth. If there were two regions marked in a vowel-associated channel and one of these regions appeared to occur during the consonant closure, that region was deleted. In general, these problems arose only for the vowels and not for consonants in Lip Aperture and the Tongue Tip.

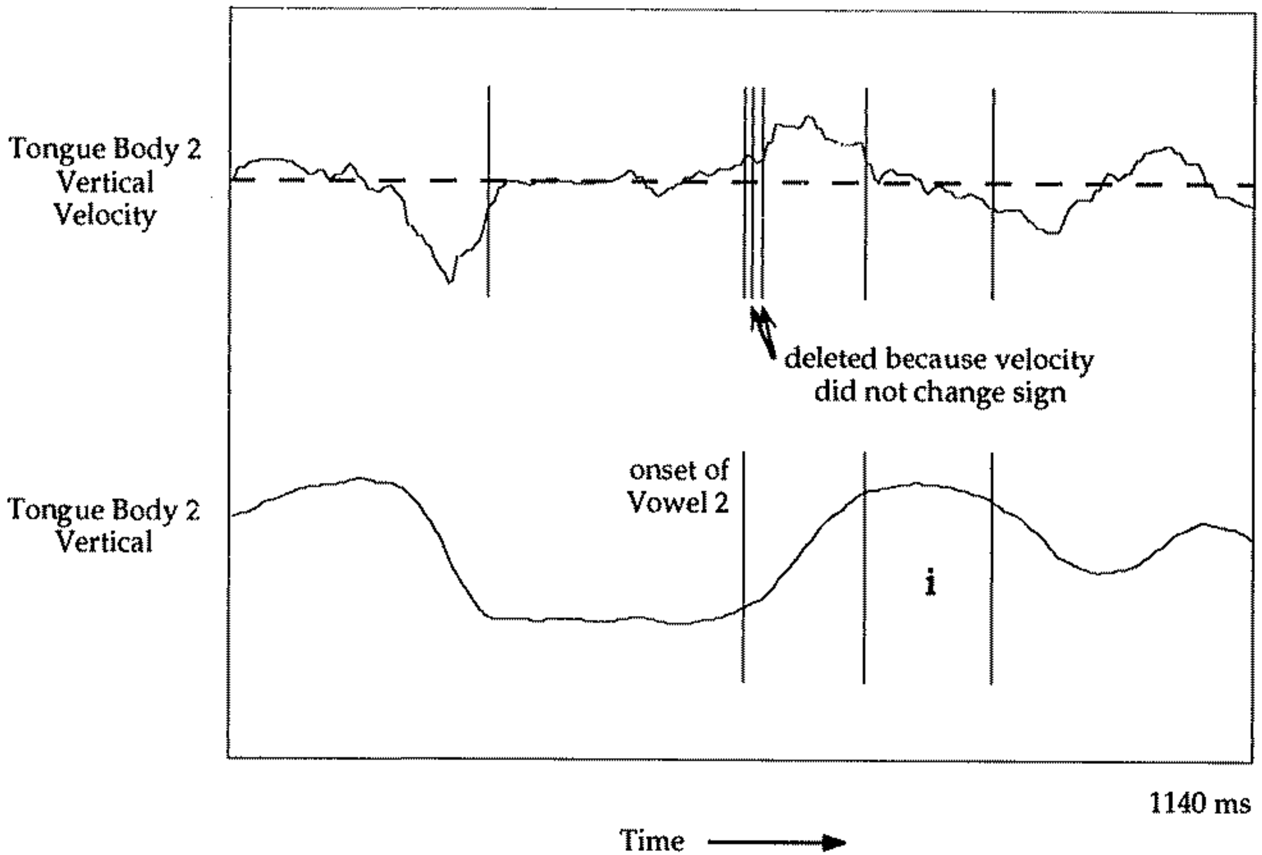


Figure 2.15. Production of /mami/ by Italian speaker I1, showing events automatically marked in the velocity, and those that were retained in the displacement signal.

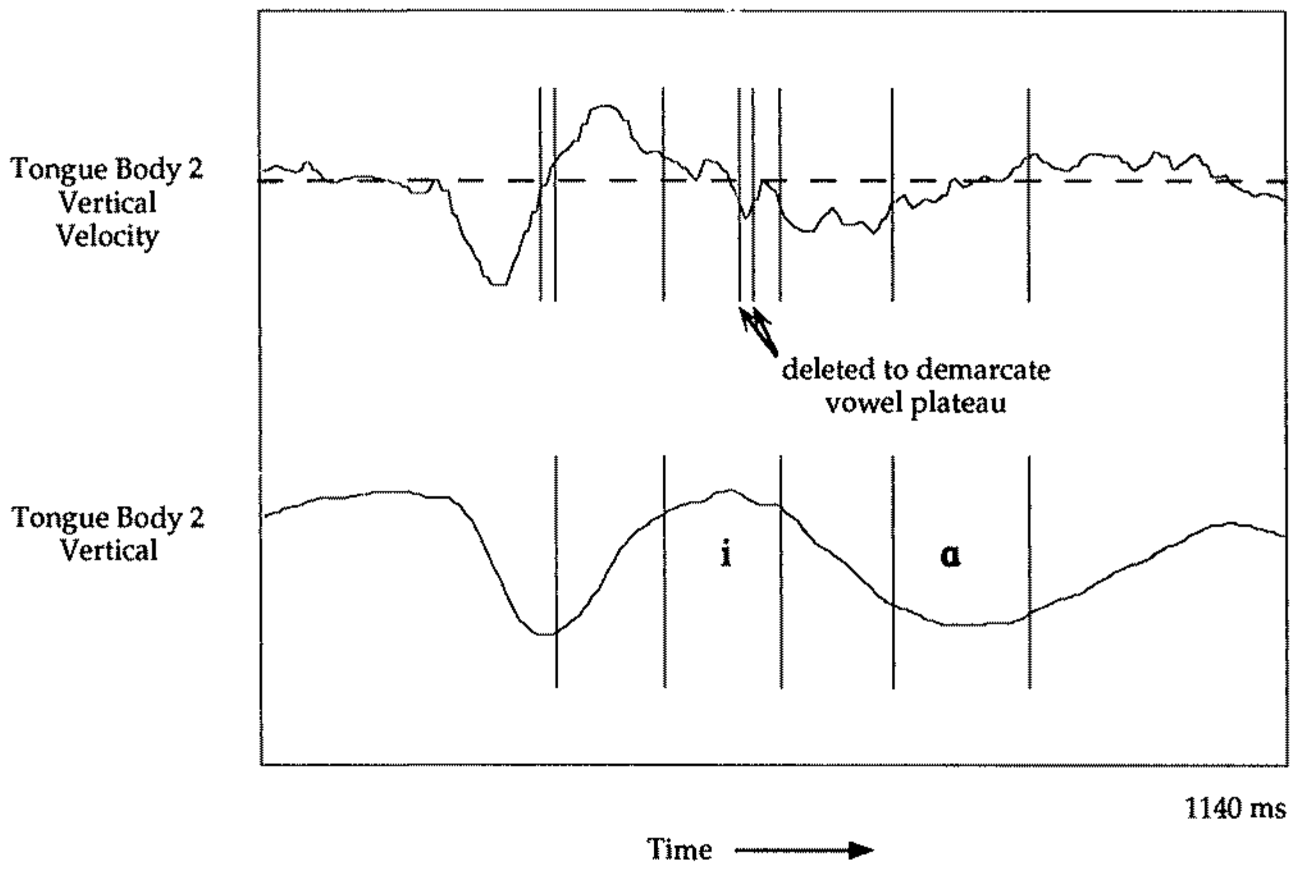


Figure 2.16. Production of /mimma/ by Italian speaker I1, showing events automatically marked in the velocity, and those that were retained in the displacement signal.

Other tokens presented the opposite problem: a portion of the trajectory in which a vowel was being produced that did not have any regions of zero velocity marked. The following techniques were used to identify appropriate locations for marking the beginning and end of such vowels. The most common reason for not detecting an edge was when the velocity fluctuated around zero and remained within the zero region beyond the portion of the trajectory that appeared to be associated with a particular vowel. This happened frequently at the offset of /a/ in the second syllable, as shown in Figure 2.17, which shows Japanese speaker J1 producing the utterance /mima/. The missing event (shown by a dotted line in the figure) was inserted by hand either at the maximum velocity that occurred within an appropriate part of the velocity signal if position was increasing or at the minimum velocity if position was decreasing (as shown in Japanese speaker J1's production of /mima/ shown in Figure 2.17). The vast majority of events that were inserted by hand (1091 in all, approximately 4% of the total) were inserted in this way. However, there were more problematic cases, when an inflection point in the velocity was used because no maximum or minimum occurred during the appropriate part of the trajectory. No more than two events were inserted by hand within a single channel of one token; if three or more events were not detected automatically, that token was discarded. Four tokens were discarded for this reason. For Japanese speakers J1 and J2, since there tended to be little or no movement between the /a/ and the /o/ that followed in the carrier phrase, the offset of the second vowel was often not labeled automatically in tokens that had /a/ in the second syllable. In some of these tokens, this event was left missing, and measurements involving that location excluded such tokens from further analysis.

2.5. Statistics

Tokens were identified as to Vowel pattern (/a/ in the first syllable and /i/ in the second, or the reverse), Consonant Length (single, geminate or /mp/ cluster), Nasality (oral, nasal or cluster), and Place (bilabial or alveolar).

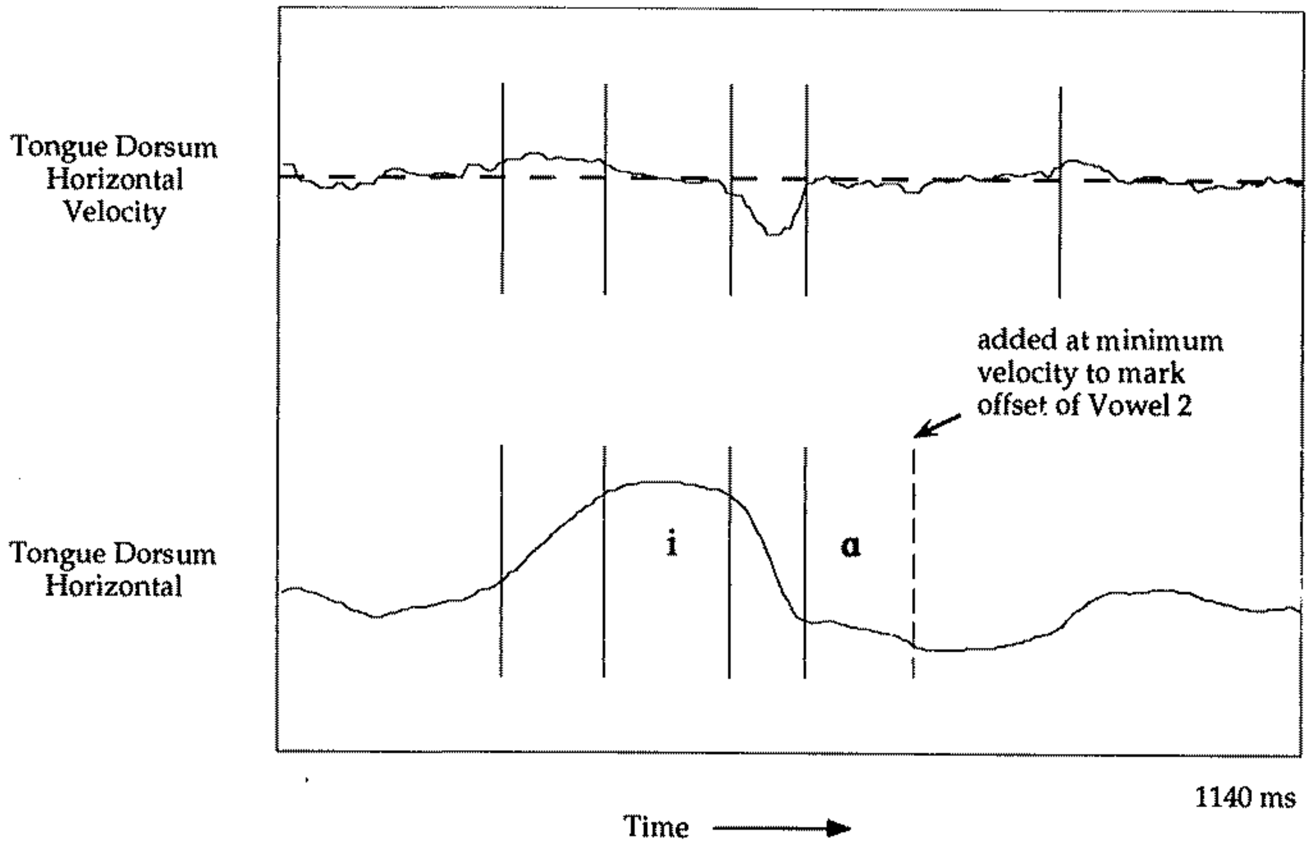


Figure 2.17. Production of /mima/ by Japanese speaker J1, showing an event marked by hand in the displacement signal where the automatic procedure failed.

Analyses of variance on the different intervals were performed using BMDP, to test whether the length of the intervocalic consonant affected the timing of the utterance. Preliminary analyses combining both vowel patterns and consonantal places of articulation had shown interactions with these factors for virtually every measure. Therefore it was believed that little information would be lost by analyzing each vowel pattern and place of articulation separately. Further reasons for analyzing the two vowel patterns separately were that fewer events had been identified in the utterances with the a-i vowel pattern, and the different shapes of the articulatory trajectories meant that the locations associated with the various events were not clearly comparable between the two vowel patterns. Utterances with bilabial and alveolar consonants were also analyzed separately, because difficulty isolating the high vowel /i/ from the alveolar consonantal gestures resulted in great variability in measures of this vowel in the utterances having alveolar intervocalic consonants. For this reason, measures of utterances having bilabial intervocalic consonants seemed to give clearer results and these will be emphasized. Results of alveolar utterances contrasted with them in some cases. Thus, the utterances for each speaker were divided into four classes, which will be referred to as a-i bilabials, i-a bilabials, a-i alveolars and i-a alveolars.

Two sets of analyses of variance were performed on each of these classes: one of utterances with single and geminate consonants only with grouping factors Length (single or geminate) and Nasality (oral or nasal), and for those speakers for whom /mp/ clusters were collected, a second analysis of those bilabial utterances that have geminates or clusters intervocalically, with a single grouping factor (/pp/ or /mm/ or /mp/). Effects for which $p < .05$ were considered significant.

Chapter III

RESULTS

1. Acoustic measures

1.1. Italian

For acoustic measures of all three Italian speakers, two-way analyses of variance (grouping factors Length: single vs. geminate and Nasal: oral vs. nasal) were run for utterances with vowel pattern a-i and bilabial consonants, for i-a utterances with bilabials, a-i utterances with alveolars, and i-a utterances with alveolars. The different classes of utterances were separated for these analyses for comparability with the articulatory measures, in which it had been found desirable to separate the vowel patterns and consonantal places of articulation. The results of this ANOVA are listed in Appendix 2.

The dependent variables were the acoustic intervals corresponding to the durations of the first vowel, the intervocalic consonant closure, and the second vowel. Since in some utterances with voiceless stops there was a short lag between the release of the stop closure and the onset of voicing for the following vowel, an additional dependent measure was used, corresponding to the total time between consonant closure and the onset of voicing of the following vowel. This measure will be referred to as total consonant duration. Vowel durations in such cases were measured from voicing onset. The durations of the acoustic segments are graphed in Figures 3.1-3.3.

The speakers showed quite uniform effects of Consonant Length on their acoustic durations. The durations of the consonant closure (excluding VOT) and of the total consonant duration (including VOT) were significantly longer for geminates for all speakers in all utterances. The duration of a vowel preceding a geminate was significantly shorter than a vowel preceding a single consonant for all speakers in all utterances. The duration of a vowel following a geminate was significantly shotter than a vowel following a single consonant for speaker I1 in a-i bilabial utterances, i-a bilabials

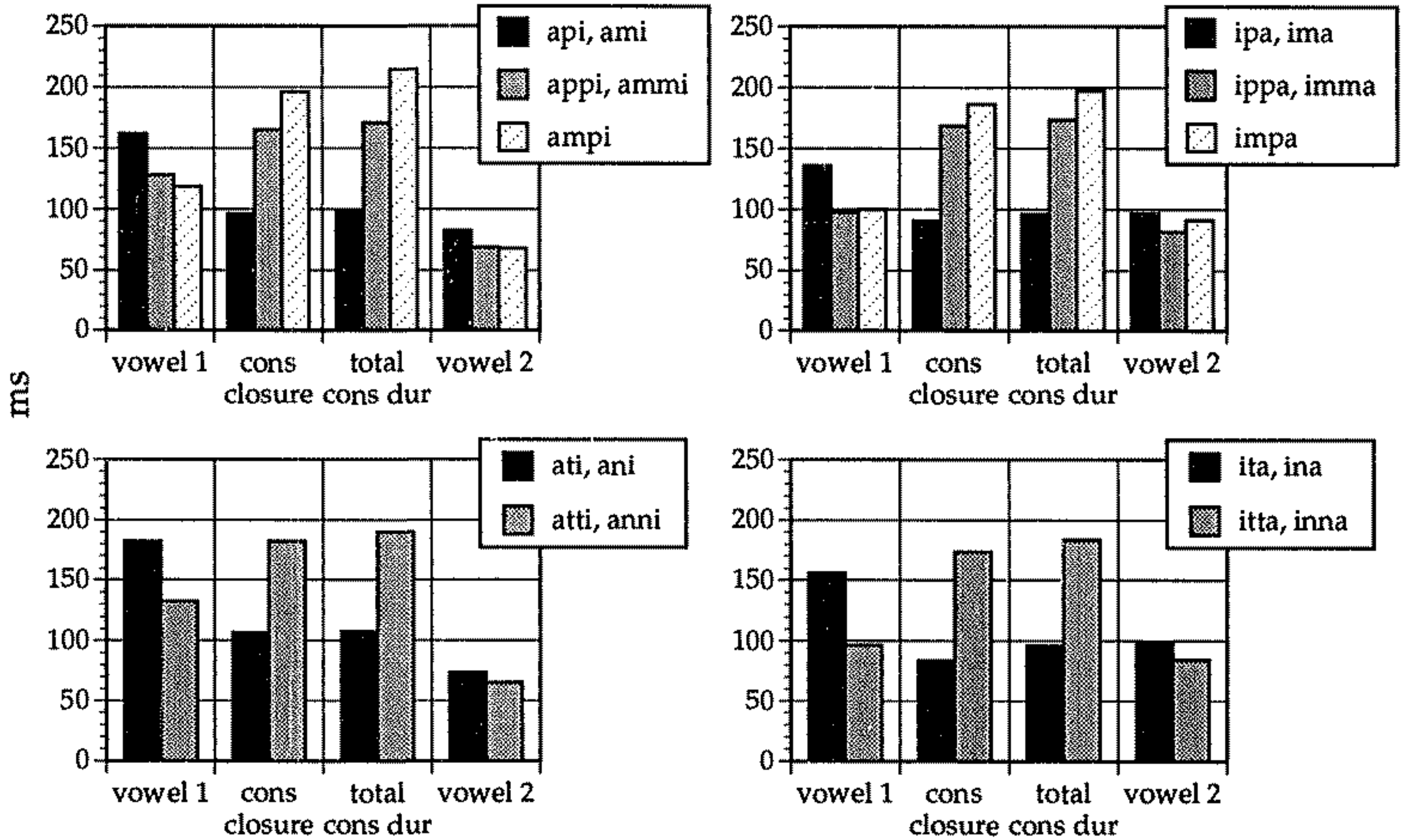


Figure 3.1. Acoustic durations for Italian speaker I1.

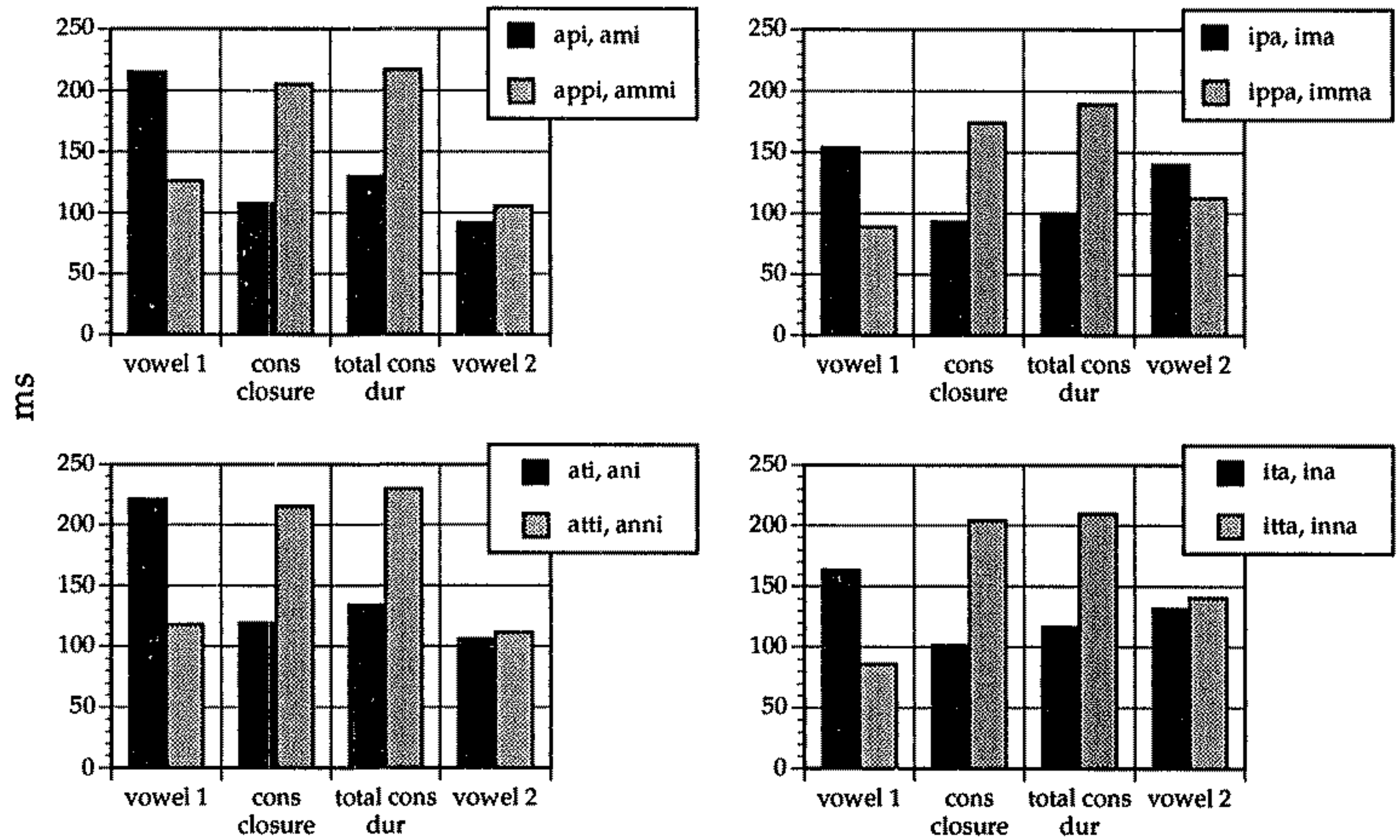


Figure 3.2 Acoustic durations for Italian speaker I2.

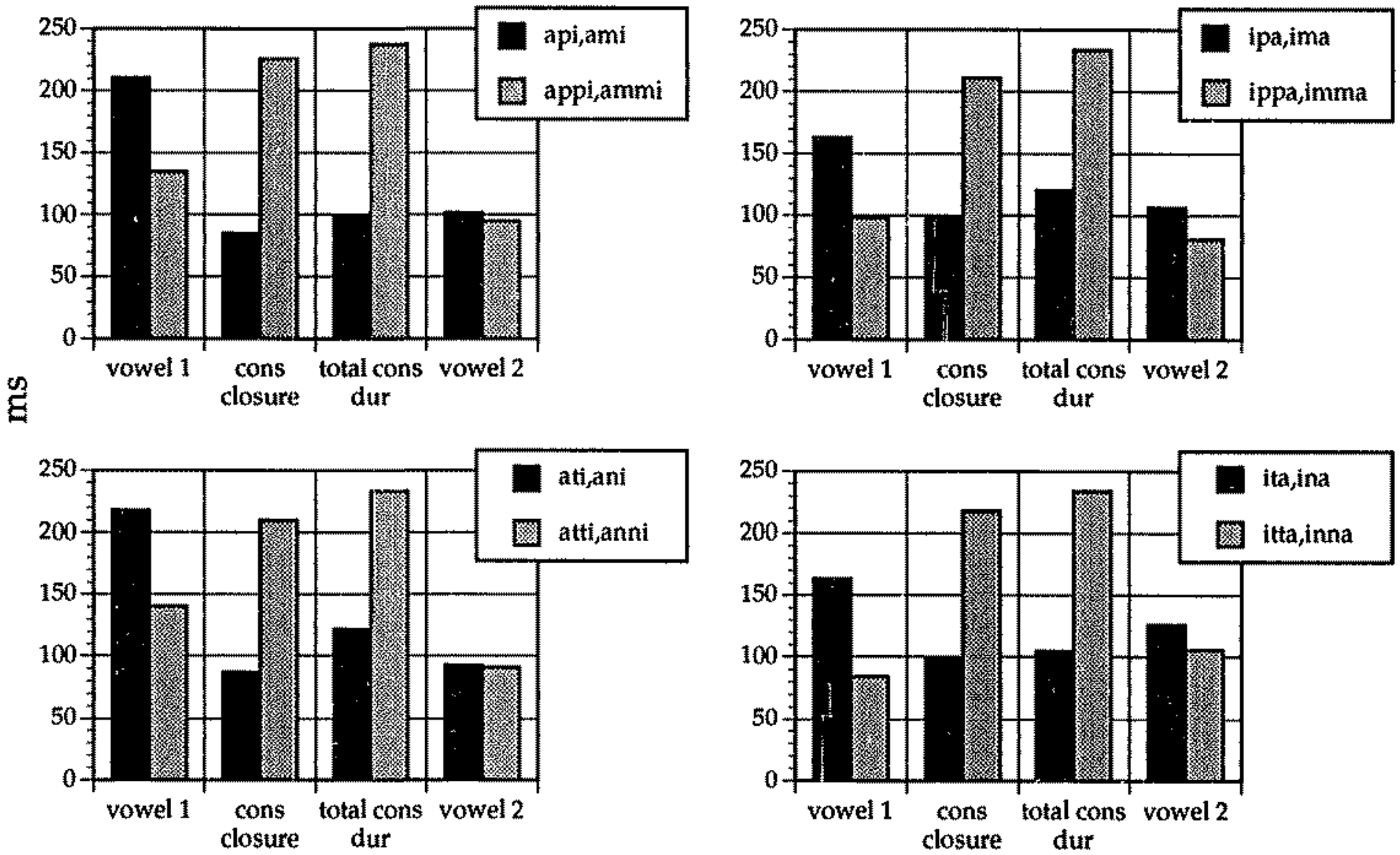


Figure 3.3. Acoustic durations for Italian speaker I3.

and i-a alveolars, and speakers I2 and I3 in i-a bilabials. Elsewhere the difference was not significant.

There were also interactions between the effects of Length and Nasal in some utterances. For speaker I1's i-a alveolar utterances, the shortening of vowels in utterances with geminates was accentuated when the consonant was nasal. Speaker I2 had significant interactions in the duration of the consonant closure for a-i bilabials, where the increase in length was greater for /pp/ compared to /p/ than /mm/ compared to /m/, and in the total consonant duration for a-i alveolars, where the difference was greater between /n/ and /nn/ than /t/ and /tt/. An interaction between Length and Nasal was also found in the total consonant duration of speaker I3's i-a alveolar utterances, where the difference was greater between /t/ and /tt/ than /n/ and /nn/, the opposite of that found with speaker I2.

Vowels consistently tended to be longer and the intervocalic consonant shorter when the consonant was nasal, but this effect was less often significant than the effect of Consonant Length. For speaker I1, the first vowel was significantly longer preceding a nasal than an oral consonant in the a-i alveolars, the i-a bilabials and the i-a alveolars. The second vowel was significantly longer following a nasal consonant in all but the i-a bilabial utterances, where it was significantly shorter. Nasal consonants themselves were significantly shorter than oral ones in all utterances, with or without the inclusion of the period of VOT for the oral consonants. For speaker I2, the first vowel was significantly longer preceding nasal consonants in the a-i bilabial utterances, the a-i alveolars, and the i-a alveolars. The second vowel was significantly longer following nasal consonants in the a-i alveolars, the i-a bilabials and the i-a alveolars. The consonant closure was shorter for nasals only in the i-a alveolars, but when the period of VOT was included for oral consonants, the difference was significant for all utterances. For speaker I3, both vowels were significantly longer with nasal consonants in the a-i alveolar utterances, but there was no significant effect of Nasal in the vowels of the other utterances. The consonant closure was shorter for nasals only in the i-a bilabials, but when the period of VOT was included for oral consonants, the difference was significant for all utterances.

For speaker I1, utterances with the intervocalic cluster /mp/ were also measured. These were compared to the geminates /pp/ and /mm/ in a one-way ANOVA on Long Consonant Type, shown in Appendix 2, and then a post-hoc Tukey test was used to determine which of the three utterances were significantly different from the others. (Effects at the .05 level were considered significant in the Tukey test, and only these will be reported.) The effect of long consonant Type was significant in all acoustic segments in both a-i and i-a bilabial utterances, although sometimes this was due to differences between /pp/ and /mm/ rather than between the cluster and the geminates. The measures of consonant closure duration and total consonant duration for /mp/ were always significantly longer than for /mm/, but significantly longer than for /pp/ only in the a-i utterances. Both vowels in /ampi/ were significantly shorter than the vowels in /ammi/ but did not differ significantly from the vowels in /appi/. The initial /i/ in /ippa/ was significantly shorter than in /imma/, but neither of these differed significantly from initial /i/ of /impa/. Contrary to the usual pattern of vowels being longer with nasal consonants, final /a/ in /imma/ was significantly shorter than final /a/ in /impa/ or /ippa/.

The results for the effect of consonant nasality corresponded with results of previous studies such as Fametani and Kori (1982) who reported a similar pattern of longer vowels before nasals, with shorter closures for nasal than oral consonants. This pattern has also been reported for Japanese by Han (1962) and for English by numerous investigators (e.g., House and Fairbanks 1953; Umeda 1975).

1.2. Japanese

Similar analyses were performed on the acoustic measures for the Japanese speakers as for the Italian. For acoustic measures of Japanese speakers J1 and J3's productions, two-way analyses of variance, with factors Length and Nasal, were run for utterances with vowel pattern a-i and bilabial consonants, for i-a utterances with bilabials, and i-a utterances with alveolars. For a-i utterances with alveolars, because there were no /ati/ or /atti/ utterances, a one-way analysis of variance (grouping factor Length) was run for utterances with intervocalic consonants /n/ and /nn/. The same measures were made for speaker J2 except that no measures were made of the i-a alveolars as these could not be measured in the articulation, as this speaker had no Tongue Tip pellet.

The same acoustic segments were measured as for the Italian speakers, except for speaker J3, for whom only one measure of consonant duration, total consonant duration, was used. The results of the ANOVAs are shown in Appendix 2, and the durations of the acoustic segments are plotted in Figures 3.4-3.6. Utterances with the intervocalic cluster /mp/, discussed below, are also graphed in these figures.

Measurements made of acoustic segments in the waveform showed that for all speakers almost all the acoustic segments were significantly longer when the intervocalic consonant was a geminate than when it was a single consonant. For speaker J1, the only exceptions were in the second vowel. In a-i bilabials, there was no significant effect of Length of the consonant on the second vowel. In i-a alveolars, the second vowel was significantly shorter following a geminate consonant, and this difference was greater following /nn/ than following /tt/. The first vowel was always longer preceding a geminate; the interaction of Length × Nasal was significant in a-i bilabials, i-a bilabials, and i-a alveolars because the difference between vowels preceding single and geminate consonants was greater when the consonant was nasal. Nasal consonants were shorter than oral consonants, but vowels were longer in utterances with nasal consonants than with oral consonants.

For speaker J2 as for speaker J1, the only exception to the generalization that acoustic segments are longer in geminate utterances was the second vowel, this time in a-i alveolar utterances, where there was no significant effect of Consonant Length. The main effect of Nasal was significant everywhere except in bilabial consonants in i-a utterances. As was the case for speaker J1, nasal consonants were shorter than oral

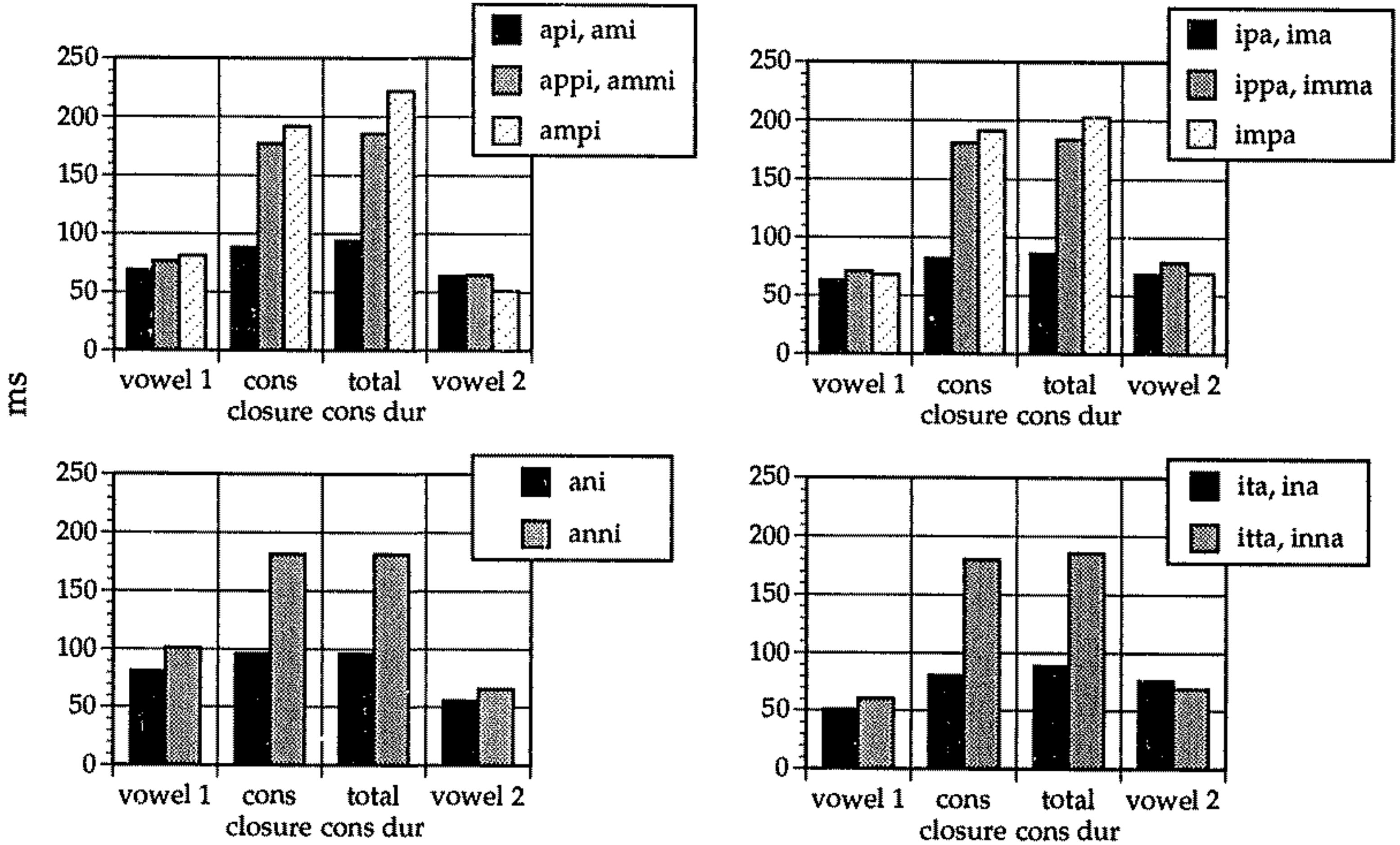


Figure 3.4. Acoustic durations for Japanese speaker J1.

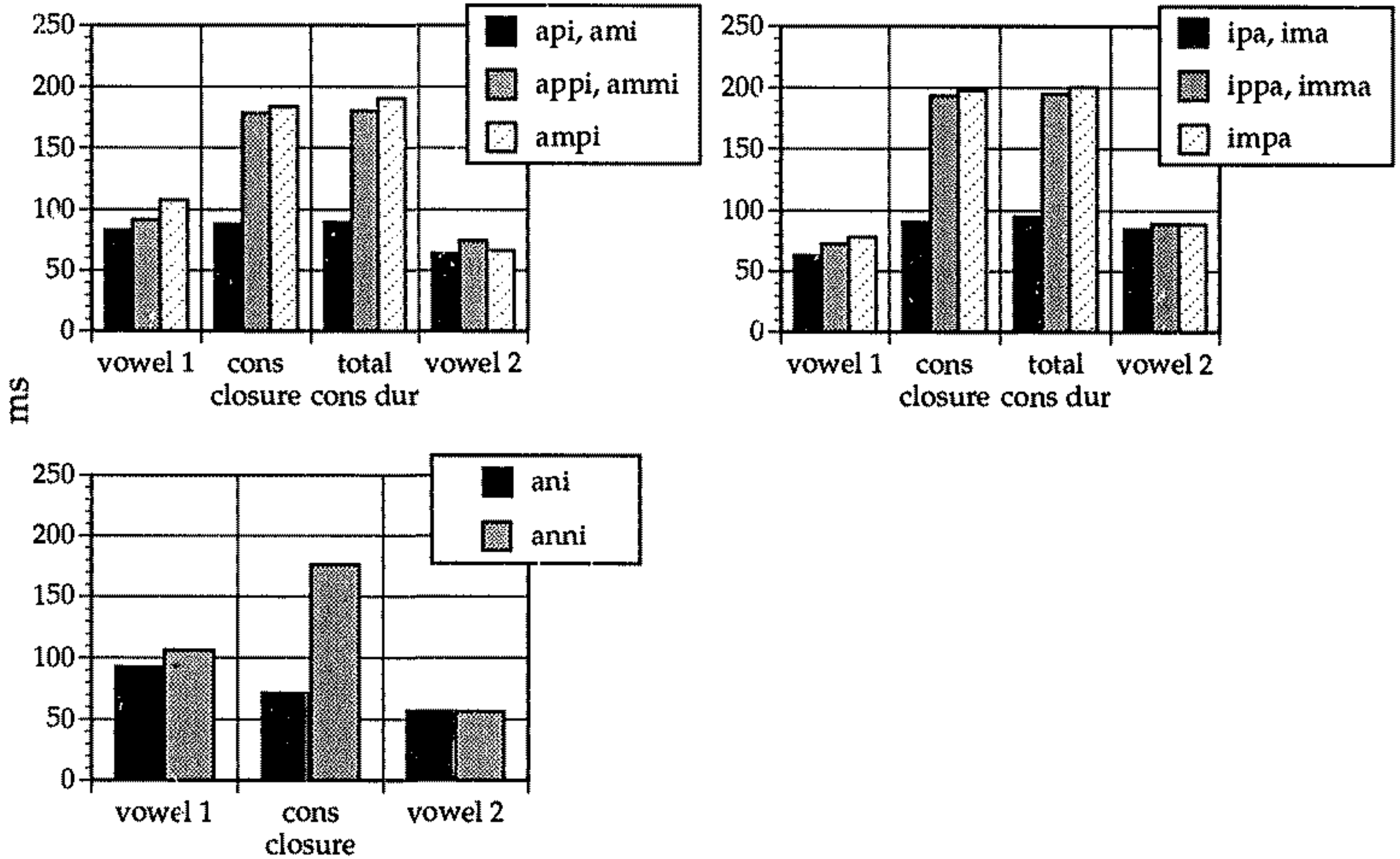


Figure 3.5. Acoustic durations for Japanese speaker J2.

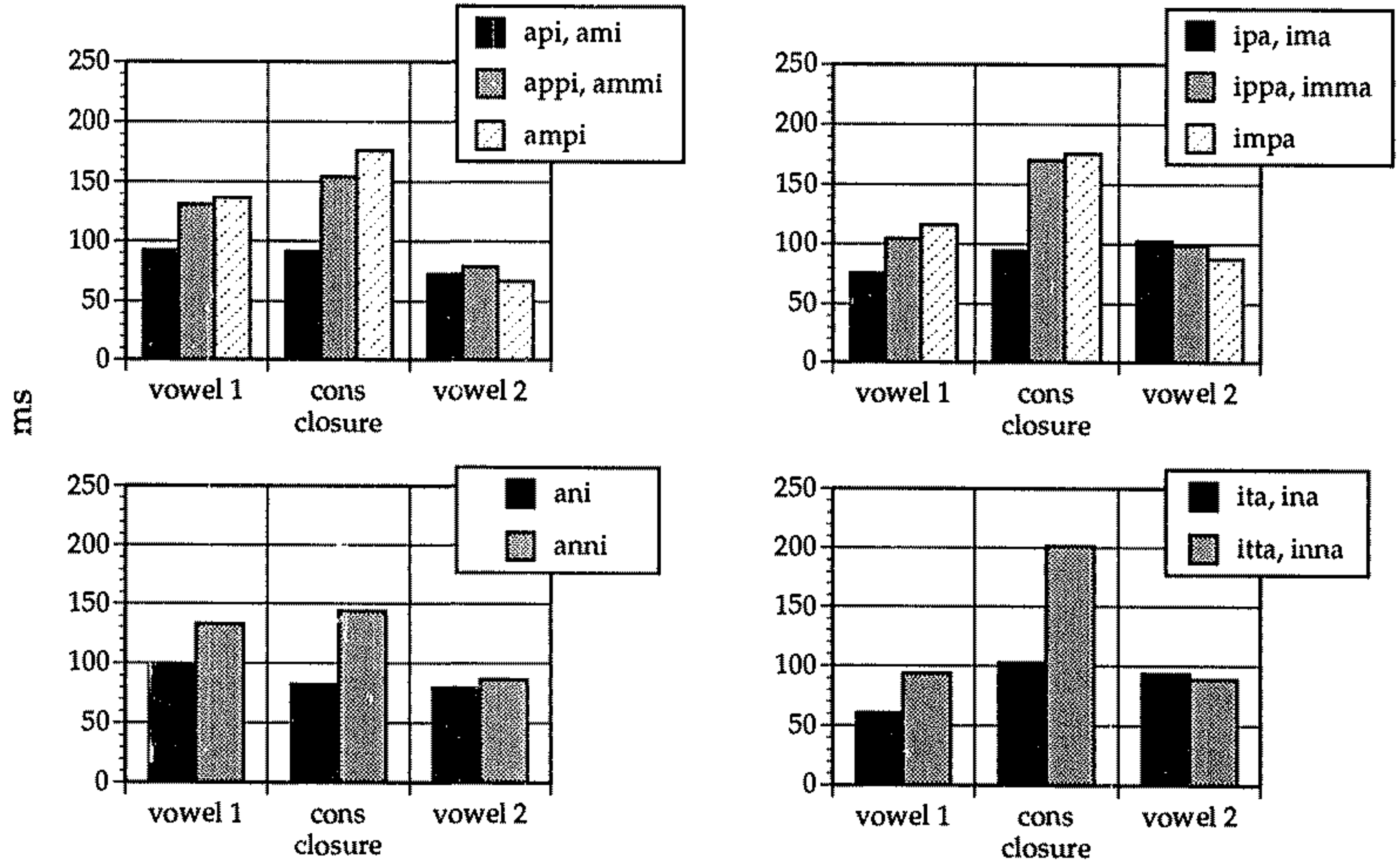


Figure 3.6. Acoustic durations for Japanese speaker J3.

consonants, and vowels were longer in utterances with nasal consonants. The only significant interaction of Length × Nasal was in the second vowel of i-a bilabial utterances, where the vowel lengthening was greater following a nasal consonant.

Speaker J3's vowels preceding geminate consonants were significantly longer than her vowels preceding single consonants, and the difference was greater preceding nasal consonants. Naturally, the geminate consonants themselves were significantly longer than the single consonants; there was a significant interaction of Length × Nasal for i-a utterances with bilabial and alveolar consonants, because the difference between singletons and geminates was greater in oral consonants than in nasal ones. However, unlike speakers J1 and J2 for whom the second vowel was also generally longer following geminate consonants, for speaker J3 there was never a significant effect of Length on the second vowel. Like the other speakers, speaker J3 had shotter nasal than oral consonants, but longer vowels in utterances with nasal consonants. The only exception was the first vowel in i-a alveolars, in which there was no significant effect of Nasal.

These results show that all three speakers had very reliable differences between utterances with single and geminate consonants. The consistent lengthening of all segments of the acoustic waveform in the utterances with geminate consonants corresponds to previous results obtained for Japanese speakers (e.g. Han 1962, Homma 1981). Total duration of the utterance also increased for all the speakers. This is in agreement with the proposal that the duration of utterances in Japanese is proportional to the number of moras making them up (see, for example, Port et al 1987). For these speakers, the ratio of the acoustic duration of the utterances with single consonants to the duration of the utterances with geminate consonants was close to that predicted by the number of moras (2 moras vs. 3 moras), as shown in Table 3.1.[1]

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[1]Note that, because the initial /m/ was not measured, the measurements listed in the table include only the vocalic portion of the first mora of these utterances, and therefore do not correspond exactly to 2 or 3 moras.

	Total duration VCV	Total duration VCCV	ratio
speaker J1	223.2 ms	330.7 ms	1.48
speaker J2	234.0 ms	347.5 ms	1.49
speaker J3	261.5 ms	371.2 ms	1.42
Expected ratio of utterance with 3 moras : utterance with 2 moras			1.5

Table 3.1. Ratio of total acoustic durations of Japanese utterances with single and geminate consonants, compared with number of moras.

An additional question is the behavior of utterances with the intervocalic cluster /mp/. As was done for speaker I1, the utterances with the cluster were compared to the geminates /pp/ and /mm/ in a one-way ANOVA, shown in Appendix 2, and then a post-hoc Tukey test was used to determine which of the three utterances were significantly different from the others. In general, the duration of /mp/ was intermediate between the longer /pp/ and the shorter /mm/, although significances varied. For the consonant closure duration, there was no main effect for speaker J1 or for i-a utterances for speaker J2. For a-i utterances for speakers J2 and J3, the duration of /mp/ was significantly longer than the duration of /mm/ (but not significantly different from /pp/). In i-a utterances for speaker J3 the duration of /mp/ was significantly shorter than the duration of /pp/, as well as being longer than /mm/. For the total consonant duration (different from closure duration for speakers J1 and J2), there was again no main effect in i-a utterances for speaker J2. For a-i utterances for speaker J2 and for speaker J1 the total consonant duration of /mp/ was significantly longer than /mm/. The total duration of /mp/ was significantly longer than the total duration of /pp/ only in a-i utterances of speaker J1; elsewhere there was no difference.

For the durations of the vowels, all speakers had a significant main effect of consonant Type in both a-i and i-a utterances. Given that the /mp/ cluster closes the preceding syllable with /m/, it is not surprising that the duration of its preceding vowel generally behaves like the vowel preceding /mm/ and differently than the vowel preceding /pp/, which is shorter. The duration of vowel 1 was significantly longer preceding /mp/ than preceding /pp/ everywhere except in i-a utterances for speaker J1, where there was no significant difference. Relations between /mp/ and /mm/ were more inconsistent. For speaker J1, the first vowel was shorter preceding /mp/ than preceding /mm/ in both a-i and i-a utterances. For speaker J3 there was no significant difference in the vowels preceding /mp/ and /mm/, which was also the case in i-a utterances for speaker J2. In J2's a-i utterances, however, the vowel preceding /mp/ was significantly longer than the vowel preceding /mm/. The duration of the vowel following /mp/ was always significantly shorter than the vowel following /mm/ for all three speakers. It was significantly shorter than the vowel following /pp/ only in a-i utterances for speaker J1; elsewhere there was no significant difference between them. Again, this suggests that the vowel adjacent to one side of the cluster is patterning like the vowel adjacent to the stop that matches that side of the cluster.

While the durations of acoustic segments in utterances containing the cluster /mp/ were sometimes significantly different from their durations with geminate consonants, they were all longer than with single consonants. The fact that both the cluster and the geminate add a mora to the length of the utterances with single consonants suggests that the durations of utterances containing this cluster should pattern like the utterances containing geminate consonants. In accordance with previous research, the results presented here show that this increased consonant length, whether occurring as a geminate or a cluster, is found with significant lengthening in both vowels as well as in the consonant.

In summary, Consonant Length showed similar patterns in the two languages, with geminate consonants longer than single consonants in both Japanese and Italian. The major difference between Japanese and Italian was found in the acoustic durations of the vowels. In both, the first vowel was affected by lengthening of the intervocalic consonant more consistently than the second vowel, although the vowels showed opposite effects in the two languages, lengthening in Japanese and shortening in Italian.

2. Articulatory measures of utterances with bilabial intervocalic consonants

Unlike measures of the acoustic signal, measures of the articulatory data make it possible to identify vowels and consonant gestures in the trajectories of distinct articulators, which means that potential temporal overlap/simultaneity between vowels and consonants can be identified. As a result, in the articulation the boundaries of the regions in the trajectories that are associated with the vowels and consonants are not mutually dependent, as in the acoustics, so the durations of these intervals are also independent.

For both Japanese and Italian speakers, the utterances with single and geminate bilabial consonants were analyzed in two-way ANOVAs with grouping factors Length and Nasal, with separate analyses for the utterances with the a-i and i-a vowel patterns. Simple main effects tests were performed where there was a significant interaction between these factors to determine the extent of significance of the effect of Length. Results for the main effect of Nasal and for interactions of Length × Nasal will be reported only where they were significant. For the Japanese speakers and Italian speaker I1 who produced utterances with the intervocalic cluster /mp/, they were compared to the geminates /pp/ and /mm/ in a separate one-way ANOVA with factor long consonant Type. If this effect was significant, Tukey tests were used to determine which among the three consonants were significantly different. Only significant results of the Tukey tests will be reported; where a particular comparison is not mentioned, it was not significant (i.e., often utterances with the cluster only differed significantly from one of the geminates).

Measures were made of the durations of numerous intervals in the articulatory movements; the results of the statistical analyses of these measures are listed in

Appendix 2. The endpoints of the intervals, identified stages in the movements which will be referred to as "events", are marked with vertical lines in Figures 3.7 through 3.18, which show sample pairs of utterances with single and geminate consonants. The events that were marked in the trajectories were the onset of movements (where the velocity of the movement exceeded a threshold), the achievement of target (where the movement approached its steady-state or most extreme position and its velocity fell below threshold), and additionally for the consonant, the offset of the target interval (where the movement left a steady-state and its velocity exceeded threshold). The target interval itself is defined as the relatively flat plateau in the trajectories between the target and offset. In tokens where the initial vowel was /a/, it was not possible to identify the onset and target of the first vowel; these tokens have only 3 events marked in the vowel trajectories rather than the 5 that were marked when the first vowel was /i/. For the vowels, the offset of one vowel could not be distinguished from the onset of movement towards the next vowel. The event marked in the figures at the end of the target interval for the first vowel and the beginning of movement towards the second vowel will be referred to as the onset of vowel 2. The event marked at the end of the target interval for the second vowel will be referred to as the offset of vowel 2, although it could also correspond to the onset of movement towards a vowel in the next word. Where a vertical line is dashed, the automatic labelling procedure failed and the event was marked by hand, as described in Chapter II.

Movements associated with the bilabial consonants were measured in Lip Aperture (Lower Lip vertical for speaker J1 for whom Lip Aperture was not available). Movements associated with the alveolar consonants were measured in the Tongue Tip vertical trajectory. Movements associated with the vowels were measured in the factors and in TB2y and TDx, except for speaker I3 for whom TBy and TBx were used. (See Table 2.2 in Chapter II.)

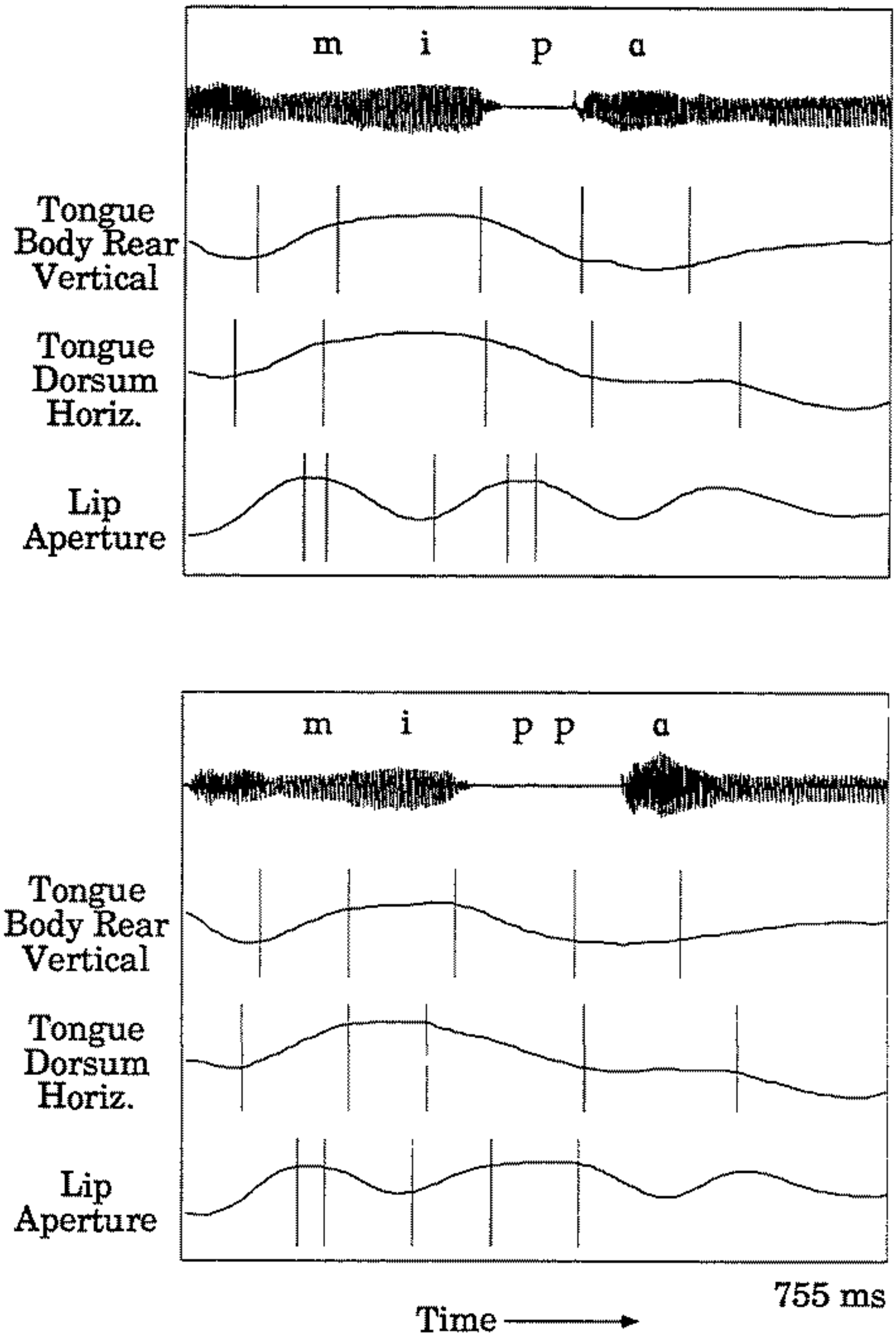


Figure 3.7. Productions of /mipa/ and /mippa/ by Italian speaker I1.

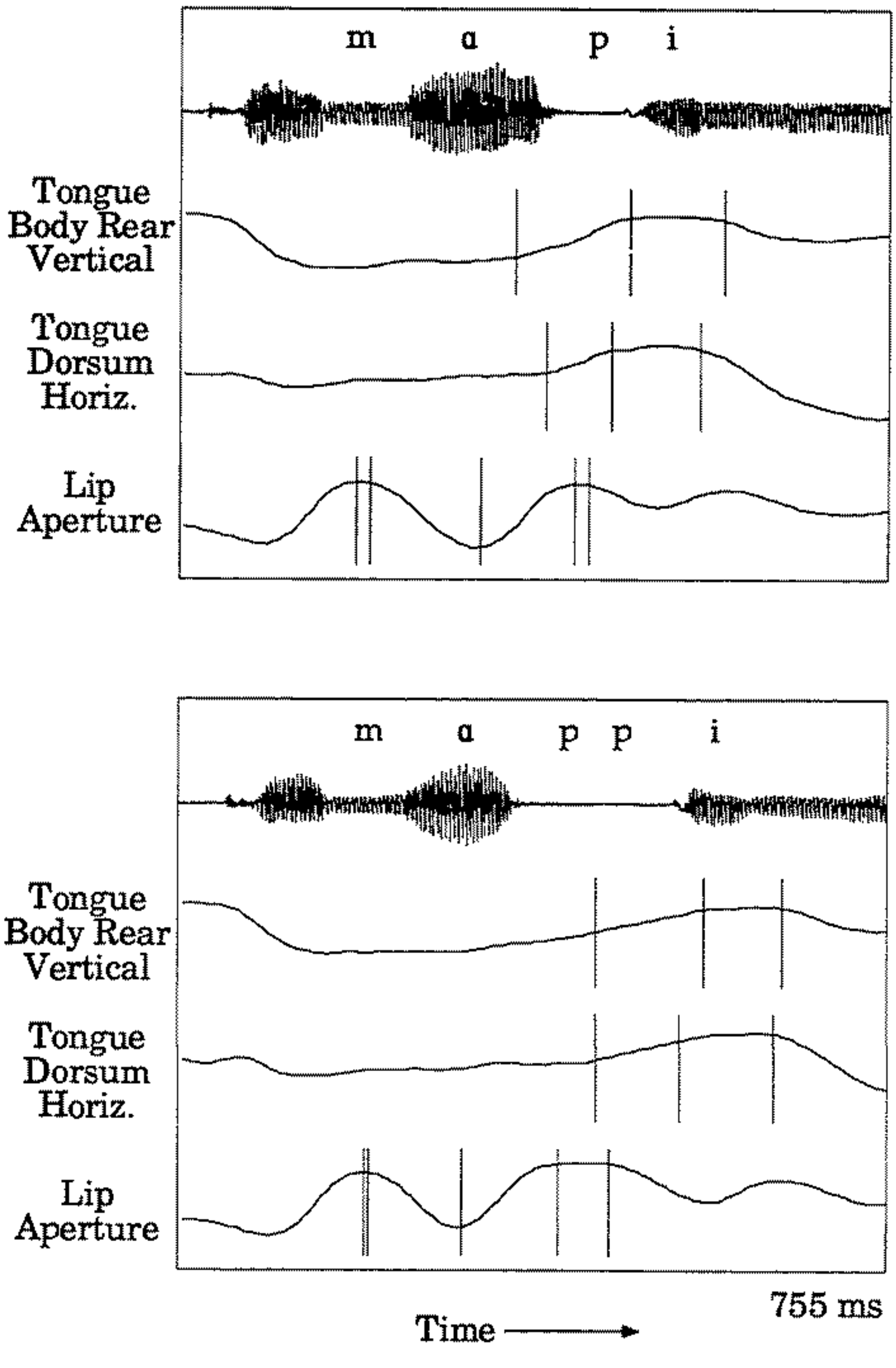


Figure 3.8. Productions of /mapi/ and /mappi/ by Italian speaker I1.

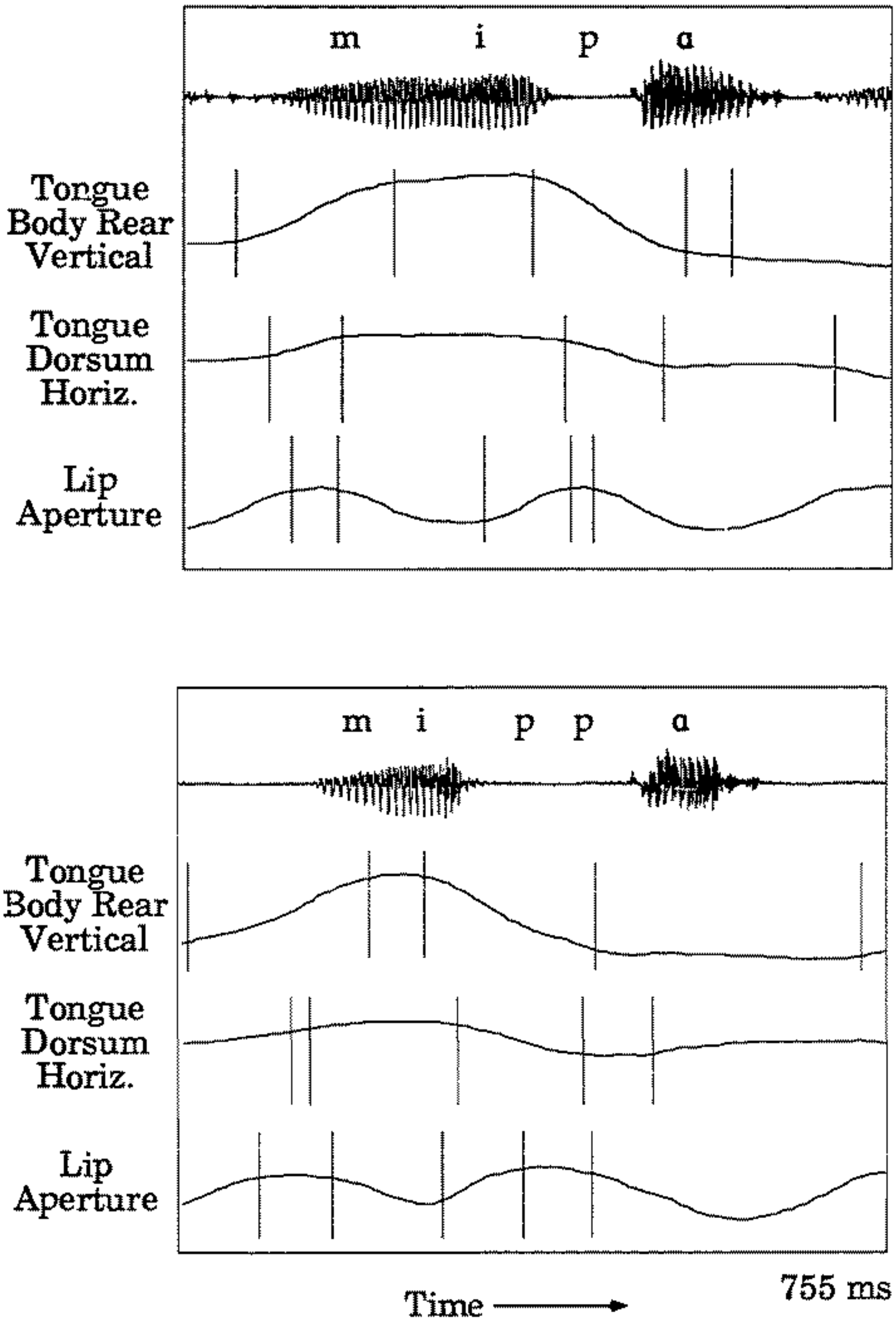


Figure 3.9. Productions of /mipa/ and /mippa/ by Italian speaker I2.

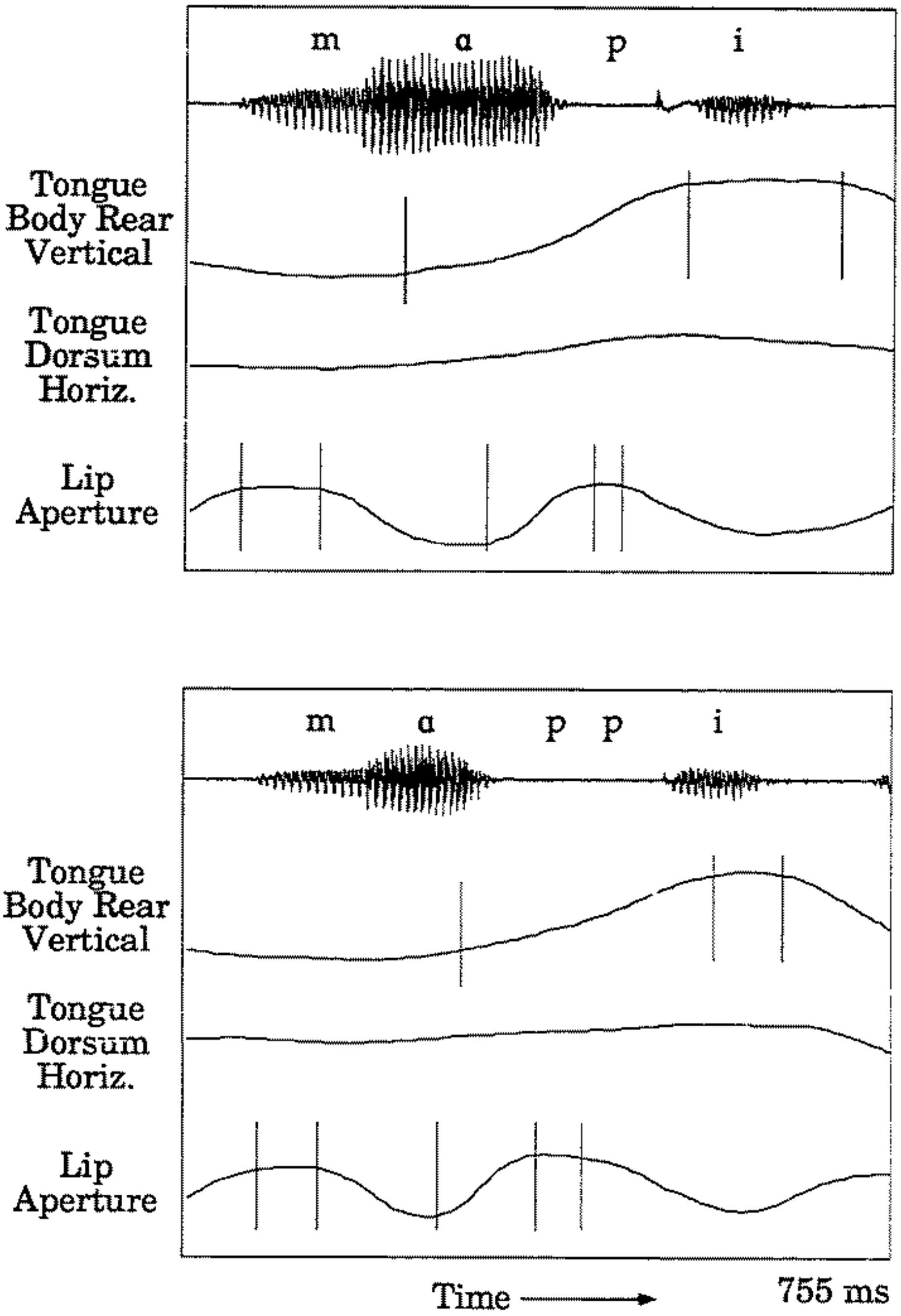


Figure 3.10. Productions of /mapi/ and /mappi/ by Italian speaker I2.

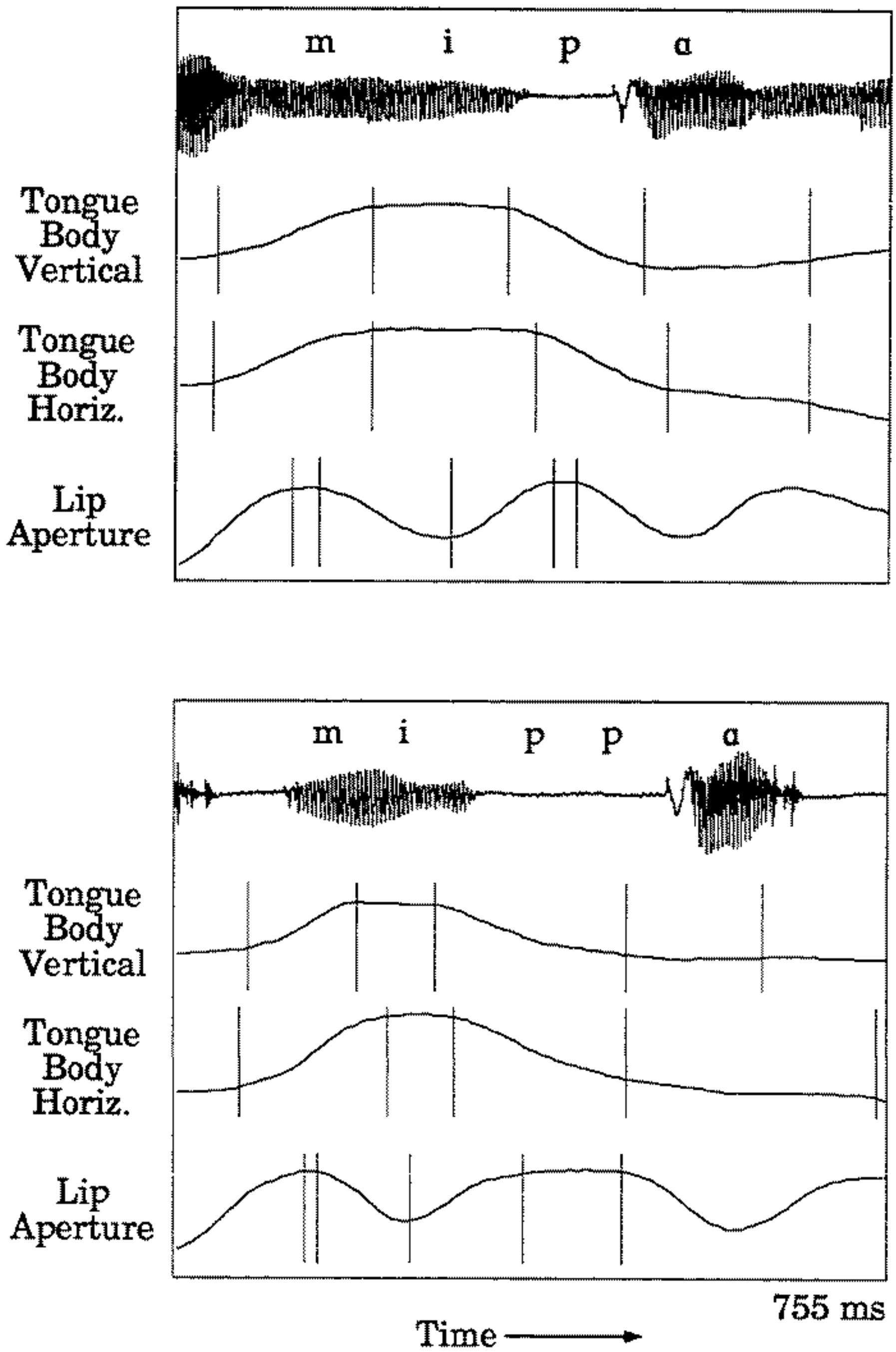


Figure 3.11. Productions of /mipa/ and /mippa/ by Italian speaker I3.

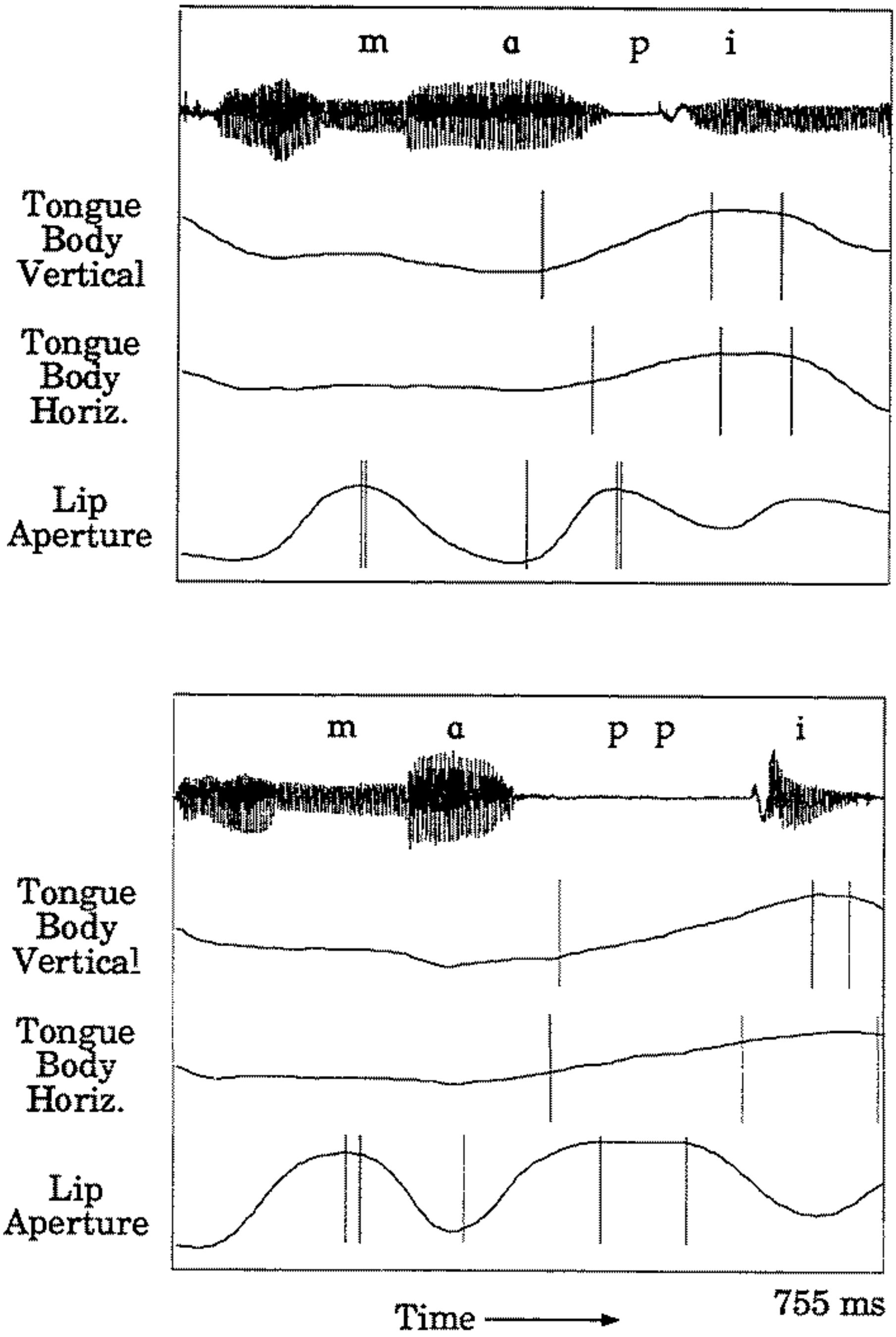


Figure 3.12. Productions of /mapi/ and /mappi/ by Italian speaker I3.

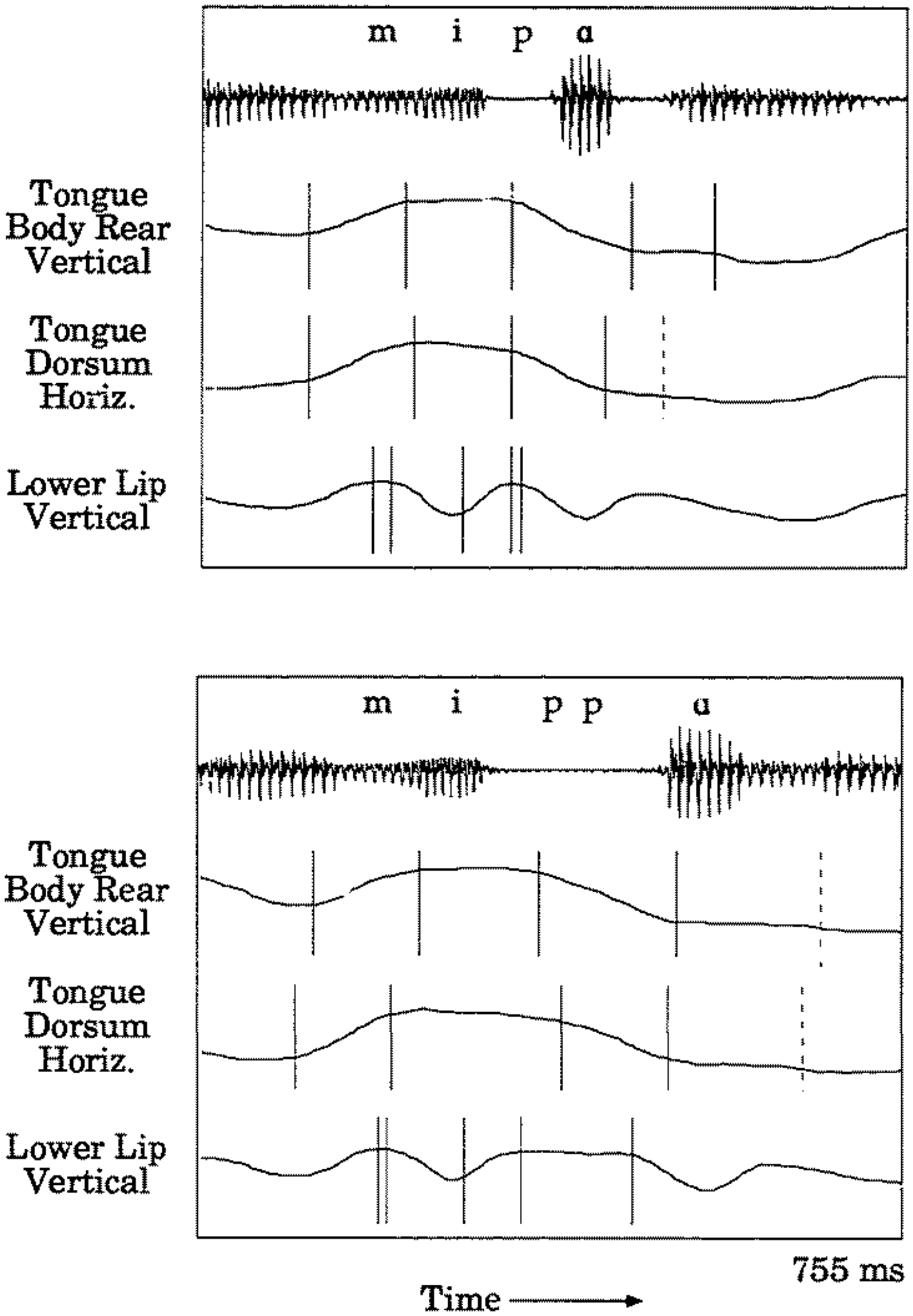


Figure 3.13. Productions of /mipa/ and /mippa/ by Japanese speaker J1.

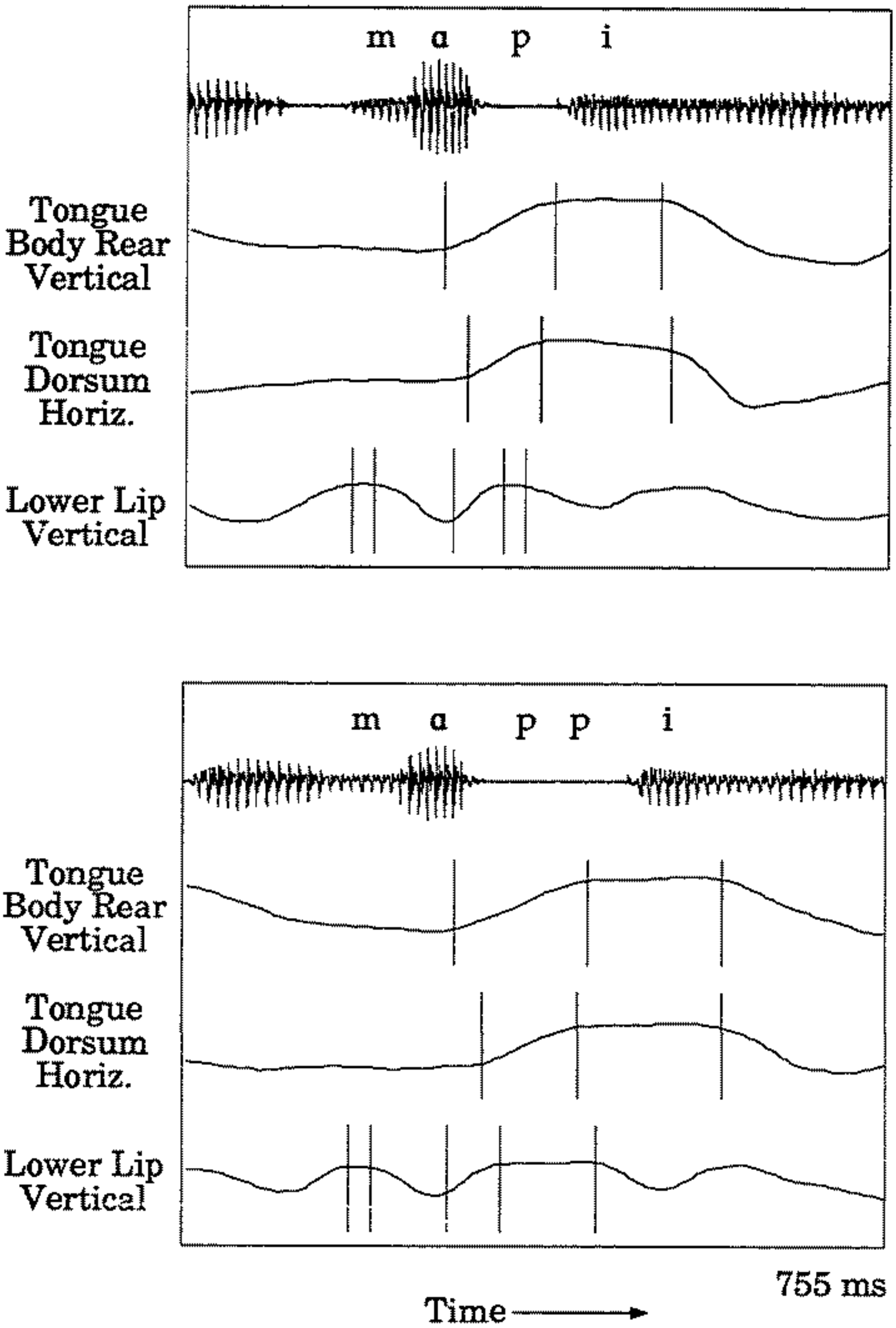


Figure 3.14. Productions of /mapi/ and /mappi/ by Japanese speaker J1.

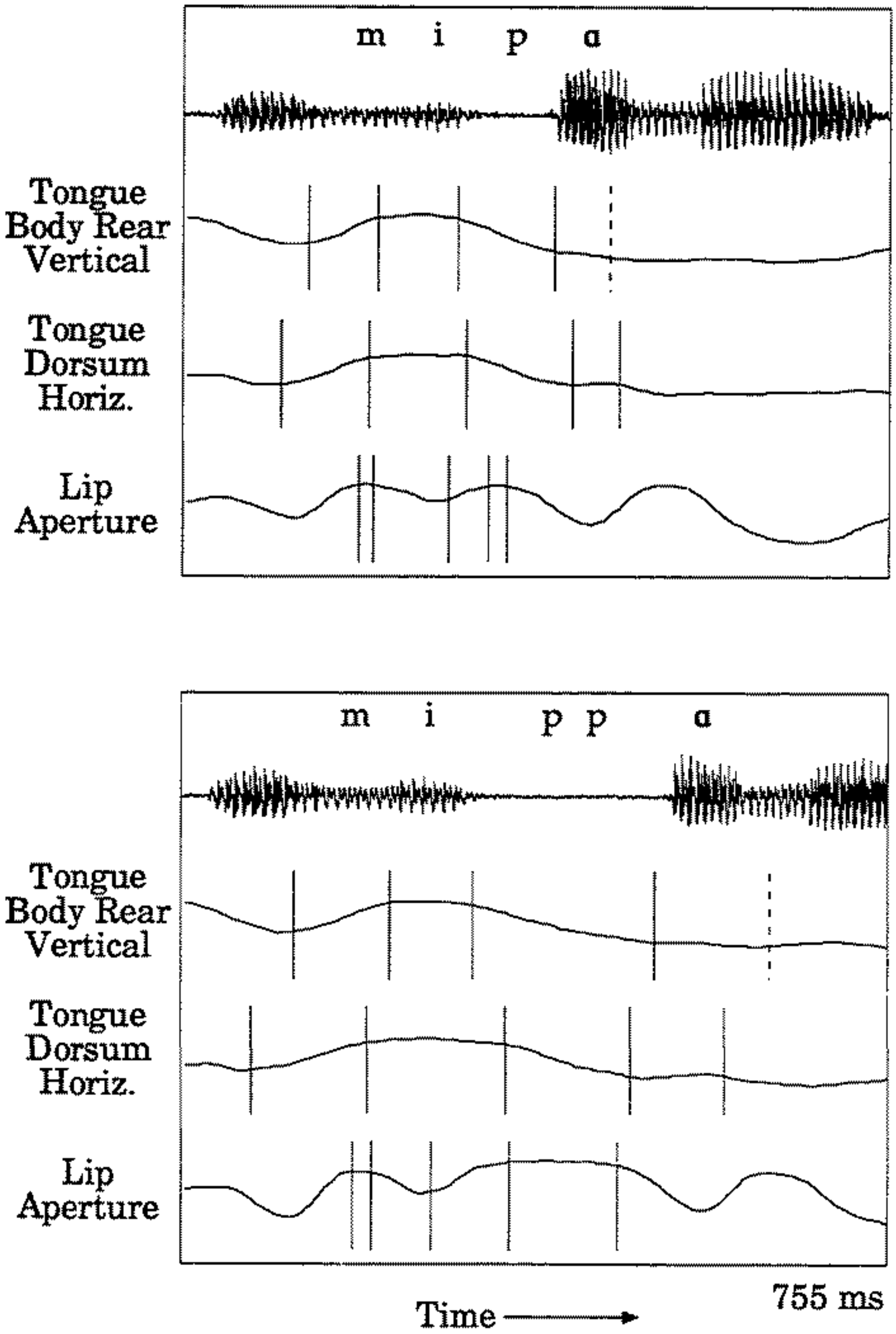


Figure 3.15. Productions of /mipa/ and /mippa/ by Japanese speaker J2.

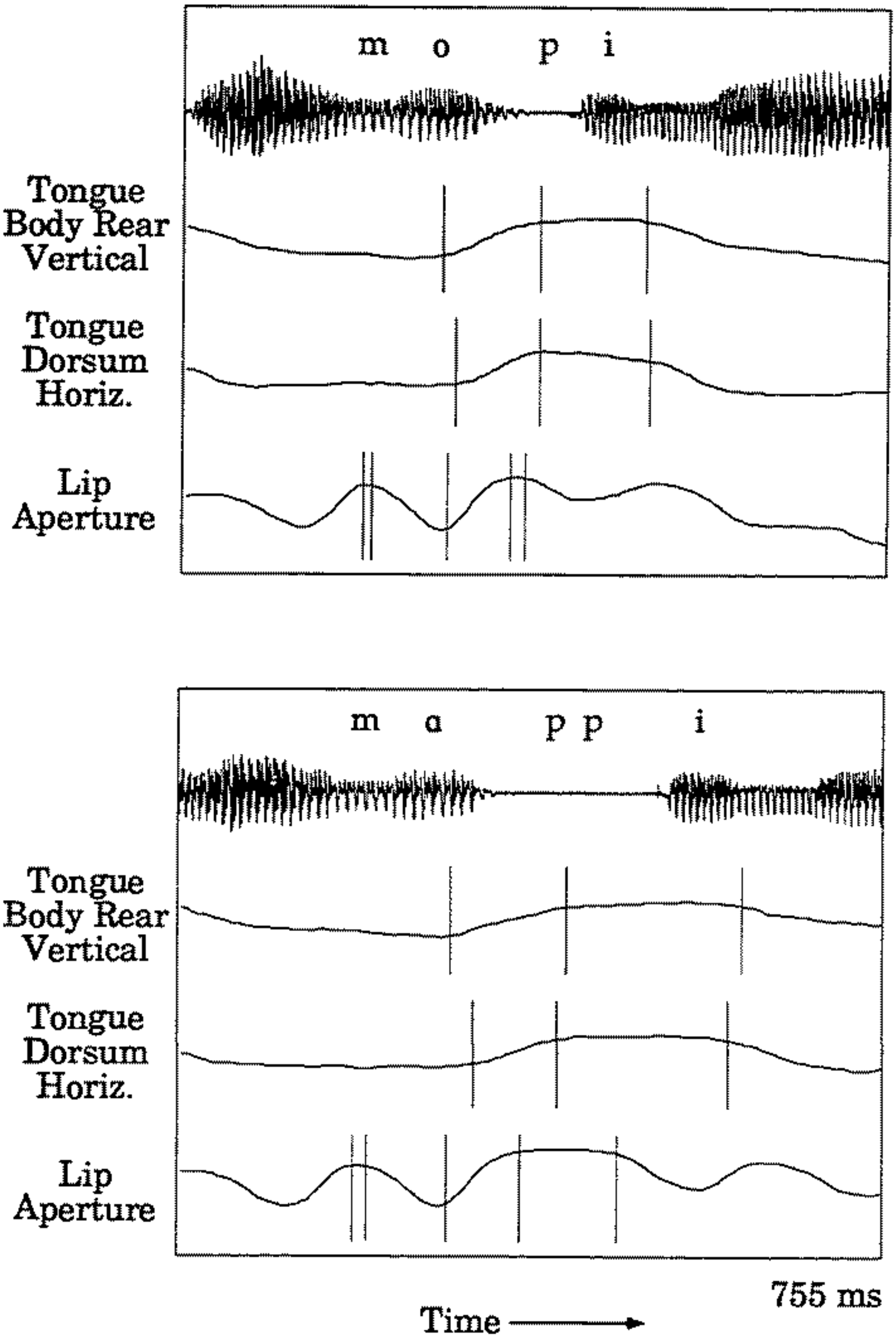


Figure 3.16. Productions of /mapi/ and /mappi/ by Japanese speaker J2.

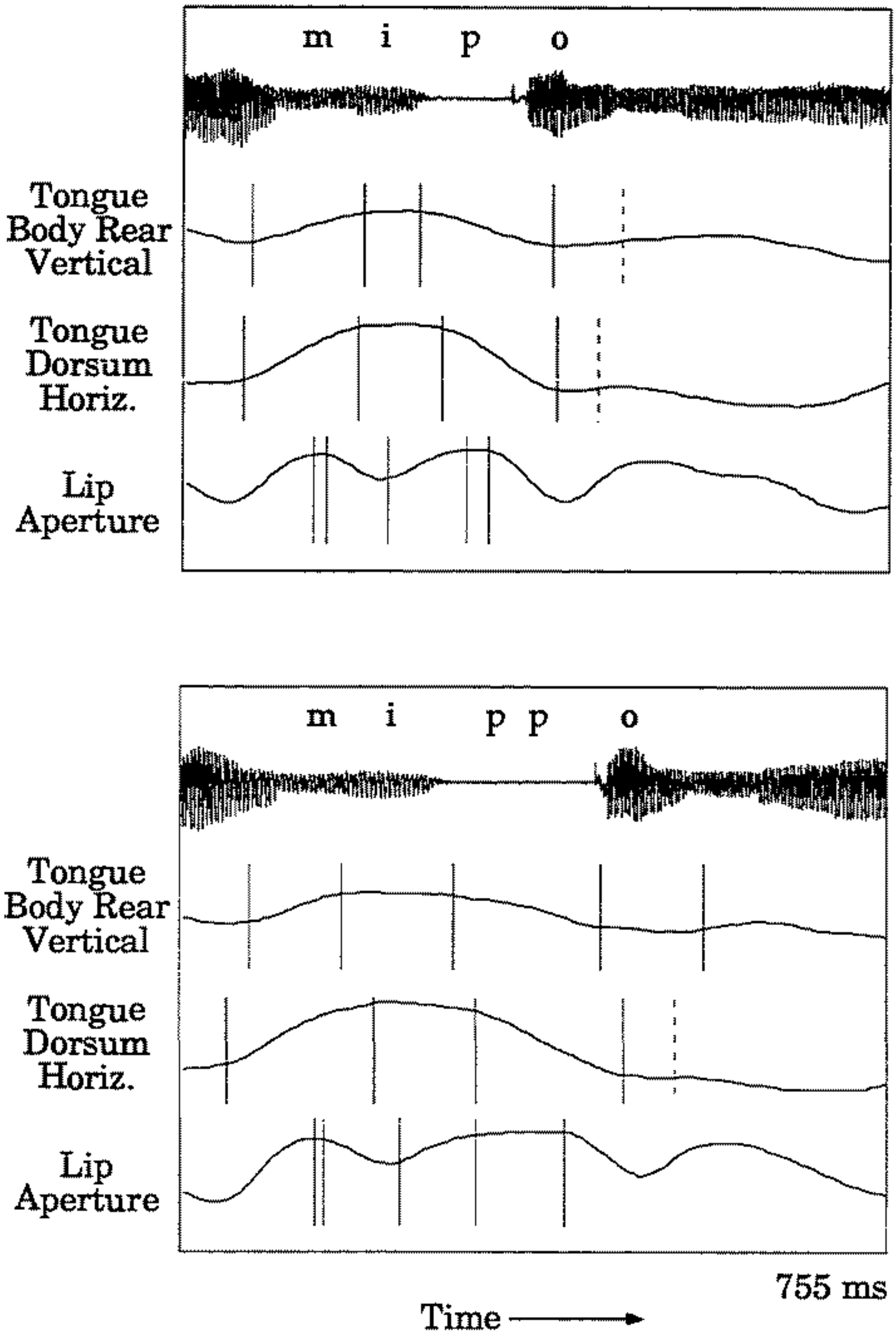


Figure 3.17. Productions of /mipa/ and /mippa/ by Japanese speaker J3.

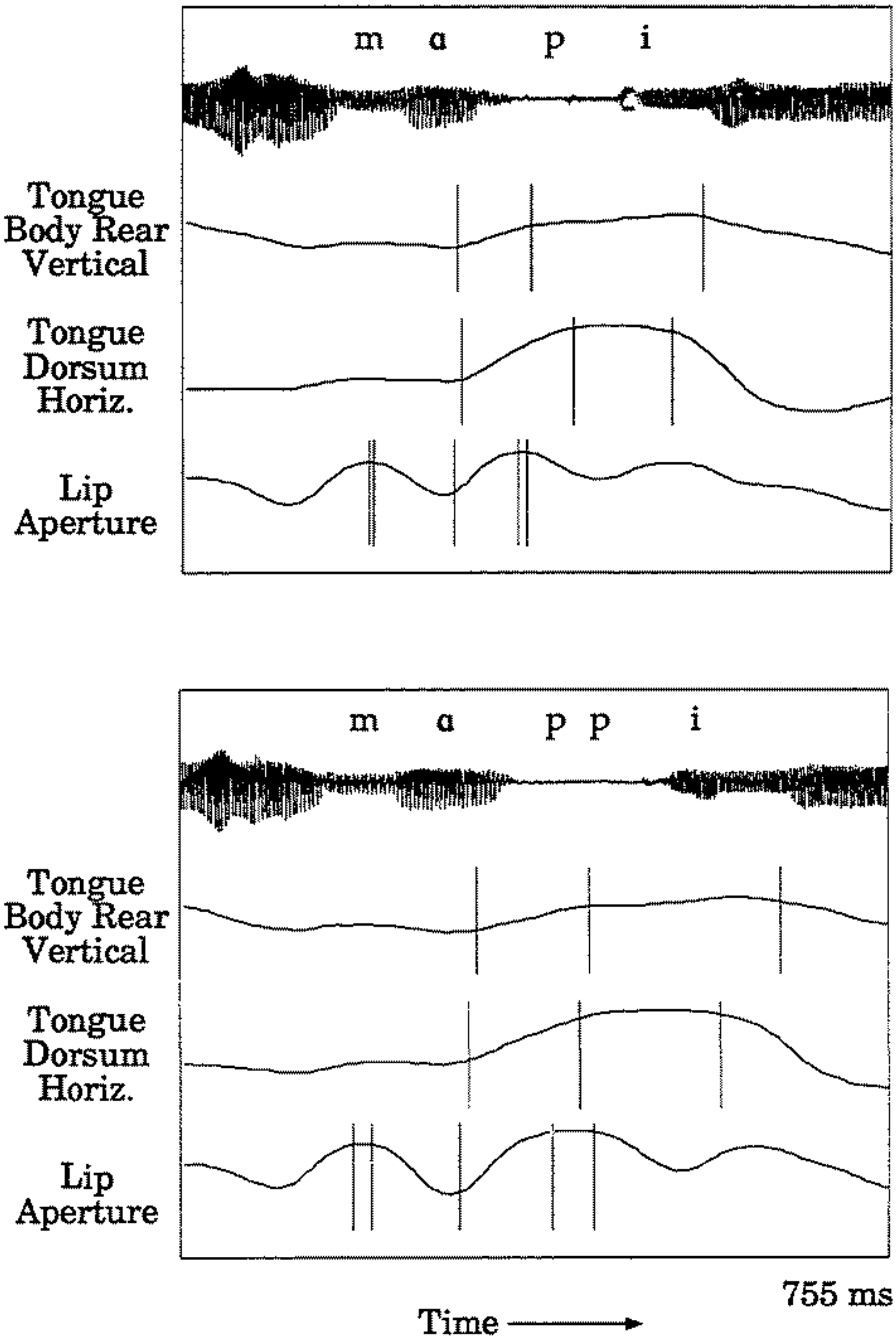


Figure 3.18. Productions of /mapi/ and /mappi/ by Japanese speaker J3.

The effect of Consonant Length on the durations was of principal interest; this should show whether differences in timing among the gestures in the utterance are found when the consonant is a single or geminate. Looking at utterances with an intervocalic cluster as well as geminates should show whether such a difference is due to some special characteristic of the geminates or whether it is a consequence of a longer consonant sequence. Recall that for Italian, it was predicted that there would be no difference in the coordination of the vowel gestures in the context of different consonant lengths. In terms of the movement trajectories, this means that at least some interval(s) measuring time between the two vowels should be unaffected by Consonant Length. For Japanese, it was predicted that the coordination between vowel gestures would differ with different length consonants, suggesting that measures from one vowel to the other would show an effect of Consonant Length, with the time from the first to the second vowel longer in the case of geminates and clusters.

As expected, the most basic difference between the results for Japanese and Italian was that virtually every interval measured was significantly longer in the context of geminates for Japanese, but not for Italian. Not only were many of the intervals shorter rather than longer in Italian, but fewer of them showed any significant difference in either direction. A check was made to ensure that this difference was not due solely to the larger number of tokens analyzed for the Japanese speakers. The same ANOVA for utterances with single and geminate consonants was run on a randomly selected half of the tokens analyzed for Japanese speaker J1, reducing the number of tokens to approximately the same number as were analyzed for Italian speaker I1. Although the F and p values differed, the same effects were significant.

In this section, results for measures of utterances with bilabial intervocalic consonants are reported; section 3 reports on the utterances with alveolar intervocalic consonants. These results are organized in the following way. First, results for the duration of the consonant target interval, which corresponds most closely to the period of closure, are presented. Next will be reported the various intervals relevant to assessing the relative timing of the two vowels, including the intervals corresponding to the movements of the tongue towards the target positions for these vowels, and the durations of the target intervals for these vowels, which are a subset of the interval between the vowel targets. Finally, measures describing the relative timing of the consonant with respect to the vowels will be discussed.

2.1. Consonant target interval

In comparing the utterances with single and geminate consonants, an obvious comparison is the duration of some aspect of the consonants themselves. The duration of the plateau region corresponding to a minimum of Lip Aperture was measured as shown in Figure 3.19, where it is labeled "Consonant target interval". (The vertical position of the lower lip is shown for speaker J1 in the figure, for whom Lip Aperture was not available.)

2.1.1. Italian

The bilabial intervocalic consonants were measured in Lip Aperture for all three Italian speakers. As expected, the target interval associated with the closure for geminate consonants was significantly longer for all speakers than the target interval for a single consonant closure. The durations of these target intervals are shown for the three speakers in the graphs in Figure 3.20. In the i-a utterances for speaker I1, the target intervals for /mp/ and /pp/ were significantly longer than for /mm/; for speaker I2's i-a utterances the target interval for oral consonants was significantly longer than for nasal consonants. In utterances with the vowel pattern a-i, for speaker I1 the target interval for /mp/ was significantly longer than for either /pp/ or /mm/, with a larger difference than was found between cluster and geminates for the Japanese speakers. There were no other differences between oral and nasal consonants.

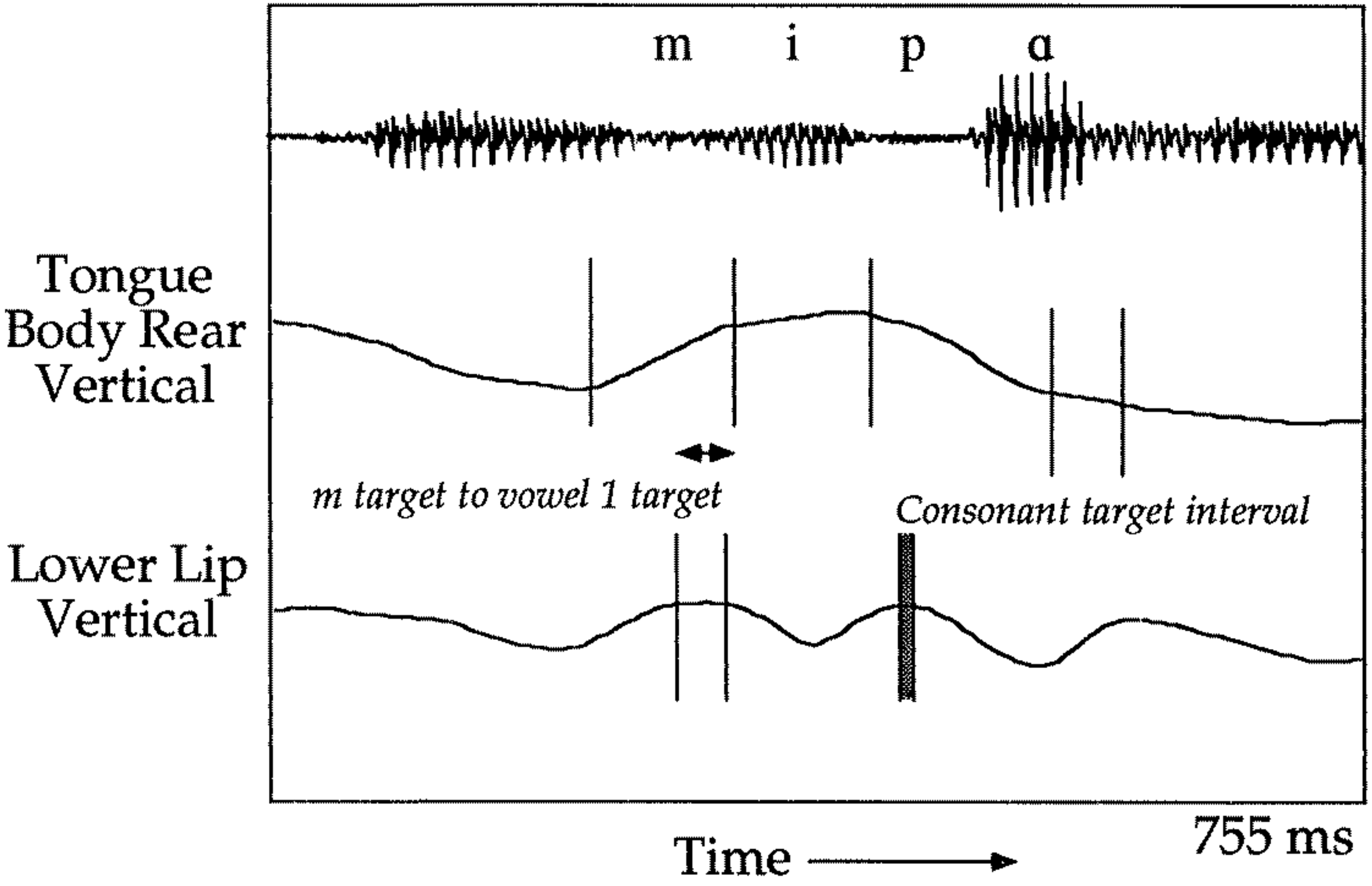


Figure 3.19. Sample production of /mipa/ by Japanese speaker J1, showing the measured intervals referred to as *consonant target interval* and *m target to vowel 1 target*.

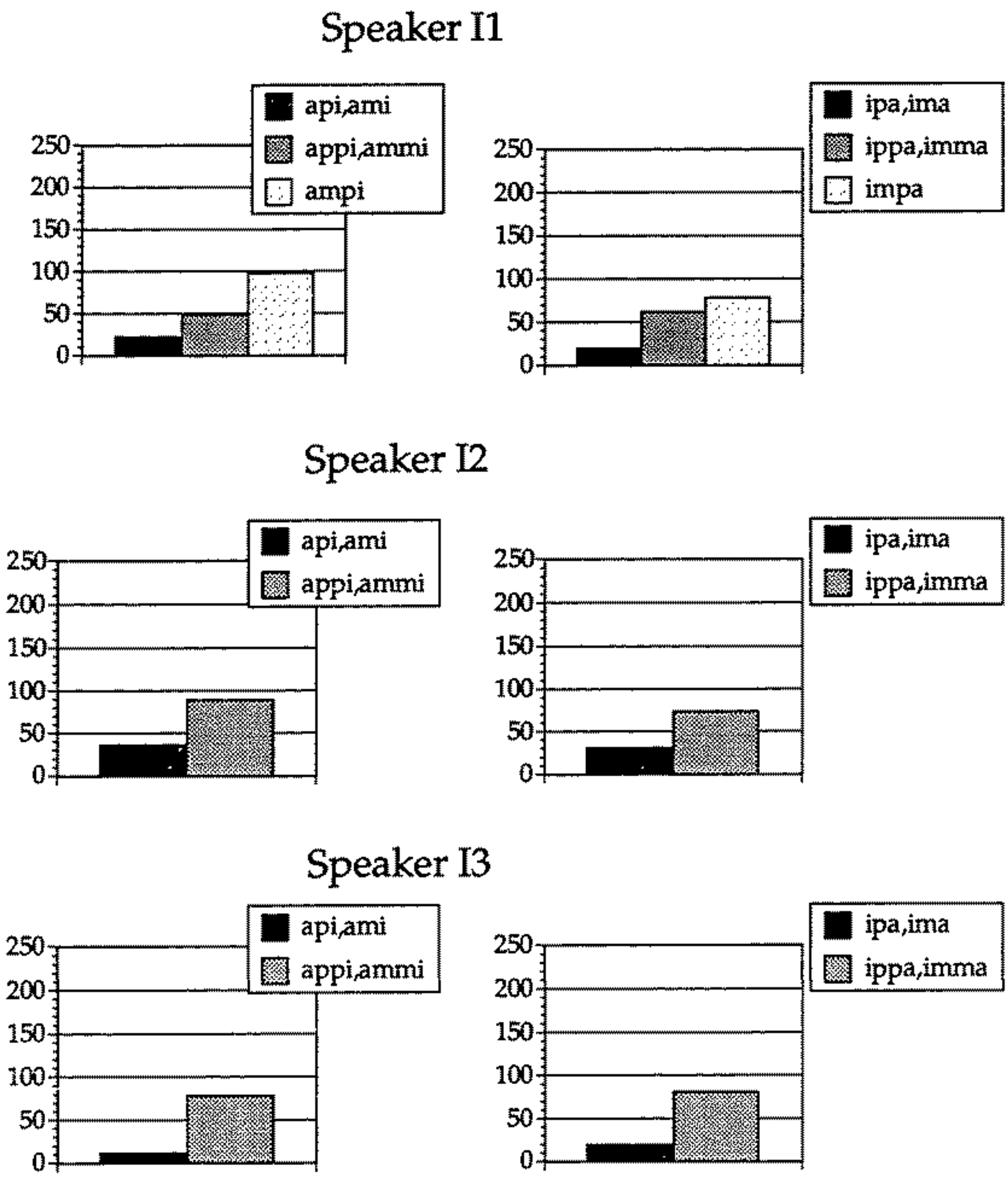


Figure 3.20. Duration of intervocalic consonant target interval for 3 Italian speakers.

2.1.2. Japanese

The target interval for geminate intervocalic consonants, measured in Lip Aperture for speakers J2 and J3, vertical movement of the Lower Lip for speaker J1, were significantly longer than their single counterparts in both a-i and i-a utterances for all three speakers. This effect can be seen in the graphs in Figure 3.21, which show the durations of the consonant target interval for single, geminate and cluster consonants for the three Japanese speakers. There were significant interactions of Length × Nasal for speaker J3's i-a utterances and speaker J2's a-i utterances, where the lengthening of the geminates compared to the singletons was much greater in the oral consonants, but significant for both oral and nasal consonants. Nasal consonants were significantly shorter than oral consonants for speaker J3 for both a-i and i-a utterances; for speaker J2 nasal consonants were also significantly shorter, as they were in the acoustic measurements of duration. The separate ANOVA comparing the geminates with the cluster /mp/ showed that in many cases the durations of the target intervals for /pp/, /mm/, and /mp/ did not differ from one another. Indeed, for speaker J1, the only factor in either analysis that significantly affected consonant target interval duration was the single/geminate contrast. For speaker J2, the geminate /mm/ was significantly shorter than /mp/ in a-i utterances. The main effect of long consonant Type was also significant in i-a utterances for speaker J3 but this was due to /mm/ being shorter than /pp/; the cluster /mp/ did not differ significantly from either. Thus the most generalized contrast was between the single and the long consonants, not within either group.

Both languages, then, showed substantially longer target intervals for the geminate consonants, with roughly comparable increases from single to geminate except that Italian speaker I1 had slightly smaller increases. In both languages nasal consonants tended to be shorter than oral ones, but this was significant more often in Japanese than in Italian, whereas the duration of the cluster was closer to that of the geminates in the Japanese speakers than in Italian speaker I1. In Japanese, if the number of moras in an

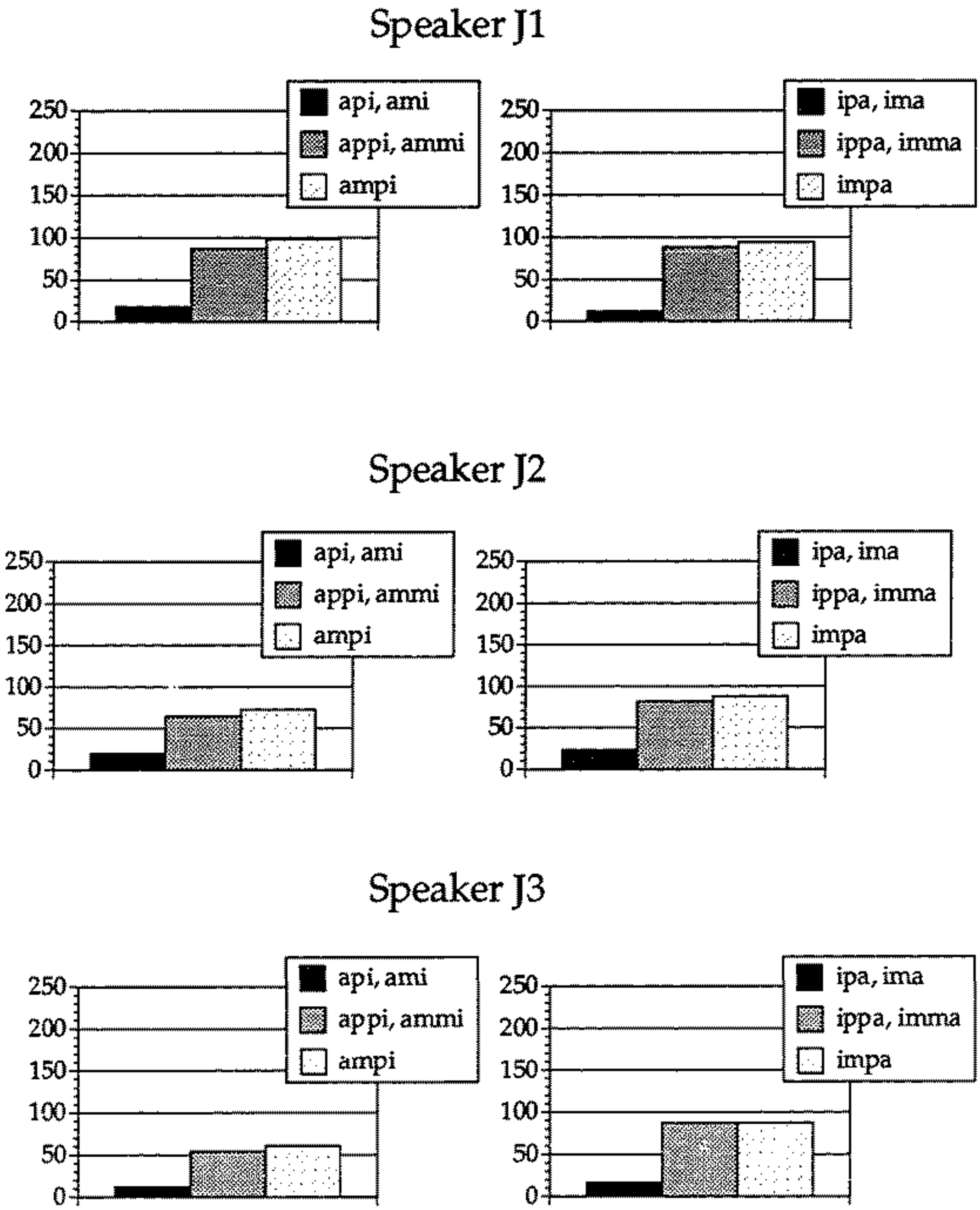


Figure 3.21. Duration of intervocalic consonant target interval for 3 Japanese speakers.

utterance is indeed the primary determiner of duration, the difference between the geminates and the cluster should be smaller than the difference between the singletons and any of the long consonants.

2.2. Intervals between vowel 1 and vowel 2

The full set of events used in constructing intervals to be measured could only be marked in the trajectories for the i-a utterances. Because the onset and target of the first vowel could not be measured in utterances with initial /a/, the same set of intervals could not be compared between the utterances with different vowel patterns. Therefore, it is useful to find alternative measures to substitute for the events that could not be measured in a-i utterances.

With the goal of constructing such alternate measures, the interval from the target of the /m/ (the beginning of the plateau) to the target of the initial /i/ in i-a utterances was tested in ANOVAs with factors Length and Nasal. This interval, illustrated in Figure 3.19, was almost never affected by the quality of the intervocalic consonant. In Japanese, the only channel in which the effect of Length was significant on this interval was in TB2y for speaker J2 (Length: $F(1,74) = 4.08$, $p<.05$). In Italian, the effect of Length was significant only for speaker I3 in TBx (Length: $F(1,11) = 5.16$, $p<.05$).

The almost complete absence of any effect of Length on the interval between the target of the initial /m/ and the /i/ in the first syllable implies that intervals in which the /m/ target is substituted for the vowel 1 target might be expected to reflect the same sources of variability as intervals measured from the vowel 1 target. This hypothesis could be tested by comparing, in i-a utterances, the results obtained from the two sets of intervals. For a-i utterances such substituted intervals provide the only way of estimating the timing of vowel 1.

2.2.1. Relation between the targets of the vowels

2.2.1.1. Italian

This relation comes closest to being a direct test of the two timing hypotheses (vowel-to-vowel and vowel-to-consonant). Recall that the vowel-to-vowel hypothesis, expected to hold in Italian, predicts no temporal change between the two vowels when the intervocalic consonant length changes, whereas the vowel-to-consonant hypothesis predicts a possible change. Since there are many possibilities for specifying the coordination of the vowels with respect to one another, intervals between many different pairs of points in the vowel gestures might conceivably be compared. However, it seems most likely that an interval relevant to the coordination between vowels would be one whose endpoints are times at which the vocalic gestures dominate control of the vocal tract, such as at the targets of the two vowels. This interval, which could be measured only in the i-a utterances, is illustrated in Figure 3.22.

2.2.1.1.1. Vowel 1 target to vowel 2 target (Vowel 1 = i)

For Italian speaker I1 there was no significant effect of Length of the intervocalic consonant on the duration of the interval between the targets of the two vowels. The absence of any effeet of Length suggests that, indeed, the timing relation between the vowel targets is stable and not affeeted by the consonant, at least for utterances with the i-a vowel pattern. There was also no effect of Length for speaker I3 when the target-to-target interval was measured in TBy. In the other channels (TBx and the Horizontal factor), speaker I3 had a significantly shorter interval between vowel targets with geminates. For speaker I2 the interval between vowel targets was also significantly shorter with geminates. These patterns can be seen by comparing single and geminate pairs in Figures 3.7, 3.9, and 3.11. The durations of this interval are plotted in Figures 3.23-3.25.

Although speaker I1 showed no effect of Length, this interval was significantly longer in the context of nasal consonants than oral ones in all channels. (There was no

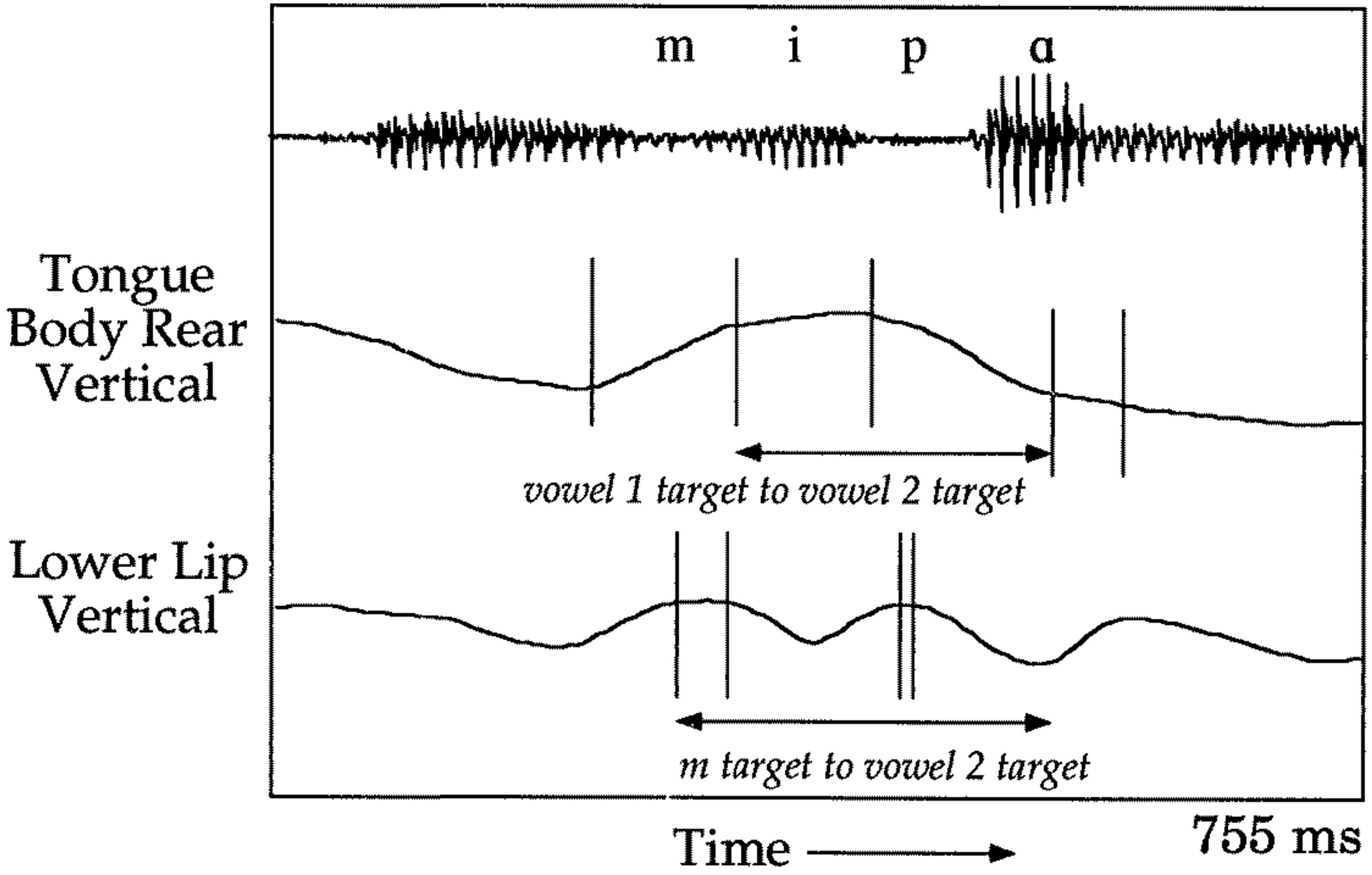
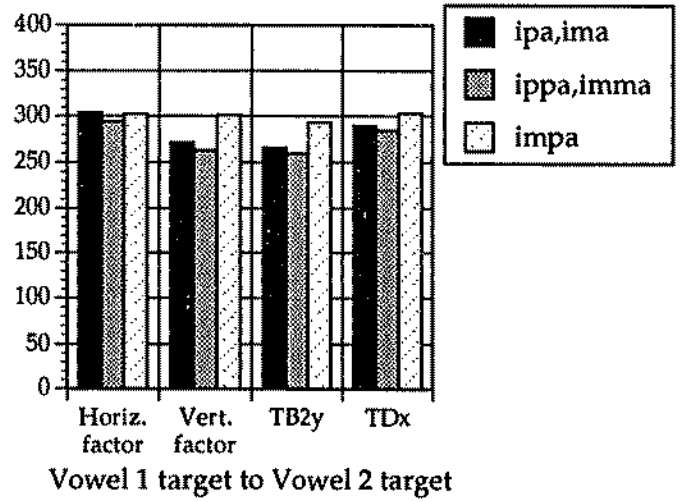
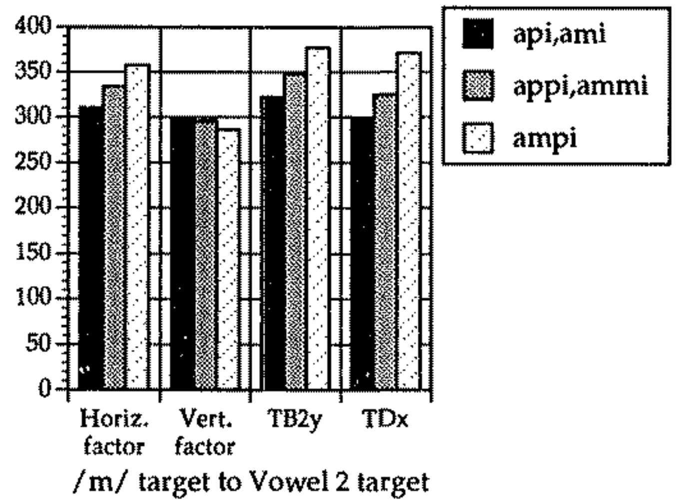


Figure 3.22. Sample production of /mipa/ by Japanese speaker J1, showing the measured intervals referred to as *vowel 1 target to vowel 2 target* and */m/ target to vowel 2 target*.





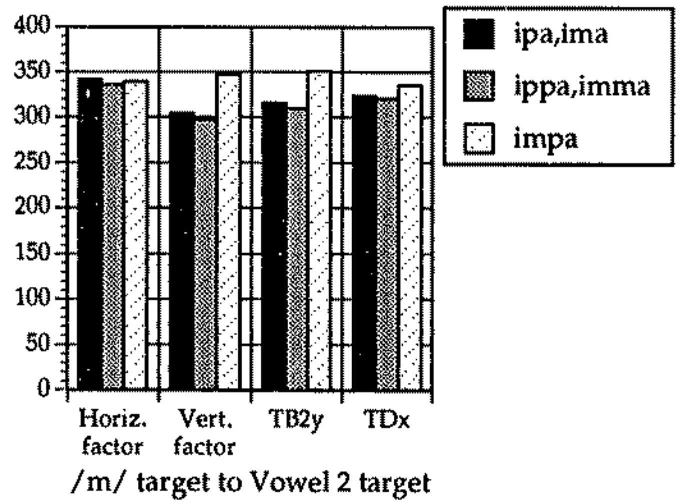
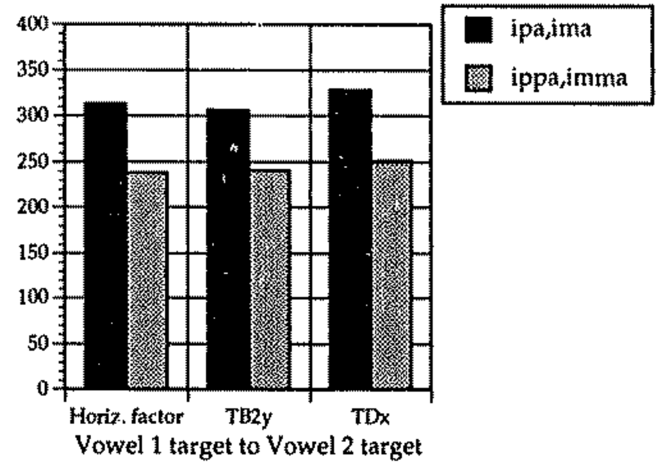
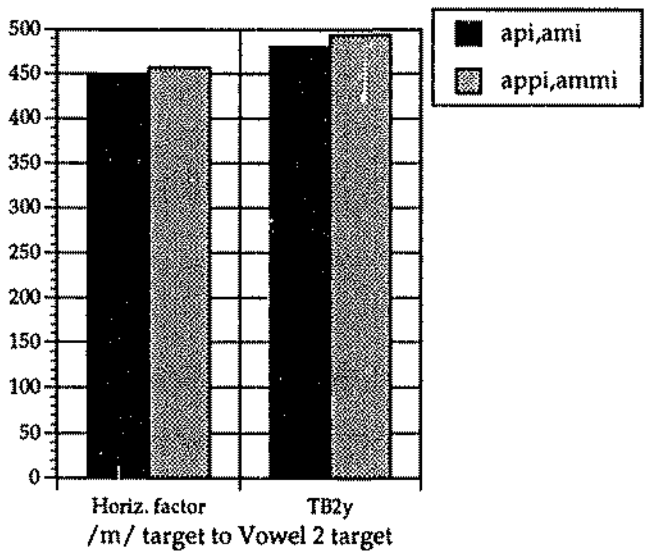


Figure 3.23. Graphs of *vowel 1 target to vowel 2 target* and */m/ target to vowel 2 target* for Italian speaker I1.

Figure 3.24. Graphs of *vowel 1 target to vowel 2 target* and */m/ target to vowel 2 target* for Italian speaker I2.





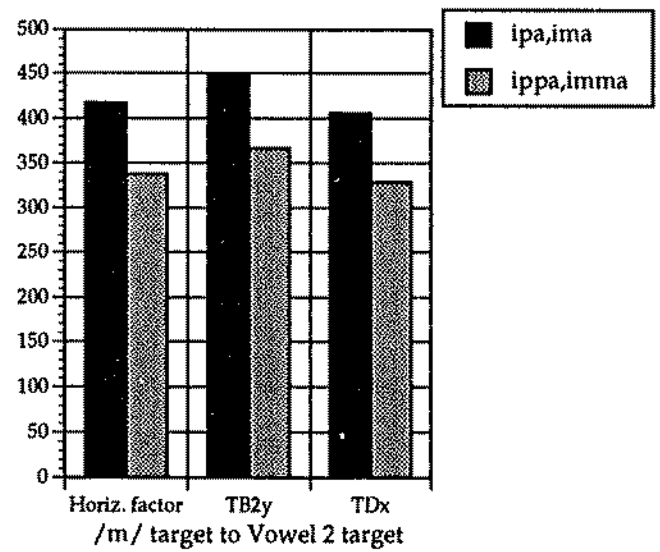
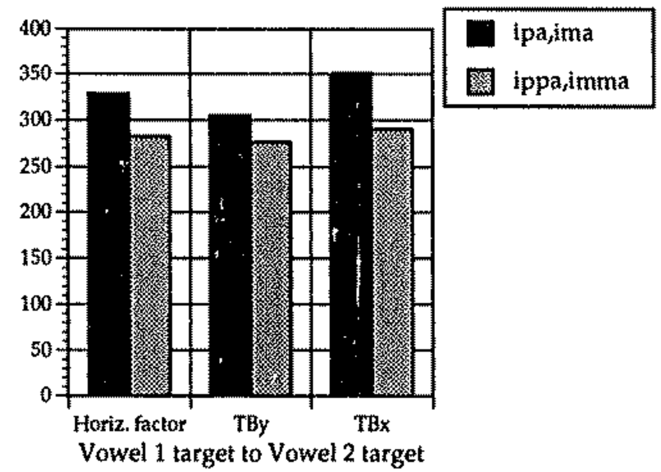
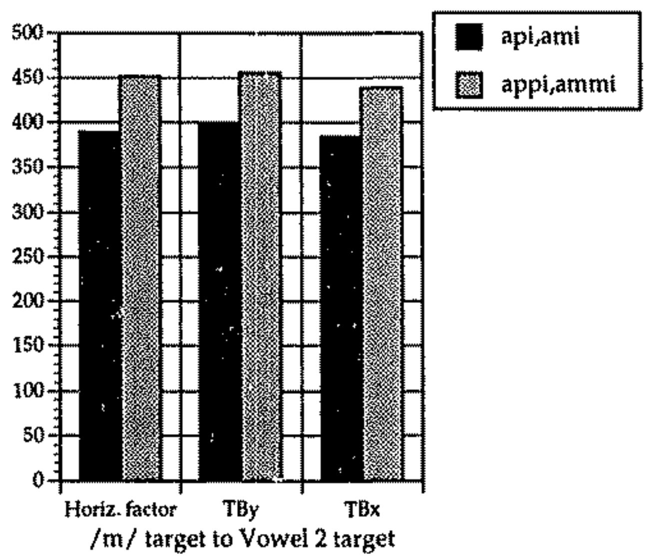
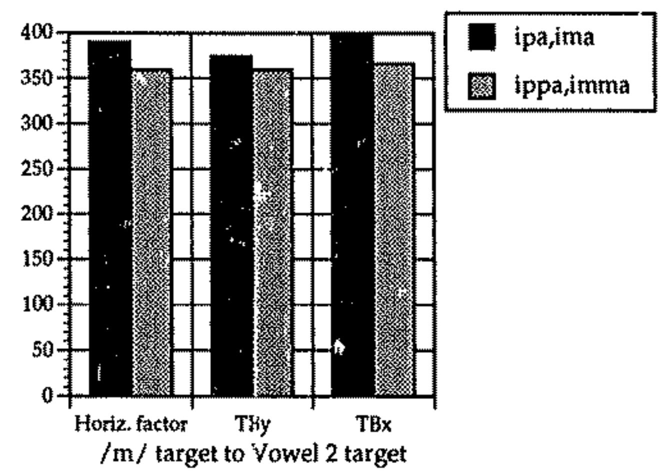


Figure 3.25. Graphs of *vowel 1 target to vowel 2 target* and */m/ target to vowel 2 target* for Italian speaker I3.







effect of Nasal for the other speakers.) However, consonant nasality did not affect the stability of the interval's duration in the context of different consonant lengths; in the analysis of single and geminate consonants, the interaction of Length and consonant Nasality was significant only for the Horizontal factor, where the lengthening attributable to nasality in the consonant was greater in the utterances with geminates, although also significant with singletons, but there was little difference between utterances with singles and geminates whether they were oral or nasal. A similar pattern was found in the analysis of utterances with intervocalic geminates and /mp/, where the interval between vowel targets was significantly longer in utterances with /mp/ and /mm/ than with /pp/.

2.2.1.1.2. Interval between the /m/ target and the target of vowel 2 (Vowel 1 = a)

A different measure, expected to be comparable to the interval between vowel targets, is the interval from the target of the initial /m/ to the target of vowel 2, illustrated in Figure 3.22. The results using this interval were similar to those for the interval between vowel targets that was discussed above. For i-a utterances there was no significant effect of Length on this interval for speakers I1 and I3; speaker I2 had significantly shorter intervals with geminates in all channels. The durations of this interval are graphed in Figures 3.23-3.25. It is easy to see that this interval is patterning much like the interval between vowel targets. Also like the interval between vowel targets, there was no effect of Nasal for speakers I2 and I3, but there was for speaker I1, with significant lengthening in the context of nasal consonants compared to oral ones. This interval was also longer in the context of /mp/ than /pp/ in all channels for speaker I1.

Thus for these i-a utterances, the /m/ target to vowel 2 target interval shows results similar to the vowel to vowel target interval: no difference due to Consonant Length for speaker I1, shortening with geminates for speaker I2, and either no difference or less shortening for speaker I3. So it might be assumed that in the a-i utterances where the vowel to vowel target interval could not be measured, the /m/ target to vowel 2 target interval can be used as an indication of the patterns that would have been found between the vowel targets, although there is of course no data available on the relation between the /m/ target and the first vowel in these utterances to support the supposition that that relation never varies. As is apparent from comparing the graphs in Figures 3.23-3.25, the patterns in the a-i utterances proved to be very different from what was observed in the i-a utterances: speaker I2 showed no significant effect of Length, but speakers I1 and I3 did in all channels, except for the Vertical factor for speaker I1. In these cases, the interval was significantly longer when the consonant was a geminate, the opposite of what was found in the i-a utterances This lengthening was significant for both oral and nasal consonants (although greater with oral consonants) in TBy for speaker I3, where there was an interaction of Length × Nasal.

For speaker I1 there was, in the a-i utterances as in the i-a utterances, a significant effect of Nasal, but this time the interval was shorter in the context of a nasal intervocalic consonant than an oral one, the opposite of the i-a utterances. The effects found in the i-a utterances were robust, being the same measured in the vowel-to-vowel interval or the /m/-to-vowel interval. Therefore, the reversal of effect in the a-i utterances suggests that either the /m/ to /a/ interval is changing (between singles and geminates and between nasal and oral consonants), and the effects are the same from the actual vowel 1 target to vowel 2 target for both vowel patterns, or that the actual vowel 1 to vowel 2 timing in the a-i utterances is different from that of the i-a utterances.

Nasal was also significant in the Horizontal factor for speaker I2, for whom Nasal was not significant in the i-a utterances. In this factor there was also a significant interaction between Length and Nasal, with the interval longer in the context of /m/ than /p/, but shorter in the context of /mm/ than /pp/. Because for this speaker this interval was not significantly longer with geminates, nor was the effect of Nasal consistent, it seems likely that he is not showing the overall difference between the two vowel patterns that was found with speaker I1. There was no effect of Nasal for speaker I3, for whom this interval was significantly longer in the context of geminates, but there was a significant interaction between Length × Nasal in TBy, where the lengthening with geminates was greater with oral consonants than with nasals.

All three Italian speakers showed different patterns in the a-i utterances than in the i-a ones. Speaker I1 had no effect with i-a utterances, but some lengthening with a-i utterances, whereas I2 had no significant effect of Length on the duration of this interval for a-i utterances, but substantial shortening with geminates for i-a utterances. Speaker I3 had, at least in certain measures, a significant effect for both sets of utterances, but in opposite directions.

2.2.1.2. Japanese

2.2.1.2.1. Vowel 1 target to vowel 2 target (Vowel 1 = i)

The interval between the targets of the vowels was significantly longer in all channels for all speakers in utterances where the consonant was a geminate compared to those where it was a singleton. This can be seen in the graphs on the right-hand side of Figures 3.26-3.28, which show the duration of this interval with single, geminate and cluster bilabial consonants. The target-to-target interval was also significantly longer across nasal intervocalic consonants than across oral ones for speaker J1 in the Vertical factor, for speaker J2 in the Vertical factor and TB2y, and for speaker J3 in the Front Vertical factor (incl. Tongue Tip). This interval tended to be longer in the context of nasal consonants in Italian as well, although the effect of the consonant geminating was different in the two languages.

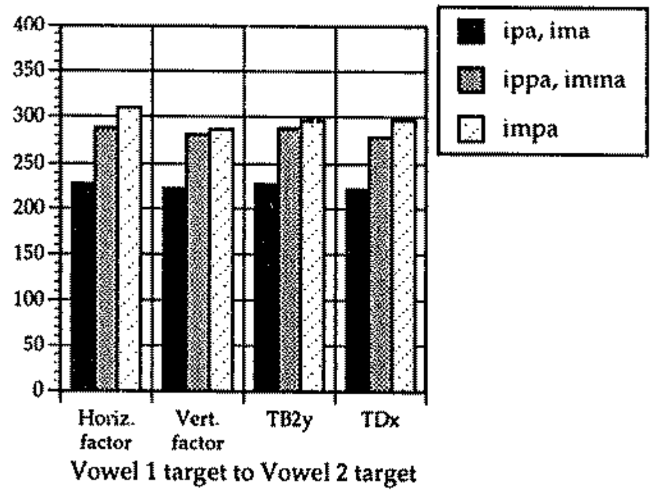
In the comparison of geminate consonants with the cluster /mp/, the most common pattern across the speakers was for the interval to be longer with an intervocalic cluster /mp/ than with a geminate /pp/ but not to differ significantly between /mp/ and /mm/. This is the same result as was found for Italian speaker I1. For Japanese speaker J3, the effect of long consonant Type was significant only for the Front Vertical factor (incl. Tongue Tip), where the interval was significantly longer across /mp/ than /pp/.

Speaker J1 showed similar effects, with the same pattern significant in the Horizontal factor and TDx. The results for speaker J2 were only slightly different. The vowel-to-vowel interval was, as for the other speakers, significantly longer with /mp/ than /pp/ in the Horizontal factor, the Vertical factor, and TDx, but in TB2y it was significantly longer with /mm/ than with /mp/.

2.2.1.2.2. Interval between the /m/ target and the target of vowel 2

As was done for the Italian speakers, the interval between the target of the initial /m/ and the target of the second vowel was also measured in Japanese to provide an additional measure of the vowel-to-vowel relation that could be measured in a-i utterances. Durations of this interval can be seen in the graphs on the bottom of Figures 3.26-3.28. The interval was significantly longer across a geminate consonant than a single consonant for both a-i and i-a utterances in all channels for all speakers except for speaker J2 in a-i utterances measured in the Vertical factor, where there was no significant difference between singles and geminates. In general the differences between singles and geminates were smaller for a-i utterances than for i-a utterances. In many channels there were interactions between Length and Nasal, because the difference in the duration of the interval in the contexts of single and geminate consonants was greater with nasal consonants, although significant everywhere. Interactions were found in a-i utterances in all channels for speaker J1, in the Vertical factor and TB2y in i-a utterances for speaker J2, and in a-i utterances in the Horizontal factor (no Tongue Tip), Horizontal factor (incl. Tongue Tip), and TDx, and i-a utterances in TB2y for speaker J3. The interval was significantly longer when the intervocalic consonant was nasal in a few channels for each of the three speakers: for speaker J1 in all channels in a-i utterances, and in the Vertical factor in i-a utterances, for speaker J2 in a-i and i-a utterances in the Vertical factor and TB2y, and for speaker J3 in i-a utterances in TB2y. However, for speaker J3 in a-i utterances in TB2y, the interval was shorter when the consonant was a

Figure 3.26. Graphs of *vowel 1 target to vowel 2 target* and */m/ target to vowel 2 target* for Japanese speaker J1.



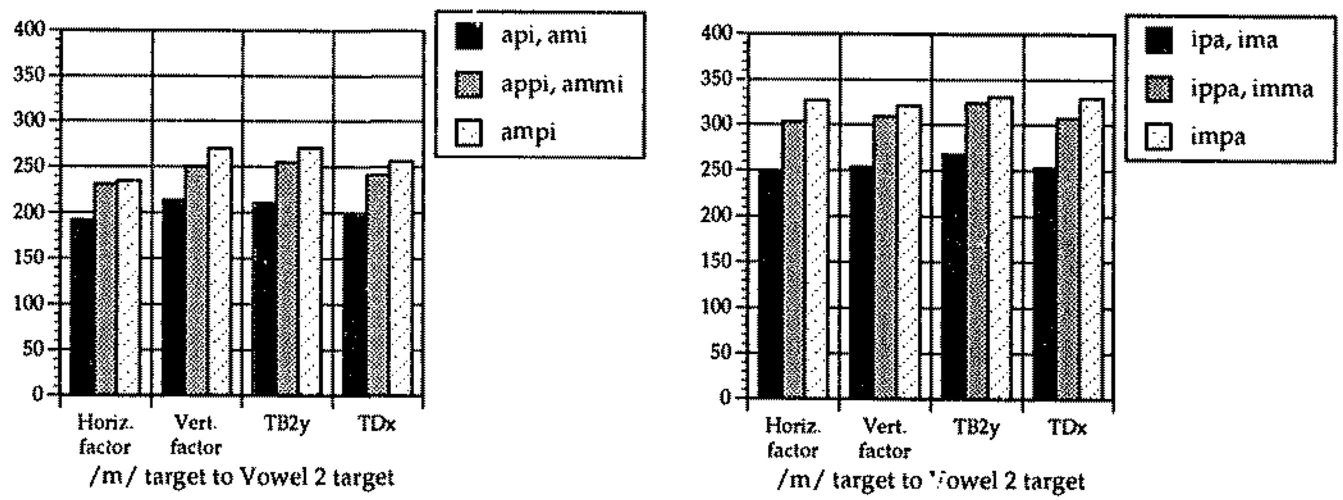
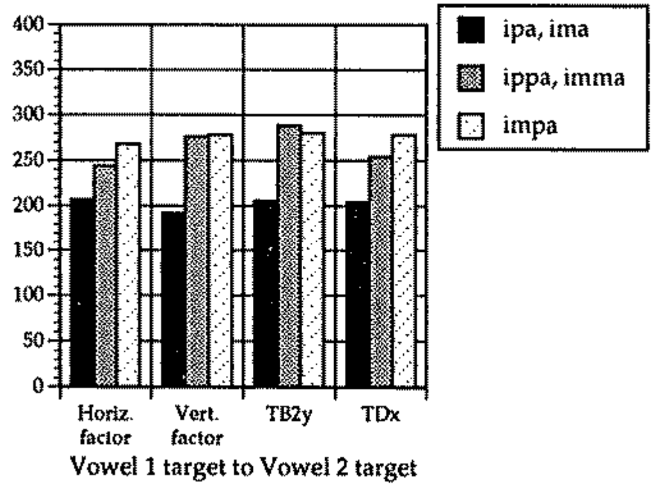
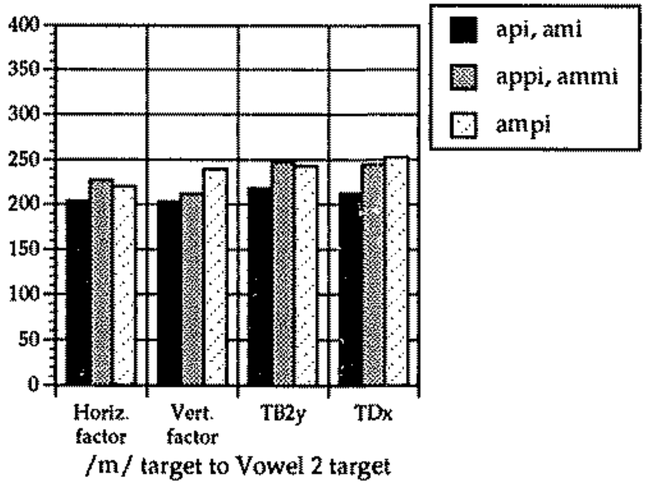


Figure 3.27. Graphs of *vowel 1 target to vowel 2 target* and */m/ target to vowel 2 target* for Japanese speaker J2.





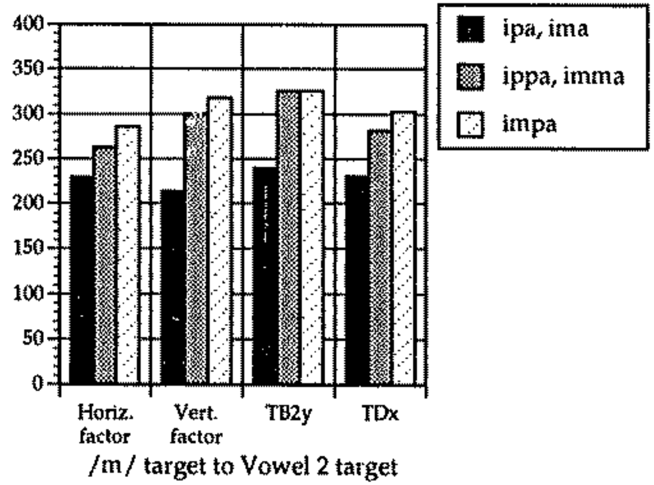
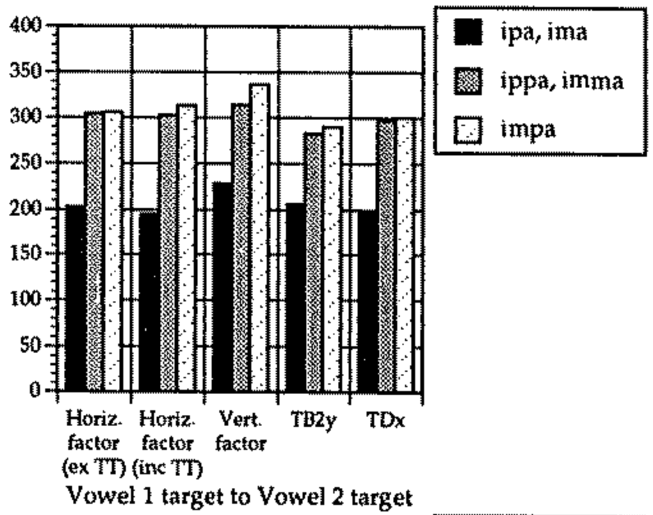
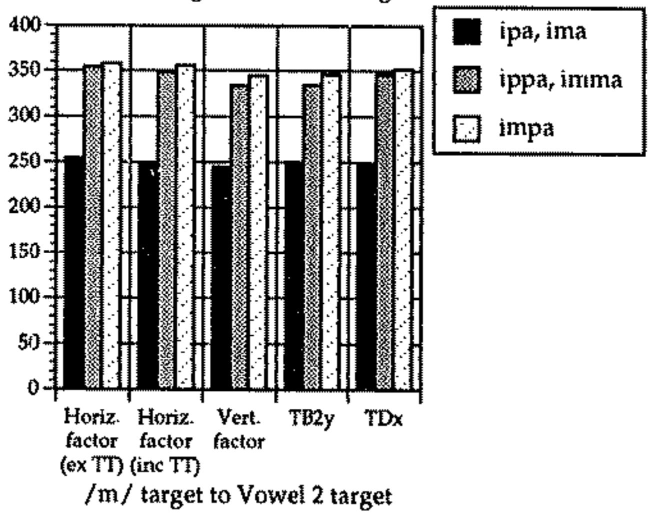
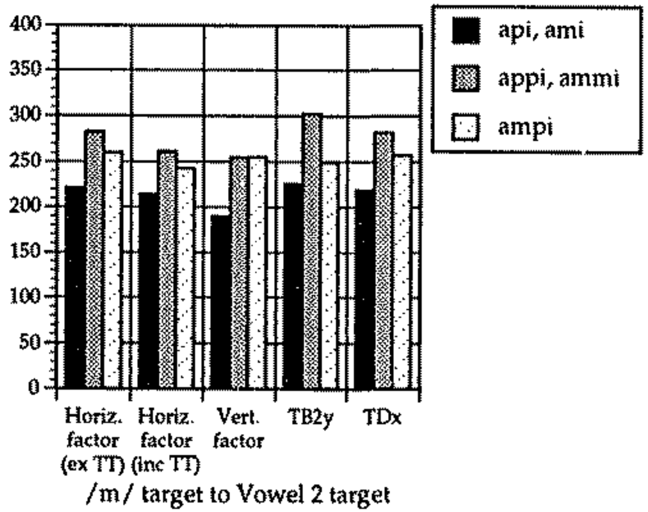


Figure 3.28. Graphs of *vowel 1 target to vowel 2 target* and */m/ target to vowel 2 target* for Japanese speaker J3.







nasal. This tendency to lengthen in the context of a nasal consonant is virtually identical to what was found in the vowel target to vowel target interval.

For the Japanese speakers, this interval also patterned much like the vowel target to vowel target interval with respect to the comparison between /mp/ and the geminate consonants. Most often, for speakers J1 and J2 the interval was significantly longer with /mp/ than with /pp/. This was true for speaker J1 in a-i utterances in the Vertical factor, TB2y and TDx and for i-a utterances in the Horizontal factor, the Vertical factor and TDx. For speaker J2 it was true in i-a utterances in all channels and in a-i utterances in the Vertical factor. For speaker J3 it was true only in i-a utterances in TB2y. For the other channels the interval's duration in the contexts of /pp/, /mm/, and /mp/ fell into various patterns, and in at least one channel/utterance combination for each speaker the effect of long consonant Type was not significant overall.

In Japanese, the lengthening of this interval in the context of long consonants was almost as regular for utterances with both vowel patterns as the lengthening of the interval between the vowel targets. Clearly Japanese showed much more, and more consistent, lengthening than the occasional lengthening that was found in a-i utterances in Italian. The Japanese speakers showed the same pattern in utterances with both vowel patterns, whereas the Italian speakers showed different patterns of small effects.

2.2.2. Measures of vowel 1

Measures of the target-to-target intervals provided some evidence of different durational patterns in the two languages. In order to locate the part of the utterances responsible for these differences, the target-to-target interval was divided into two sub-intervals, the interval between vowel 1 target and the onset of vowel 2 (referred to as the vowel 1 target interval), and the interval between the onset and target of vowel 2 (referred to as the movement into vowel 2). In the a-i utterances, the interval between the /m/ target and the onset of vowel 2 was substituted for the vowel 1 target interval. For Italian, where there were small, inconsistent differences in the effect of Consonant Length on the target-to-target intervals, analysis of these sub-intervals will show to what extent any part of the utterance is affected consistently by Length. For Japanese, where the target-to-target interval showed consistent lengthening, measures of the sub-intervals will show whether this lengthening was distributed equally through the entire utterance.

2.2.2.1. Italian

2.2.2.1.1. Vowel target interval (Vowel 1 = i)

The duration of the target interval of the first vowel was defined as the interval between the achievement of target for the first vowel (when the velocity approached within the noise criterion of zero) and the onset of movement towards the second (when the velocity exceeded the noise criterion), as labeled in Figure 3.29. This interval could only be measured in the vowel /i/. The target interval is also referred to as the duration of the first vowel, although the gesture for this vowel is active long before, during the movement towards this target interval. The results, which coincide with previous results for Italian vowels (e.g. Farnetani & Kori 1982, 1986; Josselyn 1900), are graphed in Figures 3.30-3.32. For all three speakers this vowel was significantly shorter before geminates in all channels except, for speaker I1, in the Vertical factor, and before nasal consonants in TB2y and TDx where there were significant interactions with Nasal. Speaker I1 also had significantly longer vowels preceding nasal consonants in all channels, and in the analysis comparing the cluster and geminates, the vowels were significantly longer preceding /mm/ or /mp/ than /pp/ in all channels except the Horizontal factor. The other speakers showed no significant differences between the contexts of oral and nasal consonants.

2.2.2.1.2. Interval from the /m/ target to the onset of vowel 2

Because the duration of the target interval of the first vowel could be measured only for /i/, the interval from the target of the initial /m/ to the onset of movement towards the second vowel was substituted as an alternative, as suggested above. This interval is shown in Figure 3.29. For the i-a utterances, the results using this interval

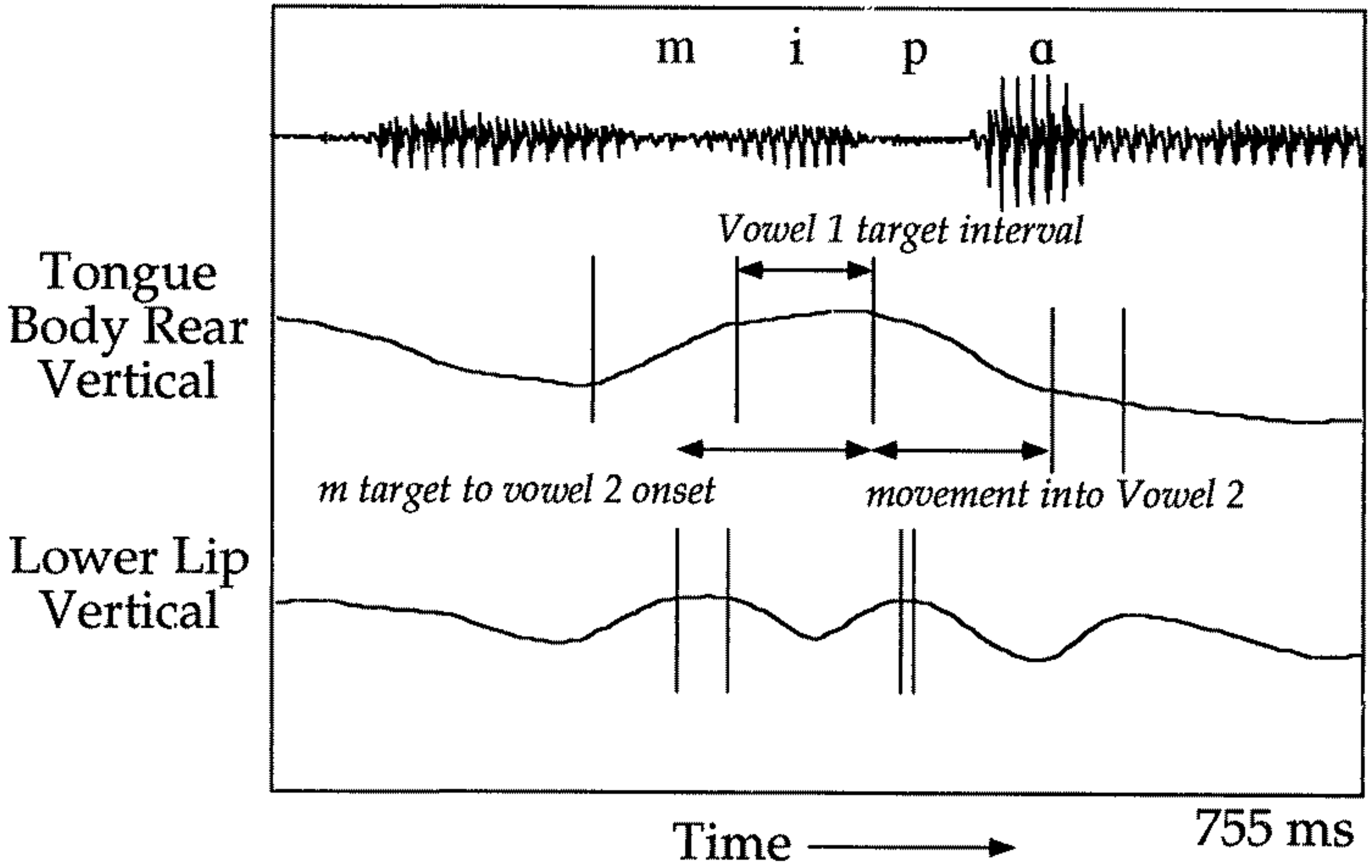
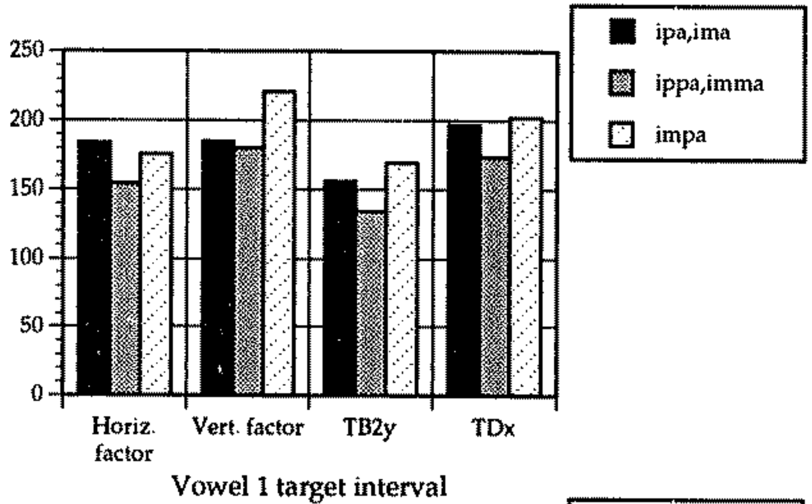


Figure 3.29. Sample production of /mipa/ by Japanese speaker J1, showing the measured intervals referred to as *vowel 1 target interval*, */m/ target to vowel 2 onset*, and *movement into vowel 2*.

Figure 3.30. Graphs of *vowel 1 target interval* and */m/ target to vowel 2 onset* for Italian speaker I1.



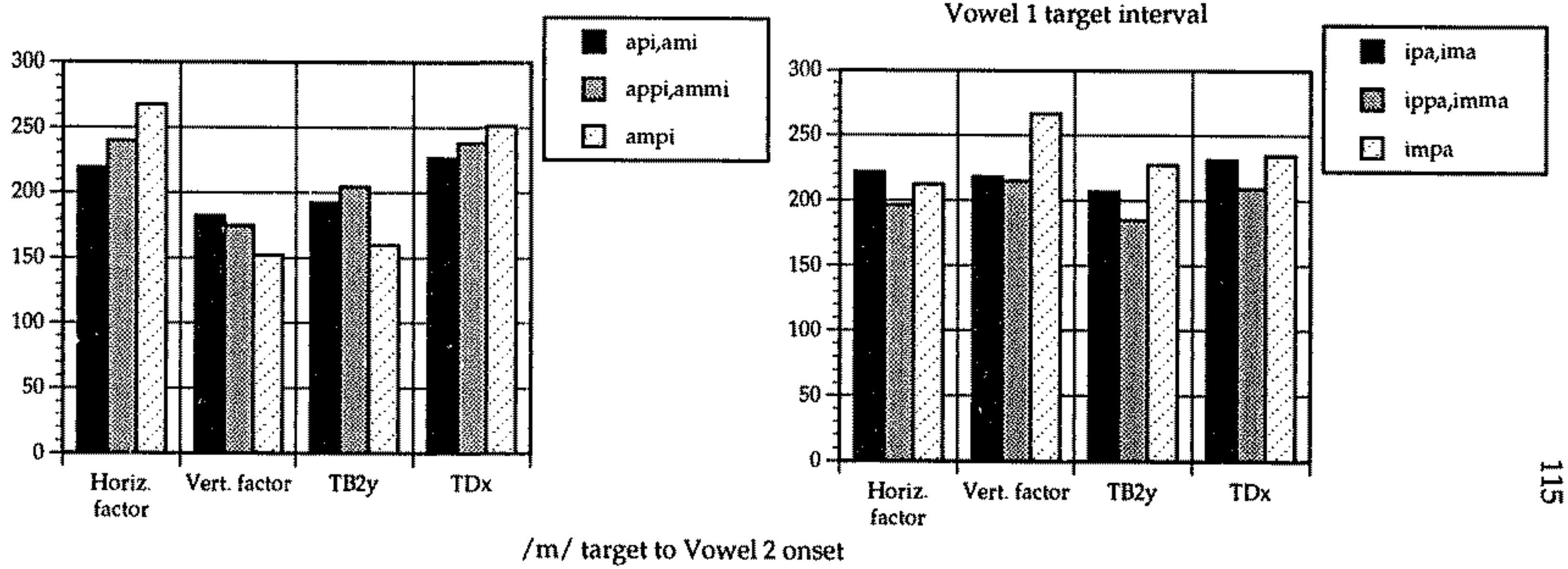
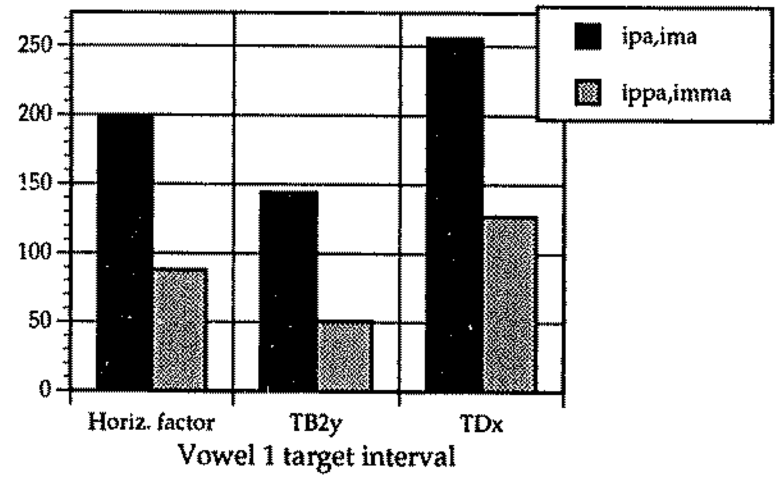


Figure 3.31. Graphs of *vowel 1 target interval* and */m/ target to vowel 2 onset* for Italian speaker I2.



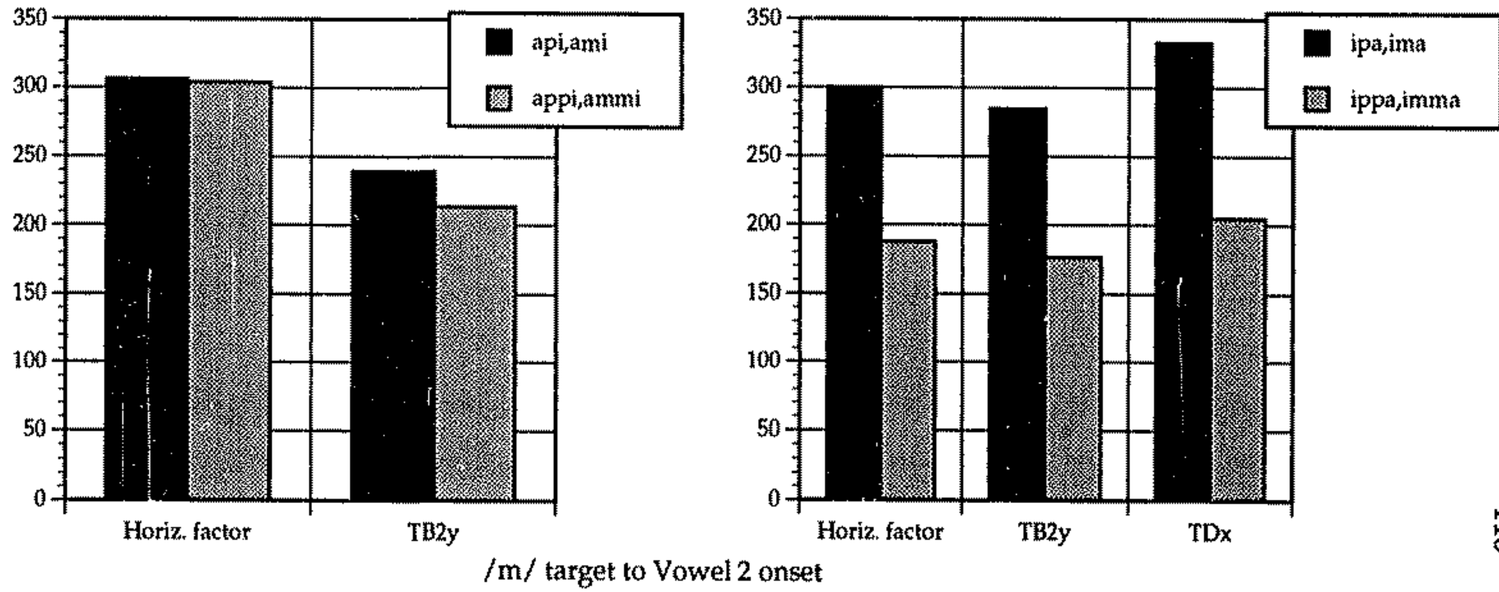
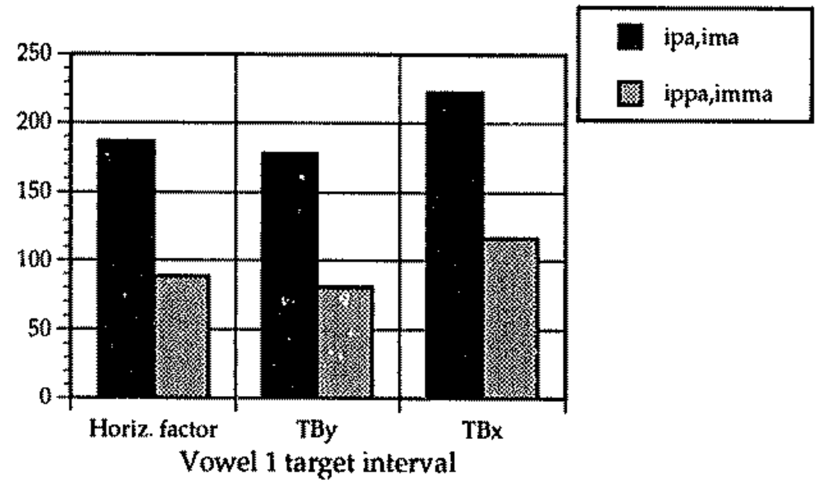
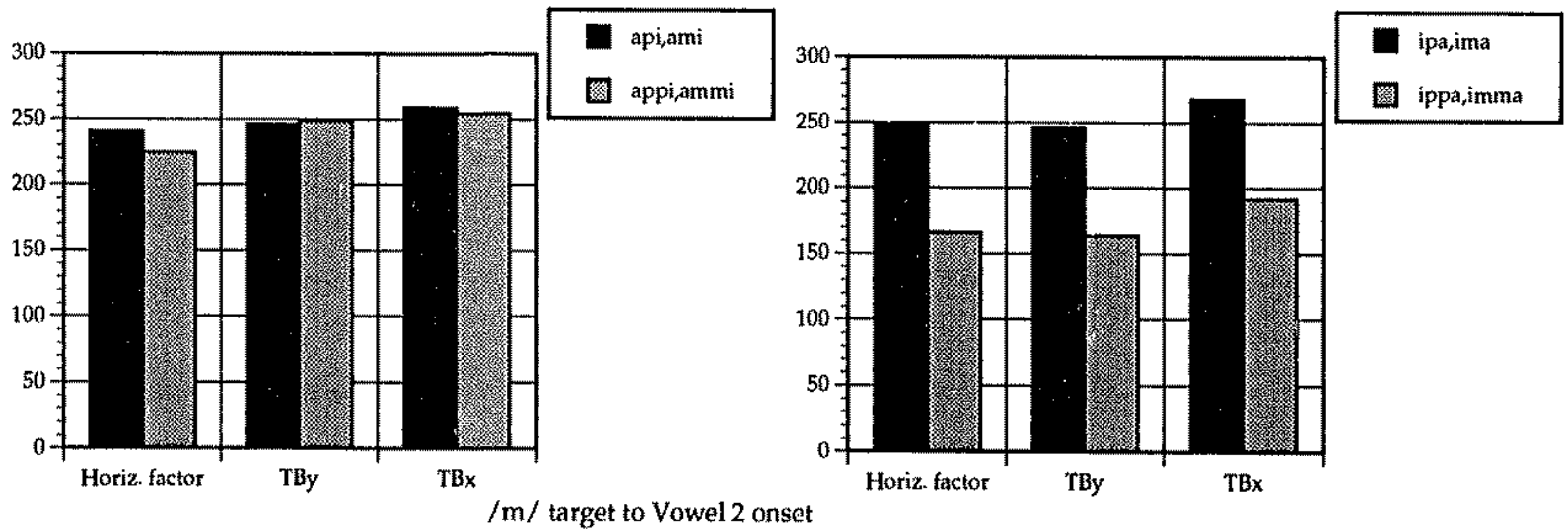


Figure 3.32. Graphs of *vowel 1 target interval* and */m/ target to vowel 2 onset* for Italian speaker I3.





were almost identical to the results of measuring the vowel target interval. Its durations are plotted in Figures 3.30-3.32. The interval from the /m/ target to the onset of /a/ was significantly shorter with geminates in all channels for all speakers except the Vertical factor for speaker I1, and except for utterances with nasal consonants in TB2y, also for speaker I1, where there was an interaction of Length × Nasal. Speaker I1 also had a significant main effect of Nasal in all channels, and speaker I3 did in TBy, with this interval longer in the context of nasal consonants. In the analysis of utterances with long consonants, for speaker I1, this interval was significantly longer before /mm/ and /mp/ than /pp/ in all channels.

In the a-i utterances, no main effects were significant for speakers I2 and I3. For speaker I1, this interval was significantly longer in the Horizontal factor in the context of a geminate consonant. The /m/ to onset of vowel 2 interval was also significantly longer in the context of oral than nasal consonants in the Horizontal factor, in TB2y and TDx. The effect of long consonant type was significant in TB2y, with the interval longer in utterances with /pp/ than with /mm/ or /mp/.

As was the case for the target-to-target intervals, the two vowel patterns are behaving somewhat differently with respect to the duration of intervals associated with the first vowel. The target interval for first-syllable /i/ tended to be shorter before geminates. In contrast, first-syllable /a/ usually had the same duration with singles and geminates. This inconsistency could suggest that the target interval is not crucial to the contrast between singles and geminates in Italian.

2.2.2.2. Japanese

2.2.2.2.1. Vowel target interval (Vowel 1 = i)

Unlike Italian, where vowels shortened preceding geminates, in Japanese they lengthened as consistently as the consonants themselves. The vowel target interval for /i/ was significantly longer preceding geminate consonants than single consonants for all channels for all speakers. These durations can be seen in the top graphs of Figures 3.33-

3.35. The vowel target interval was significantly longer preceding nasal consonants only in some channels: in TB2y for all three speakers, and in the Horizontal factor and TDx for speaker J1, and in the Vertical factor for speaker J2. Interactions of Length × Nasal were significant for speaker J1 for TB2y and TDx; in these cases the significant difference between vowels preceding single and geminate consonants was larger preceding nasals.

The /i/ preceding the /mp/ cluster tended to be longer than preceding the geminate consonants. The effect of long consonant Type was significant for all channels for speaker J3, with the vowel target interval before /mp/ always longer than before /pp/, and longer than the vowel before /mm/ in the Horizontal factor (no Tongue Tip) and the Front Vertical factor (incl. Tongue Tip). Similarly, the effect of consonant Type was significant for speaker J1 in the Horizontal factor, TB2y and TDx, and in TB2y for speaker J2, with the vowel target interval before /mp/ longer than before /pp/. As was the case for Italian speaker I1, the durations of the vowel target interval preceding /mp/ seem to be closest to the durations for /mm/, which makes sense since in both cases the vowel is actually preceding the same consonant (/m/).

2.2.2.2.2. Interval from the /m/ target to the onset of vowel 2

The alternate measure for the duration of the target interval of the first vowel, the interval from the target of the /m/ to the onset of the second vowel, also showed a significant main effect of Consonant Length for all channels for all speakers (see Figures 3.33-3.35), as was true of the first vowel target interval. This interval was significantly longer before geminates than before single consonants in all cases except for speaker J1's a-i utterances in the Vertical factor and TB2y where the interaction Length × Nasal restricted the significance to utterances with nasal consonants. For this speaker there were also interactions between Length and Nasal in a-i utterances in the Horizontal factor, and in i-a utterances in TB2y and TDx. In each of these channels the difference in the duration of the interval preceding single and geminate consonants was greater before

Figure 3.33. Graphs of *vowel 1 target interval* and */m/ target to vowel 2 onset* for Japanese speaker J1.

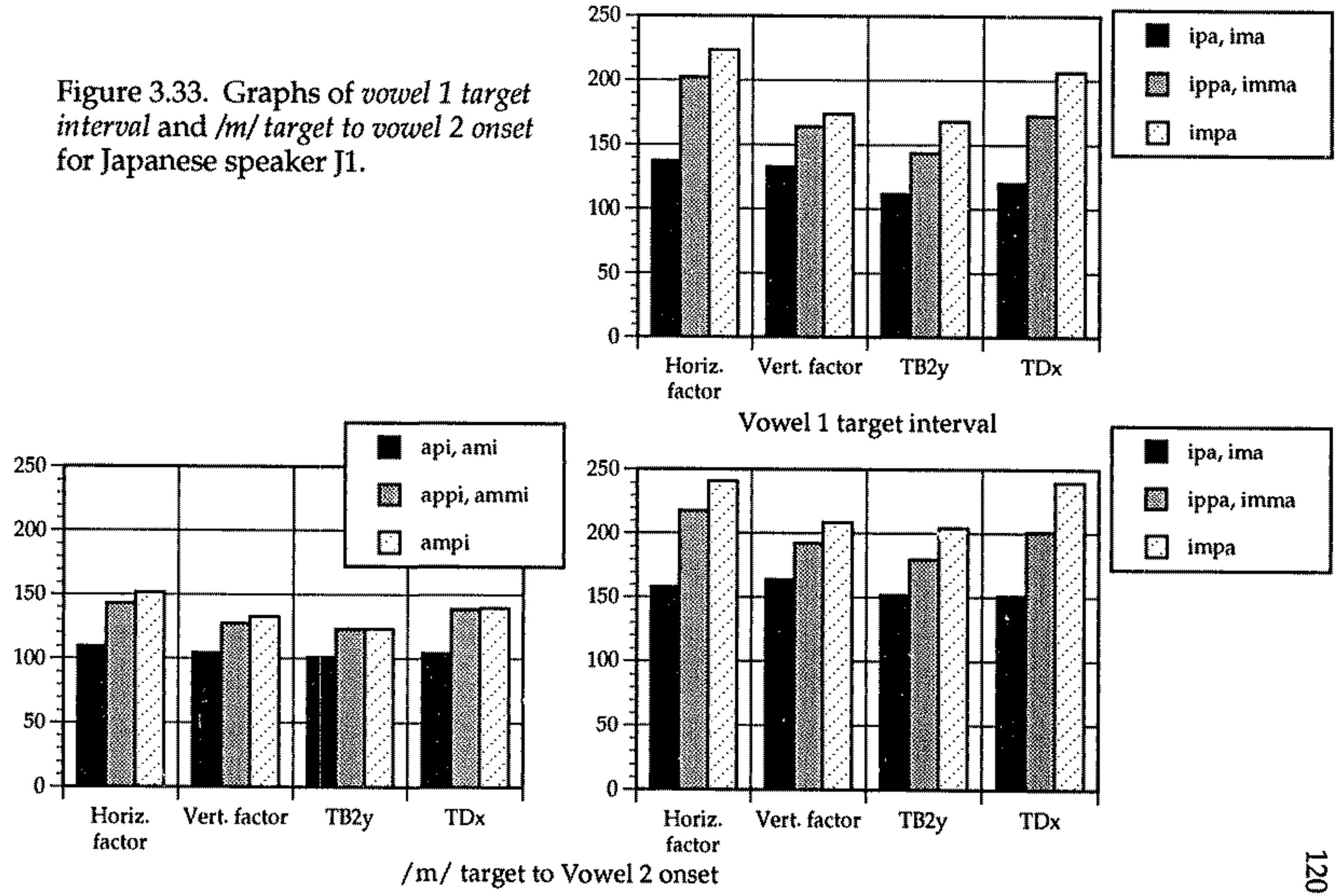
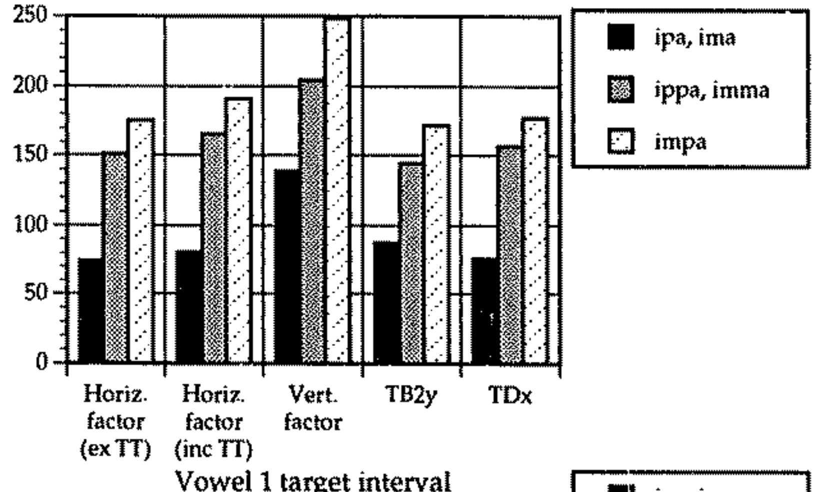
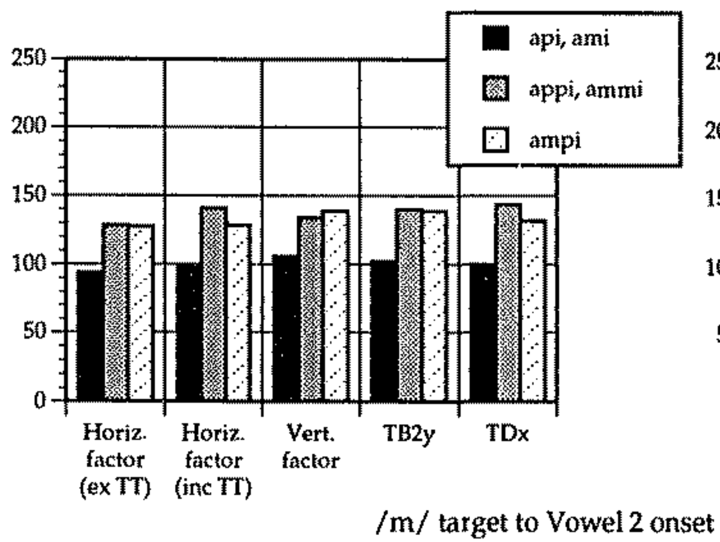


Figure 3.34. Graphs of *vowel 1 target interval* and */m/ target to vowel 2 onset* for Japanese speaker J3.





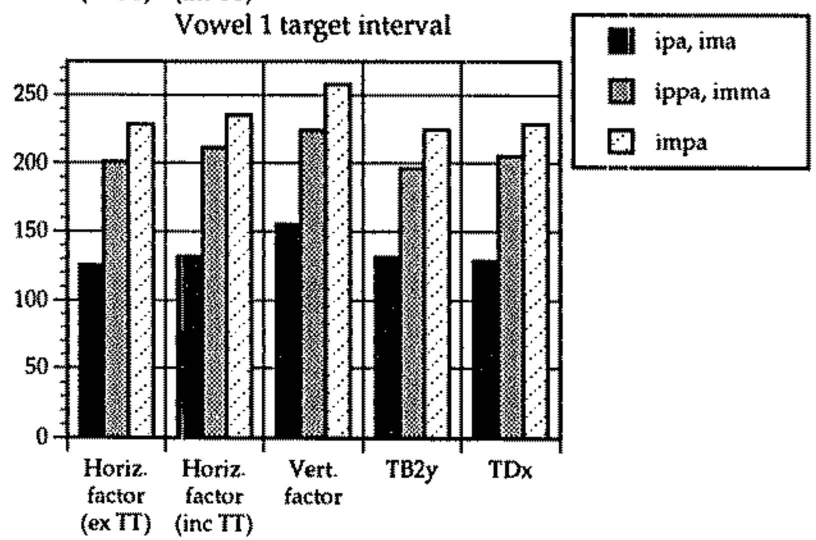
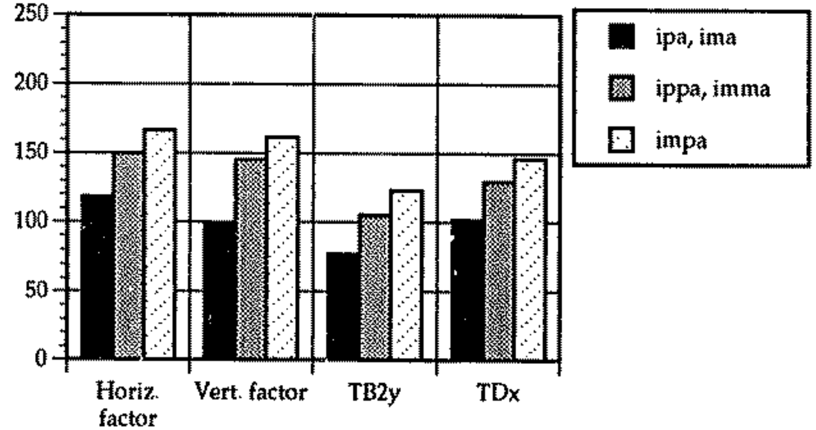
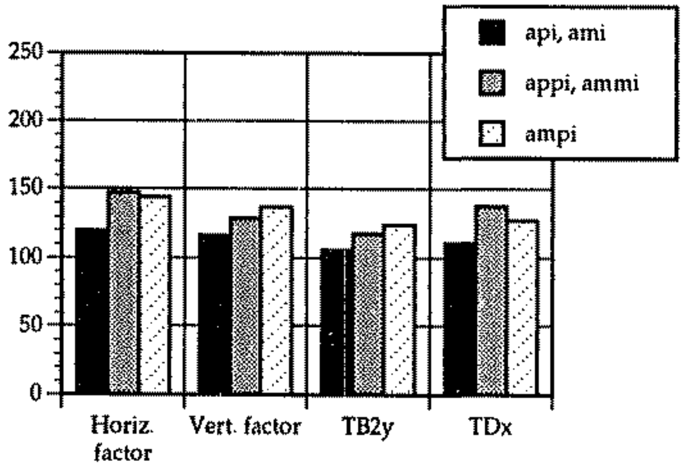
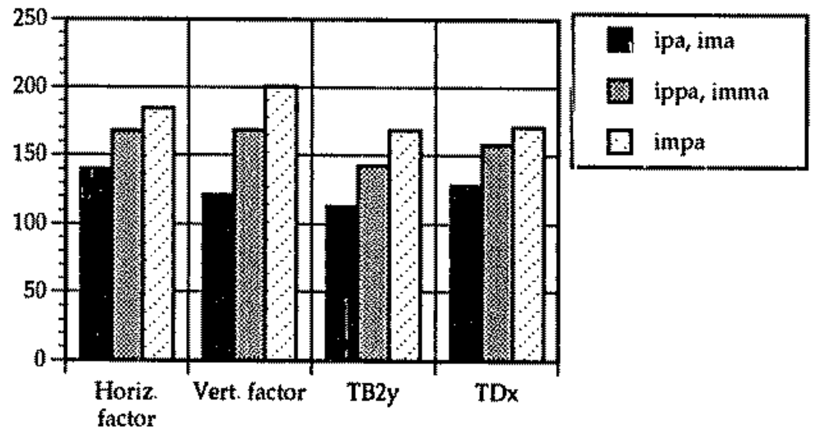


Figure 3.35. Graphs of *vowel 1 target interval* and */m/ target to vowel 2 onset* for Japanese speaker J2.



Vowel 1 target interval





/m/ target to Vowel 2 onset

nasal than before oral consonants. There were also interactions of Length × Nasal for speaker J3. In i-a utterances in the Horizontal factor (no Tongue Tip), Horizontal factor (incl. Tongue Tip), and TDx, and in a-i utterances in the Horizontal factor (no Tongue Tip), the duration of the interval was about the same before /p/ and /m/, or even slightly shorter before /m/, but with a much greater increase in duration before /mm/ than before /pp/. In i-a utterances the interval when measured in TB2y was longer overall before nasal consonants. The main effect of Nasal was also significant in all channels for speaker J1 for both a-i and i-a utterances, with the interval longer before nasal than oral consonants. For speaker J2, the interval was significantly longer before nasal consonants than before oral ones in both a-i and i-a utterances measured in the Vertical factor and TB2y. Thus, as was found for the first vowel target interval, the tendency towards longer vowels before nasals was found in many channels but was not as consistent as the tendency towards longer vowels before geminates. Although the difference between vowels before single and before geminate consonants was significant almost everywhere, it was in general much smaller in the a-i utterances. This is similar to what was observed for the Italian speakers, particularly I2 and I3, where /a/ was less often significantly shorter before a geminate than /i/, using the /m/ target to vowel 2 onset interval.

Comparing the duration of this interval before /mp/ and before the geminate consonants also showed similar patterns to what was found with the duration of the first vowel target interval. For speaker J1, the effect of long consonant Type was significant in all channels in a-i and i-a utterances. The interval was significantly longer preceding /mp/ than preceding /pp/ in i-a utterances in all channels, and in a-i utterances in the Horizontal factor; there was never a significant difference between the durations of this interval preceding /mm/ or /mp/. Similarly, for speaker J2 the interval was significantly longer before /mp/ than before /pp/ in i-a utterances in the Vertical factor and TB2y and in a-i utterances in TB2y; elsewhere the effect of consonant Type was not significant for this speaker. For speaker J3, consonant Type was significant only in i-a utterances, where the interval was longer preceding /mp/ than preceding /pp/ in all channels. Thus once again it appears that the cluster patterns most closely with /mm/ in its effect on the preceding vowel, although the type of long consonant was less likely to affect a preceding /a/ than a preceding /i/.

These results suggest that this interval was indeed patterning much like the duration of the first vowel measured in /i/. That is, any effects due to using the target of the /m/ as the starting point for the interval instead of the target of the vowel itself do not seem to be changing the basic pattern of vowels being longer preceding geminates and nasals. There was a less systematic difference between geminates and the cluster in their effect on the vowel target interval duration, suggesting that they behave similarly and that the difference between the single consonants and the long consonants is more likely due to the increased duration of the consonants than to some geminate-specific factor. The a-i utterances showed slightly more limited effects from the intervocalic consonant on the duration of this interval than did the i-a utterances, but where the effects were significant, they were in the same direction in both vowels. Thus the fact that the initial vowel could not be directly measured in the a-i utterances does not seem to be hiding any major difference between the /i/ and /a/ with respect to this interval.

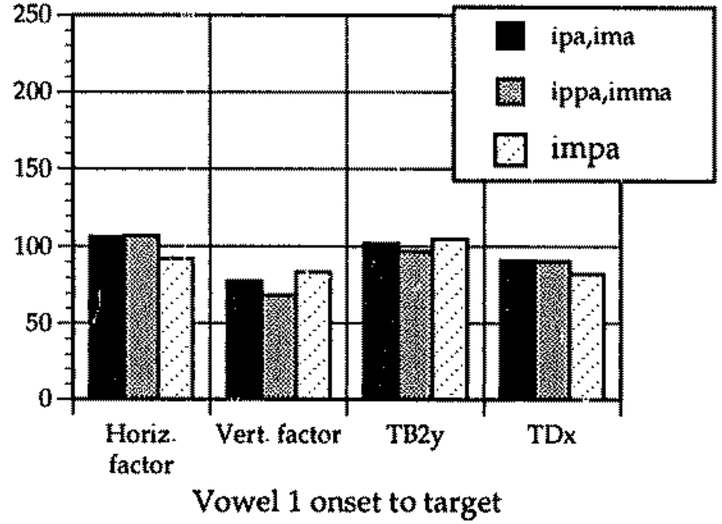
2.2.3. Movement into the second vowel

The interval between the onset of the second vowel (the offset of the target interval for the first vowel) and the target of the second vowel corresponds to the movement into the second vowel. This interval could be measured in utterances with both a-i and i-a vowel patterns, and is illustrated in Figure 3.29.

2.2.3.1. Italian

The interval between the onset and target of the second vowel tended to be longer in the utterances with geminates. The durations of this interval are plotted in the bottom graphs of Figures 3.36-3.38. In the i-a utterances, the interval was significantly longer in the context of geminates in all measures for all speakers except in the Vertical factor and

Figure 3.36. Graphs of *vowel 1 onset to target* and *vowel 2 onset to target* for Italian speaker I1.



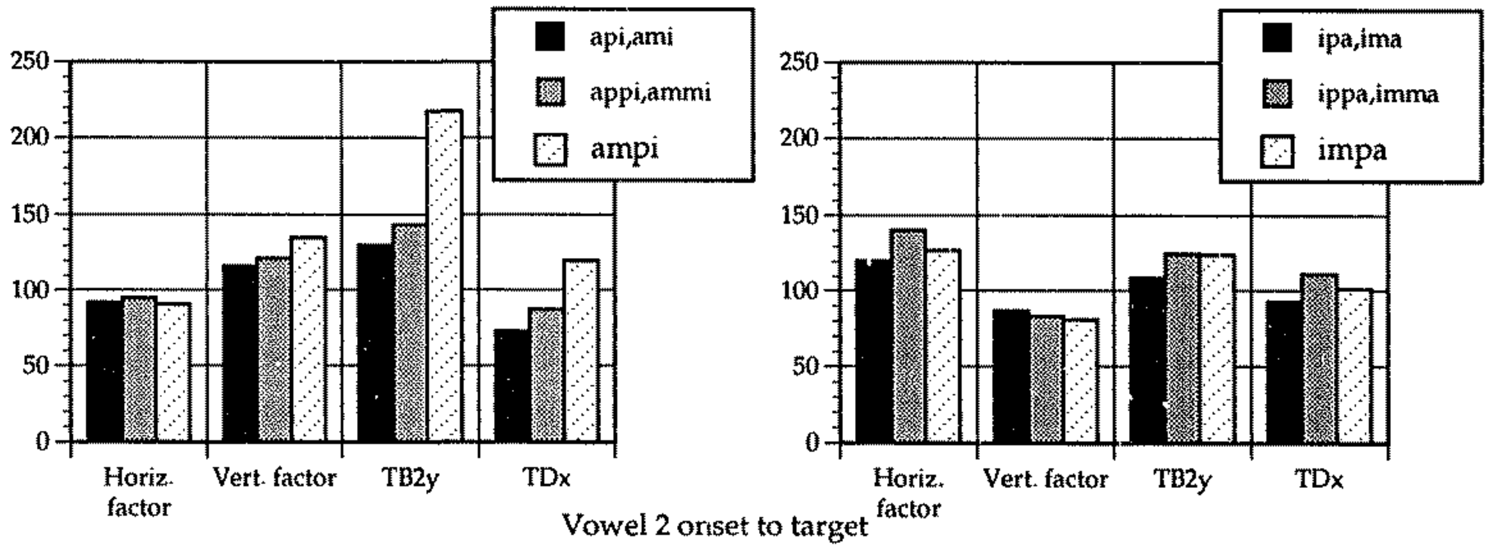
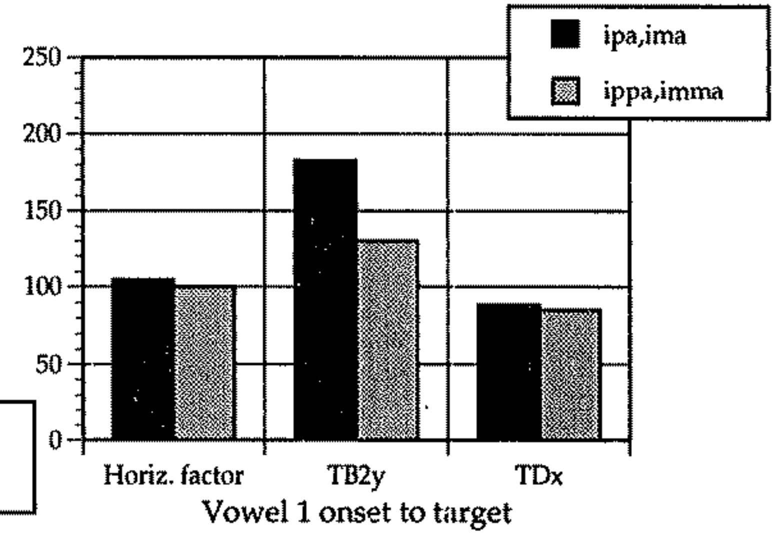
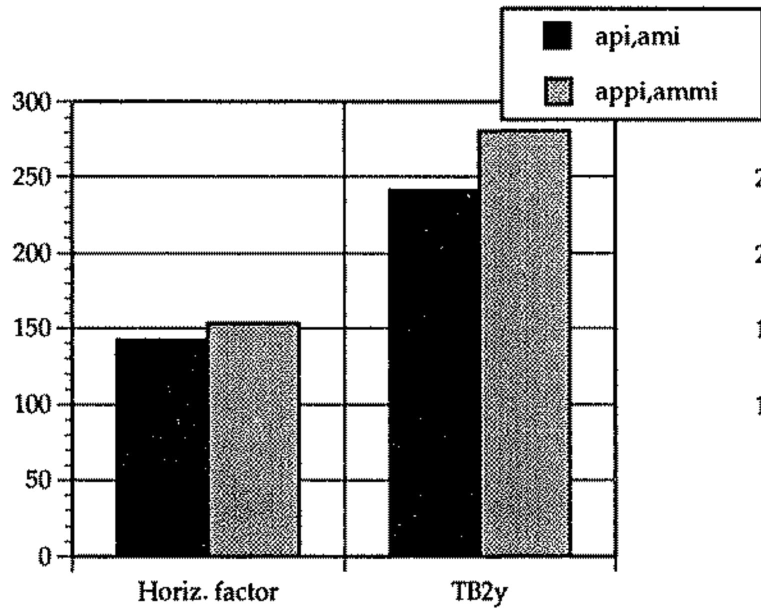
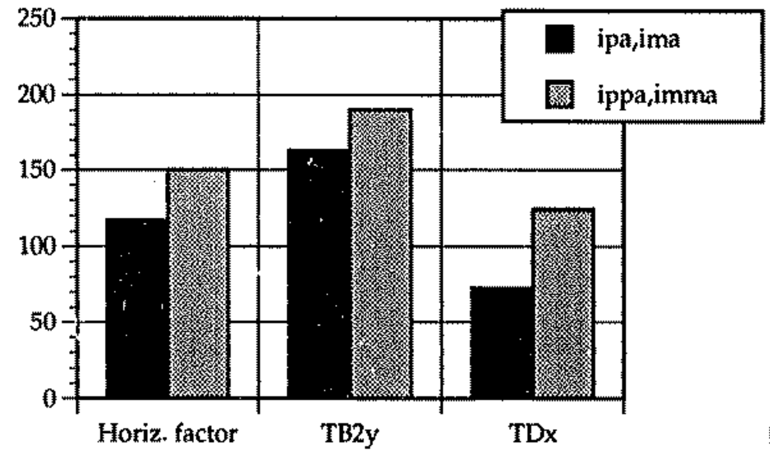


Figure 3.37. Graphs of *vowel 1 onset to target* and *vowel 2 onset to target* for Italian speaker I2.







Vowel 2 onset to target

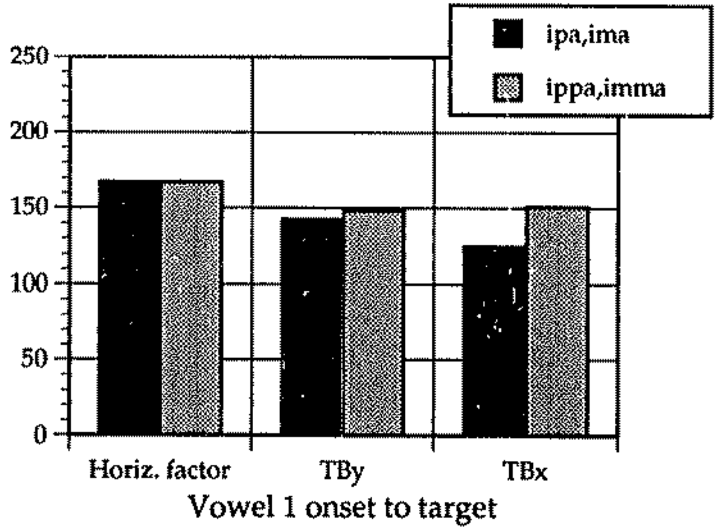
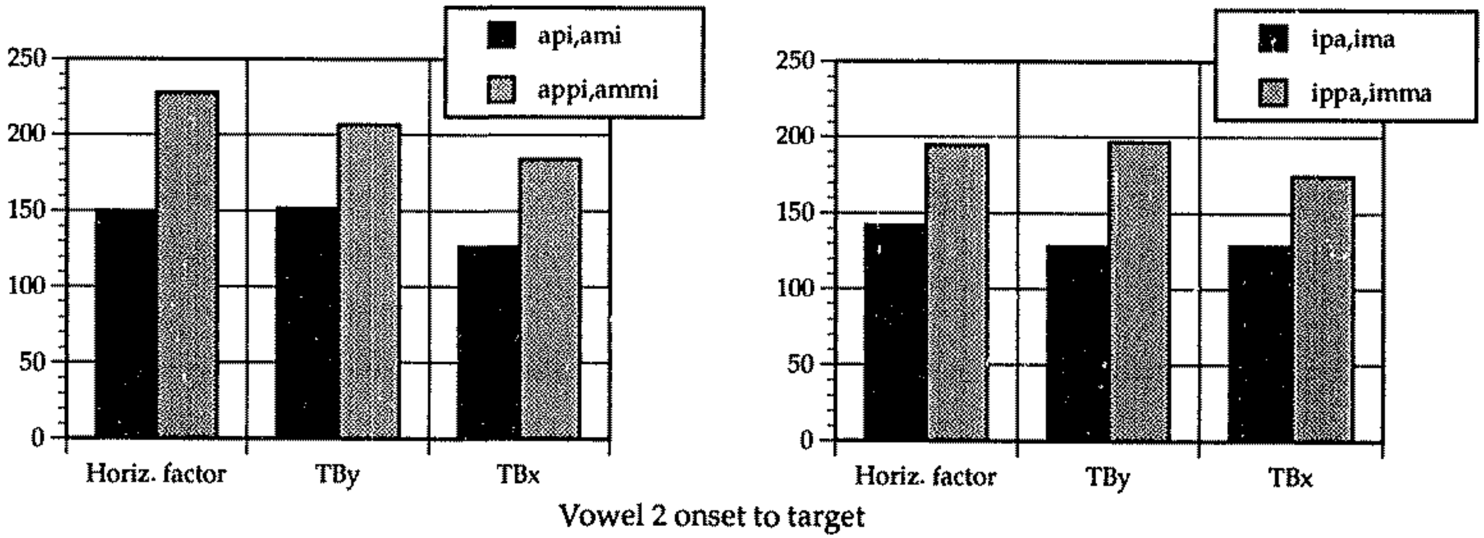


Figure 3.38. Graphs of *vowel 1 onset to target* and *vowel 2 onset to target* for Italian speaker I3.



in TB2y with nasal consonants for speaker I1. In a-i utterances, it was significantly longer in all three measures for speaker I3, in none for I2, and in TDx for speaker I1. This is similar to the pattern of lengthening of the interval between the target of the initial /m/ and the target of the second vowel, which was also significantly longer in all channels for speaker I3, none for I2, and some for I1.

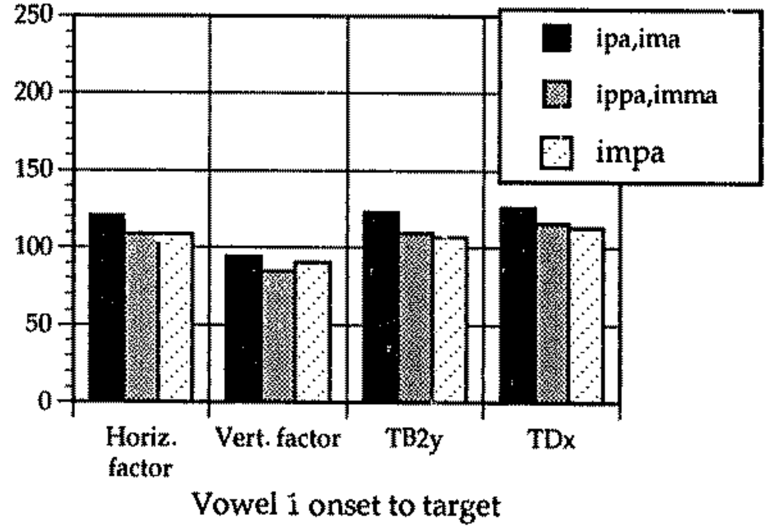
There were scattered effects of Nasal on the duration of the movement into the second vowel. In the a-i utterances it was significant only for speaker I1, in the Vertical factor and in TDx. The intervocalic consonant being nasal had opposite effects on these channels: the interval was shorter with nasals in the Vertical factor and longer in TDx. In TB2y, it was significantly shorter in the context of /pp/ and /mm/ than /mp/. In the i-a utterances, the interval was shorter with nasal consonants in the Vertical factor for speaker I1 and in TDx for speaker I2.

2.2.3.2. Japanese

The interval from the onset to the target of vowel 2 was significantly longer with geminate consonants in most, but not all, channels for the three speakers, similar to the results found in Italian. There were no significant reversals in direction, however. Unlike the other intervals measured in Japanese, its duration in utterances with the intervocalic cluster was sometimes as close to its duration with singletons as to that with geminates. This can be seen in the plots at the bottom of Figures 3.39-3.41, particularly in Figure 3.41 for speaker J3.

In the a-i utterances, this interval was significantly longer in utterances with geminate consonants for speaker J1 in the Vertical factor, TB2y and TDx, for speaker J2 in TB2y, and in all channels for speaker J3, except in TDx where an interaction of Length $\times$ Nasal restricted the significance to utterances with nasal consonants. There was also an interaction in the Horizontal factor (no Tongue Tip), where the increased duration with geminate consonants was greater in nasal consonants than in oral ones. In the i-a utterances, the interval was significantly longer in the context of geminate consonants for

Figure 3.39. Graphs of *vowel 1 onset to target* and *vowel 2 onset to target* for Japanese speaker J1.



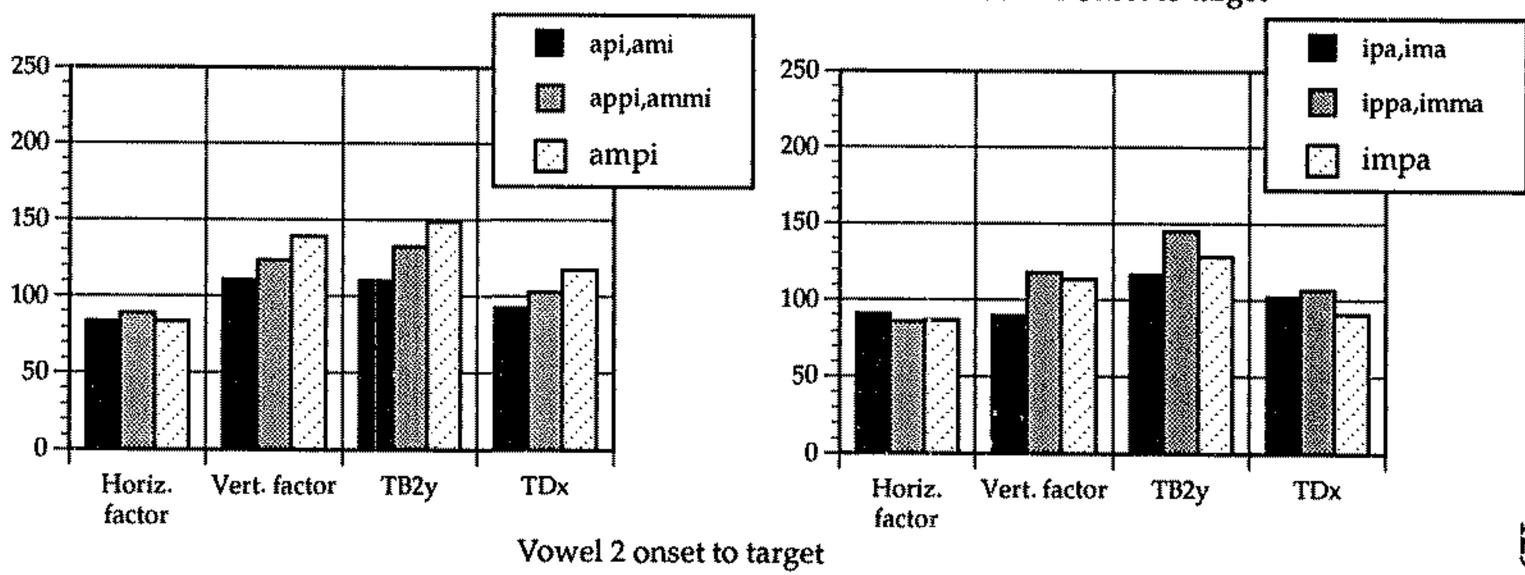
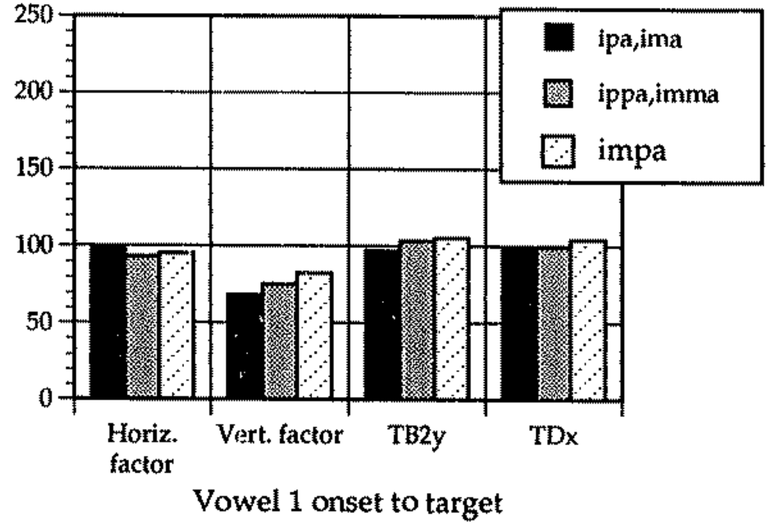


Figure 3.40. Graphs of *vowel 1 onset to target* and *vowel 2 onset to target* for Japanese speaker J2.



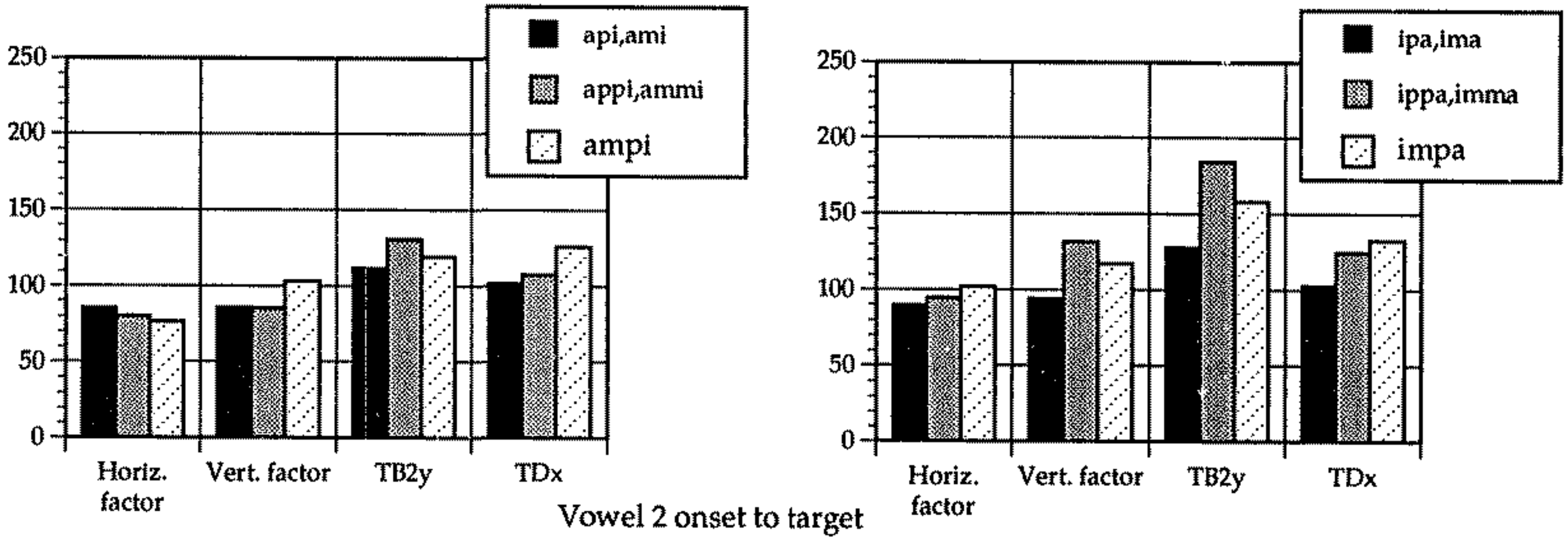
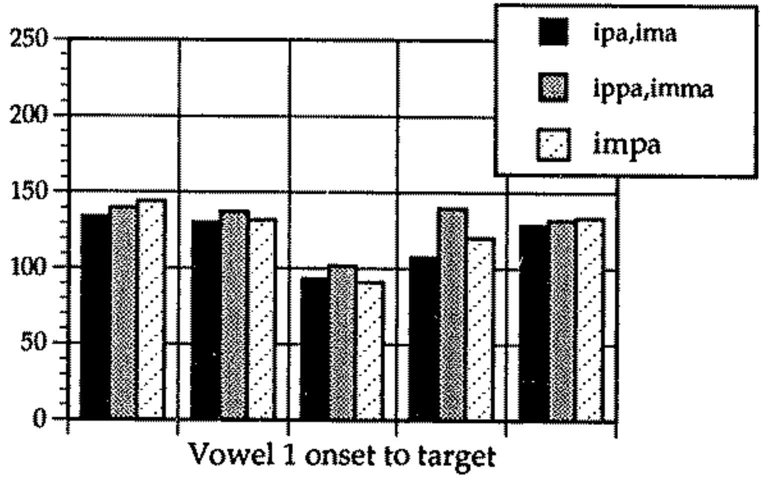
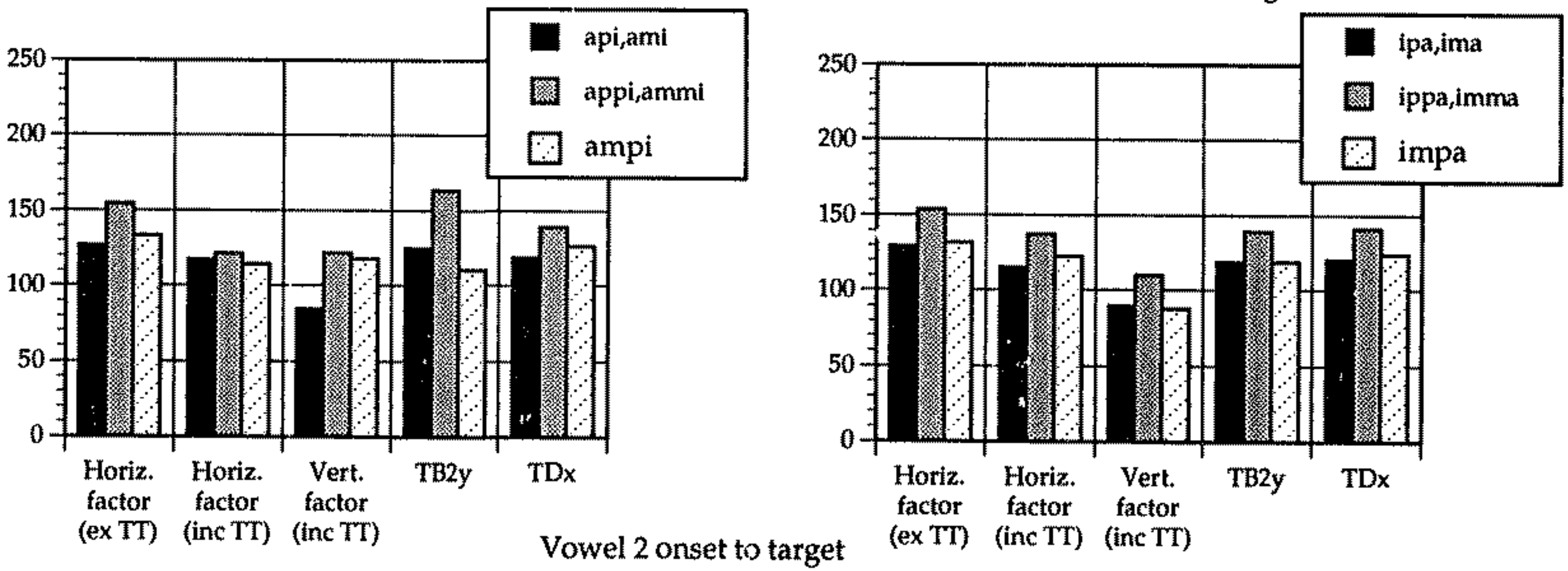


Figure 3.41. Graphs of *vowel 1 onset to target* and*vowel 2 onset to target* for Japanese speaker J3.





speaker J1 in the Vertical factor and TB2y, for speaker J2 in the Vertical factor, TB2y, and TDx, and for speaker J3 in all channels except the Horizontal factor (incl. Tongue Tip). For J3, there were significant interactions of Length × Nasal in the Horizontal factor (no Tongue Tip), Horizontal factor (incl. Tongue Tip), and TDx, where the increased duration with geminate consonants was greater in oral consonants than nasal, but significant in both.

The speakers varied more in the effect of consonant nasality. The interval was significantly shorter with nasal consonants than oral ones for speaker J1 in i-a utterances in the Horizontal factor and TDx, and for speaker J3 in both a-i and i-a utterances measured in TB2y. It was significantly longer with nasal consonants than oral ones for speaker J1 in i-a utterances in the Vertical factor, and for speaker J2 in the Vertical factor and TB2y for both a-i and i-a utterances.

Utterances with the cluster patterned inconsistently compared to those with the geminates, with the interval more often being shorter (particularly for speaker J3), but occasionally longer, in the context of the cluster than the geminate consonants. The interval was significantly shorter with /mp/ than with /pp/ for speaker J1 in i-a utterances in TB2y and TDx, and for speaker J3 in i-a utterances in the Horizontal factor (no Tongue Tip), Horizontal factor (incl. Tongue Tip), TB2y, TDx, and in a-i utterances in TB2y. For speaker J3, it was also significantly shorter for /mp/ than for /mm/ in i-a utterances in the Horizontal factor (no Tongue Tip) and in a-i utterances in the Horizontal factor (no Tongue Tip) and TB2y, and for speaker J2 in i-a utterances in TB2y. It was longer for /mp/ than for /pp/ for speaker J1 in a-i utterances in TDx, and speaker J2 in a-i utterances in the Vertical factor. It was also longer with /mp/ than with /mm/ for speaker J1 in i-a utterances in the Horizontal factor.

This interval, the movement into the second vowel, showed a clear tendency for lengthening in the contexts of geminate consonants compared to singletons, but for little difference among utterances with geminate consonants and those with the intervocalic cluster. None of the Japanese speakers showed as large and consistent lengthening as Italian speakers I2 and I3 did in the i-a utterances.

2.2.3.3. Summary of intervals between the two vowels

The patterns found in the intervals that measure relations between the two vowels show substantial differences in the behavior of the two languages. For Japanese, the target interval of the first vowel, as well as the interval from the target of vowel 1 to the target of vowel 2 were longer with geminate consonants. The movement towards vowel 2 showed some tendency to be longer, but the difference was less robust for this interval. Thus the site of the lengthening effect was primarily in the target interval of vowel 1. The patterns found in Italian were more complicated, and in the i-a utterances they involved a shorter first vowel coupled with a longer movement between vowels. The significant differences between the Italian utterances with single and geminate consonants are summarized in Table 3.2 below, which shows the differences in the three classes of intervals. For the a-i utterances, the interval from the /m/ target to the onset of vowel 2 was used in place of "Vowel 1 target interval" listed in the table, and the interval from the /m/ target to the target of vowel 2 was substituted for "Vowel 1 target to vowel 2 target".

	Vowel 1 target interval	Movement into vowel 2	Vowel 1 target to vowel 2 target
a-i utterances			
speaker I1	(geminate > single Horiz. factor only)	(geminate > single TDx only)	geminate > single, except in Vert. factor
speaker I2	—	—	—
speaker I3	—	geminate > single	geminate > single
i-a utterances			
speaker I1	geminate < single, except in Vert. factor and in TB2y nasals	geminate > single, except in Vert. factor	—
speaker I2	geminate < single	geminate > single	geminate < single
speaker I3	geminate < single	geminate > single	geminate < single, except in TBy

Table 3.2. Summary of significant differences for the Italian speakers in the intervals measuring relations between the two vowels. For the a-i utterances, the results refer to measures where the /m/ target was used as a substitute for vowel 1 target.

Although there were some differences between the utterances with single and geminate consonants, suggesting that the consonant does play some role in timing in Italian, these results are compatible with the vowel-to-vowel timing model. In the i-a utterances, there seems to be a trade-off between the duration of the vowel 1 target interval and the movement into vowel 2, suggesting a tendency towards a constant interval between vowel targets, although this constancy is not always achieved. However, this trade-off in durations between two adjacent intervals could also be due to inconsistent detection of the event that demarcates these two intervals (the onset of vowel 2).

For the a-i utterances, the most reliable result was that speakers I1 and I3 had a longer movement into the second vowel with geminates, and in the interval between the /m/ target and the vowel 2 target. Since there was not a difference in the duration of the vowel 1 target interval, presumably the longer target-to-target interval resulted from the longer movement into vowel 2. The movement into vowel 2 was also longer in the i-a utterances, suggesting that this is a regular, specified difference between utterances with single and geminate consonants.

However, for those speakers and utterances in which there was a significant difference in the duration of the target-to-target interval, it was in different directions for the a-i and i-a utterances. There are two reasons why this clash may not be indicauve of a genuine difference in vowel-to-vowel coordination in the two vowel patterns. First, because in the a-i utterances it was only possible to measure the /m/ target to vowel 2 target interval, it cannot be determined whether the opposite directions for the difference in the duration of the target-to-target intervals are reflecting differences in the timing between the two vowels or whether using the /m/ is having a different effect in the different vowel patterns. Secondly, the inconsistency in the target-to-target interval suggests that the small differences that were observed are not essential to the single/geminate contrast The interval is controlled to be roughly constant, but slightly shorter or longer durations with geminates can be tolerated.

It is also interesting that the one speaker (I2) who had a significantly shorter target-to-target interval in the i-a utterances was the only one not to have a longer target-to-target interval in the a-i utterances. For all three speakers, in one or the other of the vowel patterns there was no significant difference in the target-to-target interval. Possibly speaker I2 is producing the single/geminate contrast in a way similar to the other two speakers (keeping the target-to-target interval roughly constant), but getting the durational difference for geminates in both vowel patterns more in the direction of shortening than do the other speakers. This could be a further indication that the particular differences found over the target-to-target interval are not important to the single/geminate difference for Italian.

2.2.4. Movement into the first vowel (Vowel 1 = i)

For utterances with the i-a vowel pattern, the interval between the onset and target of the first vowel could be measured, corresponding to the movement into the first vowel. This interval is illustrated in Figure 3.42. Measurement of this interval makes it possible to characterize the movement into the first-syllable /i/, as was done for the movements into the vowels in the second syllable.

2.2.4.1. Italian

Durations of this movement for the three Italian speakers are plotted in the upper right of Figures 3.36-3.38. There were no significant effects of Length or Nasal on this interval for speaker I2 or I3. For speaker I1 it was significantly shorter in the Vertical factor in utterances with geminates, as well as being shorter with intervocalic /pp/ than with /mp/. Both of these differences were very small (about 9 ms), however. The

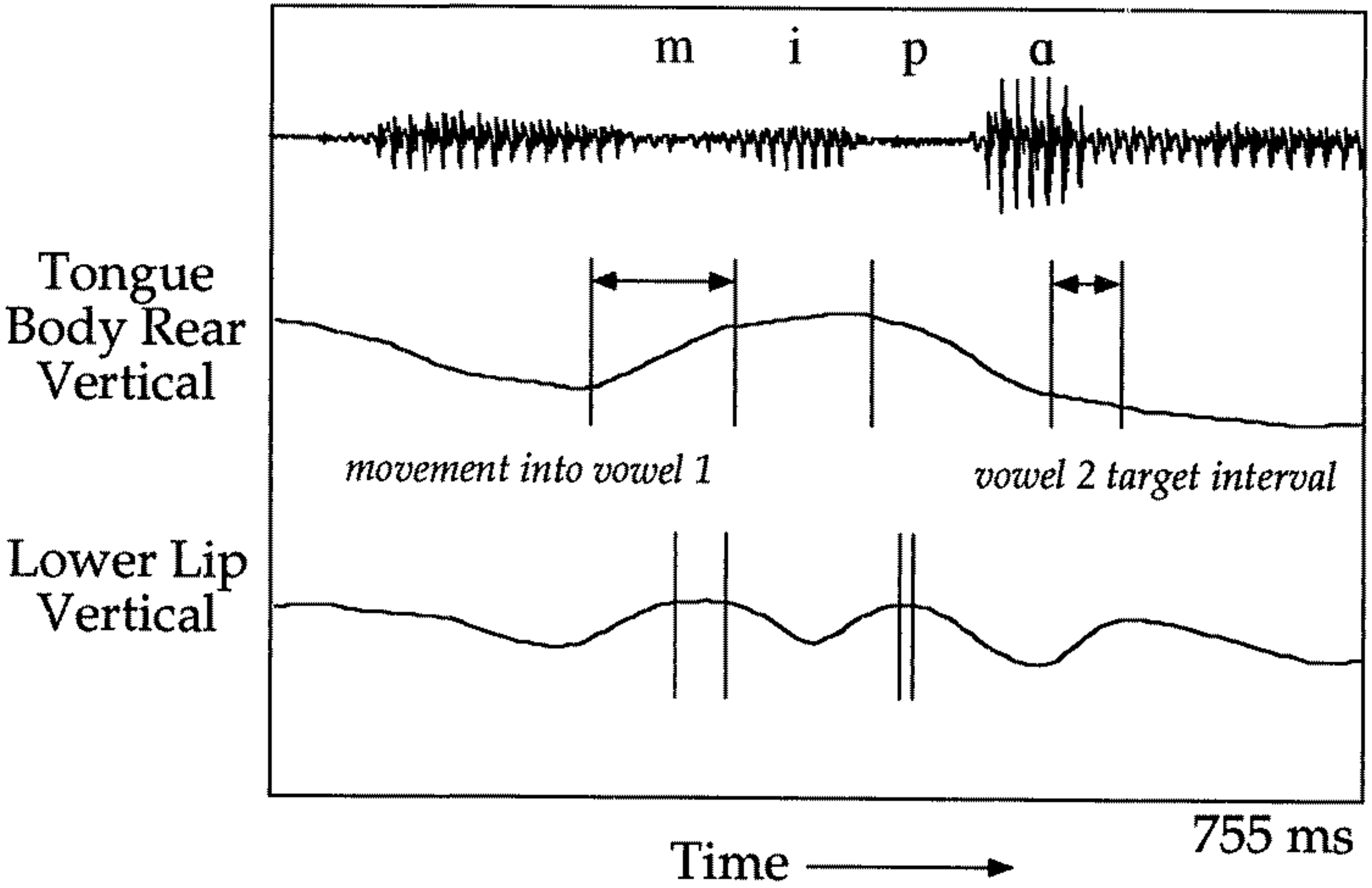


Figure 3.42. Sample production of /mipa/ by Japanese speaker J1, showing the measured intervals referred to as *movement into vowel 1* and *vowel 2 target interval*.

movement into the first vowel was also significantly longer in TB2y in utterances with nasal consonants. But, in general, there was very little variability in the duration of this interval.

2.2.4.2. Japanese

The movement into vowel 1 was affected by the length of the intervocalic consonant more often in Japanese than in Italian, but the effect of a longer consonant was not the same for all speakers. The durations of this interval are plotted in the upper right of Figures 3.39-3.41. For speaker J1, this interval was significantly shorter in utterances with geminates in the Horizontal factor and in TB2y, but in TB2y for speaker J2 and in the Vertical factor and TB2y for speaker J3 the interval was longer in utterances with geminates. There were no significant effects in the analysis comparing the geminates and /mp/. The effect of Nasal was also inconsistent: in the Horizontal factor for speaker J2 and the Front Vertical factor for speaker J3 the interval was longer with oral consonants than nasal ones, but it was shorter with oral consonants in the Vertical factor for speaker J2. As in Italian, these differences were quite small and do not suggest any major difference in the duration of this movement between utterances with single and geminate consonants.

2.2.5. Vowel 2 target interval

The target interval for the second vowel was defined as the time between the achievement of target for this vowel, and the time at which the tongue started movement towards the next vowel. This interval is illustrated in Figure 3.42. Whereas the vowel preceding the intervocalic consonant shortened regularly in Italian and lengthened in Japanese when the consonant was a geminate, the vowel following the consonant behaved less consistently. The duration of this vowel's target interval was little affected by the preceding consonant, and may relate more to coordination with the following vowel.

2.2.5.1. Italian

Speakers I2 and I3 showed no effect at all of the length of the consonant on the duration of the second vowel target interval. For speaker I1, the vowel /a/ was significantly longer following geminates in the Horizontal factor and in TDx.

In the i-a utterances, the main effect of Nasal was significant in the Horizontal factor and in TDx for speakers I1 and I2, and in the Horizontal factor for I3. For speakers I1 and I3, /a/ was shorter following nasal than oral consonants. In the analysis of long consonants for speaker I1, in the Horizontal factor /a/ was shorter following /mm/ than either /pp/ or /mp/, showing again the pattern in which an interval preceding or following the cluster patterns like the corresponding interval preceding or following the geminate that matches the adjacent portion of the cluster. For speaker I2, who also had a significant interaction of Length × Nasal, /a/ was shorter following /m/ than /p/ but longer following /mm/ than /pp/ in both the Horizontal factor and TDx.

In the a-i utterances, only speaker I1 showed a significant effect of Nasal, with /i/ longer following nasal consonants than oral ones in TB2y and TDx, unlike /a/ which tended to be shorter following nasals. Also for speaker I1, in the Vertical factor /i/ was significantly longer following the cluster than either of the geminates. No other main effects were significant for any of the speakers.

2.2.5.2. Japanese

The trend for the Japanese speakers to lengthen all parts of the utterance in the context of a longer intervocalic consonant was found in the second vowel as well. Similarly, Homma (1981) found small but consistent lengthening of the second vowel in acoustic measures. In a-i utterances, the /i/ was significantly longer in the context of a geminate consonant in all measures for all three speakers. For speaker J3 in the Front Vertical factor (incl. Tongue Tip), there was an interaction of Length × Nasal: the lengthening of the vowel following the geminate was greater following nasal consonants than oral ones (but significant for both). In i-a utterances the second vowel was significantly longer in both factors for speaker J1, in the Front Vertical factor (incl.

Tongue Tip) and TB2y for speaker J3, and in TDx for speaker J2. It was also significantly longer in the Horizontal factor for speaker J2, but only in utterances with nasal consonants because of an interaction of Length × Nasal.

Although the tendency to lengthening was quite widespread, in contrast for speaker J3 /a/ was significantly shorter after a geminate in the Horizontal factor (no Tongue Tip) and in TDx. There was also at least one channel for each speaker in which there was no significant difference in the length of /a/ following single and geminate consonants. The fact that it was always /a/ and not /i/ that showed a non-significant difference may be a reflection of the different shapes of the pellet trajectories for the two vowel patterns, which can be seen by comparing the two types of utterance in Figures 3.13-3.18. The lack of effect from the length of the preceding consonant could be due in part to the tendency of /a/ to be shorter than /i/ in this position and in part to the possibility that the measured durations of the target interval for /a/ are unduly affected by idiosyncrasies in the slope of the trajectory. In the utterances in which the second vowel is /a/, the region associated with /a/ is merely a flattening-out at a point of inflection of the trajectory, not an actual peak or valley plateau as /i/ is in both syllables, so a small change in the velocity of the curve's descent could have a comparatively large effect on where the edges of the plateau for the target interval were marked. These considerations could camouflage any systematic effect of the length of the preceding consonant.

The second vowel target interval tended to be shorter following nasal consonants than oral ones, as was the case for two of the Italian speakers. Like the effect of Length, this effect was more often significant in a-i utterances than in i-a utterances. The second vowel was significantly shorter following nasal consonants for speaker J3 in a-i utterances in the Horizontal factor (no Tongue Tip), the Front Vertical factor (incl. Tongue Tip), and TDx and in i-a utterances in the Front Vertical factor (incl. Tongue Tip); for speaker J2 in a-i utterances in the Vertical factor and TB2y and in i-a utterances in the Vertical factor; and for speaker J1 in a-i utterances in the Horizontal factor, TB2y, and TDx. For speaker J1 the effect of Nasal was also significant in i-a utterances in the Vertical factor, but here /a/ following a nasal was significantly longer than /a/ following an oral consonant, the opposite of the more common pattern.

The comparison among the long consonants was usually not significant in the second vowel, but when it was, the most common pattern was for the vowel following /mp/ to be longer than the vowel following /mm/. This pattern was significant for speaker J1 in a-i utterances measured in the Horizontal factor, TB2y, and TDx. Elsewhere the main effect of long consonant type was not significant for this speaker. The same pattern was found for speaker J3 in a-i utterances measured in the Horizontal factor (no Tongue Tip), TB2y and TDx, and in i-a utterances in TDx. For speaker J2 this pattern was found only in a-i utterances in TB2y and in i-a utterances in the Vertical factor. In addition the /i/ following /mp/ was longer than the /i/ following /pp/ when measured in TB2y for speaker J3 and in the Horizontal factor for speaker J2. The extent of significance of this effect was fairly limited, and often the duration of the target interval of the vowel after the cluster was not different from vowels after the geminates.

2.3. Relation between events in the consonant and events in the vowels

The intervals discussed in section 2.2 measured vowel-related durations, relevant to testing the hypotheses of vowel or vowel-and-consonant based timing. But both timing models must also account for the relation of the consonant to the vowels. This was investigated by measuring intervals from each vowel to the intervocalic consonant. Various pairs of events could be used to describe these relations, but here the events used for reference in both vowel and consonant gestures will be their targets. The targets of all the gestures involved could be identified, whereas not all the onsets and offsets could be. In addition, the definition of how some of these events were identified in the movement trajectories is ambiguous: the event labeled as the onset of the second vowel was treated as being the same as the offset of the first vowel. The same is true for what was labeled as the offset of the second vowel in these words: this location represents the transition from one gesture to the next, but at the end of the word the next gesture is in the next word.

The measured intervals discussed in this section are illustrated in Figure 3.43.

2.3.1. Italian

2.3.1.1. Interval between the targets of the first vowel /i/ and the consonant

For all the Italian speakers, the interval between the target of the first vowel and the target of the intervocalic consonant tended to be shorter when the consonant was a geminate. This difference can be seen in the graphs in Figure 3.44, and it was significant in all three channels for speaker I2 and I3, and in the Vertical factor and TB2y for speaker I1. The shortening was also significant with oral consonants in the Horizontal factor and TDx for speaker I1, because of an interaction of Length × Nasal. Also for speaker I1, in all channels the main effect of Nasal was significant, the interval being significantly shorter with oral consonants than with nasal. There was not a significant difference between the duration of the interval in utterances with the cluster from those with the geminate consonants.

The shortening of this interval when the intervocalic consonant is a geminate means that the target interval for the longer geminate starts earlier relative to the beginning of the target interval for the preceding vowel, which itself is shorter. This relation can be seen in the single/geminate pairs of utterances in Figures 3.7-3.12. One consequence of this pattern is that the vowel preceding the geminate shortens acoustically even more than its associated target interval does in the articulatory movement, since the earlier closure of the lips for the geminate means that the acoustic segment for the vowel ends earlier before a geminate consonant.

2.3.1.2. Interval between the targets of the consonant and the second vowel

Unlike the interval between the first vowel and the consonant, the interval between the consonant and the second vowel tended to be longer when the consonant was a geminate, in both the a-i and i-a utterances. This can be seen in the graphs in Figures

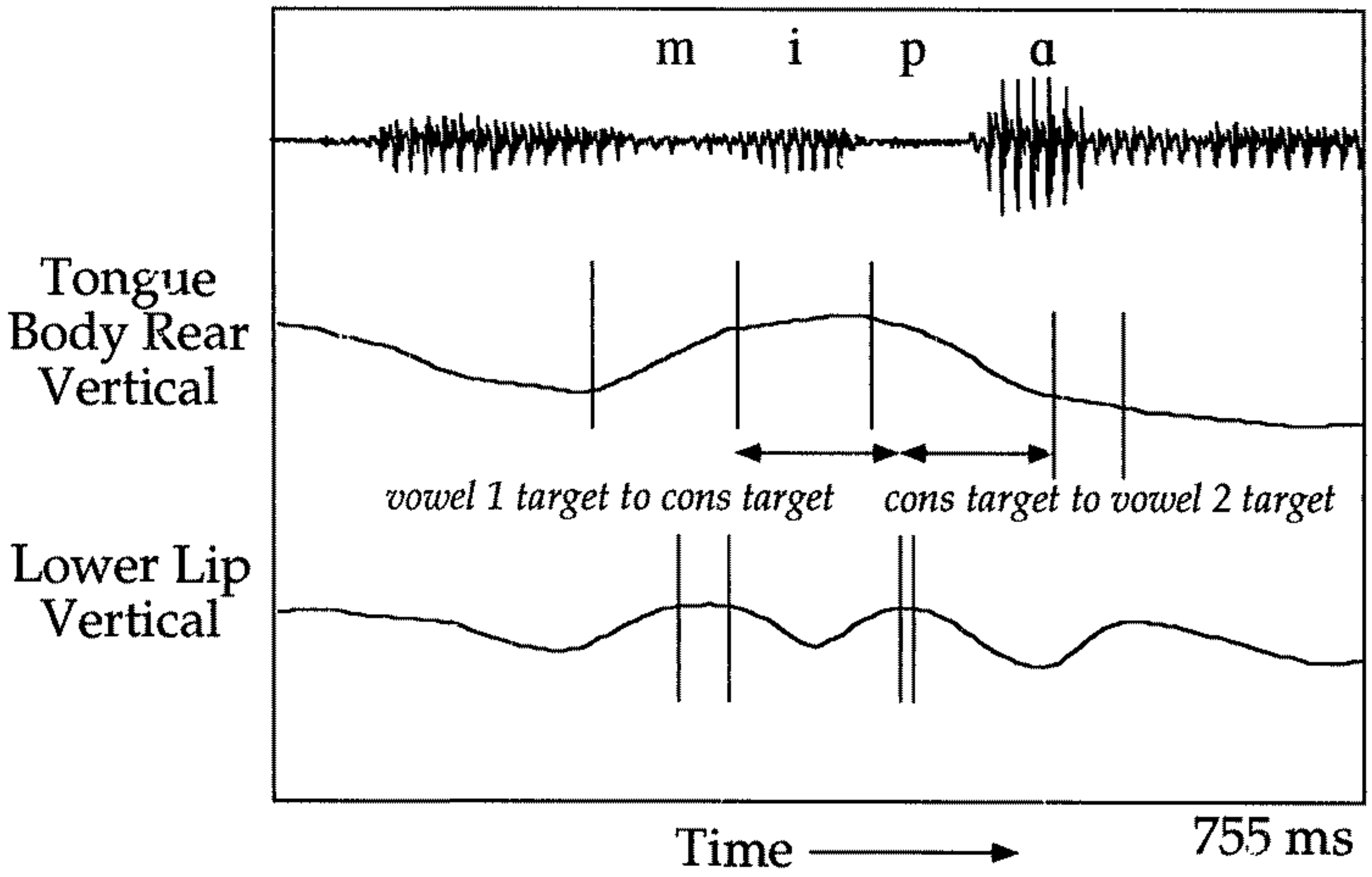


Figure 3.43. Sample production of /mipa/ by Japanese speker J1, showing the measured intervals referred to as *vowel 1 target to consonant target* and *consonant target to vowel 2 target*.

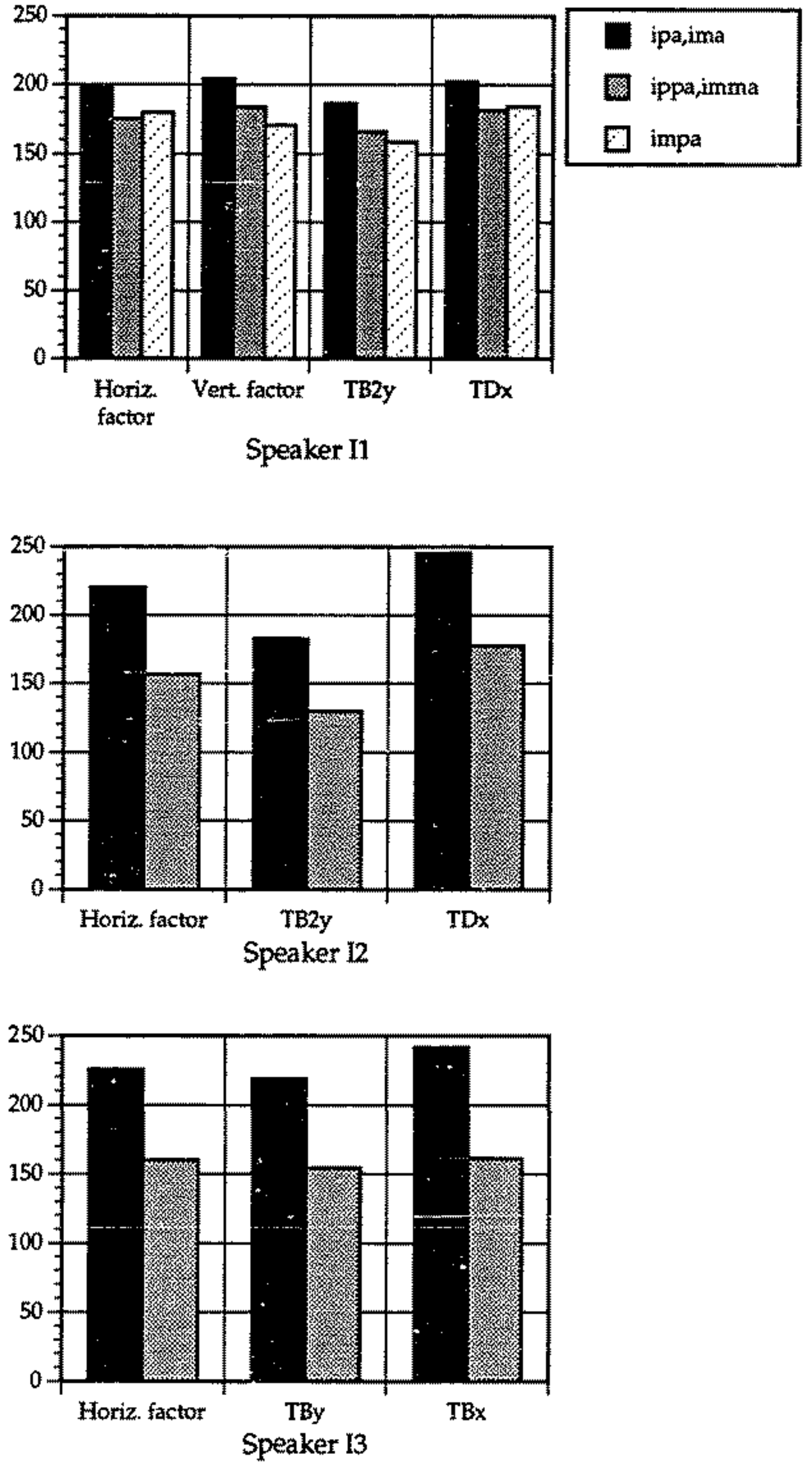


Figure 3.44. Graphs of *vowel 1 target to consonant target* for 3 Italian speakers.

3.45-3.46. In the a-i utterances, the interval was significantly longer in the Horizontal factor for all three speakers, and also in TB2y and TDx for speaker I1, in TB2y for speaker I2 and in TBy and TBx for speaker I3. There were interactions of Length × Nasal in the Horizontal factor for speakers I2 and I3 and in TBy for speaker I3, but the main effect of Length was significant in all instances. However, the interaction limited the effect of Nasal for speaker I2 to geminate consonants, with the interval shorter with /mm/ than with /pp/. For speakers I1 and I3, the interval was significantly shorter with nasal consonants in all channels. For speaker I1, there were also some significant differences between utterances with the cluster and with the geminates. In TB2y, the interval was longer with the cluster than with /mm/, and in TDx, it was longer with /pp/ than /mm/, and still longer with the cluster.

In the i-a utterances, this interval was significantly longer in utterances with geminates than in those with single consonants in all channels measured for speaker I1 and in the Horizontal factor and TBy for speaker I3. There was no significant effect of Consonant Length for speaker I2; in fact, as can be seen in the middle graph of Figure 3.46, the interval appears slightly shorter for this speaker. For speaker I1 the interval was significantly longer in utterances with /mp/ than with either of the geminates in the Vertical factor and in TB2y. The i-a utterances differed from the a-i utterances in that the effect of Nasal, for speaker I1, was to make the interval longer (rather than shorter) in the context of nasal consonants than oral ones. This difference was significant in the Horizontal factor, TB2y, and TDx. There was no effect of Nasal for either of the other speakers. Thus, as was often the case in these data, the direction of the effect of Consonant Length was more consistent across speakers and utterances than the effect of Nasal.

These intervals between the vowels and the consonant show exactly the pattern of differences between singles and geminates that is predicted by the vowel-to-vowel timing model. This model predicts that the relation between the vowels will be fixed, which

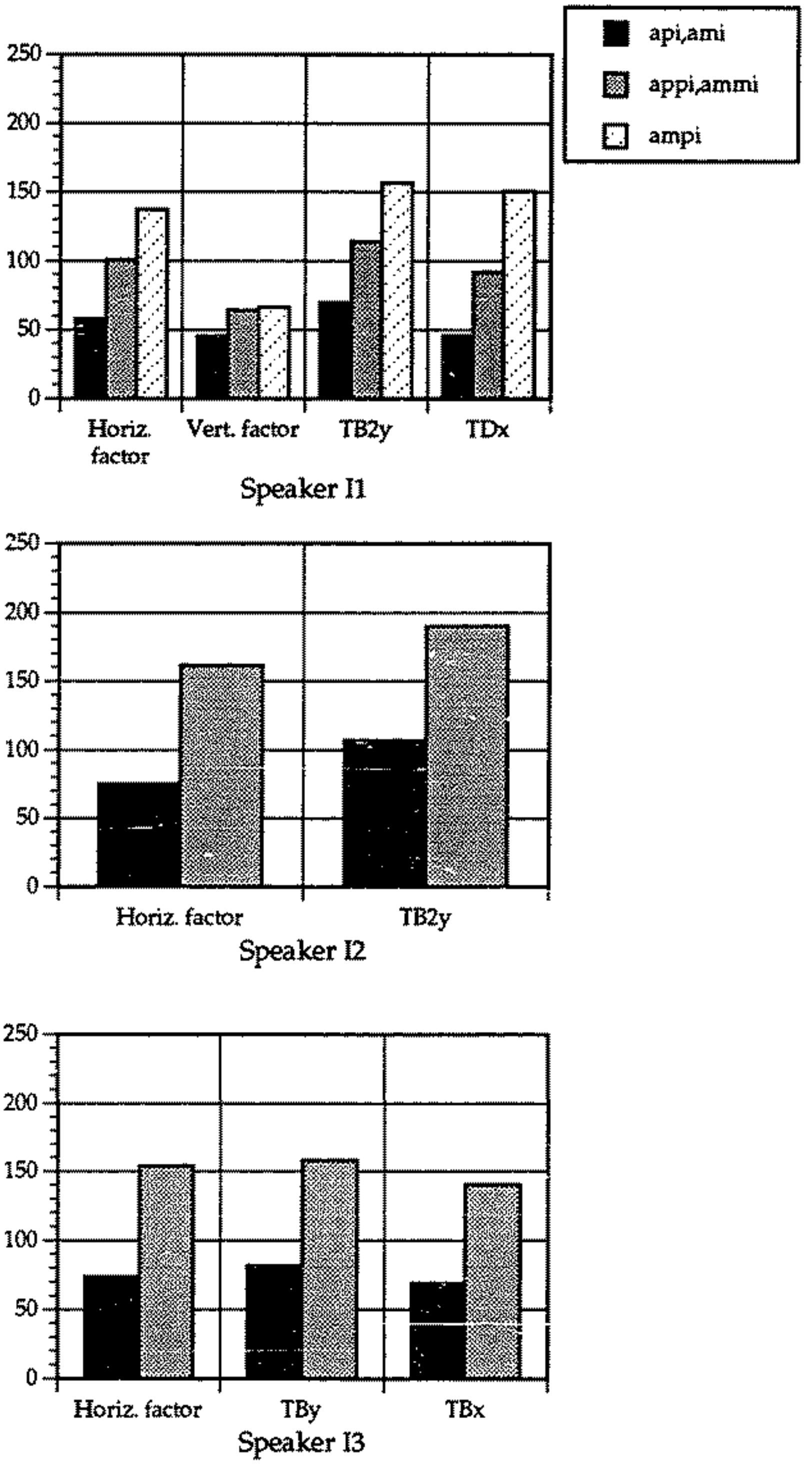


Figure 3.45. Graphs of *consonant target to vowel 2 target* in a-i utterances for 3 Italian speakers.

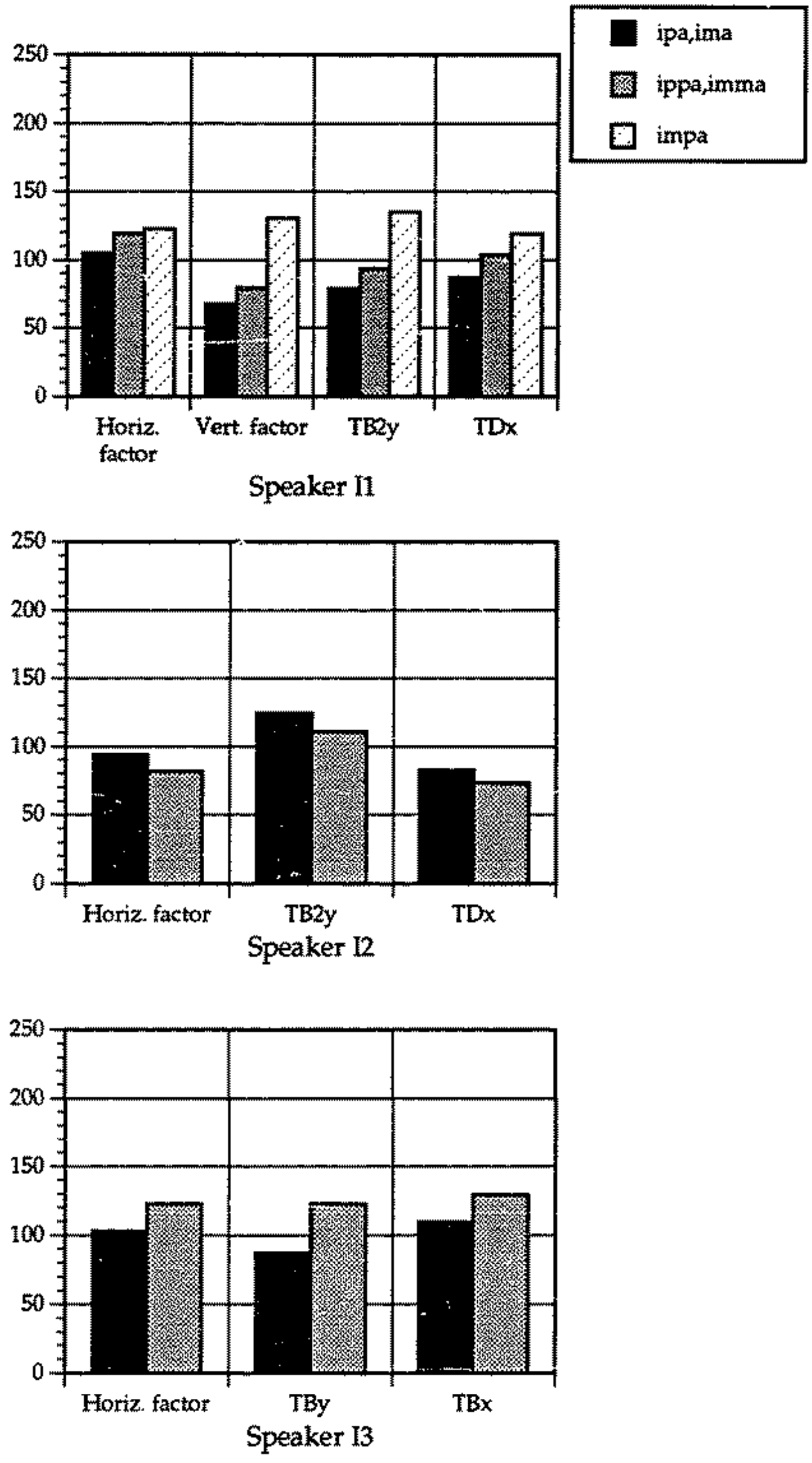


Figure 3.46. Graphs of *consonant target to vowel 2 target* in i-a utterances for 3 Italian speakers.

would mean that if the consonant target occurs earlier relative to the target of one of the vowels, it must also be earlier relative to the target of the other. Thus, with the shorter interval from the first vowel to the consonant target (meaning that the consonant is earlier relative to this vowel), the consonant must also be earlier (i.e. further away) relative to the target of the second vowel. These are the results that were found for the Italian speakers.

2.3.2. Japanese

2.3.2.1. Interval between the targets of the first vowel /i/ and the consonant

The Japanese speakers showed the opposite pattern from the Italian speakers for the effect of consonant gemination on this interval, as it tended to be longer before a geminate consonant than a single one. The durations of this interval for the three speakers are plotted in Figure 3.47. This difference was significant in all channels for speakers J2 and J3. There was an interaction of Length × Nasal in the Front Vertical factor for speaker J3, but the interval was significantly longer with both oral and nasal geminates. However, the effect was much less widespread for speaker J1: the interval was significantly longer with geminates only when measured in the Horizontal factor and with nasal consonants in TDx, because of an interaction of Length × Nasal.

As was the case for the Italian speakers, in many channels, the interval was shorter with oral consonants than with nasals. This difference was significant for speakers J1 and J2 in the Horizontal factor, in TB2y and TDx, and for speaker J3 in the Front Vertical factor. There was seldom any significant difference between the duration of the interval in utterances with /mp/ from those with the geminate consonants; however, it was significantly shorter before /pp/ than before /mp/ for speaker J1 in TB2y, speaker J2 in TDx, and speaker J3 in the Front Vertical factor.

2.3.2.2. Interval between the targets of the consonant and the second vowel

Changes between utterances with single and geminate consonants were less consistent for this interval, particularly in the a-i utterances, than for most of the intervals measured in the Japanese speakers' productions. These can be seen in the graphs in

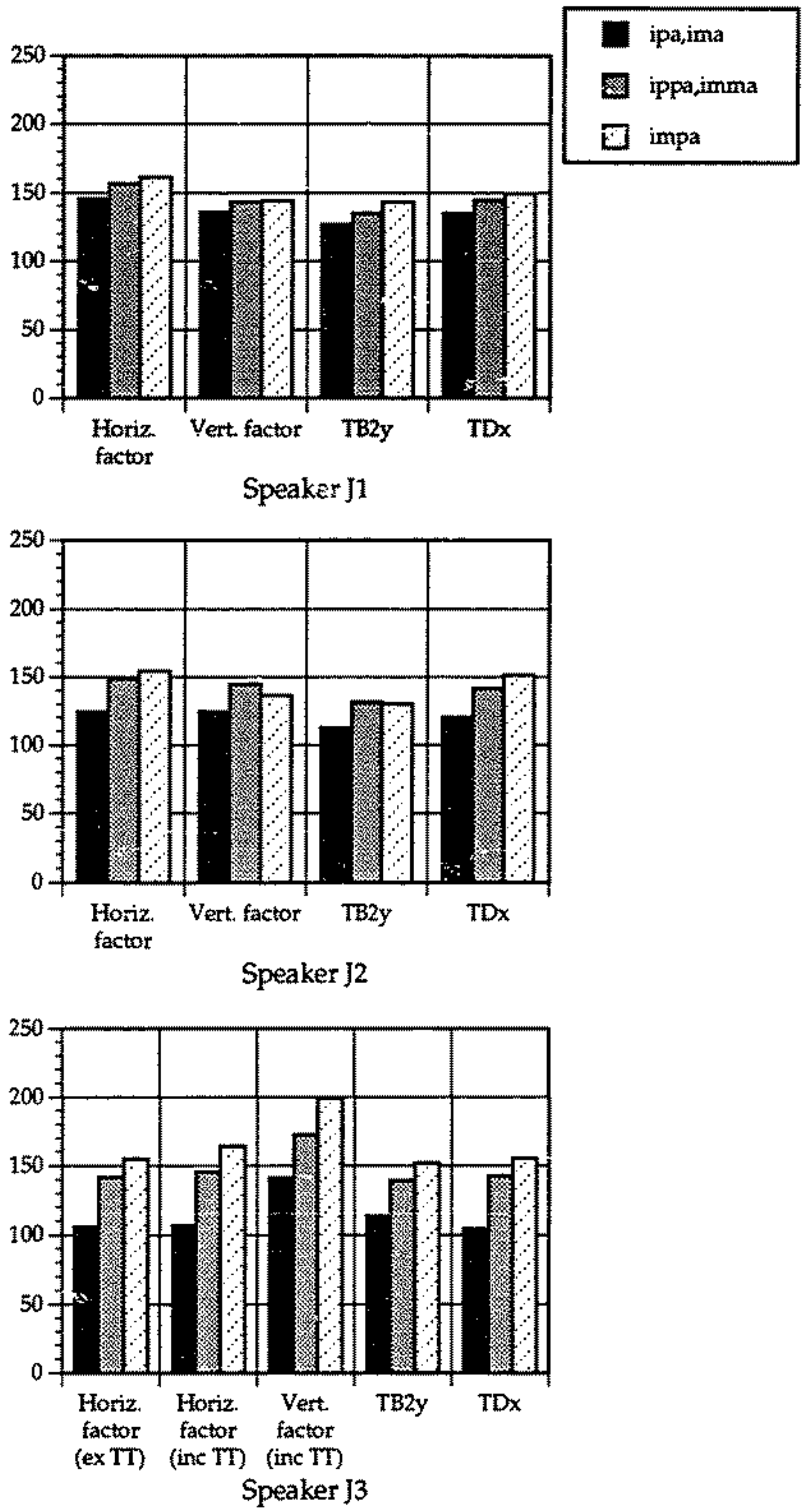


Figure 3.47. Graphs of *vowel 1 target* to *consonant target* for 3 Japanese speakers.

Figure 3.48. For speaker J1, the interval was significantly longer in utterances with geminate consonants than in utterances with singletons in all channels, except in the Vertical factor with oral consonants where the effect was not significant, because of an interaction of Length × Nasal. For speaker J3, the interval was significantly longer with geminates only in TB2y and with oral consonants in the Front Vertical factor, again because of an interaction. Unlike speakers J1 and J3, and even to the Italian speakers who all tended to have this interval longer in utterances with geminates, speaker J2 had a slightly, but significantly shorter interval in the Vertical factor in the context of geminate consonants.

Also in the a-i utterances, speaker J2 showed differences in the effect of Nasal on this interval, which was shorter with nasal consonants in the Horizontal factor and in TDx, but longer in the Vertical factor. There was also a significant interaction of Length × Nasal in the Horizontal factor. For speaker J3, the interval was shorter with nasal consonants in the Front Vertical factor and in TB2y; also in TB2y, the interval was shorter with /mp/ than with /pp/. For speaker J1, the main effect of Nasal was not significant but the interval was again shorter with /mp/ than with /pp/ in the Horizontal factor.

In the i-a utterances, this interval was significantly longer in utterances with geminate consonants in all channels for all speakers; the durations can be seen in the graphs in Figure 3.49. Furthermore, there were no interactions with Nasal. Where there were significant differences between the duration of the interval with /mm/ or /pp/ and with the /mp/ cluster, it was more often longer with the cluster. It was significantly longer with /mp/ than with /mm/ in the Horizontal factor for speakers J1 and J2, and in the Horizontal factor (excluding Tongue Tip) for speaker J3, and longer with /mp/ than /pp/ in the Vertical factor for speaker J2. However, it was significantly shorter with /mp/ than /mm/ in the Horizontal factor (including Tongue Tip) for speaker J3 and in TB2y for speaker J2.

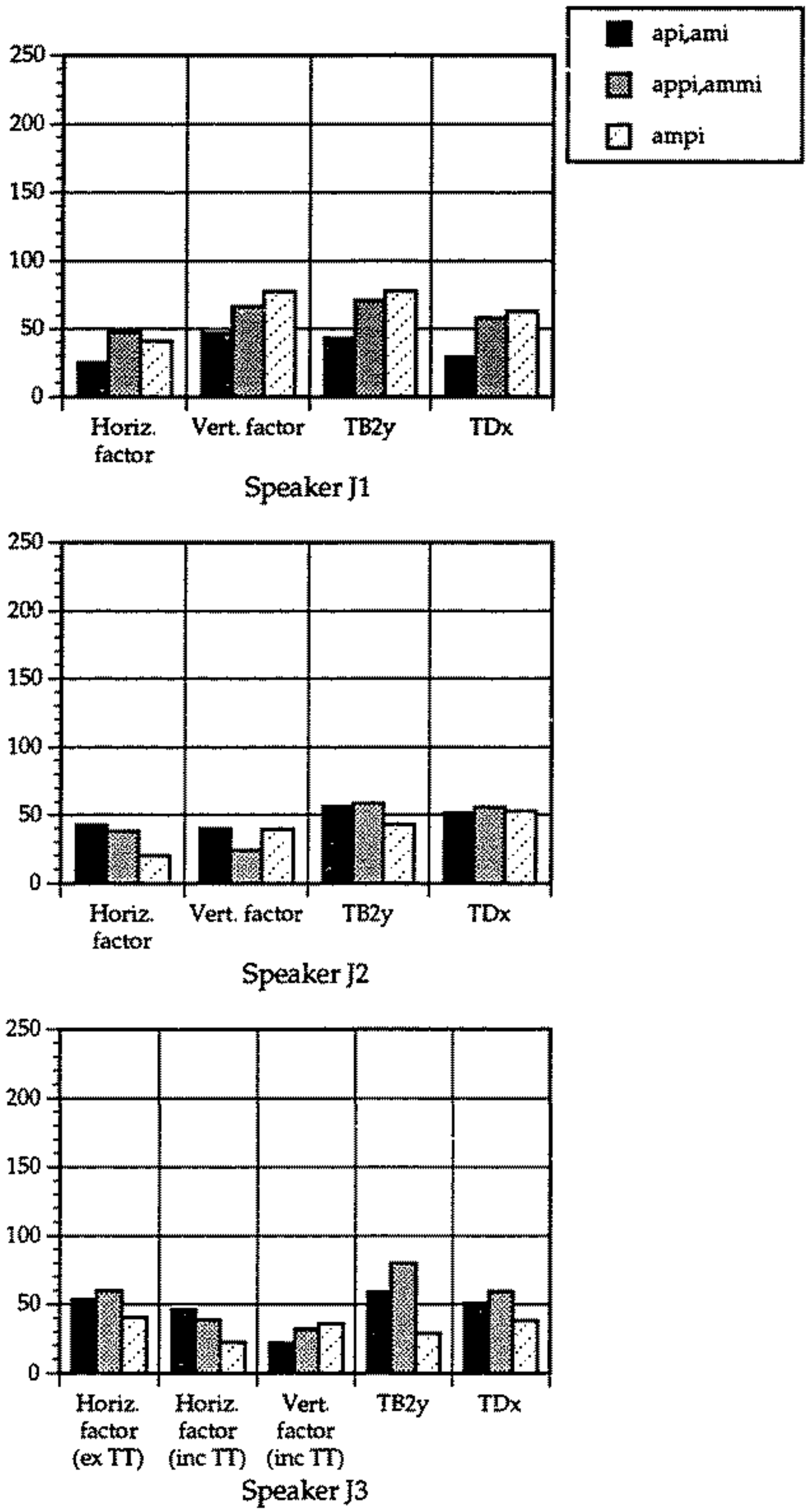


Figure 3.48. Graphs of *consonant target* to *vowel 2 target* in a-i utterances for 3 Japanese speakers.

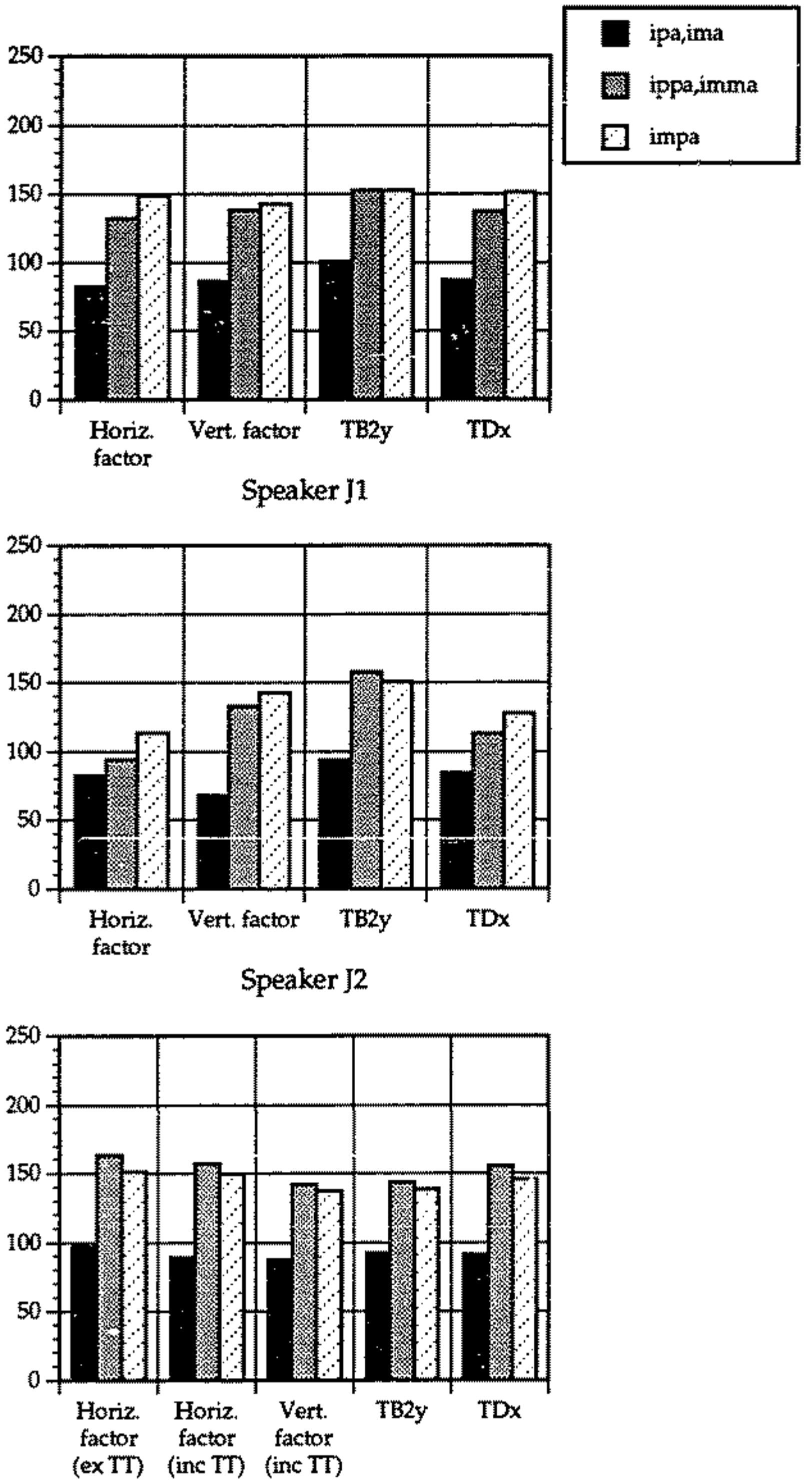


Figure 3.49. Graphs of *consonant target* to *vowel 2 target* in i-a utterances for 3 Japanese speakers.

The effect of Nasal was still somewhat inconsistent, as it was in the a-i utterances for both Japanese and Italian speakers. The interval was shorter in utterances with nasal consonants in the Horizontal factor and TDx for speaker J1, in the Horizontal factor for speaker J2, and in both Horizontal factors for speaker J3. However, it was longer with nasal consonants in the Vertical factor and in TB2y for speaker J2, the same channels as this lengthening was found in the a-i utterances. Neither the effect of Nasal nor the effect of Length was particularly consistent over this interval in Japanese, suggesting that it is perhaps not reflecting the control or coordination between the consonant and the following vowel gesture.

In the measures between the consonant and the two vowels, the Japanese speakers do not show the pattern of reciprocity found for the Italian speakers. In fact, they showed the pattern of longer intervals with geminates that was observed for virtually every interval. The target of the consonant was reached later relative to the first vowel when the consonant was longer, and the following vowel tended to be reached later relative to the consonant. These delays support the notion that with the longer consonant is found an overall lengthening of the utterance, suggesting that the length of the consonant must enter into the organization of timing, as predicted by the combined vowel-and-consonant model. In contrast, the Italian speakers had opposite patterns for the intervals between the consonants and the two vowels, which, as argued above, is predicted by the vowel-to-vowel timing model.

2.4. Summary

The most general tendencies for the differences between utterances with single and geminate consonants are summarized in the table below. When the entry in the table is "shorter" or "longer", this does not mean that the difference was significant everywhere, only that there was a fairly consistent trend in this direction for all speakers. "Same" means that in most cases there was no significant effect of Consonant Length.

"Variable" means that significant differences were found in both directions, as well as a lack of significance in some channels.

Interval	Italian		Japanese	
	a-i	i-a	a-i	i-a
Consonant target interval	longer	longer	longer	longer
Targets Vowel 1 to Vowel 2	–	same or shorter	–	longer
Targets /m/ to Vowel 2	same or longer	same or shorter	longer	longer
Vowel 1 target interval	–	shorter	–	longer
/m/ target to Vowel 2 onset	same or longer	shorter	longer	longer
Vowel 2 onset to target	same or longer	longer	longer	longer
Vowel 1 onset to target	–	same	–	variable
Vowel 2 target interval	same	same	longer	variable
Targets Vowel 1 to Cons	–	shorter	–	longer
Targets Cons to Vowel 2	longer	same or longer	variable	longer

Table 3.3. General trends for differences resulting from the effect of Consonant Length. – means an interval could not be measured in the a-i utterances.

As was stated at the beginning of section 2, in Japanese almost all intervals are longer with the geminate consonants, but Italian shows a more complex pattern of durational changes. This result alone suggests that while in Japanese the longer consonant tends to "spread out" all the gestures in the word, in Italian the changes in relations among the gestures are not all in the same direction. The data even suggest that in Italian certain intergestural relations may not necessarily change at all when the consonant geminates, the interval between the target of /m/ or vowel 1 and the target of vowel 2, for example. The gestures in Italian must be coordinated in such a way that the interval between the targets of the vocalic gestures does not depend directly on the amount of consonantal gesture intervening between them. This supports in general the prediction of the vowel-to-vowel timing model that some interval between the vowels would remain unaffected by difference in Consonant Length, although differences between the utterances with the two vowel patterns suggest that more details of the coordination among vowel and consonant gestures must be taken into account, and that the nature of the intervocalic consonant is not as irrelevant to the timing of vowels as the strong form of vowel-to-vowel timing would predict. In contrast, in Japanese the interval between the vocalic gestures seems to be more directly influenced by the consonant duration. This interval is longer with longer consonants, supporting the prediction of the combined vowel-and-consonant model that Consonant Length could affect some measure of the interval between vowels.

While the results presented here support, in a general sense, the hypothesis that Italian demonstrates the vowel-to-vowel coordination pattern and Japanese the combined vowel-and-consonant, they do not show that models specifying intergestural phasing in different ways (examples (1) and (2) in Chapter I) can account for the patterns of differences between utterances with single and geminate consonants that were observed here. The next chapter will illustrate possible models specifying gestural parameters and phasing that can account for the durational patterns of the two languages.

3. Articulatory measures of utterances with alveolar intervocalic consonants

In addition to the utterances with bilabial intervocalic consonants, utterances with intervocalic /t/ and /n/ were also measured for speakers J1 and J3, and for all three Italian speakers. Since speaker J2 did not have a pellet attached to the tongue tip, no measurements were made of his productions of utterances with alveolars. In Japanese, /ti/ sequences were not collected because the /t/ would palatalize in this environment, so only intervocalic /n/ was used in the a-i utterances. Separate ANOVAs were run for alveolar utterances with the vowel patterns a-i (with factor Length in Japanese, and factors Length and Nasal in Italian) and i-a (with factors Length and Nasal, the same as in the ANOVAs for the utterances with bilabial consonants).

As described in Chapter II, there were more problems in measuring the utterances with alveolar consonants than those with bilabial consonants. Figures 3.50-3.51 show pairs of utterances with intervocalic /t/ produced by speaker I3, which illustrate some of these problems. For example, in the a-i utterances, particularly in Tongue Body Horizontal, the target interval for the second vowel /i/ is very long. It includes the period of time during which the tongue tip is raised to form the alveolar closure. Thus the duration of this target interval and its timing relative to other parts of the utterance is quite different from the corresponding utterance with intervocalic /p/ (compare Figure 3.12), and seem to reflect measurements that were less successful at isolating portions of the movement trajectories that can be associated with individual gestures.

With the bilabial consonant, the timing of the tongue movement is assumed to be controlled by the Tongue Body constriction gesture for the vowel and is more or less independent of the consonant gesture (assumed to control Lip Aperture), even though the jaw is part of the coordinative structure for both vowel and consonant gestures. When the consonant is alveolar, movement of the tongue is controlled by the Tongue Body gesture for the vowel, but also by the Tongue Tip gesture, since the tongue body is assumed to be

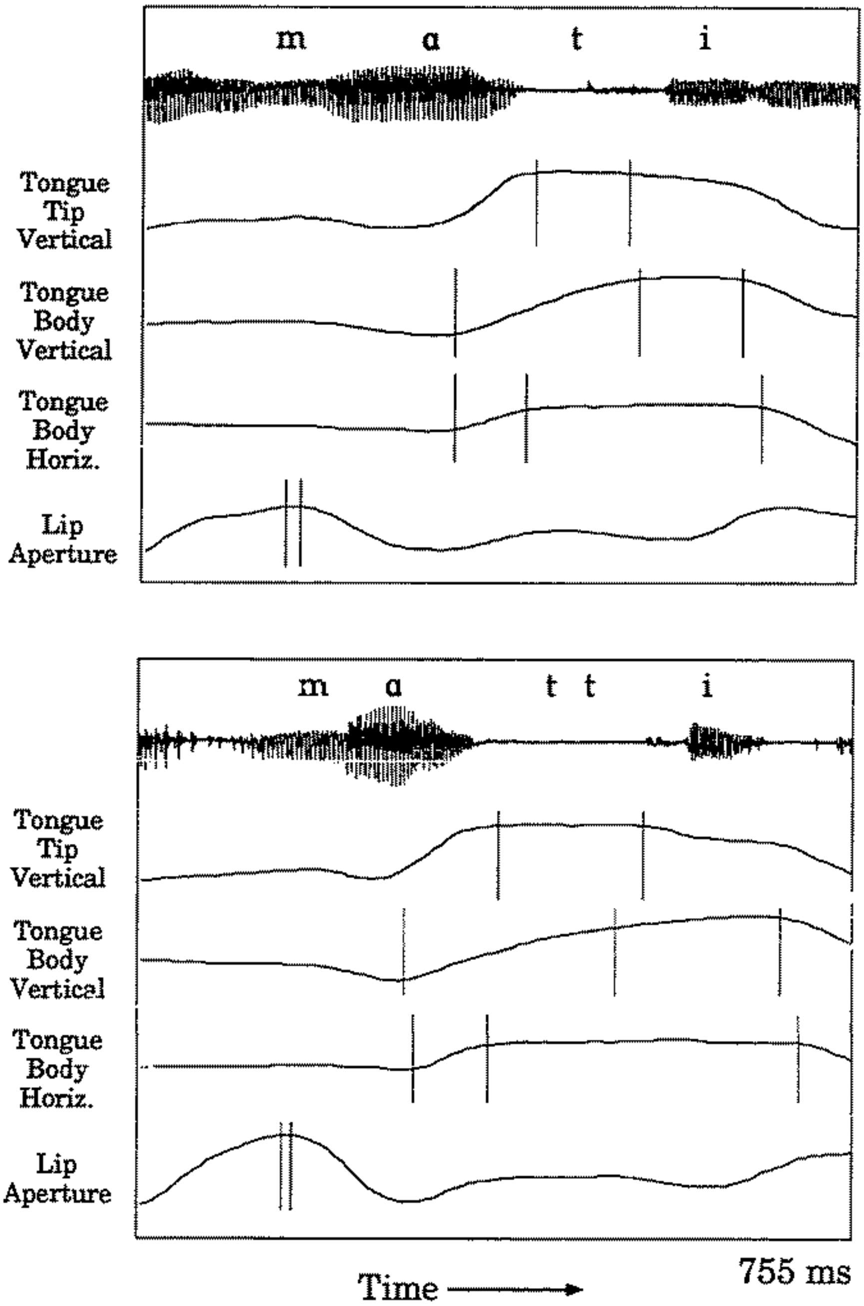


Figure 3.50. Productions of /mati/ and /matti/ by Italian speaker I3.

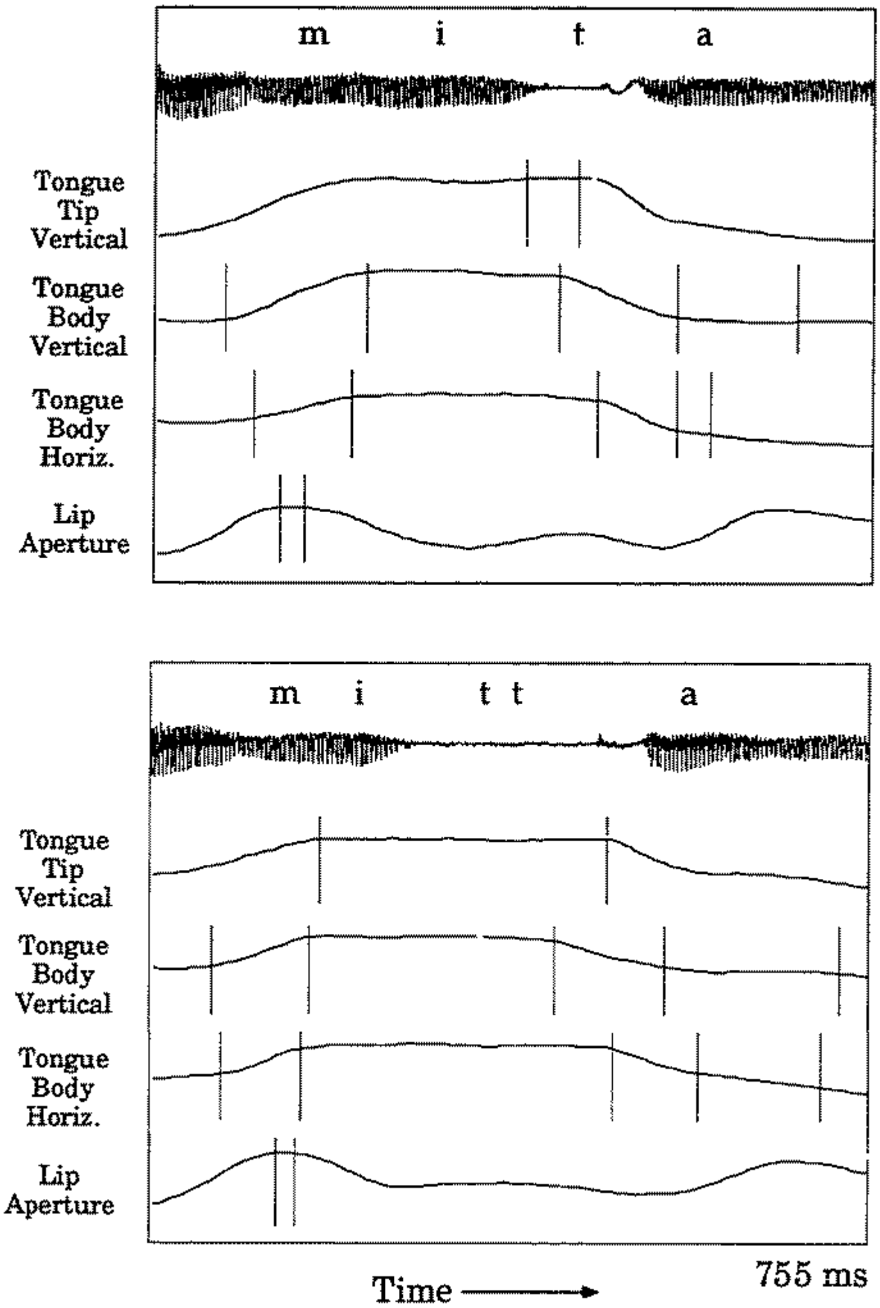


Figure 3.51. Productions of /mita/ and /mitta/ by Italian speaker I3.

one of the articulators involved in positioning the tongue tip (Saltzman & Munhall 1989). Furthermore, the tongue body plays a critical role in positioning the tongue tip, which cannot be compensated for by intrinsic activity of the tip because of anatomical constraints on how much the tongue can stretch: in order for the tongue tip to achieve an alveolar closure, the tongue body must be in a suitable position, particularly with respect to horizontal positioning, as can be seen in Figures 3.50 and 3.51. Thus for the utterances with alveolars, the measurements of the vowel target intervals in the tongue body movements are confounded to some extent by the consonantal tongue tip gestures, and likely do not represent the timing of the vowel gestures as directly as do the trajectories for the utterances with bilabial consonants.

These differences between the utterances with bilabials and with alveolars seem to have been much greater for the Italian speakers than the Japanese. Such differences with respect to the portion of the trajectories that were associated with the various gestures imply that it may be less appropriate to draw conclusions about the gestures' timing from the utterances with alveolars. For this reason, the results were given in detail only for the utterances with bilabial consonants.

Below is a brief discussion of some divergences in the results for the alveolars from the results for the bilabials.

3.1. Japanese

The most striking result of the analyses of utterances with alveolar consonants was their similarity with the results obtained for bilabials. In every instance where there was a significant effect of Consonant Length on the duration of an interval for both bilabials and alveolars, the effect was in the same direction for both places of articulation. The main difference between the results for the alveolars and the results for the bilabials was that the difference between utterances with single and geminate consonants was significant less often with the alveolars than with the bilabials.

The less frequent significance of the effect of Length may in some cases be attributed to articulatory characteristics of the utterances with alveolar consonants. A few examples follow. Differences in the effect of Consonant Length on the interval from the target of the intervocalic consonant to the target of the second vowel can illustrate some of the consequences of the constraints that production of alveolar consonants places on the tongue movements associated with vowels. In the graphs in Figures 3.48-3.49 it can be seen that for speaker J1, the interval between the target of a bilabial intervocalic consonant and the target of the second vowel was always significantly longer when the intervocalic consonant was a geminate, consistent with the overall lengthening of the utterance. However, when this consonant was an alveolar, the interval was significantly longer only in utterances with the i-a vowel pattern.

The most likely explanation for the lack of significance of the effect of Consonant Length in the a-i alveolars is in the nature of the movement of the tongue in these utterances. Raising of the tongue tip, and to some degree the tongue body, to form the alveolar closure occurs before the formation of the constriction for /i/, so that because the tongue is already high, no additional raising is needed for the /i/. Therefore there is likely to be no tongue body movement between the alveolar and the /i/, with the result that the target interval for /i/ may be labeled in such a way as to include the time of the alveolar closure. The point labeled for the target of /i/ may in fact coincide with the target for the alveolar consonant. If these two points coincide, there could not be any effects on this interval because both its endpoints would be measuring essentially the same event. (There might be a small difference in time between the points labeled in the different trajectories because the different parts of the tongue do not move synchronously.)

For speaker J3, there is significant lengthening of the interval between the target of a bilabial intervocalic consonant and the target of the second vowel with both bilabial and alveolar geminate consonants in i-a utterances. However, for a-i utterances with bilabial consonants, lengthening of this interval in the context of geminate consonants was found only in measures of vertical movement (the vertical factor and TB2y); such lengthening is absent in a-i utterances with alveolars. This absence of significance could be interpreted in the same way as for speaker J1, as resulting from merging of the tongue raising for the alveolar closure and for the /i/ constriction.

In these examples, the lack of significance of Consonant Length in the utterances with alveolars seems to be due to misparsing the tongue body movement. Achievement of target for the consonant results in an event in the tongue body measures that is indistinguishable from achievement of target for the vowel. However, another potential reason for the reduced frequency in the significance of Length is the greater variability of the durations of the measured intervals in the utterances with alveolars. Table 3.4 lists the mean standard deviations for the entire set of measured intervals in each channel for each set of utterances. In all of these comparisons for speaker J1, and for most of them for speaker J3, the utterances with bilabials have a smaller mean standard deviation than the utterances with alveolars. This alone will tend to make effects of similar magnitude significant more often with the bilabials than with the alveolars. The greater variability may also be partly a result of the application of a simple-minded event-marking algorithm to movements resulting from the blending of consonant and vowel gestures. Small variations in the position of the tongue pellets, which might signal a transition from alveolar consonant to /i/ or vice versa, were likely to be combined into a single plateau. As a result of this, small variations in the speaker's productions could result in events being marked at rather different times in the movement trajectories, increasing the variability of the measured intervals.

speaker	channel	vowel pattern	SD for utterances with bilabials	SD for utterances with alveolars	Higher S.D.?
J1	Horizontal factor	a-i	22.49	35.94	alveolars
		i-a	24.93	37.38	alveolars
	Vertical factor	a-i	27.40	43.81	alveolars
		i-a	31.60	34.14	alveolars
	TB2y	a-i	24.20	33.39	alveolars
		i-a	28.82	33.27	alveolars

	TDx	a-i	23.06	34.39	alveolars
		i-a	24.38	36.52	alveolars
J3	Horizontal factor (ex. TT)	a-i	18.38	14.50	bilabials
		i-a	16.19	23.35	alveolars
	Horizontal factor (inc. TT)	a-i	25.32	29.61	alveolars
		i-a	19.07	37.15	alveolars
	Vertical factor (inc. TT)	a-i	19.28	48.54	alveolars
		i-a	21.93	35.14	alveolars
	TB2y	a-i	26.83	26.63	–
		i-a	21.63	31.02	alveolars
	TDx	a-i	21.47	18.33	bilabials
		i-a	17.17	22.92	alveolars

Table 3.4. Mean Standard Deviations for Japanese speakers J1 and J3, comparing utterances with bilabial and alveolar consonants over all the intervals measured for each combination of vowel pattern and consonant in each channel.

Despite the greater variability in the measures of utterances with alveolars, the durational results obtained generally agreed well with the results from the utterances with bilabial consonants. For Japanese, analysis of the results from the bilabial utterances may be expected to hold for the alveolar utterances as well.

3.2. Italian

The Italian speakers showed greater differences between the utterances with alveolars and those with bilabials. It seems that particularly for the horizontal trajectories (Horizontal factor and TDx), the position of the tongue for /i/ was almost identical to its position for an alveolar consonant. Thus there was very little movement between the vowel and consonant, with the result that the points in the trajectories labeled as corresponding to events in these different gestures tended to be close together. This can be seen most clearly in the lower picture of Figure 3.51, where the endpoints of the target intervals are almost simultaneous for the first vowel in Tongue Body Horizontal and the consonant in Tongue Tip Vertical. That this is true more of the horizontal than the vertical trajectories, at least for this speaker, could be a consequence of the tongue tip being able to raise and lower without involving the tongue body to a greater extent than it can move forward and backward.

In comparing the effect of Consonant Length in the two sets of utterances, there were numerous measures for which there was a significant effect with the bilabials and not with the alveolars, or vice versa. Unlike the Japanese speakers, in a few cases there were significant effects in both sets of utterances that were in opposite directions. This difference between the two languages may have occurred because for Japanese, the significant effects were always in the direction of intervals being longer with geminates, but in Italian some intervals were longer and some shorter with geminates. In Japanese, any pair of labeled events associated with two different gestures tended to be further apart in time in a geminate utterance. If one of the events marked as part of the vowel gesture in an alveolar utterance were, in fact, closer in time to the events marked for the consonant than would be true for a bilabial utterance, intervals involving these events would still be longer with geminates because the intervals between vowels and consonant were longer as well as the intervals between vowels. But with bilabials in Italian, the consonant was closer to the first vowel with a geminate but further from the second vowel. In this situation, if a vowel event in alveolar utterances was labeled at a point closer to a consonant event than it had been in the bilabials, the effect of Length could reverse.

For Italian, only those intervals discussed below had significant effects of Length in opposite directions in the utterances with bilabials and those with alveolars, and these reversals can tentatively be attributed to the kind of measurement problem in the utterances with alveolars that was discussed above.

For speaker I1, in the i-a bilabial utterances the duration of the target interval for the first vowel was significantly shorter with geminate consonants in the Horizontal factor, TB2y and TDx. However, in the i-a alveolar utterances, the vowel was significantly longer with geminates in the Horizontal factor, and not significantly different from singletons in any of the other channels. The interval between the target of the initial /m/ and the onset of the second vowel (which is presumed to behave like the target interval of the first vowel) patterned in exactly the same way. This lengthening might be due to the tongue remaining in the same horizontal location during both the /i/ constriction and the alveolar closure, resulting in a single long plateau in the trajectory that becomes even longer when the consonant lengthens. Such a trajectory can be seen in TBx in the i-a utterances for speaker I3 shown in Figure 3.51.

Speaker I3 showed the most differences between the alveolars and bilabials. As for speaker I1, the duration of the target interval for first-syllable /i/, which was significantly shorter before bilabial geminates than bilabial singletons in all channels, was significantly longer in the Horizontal factor when followed by an alveolar geminate. There was no significant difference in TB2y or TDx in the vowel's duration before single and geminate alveolars. Also in the i-a utterances with alveolar consonants, the interval between the targets of the two vowels was significantly longer with geminates in TBx, whereas with bilabial consonants it was significantly shorter. (In TBy there was no significant effect of Consonant Length on this interval in utterances with either bilabials or alveolars.) The difference in the effect of Length on the interval between vowel targets is less obviously related to the measurement problems with alveolars, but it could be a consequence of the tongue holding a fronted position longer during the geminate consonant, resulting in a delay of the lowering movement towards /a/.

In speaker I3's a-i utterances, a reversal of direction in the significant effects of Consonant Length was found only in the interval from the target of initial /m/ to the target of the second vowel. In utterances with bilabial consonants, this interval was significantly longer with geminates in all channels. In utterances with alveolar consonants, the interval was significantly shorter with geminates in the Horizontal factor and in TBx, but significantly longer in TBy. Looking at Figure 3.50 suggests that the targets of the second vowel are marked in quite different portions of the movement, in the horizontal and vertical trajectories, and that what is marked as the target of the vowel in the horizontal trajectory may in fact be closer to the target for the intervocalic consonant. This is because, as was discussed above, the horizontal position of the tongue body is very similar for the alveolar and the /i/.

In spite of these problems with the utterances with alveolars, of all the intervals measured, only those discussed above had significant effects of Length in opposite directions in the utterances with bilabials and those with alveolars. As was the case for the Japanese speakers, the Italian speakers tended to show greater variability in the measures of the alveolar utterances. Table 3.5 compares the standard deviations for the entire set of intervals measured, averaged across single and geminate consonants.

speaker	channel	vowel pattern	SD for utterances with bilabials	SD for utterances with alveolars	Higher S.D.?
I1	Horizontal factor	a-i	24.53	67.22	alveolars
		i-a	27.52	42.93	alveolars
	Vertical factor	a-i	39.18	44.67	alveolars
		i-a	26.03	28.77	alveolars
	TB2y	a-i	30.19	40.04	alveolars
		i-a	22.29	27.87	alveolars
	TDx	a-i	29.66	39.26	alveolars
		i-a	24.37	38.14	alveolars
I2	Horizontal factor	a-i	52.53	82.32	alveolars
		i-a	29.41	60.00	alveolars
	TB2y	a-i	46.12	33.30	bilabials
		i-a	35.20	33.47	bilabials
	TDx	i-a	34.97	73.51	alveolars
I3	Horizontal factor	a-i	47.25	44.52	bilabials
		i-a	32.11	46.50	alveolars
	TBx	a-i	37.83	34.03	bilabials
		i-a	28.72	34.48	alveolars
	TBy	a-i	48.56	65.62	alveolars
		i-a	36.27	54.79	alveolars

Table 3.5. Mean Standard Deviations for all Italian speakers, comparing utterances with bilabial and alveolar consonants over all the intervals measured for each

combination of vowel pattern and consonant in each channel. Utterances with intervocalic /mp/ were excluded from the calculations.

Speaker I3, who showed the most reversals in the effect of Length, had standard deviations that were most similar in magnitude between utterances with bilabials and alveolars. Possibly the significant effects in opposite directions were found precisely because the measures of the utterances with alveolars were more consistent for this speaker than for the other speakers, albeit more consistently different from the utterances with bilabials.

Chapter IV

MODELLING

1. Modelling gestural timing

The measured durations clearly suggest that Italian and Japanese are behaving differently, in a way that is consistent with the hypothesized structures of vowel-to-vowel or vowel-and-consonant timing. However, they do not directly reveal how or if the observed differences can be described in terms of gestural units and their coordination, specifically which intergestural relations are controlled, and how these controlled relations vary between single and geminate consonants. Because a large number of intervals were measured whose endpoints were chosen from a small set of labeled events, a change in one interval will very likely co-occur with changes in other intervals that involve one of the same labeled events. A statement of how the intervals change between single and geminate consonants need not (indeed, could not) involve specification of all these intervals. A single change in intra- or inter-gestural timing could result in complex changes in the durations of the measured intervals, masking the actual simplicity of the underlying changes. To provide examples showing how the measured durational changes between singles and geminates might come about from limited changes to the relations among gestures, models of timing were constructed for the two languages, with the coordination among the gestures specified in terms of phasing relations (as was done for a subset of English by Browman and Goldstein (1990a)), structured so as to instantiate vowel-to-vowel timing for Italian and vowel-and-consonant timing for Japanese.

In the model described in Browman and Goldstein (1986, 1990a) and other papers, a gesture is assumed to consist of an underlying abstract 360° cycle of an undamped second-order dynamical (mass-spring) system, whose equation in the general case, with arbitrary damping, is

$$m\ddot{x} + b\dot{x} + k(x-x_0) = 0 ,$$

where the constant system parameters are m = mass, b = damping, k = stiffness; x is the variable whose motion is being generated by the system: x is its instantaneous position, $\dot{x}$ its instantaneous velocity, and $\ddot{x}$ its instantaneous acceleration. The motion variable x corresponds in this model to the time-varying value of a controlled vocal tract goal or task variable, such as Lip Aperture, Tongue Tip Constriction Degree, or Tongue Tip Constriction Location. Figure 4.1(a) illustrates one such cycle (an undamped cosine), which oscillates around an equilibrium position (x_0) halfway between its maximum and minimum amplitudes. The duration of the gesture's cycle is determined by its stiffness (k), assuming unit mass (m) and a constant equilibrium position (x_0). A gesture with a lower stiffness value has a lower frequency, meaning that each cycle has a longer period. Figure 4.1(b) illustrates a cycle that differs from the one in Figure 4.1(a) only by having a lower stiffness, with the time from the valley of the cycle to the peak longer in (b) than in (a). (The elapsed time is the same in these two figures.) Relations among gestures are specified by synchronizing phases; that is, the phase angle (i.e., the number of degrees through the cycle) of one gesture that is simultaneous with the phase angle of another gesture. For example, Figure 4.1(c) shows 240° of one gesture phased with 240° of another, and Figure 4.1(d) shows 0° of one gesture phased with 240°.

The elapsed time between phase angles in two gestures also depends on the stiffness of the gestures. The gestures in Figure 4.1(e), like those in Figure 4.1(c), are coordinated so that 240° of the top gesture is phased with 240° of the bottom gesture. However, the bottom gesture in Figure 4.1(e) has a lower stiffness than in Figure (c), so the elapsed time between, for example, 0° of the top gesture and 360° of the lower gesture will be greater than in Figure 4.1(c). Changes in the elapsed time between events within a gesture can result from change in stiffness (compare Figures (a) and (b)). Changes to the elapsed time between events in two gestures can result from changes in phasing (Figures (c) and (d)) or stiffness (Figures (c) and (e)).

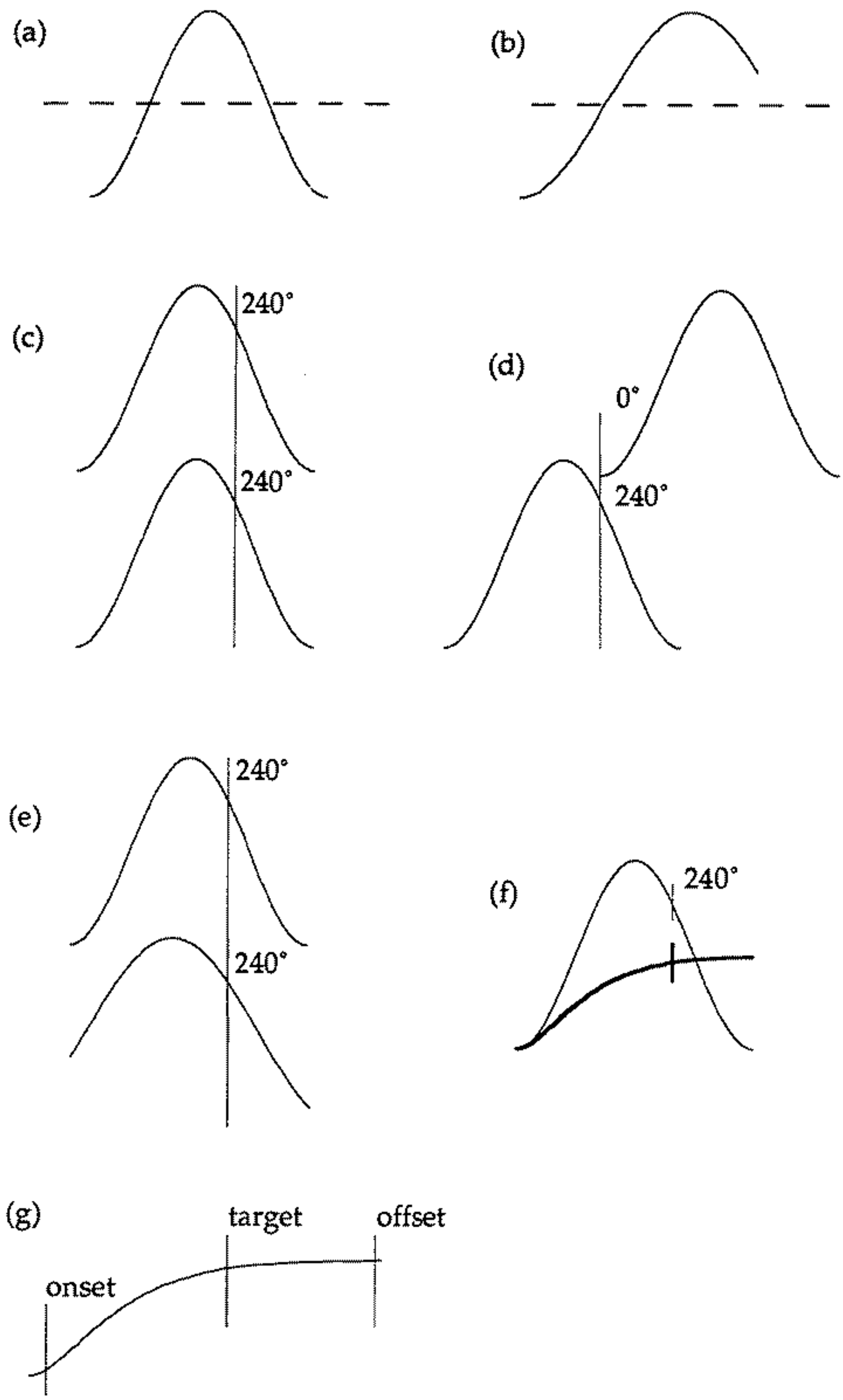


Figure 4.1. Effects of changes in stiffness and phasing to pairs of gestures.

Although they can create similar effects, stiffness and phasing represent distinct parameters that will be reflected in different kinds of variation in the durations of intervals in the utterance. A change in a gesture's stiffness would be reflected in intervals between it and any other gesture, whereas a change in one phasing relation would not imply change in all phasing relations involving that gesture. The modelling discussed here does not systematically investigate the relation between changes in stiffness and phasing, but certain durational patterns turn out to be more accurately represented by change in one of these parameters than in the other.

The underlying 360° cycle is easiest to visualize in the undamped curves shown here, but the model assumes that the gesture's trajectory is actually critically damped, like the thick curve in Figure 4.1(f). (For a discussion of the reasons for this assumption, see Hawkins 1992 and Browman and Goldstein 1990b). A critically damped system does not oscillate; it gradually approaches its equilibrium position, the "target" or "goal" of the gesture, at a rate defined by its stiffness, but would reach it only after an infinite amount of time. Therefore, for purposes of the model, the time at which the target is effectively reached is defined as being at 240° of the cycle, at which time the critically damped trajectory has come within 2% of its equilibrium position.

In relating the events in the measured pellet and factor time functions to the underlying gestural cycle, it is assumed that the movements are critically damped. That is, the point in the trajectory at which the target was marked (where the velocity decreased to within a threshold of zero) is assumed to correspond to 240°. The onset of movement (where the velocity first exceeds the threshold) is assumed to correspond to 0°, and the stiffness of the gesture is calculated on this basis. The onset and target are illustrated on a critically damped curve in Figure 4.1(g).

Also shown is the "offset" point that was labeled at the end of the plateau region in the trajectory. A gesture modeled by a critically damped cycle would stay at its target indefinitely, but at some point, the gesture must relinquish control over the vocal tract.

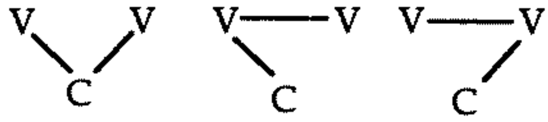
At this point, where the gesture ceases to be active, the trajectory will move away from the target. In the computational model for Articulatory Phonology (Browman, Goldstein, Saltzman & Smith 1986, Browman & Goldstein 1990a), the end of the period of activation of a gesture is assumed to occur at a fixed phase angle, with one value for vowels and a different value for consonants. In the measured data, "offsets" were labeled at the end of the plateau regions for the vowels and the consonants. The "offset" of the plateau of the intervocalic consonant was treated in the modelling reported here as corresponding to the end of activation of the consonant gesture. At that point, the articulator for the consonant moves away from the target position. For the vowels, it is not possible to distinguish the end of active control of the first vowel and the onset of the second. For purposes of the modelling, the end of the plateau region in the trajectory of the first vowel was treated as 0° of the second vowel gesture. The end of the plateau region in the second vowel was not included in the modelling, although it had been labeled in the data, because it would be associated with the vowel gesture in the following word.

2. Parameters of the model

The model attempted to represent the coordination of the oral gestures in these two-syllable words using a minimum number of parameters necessary to characterize temporal differences between utterances with single or geminate consonants, with a-i or i-a vowel patterns. The modelling was limited to representing the temporal patterns found in utterances with bilabial consonants. The parameters that were varied were gestural stiffness and phasing. (Spatial properties of the dynamical system and the data were not dealt with in the modelling.) The basic structure of the model was set for each language, and different values for phasing and stiffness were tested for the different speakers. The parameter used to vary gestural duration was not stiffness itself but settling time or period, equal to the duration of 240° of the undamped cycle, or $\frac{2}{3}$ the period of the cycle[1]. While the settling time and stiffness can be directly computed from one another, settling time provided a more convenient form of the variable for purposes of the modelling.

For a VCV utterance, there are three possible ways to coordinate the three gestures, as shown in Browman (1991):

(1)



For Japanese, the structure used was the leftmost, with each gesture phased with the preceding gesture, alternating vowels and consonants. This corresponds to the prediction of the combined vowel-and-consonant model. For Italian, the structure used was the rightmost of the examples above, with the second vowel phased with the first vowel, and the intervocalic consonant phased with the following vowel. This is a possible representation of the predictions of the vowel-to-vowel timing model.

For the sake of the modelling described in this chapter, a geminate is assumed to consist of a single gesture with different model parameters than the gesture for a single consonant. This is not to imply that this is considered the "correct" analysis of geminates, as opposed to an analysis in which they consist of two overlapping gestures. The single-gesture analysis was chosen because it required fewer additional assumptions to go from data to model parameters. (In particular, the relative timing of two gestures cannot be directly observed.) Recall that both analyses predict different behavior between vowel-to-vowel and combined vowel-and-consonant timing, as the structure of the coordination is different regardless of the composition of the C unit.

The model for Japanese is illustrated in Figure 4.2(a). The parameters that were set in the models were (1) settling time for the vowels, which corresponds to the interval

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[1] Settling time is defined as the time required for the system to settle within 2% of its target amplitude (Saltzman & Kelso 1987). Since in this model the cycle is assumed to approach within 2% of its target at 240° of the undamped cycle, the time from the onset to the target of the cycle is its settling time.

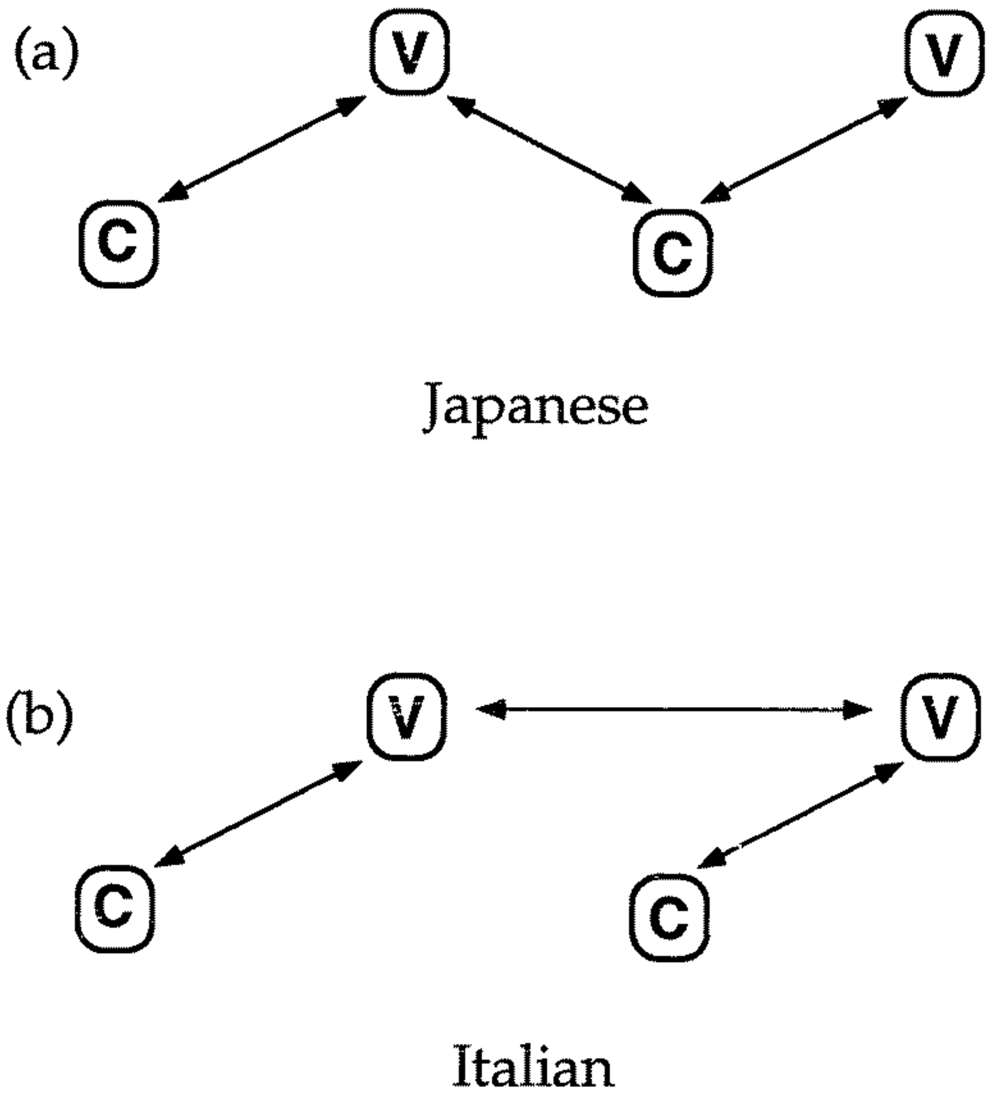

Figure 4.2. Structures of the models for the two languages.

between the onset and target of the gesture; (2) settling time for the consonants, also the interval between onset and target; (3) the deactivation phase of the consonant, considered to occur at the time that the plateau region in the articulator trajectory ends; (4) the phase angles needed to specify the relations among the gestures shown in Figure 4.2(a): consonant with following vowels (which were allowed to vary for /i/ and /a/), and vowel with following consonant.

These parameters are listed in Table 4.1. Note that the phasing parameters are specified as pairs, representing the phase angle of the two gestures that are synchronized. For example, C(i) is the phase of the consonant gesture synchronized with (C)**i** of the /i/ vowel gesture.

	parameters for Japanese models	
	vowel settling time	T_V
	consonant settling time	T_C
	deactivation phase of consonant	Ω_C
	phase angles:	
C-V:	consonant and following /i/	C(i), (C)**i**
	consonant and following /a/	C(a), (C)a
V-C:	vowel and following consonant	V(C), (V)**C**

Table 4.1. Parameters for Japanese models.

Similar parameters were used in the Italian models: vowel settling time, consonant settling time, deactivation phase of the consonant, and phase angles. The structure of the Italian models is shown in Figure 4.2(b). Because of the different structure of the model, different phasing relations were specified: phasing of the two vowels with respect to one another, and phasing of a consonant with respect to a following vowel. The vowel phases in both of these relations were allowed to vary as a function of /i/ vs. /a/.

Table 4.2 lists the parameters in the Italian models.

	parameters for Italian models	
	vowel settling period	T_V
	consonant settling period	T_C
	deactivation phase of consonant	Ω_C
	phase angles:	
V-V:	/a/ and following /i/	**a**(i), (a)**i**
	/i/ and following /a/	**i**(a), (i)**a**
C-V:	consonant and following /i/	**C**(i), (C)**i**
	consonant and following /a/	C(a), (C)**a**

Table 4.2. Parameters for Italian models.

3. Predicting durations of the intervals

Given a set of values for the model parameters, it is possible to calculate predicted durations for all the individual intervals that had been measured. The models were tested by comparing these predicted durations with the actual measured durations. A different set of intervals was used with ə-i utterances than for i-a utterances, corresponding to the intervals that could be measured in the two sets of utterances. The intervals whose durations were modeled are listed in Table 4.3.

a-i utterances	i-a utterances
consonant target interval	consonant target interval
	m target to V1 target
m target to V2 target	V1 target to V2 target m target to V2 target
m target to V2 onset	V1 target interval m target to V2 onset
movement into V2	movement into V2
	movement into V1
consonant target to V2 target	V1 target to consonant target consonant target to V2 target

intervals not discussed in the results:

m target to consonant target	m target to consonant target
V2 onset to consonant target	V2 onset to consonant target
consonant offset to V2 target	consonant offset to V2 target

Table 4.3. Intervals for which the durations predicted by the models were compared with the measured durations.

These intervals are all defined as the time between two events that were marked in the movement. Some intervals not discussed in the results were used in the modelling to include additional information about the consonant, in particular its offset (end of the target interval). In order to calculate the corresponding durations predicted by the model, the events had to be related to phase angles for particular gestures. With one exception, the events referred to in these intervals are all onsets or targets of gestures, which are assumed to correspond to 0° or 240° of the appropriate gestures, respectively. The one exception is the offset of the consonant target interval, which corresponds to its deactivation phase, whose value was a parameter of the models. The interval durations were calculated as the algebraic sum of the durations of sub-intervals whose durations could be calculated given the phasing relations among the gestures and their settling times. That is, starting at an event that was one of the endpoints of the interval, the duration (in degrees) was calculated from the phase angle corresponding to that event to another event in the same gesture, for example the phase angle to which another gesture was coordinated. The duration (in milliseconds) of the sub-interval could then be calculated, using the fact that the settling time of the gesture provides the duration in milliseconds that corresponds to 240°, and thus provides a conversion factor for converting degrees into milliseconds. The duration of other sub-intervals would then be calculated such that the total duration of the measured interval was equal to the algebraic sum of these sub-intervals.

Figure 4.3 gives an example of how these calculations were performed in the Japanese models for productions of i-a utterances. The top figure shows the phase angles that were parameters of the model. The exact expressions used in the Japanese model are listed in Table 4.4. As an example of the calculations, consider the interval from the target of the initial /m/ to the target of the first vowel. In the lower part of Figure 4.3, the targets of gestures are marked with a small vertical line. The two gestures are coordinated with respect to each other, with phase **C**(i) of the consonant synchronized with phase (C)**i** of the vowel. The desired interval can be calculated by taking the time from the coordinated point to (a) the vowel target and (b) the consonant target, and then subtracting to get the time from target to target. The first term in this expression in Table 4.4 (/m/ target to V1 target) calculates the time from the coordinated point to the vowel target, which is the difference between the vowel phase at the coordinated point and 240°, multiplied by a factor to convert this to time. This factor (S) equals the number of milliseconds per degree of the cycle. The second term does the same for the consonant.

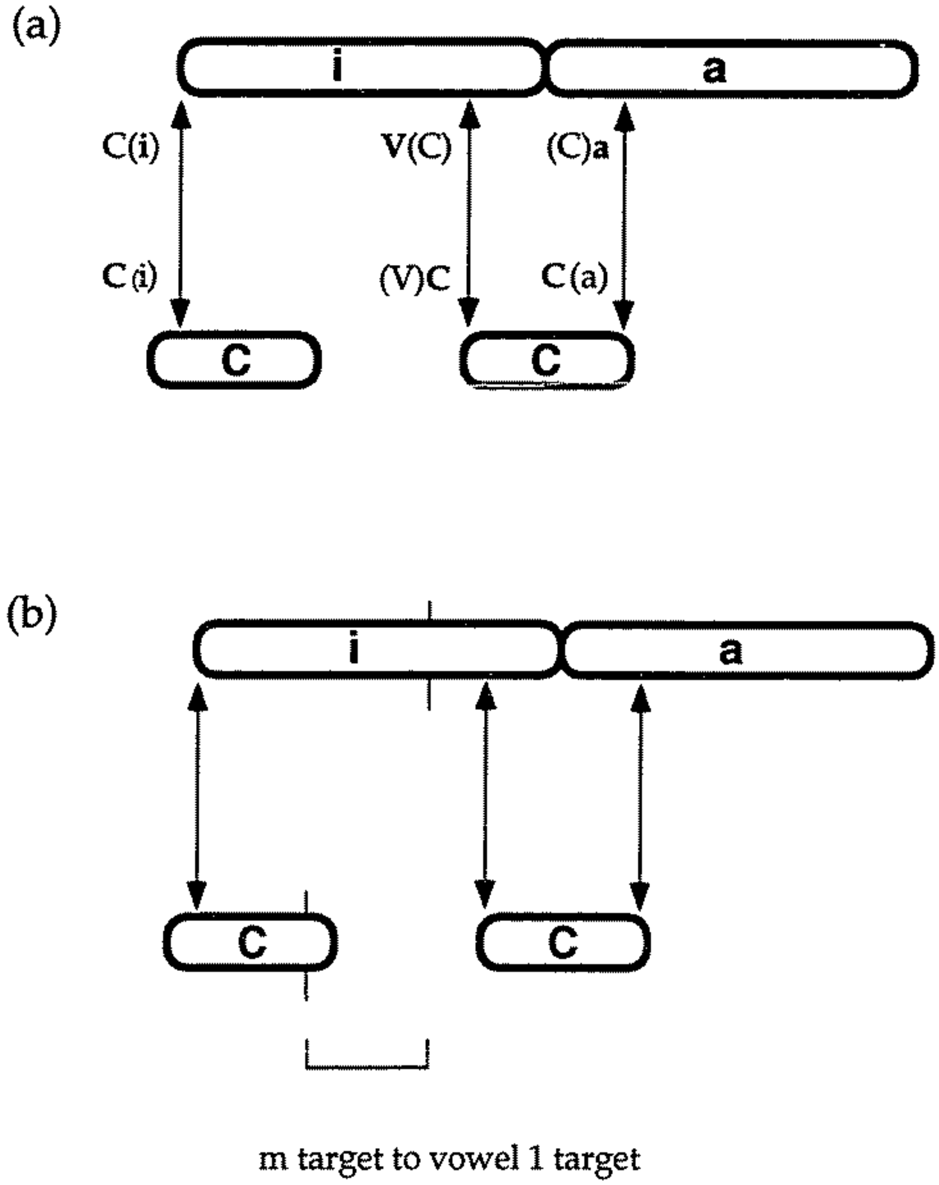

Figure 4.3. Phasing relations for Japanese.
(a) shows variables for phase angles.
(b) shows *m target to vowel 1 target* interval.

measured intervals	formula to calculate duration
consonant target interval	$[\Omega_C - 240^\circ] \times S_C$
m target to cons target	$[V(C) - (C)\mathbf{i}] \times S_V - [240^\circ - \mathbf{C}(i)] \times S_C + [240^\circ - (V)\mathbf{C}] \times S_C$
V1 target to cons target	$[V(C) - 240^\circ] \times S_V + [240^\circ - (V)\mathbf{C}] \times S_C$
movement into V1	T_V
m target to V1 target	$[240^\circ - (C)\mathbf{i}] \times S_V - [240^\circ - \mathbf{C}(i)] \times S_C$
m target to V2 onset	$[V(C) - (C)\mathbf{i}] \times S_V - [240^\circ - \mathbf{C}(i)] \times S_C + [\mathbf{C}(a) - (V)\mathbf{C}] \times S_C - [(C)\mathbf{a} - 0^\circ] \times S_V$
m target to V2 target	$[V(C) - (C)\mathbf{i}] \times S_V - [240^\circ - \mathbf{C}(i)] \times S_C + [\mathbf{C}(a) - (V)\mathbf{C}] \times S_C + [240^\circ - (C)\mathbf{a}] \times S_V$
V1 target to V2 target	$[V(C) - 240^\circ] \times S_V + [\mathbf{C}(a) - (V)\mathbf{C}] \times S_C + [240^\circ - (C)\mathbf{a}] \times S_V$
V1 target interval	$[V(C) - 240^\circ] \times S_V + [\mathbf{C}(a) - (V)\mathbf{C}] \times S_C - [(C)\mathbf{a} - 0^\circ] \times S_V$
movement into V2	T_V

V2 onset to cons target	$[(C)a - 0°] \times S_V - [C(a) - 240°] \times S_C$
cons target to V2 target	$[C(a) - 240°] \times S_C + [240° - (C)a] \times S_V$
cons offset to V2 target	$[240° - (C)a] \times S_V - [\Omega_C - C(a)] \times S_C$

Table 4.4. Calculations of predicted durations of measured intervals for model #J1. S = milliseconds per degree of settling time. For vowels $S_V = \frac{T_V}{240°}$, and for consonants $S_C = \frac{T_C}{240°}$.

4. Estimating parameter values

4.1. Procedure for determining parameter values

Both Japanese and Italian models use vowel settling time, consonant settling time and consonant deactivation phase as parameters. Values for these were estimated from the measured data of each speaker. The settling times of the vowels were estimated from measurements of the interval between the onset and target of the movement towards each vowel's target, using the Horizontal factor, as this was the most comparable measure across speakers. For each speaker, the mean duration of this interval across all utterances with bilabial consonants was used in the model for that speaker. Settling time of the consonantal movements was estimated from measures in Lip Aperture (Lower Lip vertical for speaker J1) of the interval from the onset of raising for the intervocalic consonant to its target. Because this interval had not been included in the statistical analysis, it was measured in only 5-7 tokens of each utterance for each speaker.[2] The means of the duration of this interval, averaged across /p/ and /m/ or /pp/ and /mm/ (or both), were used as the values of the settling time for the consonant gestures.

Like the settling times, the consonant deactivation phase was also varied for each speaker. It was calculated by converting the mean duration of the plateau region of the consonantal movement to a phase angle, using the consonant gesture's settling time. This phase angle, added to 240° for the portion of the consonant gesture from onset to target, gives the phase angle for the end of the gesture's activation.

While the values for the settling time and deactivation phase parameters could be determined analytically, the phase angles could not. Only the onsets and targets of the gestures were directly accessible from the data, and a much wider range of values was required in the modelling. Instead, the procedure followed was to make a rough estimate of the phase angles in a model by using the measured intervals for a particular speaker,

[2] Exceptions were utterances for which fewer tokens were available: for speaker I2, there were 4 tokens each of /ami/, /ipa/, and /ippa/, and 2 tokens each of /ammi/ and /imma/. For speaker I3, there were 3 tokens of /ima/ and 2 of /imma/.

then test the estimate in the model by comparing the predicted durations to the actual durations and modify it according to the results achieved, so as to come as close as possible to modelling the data of that speaker. For example, the measured interval from the onset of the second vowel to the target of the consonant was used in making an estimate of the phasing of the consonant with this vowel. In i-a utterances with geminate consonants, this interval had a small negative mean duration for the Japanese speakers, meaning that the target of the consonant occurred slightly before the onset of the second vowel. This implies that the onset of the vowel occurs at a point in the consonant slightly after the target, or in other words, that the onset of the vowel is phased with an angle slightly greater than 240° (the target) of the consonant. Experimentation with the models revealed that the best results were achieved by phasing the consonant with 60° of /a/, rather than with the onset. This estimate was made in part by comparing the phasing of the intervocalic consonant with a following /a/ to the phasing of the initial /m/ with a following /a/.

This procedure of developing different hypotheses for the values of the phase angles, then testing these hypotheses in the models and changing the values to fit the data was also used in deciding which phasing values needed to vary between utterances with single and geminate consonants, and which could remain invariant.

4.2. Differences in parameter values between single and geminate consonants

The purpose of the modelling was to demonstrate how the differences between utterances with single and geminate consonants could be represented. Since the structure of the models had been fixed for each language, the differences between singles and geminates had to be found in the values of the parameters. In developing the models to represent this distinction, the parameter values were varied in accordance with where the major differences between utterances with singles and geminates had been found in the results.

4.2.1. Japanese

The most obvious difference between the two sets of utterances is in the consonant itself. Consider how the Japanese model was developed. The consonant deactivation phase was varied because its value was estimated from the duration of the consonant target interval, where large differences were found between singles and geminates. The consonant settling time was also varied as it differed substantially between singles and geminates, and provided an additional source of difference between the consonant lengths.

Parameter values for a model for speaker J1 in which only the consonant settling time and deactivation phase were varied are shown in Table 4.5 below. The other parameter values are those that were calculated as best fitting the data for single consonants.

	parameter values for speaker J1	utterances with single C	utterances with geminate C
	vowel settling time	96.31 ms	
	consonant settling time	62.12 ms	80.06 ms
	consonant deactivation phase	300°	500°
	phase angles:		
C-V:	consonant and following /i/	30°, 0°	
	consonant and following /a/	270°, 60°	
V-C:	vowel and following consonant	360°, 0°	

Table 4.5. Parameter values for a model for Japanese speaker J1, varying only consonant settling time and deactivation phase.

The model in Table 4.5 was tested on speaker J1's i-a utterances by comparing the differences in duration between single and geminate consonants that the model predicted for each of the measured intervals with the actual differences in the measured durations. The r^2 between the actual differences and the differences predicted by this model was .41. This reflects how closely the model captured the pattern of differences between the single and geminate utterances. Clearly the values of other parameters must be varied in order to model these differences more closely.

Recall that one of the main sources of evidence for consonant-vowel timing in Japanese was the results that showed that the interval between vowel targets was significantly and substantially longer when the consonant was a geminate (for speaker J1, 60.29 ms). In the model in Table 4.5, a difference in the duration of this interval is predicted due to different consonant settling times, but the difference is much smaller than in the measured data (20.18 ms). Therefore, some aspect of the phasing relations must also change between single and geminate consonants in such a way that the target of the second vowel is delayed relative to the target of the first when the consonant is a geminate.

Setting the phasing of the model so that the second vowel is phased later in the consonant when the consonant is a geminate would have the effect of making the vowels "further apart" with a geminate. One natural way of doing this is to coordinate a particular phase of the vowel with the deactivation phase of the consonant, but that does not correspond to the pattern of coordination that was observed, either. In i-a utterances, the onset of the vowel is closer to the middle of the consonant target interval. Since the target interval has a different duration for single and geminate consonants, the onset of the vowel occurs at different phases in the single and geminate consonants. Thus it is not synchronous with the same event in both cases; it must be phased with different angles[3]. Experimentation with the model showed that a good fit for the i-a utterances was achieved for speaker J1 if 60° in the /a/ was phased with 270° in a single consonant and

[3] Here is where an analysis of geminates as a sequence of two units might provide a simpler analysis. It might be possible to phase the vowel invariantly with respect to the immediately preceding consonant gesture.

360° in a geminate. Note that since the target is assumed to be at 240°, the deactivation for the single consonant is 300° and for the geminate 500°, effectively the vowel is being phased in both cases to a point in the middle of the consonant target interval. The r^2 for the model obtained by adding this parametric difference was .91, and this was found to differ significantly (t=10.1, df=10, p<.01) from the value without this added difference.

For the Japanese speakers, it was found that different phasing relations held between the consonant and a following /i/ than a following /a/. The onset of a following /i/ was phased with a point shortly after the onset of the consonant. For speakers J1 and J2, the best results were found phasing the following vowels to different phases in the consonant depending on the length of the consonant, as described above for speaker J1. However, for speaker J3, this was the case for the consonant with a following /a/ but not with a following /i/. In the a-i utterances, the same value for C(i) was used for single and geminate consonants. However, what was necessary to represent the differences for this speaker was a difference in the vowel settling times between utterances with single and geminate consonants. The settling time was greater with geminate consonants, which means the duration of the same number of degrees of the vowel is longer. With the same phasing relations but greater settling time with a geminate, the vowel target is delayed after a geminate consonant compared to after a single consonant. Thus the difference in settling time has a similar effect to the difference in phase angles, but it also increases the duration of the vowel.

Using the procedure described here, models were developed to fit each of the Japanese speakers' measured intervals as closely as possible. The parameter values for these models are listed in the tables below.

(a) parameters for speaker J1 in model #J1	utterances with single C	utterances with geminate C
vowel settling period	96.31 ms	
consonant settling period	62.12 ms	80.06 ms
consonant deactivation phase	300°	500°
phase angles:		
consonant and following /i/	30°, 0°	120°, 0°
consonant and following /a/	270°, 60°	360°, 60°
vowel and following consonant	360°, 0°	

(b) parameters for speaker J2 in model #J2	utterances with single C	utterances with geminate C
vowel settling period	89.87 ms	
consonant settling period	63.96 ms	82.06 ms
consonant deactivation phase	320°	460°
phase angles:		
consonant and following /i/	90°, 0°	120°, 0°
consonant and following /a/	270°, 60°	310°, 60°
vowel and following consonant	360°, 0°	

(c) parameters for speaker J3 in model #J3	utterances with single C	utterances with geminate C
vowel settling period	130.02 ms	149.23 ms
consonant settling period	77.69 ms	98.85 ms
consonant deactivation phase	280°	420°
phase angles:		
consonant and following /i/	30°, 0°	
consonant and following /a/	270°, 60°	360°, 60°
vowel and following consonant	360°, 0°	

Table 4.6. Parameter values for Japanese speakers in the models that provided the best fits for each.

Beyond what was varied between single and geminate consonants in the model for speaker J1 shown in Table 4.5, only the phasing relations between a consonant and following /i/ or /a/ were also varied in these models in Table 4.6 (a) and (b), and also the vowel settling time in (c). But this was sufficient to capture the differences between the utterances with singles and geminates. r^2 values for each speaker's model are given in Table 4.7.

	r^2 predicted vs. actual differences	
speaker	a-i	i-a
J1	.99	.91
J2	.96	.92
J3	.92	.99

Table 4.7. r^2 values between durations of measured intervals and durations of these intervals predicted by models developed for each of three Japanese speakers.

From the tables, it is clear that the models for speakers J1 and J2 are more like each other than the model for speaker J3. The only differences between those two models are the particular values for the settling times and consonant deactivation phase, and the phase angles **C**(i) for a single consonant and **C**(a) for a geminate. The model for speaker J1 might be expected to fit speaker J2's data fairly well, and vice versa, particularly in the a-i utterances where the different **C**(a) for a geminate is not used. The phase angles for speaker J3 are closer to those in the model for speaker J1than the model for speaker J2, but speaker J3's model differed in more ways from the other two models than they did from each other. For i-a utterances, the models for speakers J1 and J3 used the same phase angles. and therefore might be expected to fit the other speaker fairly well. However, in addition to different values for the consonant settling times and the deactivation phase, the model for speaker J3 used different vowel settling times for singles and geminates, and also a different phase angle C(a) for a geminate consonant in i-a utterances.

To test to what extent the phase relations allow them to fit more than one speaker's data, all three models (referred to as #J1, #J2, #J3) were tested on all three speakers. For each speaker, the values for settling times and consonant deactivation phase came from the speaker being modeled, while the phasing parameters came from the model being tested. For the consonant deactivation phase, consonant settling times, and for the vowel settling time for model #J3, separate means for singles and geminates for each speaker were used in the models. For the vowel settling times in models #J1 and #J2, the overall mean for each speaker was used.

The complete set of intervals tested for speaker J3's i-a utterances are plotted in Figure 4.4, showing the differences in durations between single and geminate consonant conditions predicted by all three models. The r^2 between actual and predicted durations of the measured intervals for the tests of all models with all speakers are listed in the table below. Values in boldface are the r^2 values for the model developed for that speaker, which were shown in Table 4.7.

	models		
a-i utterances	#J1	#J2	#J3
speaker J1	**.99**	.85	.62
speaker J2	.87	**.96**	.81
speaker J3	.61	.74	**.92**
i-a utterances	#J1	#J2	#J3
speaker J1	**.91**	.57	.89
speaker J2	.69	**.92**	.68
speaker J3	.90	.53	**.99**

Table 4.8. r^2 values for testing 3 models on 3 Japanese speakers.

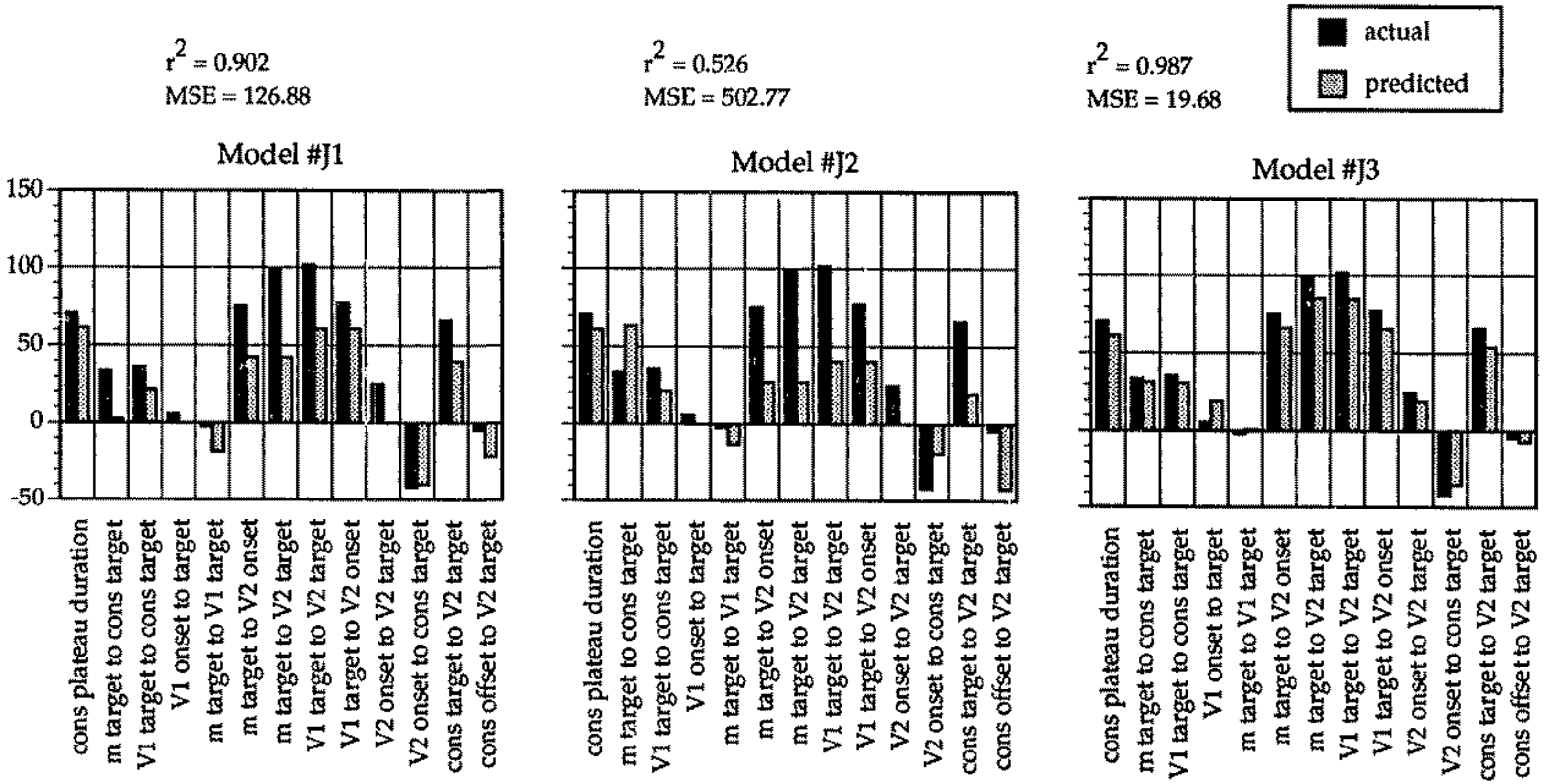

Figure 4.4. Actual vs. predicted differences between utterances with single and geminate consonants for the duration of measured intervals for speaker J3, using three different models.

As expected, for the a-i utterances model #J1 also fit speaker J2 quite closely, and model #J2 also fit speaker J1 well. These speakers were less well fit by model #J3, which did not include a difference in phasing between single and geminate consonants for the a-i utterances. For the i-a utterances, models #J1 and #J3 had the same values for the phase angles, and as expected, each fit the data from the other speaker almost as well as the data for its original speaker. Speaker J2 was less well fit by these models. These results support the hypothesis that models developed for different speakers but with similar phase relations will provide good fits for different speakers who showed similar patterns in their data.

4.2.2. Italian

A similar procedure was followed in developing the models for the Italian speakers, testing possible parameter differences between single and geminate consonants in the model by comparing actual and predicted durations of the measured intervals, then modifying the parameter values to fit the data more closely. As in the Japanese data, the consonant deactivation phase was judged likely to vary between utterances with single and geminate consonants, because there were significant differences in the duration of the consonant target interval for single and geminate consonants. However, the consonant settling time was very similar for single and geminate consonants, so that parameter was not expected to vary. In general, the measured durations showed fewer differences between the utterances with singles and geminates for Italian than for Japanese, so it might be expected that fewer differences in parameter values would be needed to model the differences between consonant lengths.

The structure of the Italian model (Figure 4.2b) phases the vowels with each other. The vowel-to-vowel hypothesis predicts that this phase relation should be invariant across single and geminate consonants, because consonants are irrelevant to the organization of the vowels. This invariance received some support in the results, as the speakers showed some tendency towards maintaining a constant duration from vowel target to vowel target, particularly in the i-a utterances. Because of this tendency, the values for the phase angles between vowels are expected to be the same for utterances with singles and geminates. If the interval between vowel targets is truly constant, as for speaker I1's i-a utterances, then the target of the second vowel (240°) should be phased with the same phase angle in the preceding vowel.

Durational differences between singles and geminates were found in the measured intervals between vowels and consonant, which suggests that the phase angles for the coordination of the consonant with the vowels would need to vary for singles and geminates. As discussed in the results, the interval between the targets of the first vowel (/i/) and the consonant was shorter when the consonant was a geminate, and the interval between the targets of the consonant and the second vowel was in general longer. In addition, the interval between the initial /m/ target and the consonant target was shorter with geminates than with single consonants, which presumably results in the acoustic shortening of the first vowel before geminates. These results suggest that the target of a geminate consonant should be phased earlier than the target of a single consonant[4]. Such a phasing difference would also increase the time between the targets of a geminate consonant and the following vowel, which is also in accordance with the results of the articulatory measurements.

4.2.2.1. Modelling Italian speaker I1

The effect of Consonant Length on the measured intervals varied considerably between the utterances with different vowel patterns and among the speakers. Consider first speaker I1, for whom the target interval of the first vowel was shorter with geminates than singles in the i-a utterances but roughly equal in the a-i utterances (or in fact, slightly longer for geminates in the Horizontal factor that is being modeled – see Table 3.2). Therefore, to begin with, separate models were constructed for a-i and i-a utterances.

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[4] Again, analyzing the geminate as two overlapping gestures might simplify the consonant-vowel phasing statements across single and geminate consonants. The second consonant of the geminate might be phased the same as single consonants, with the additional (syllable-closing) consonant phased earlier.

4.2.2.1.1. Vowel-to-vowel organization

For the a-i utterances, if the target of /i/ is phased with the same angle of /a/ in utterances with singles and geminates, the plateau for /a/ will be the same in both cases, assuming the vowel settling times stay the same. (Recall that the vowel 1 target interval is assumed to end at the onset of vowel 2.) For a-i utterances, there is, in fact, no evidence that the settling times vary, as the movements into vowel 2 do not differ substantially. As long as this is the case, any pair of points in the two vowels will have the same relation for both singles and geminates, and it does not matter which pairs of points are used to specify the phasing relation.

In contrast, speaker I1's i-a utterances showed a shorter target interval for vowel 1 before geminates, but still no difference in the vowel target to vowel target interval. (As shown in Table 3.2, the shorter target interval is accompanied by a longer movement into vowel 2, so that the two cancel out and give a stable target-to-target interval.) The stability in the target-to-target interval can be modeled by explicitly phasing the target point of /a/ to the same phase of /i/ in utterances with singles and geminates. Of course, this means phasing vowel 2 with respect to a very late point in vowel 1 (840°), long after its activation has ceased. The implications of this are discussed in section 5 below. The shorter duration of the target interval for /i/ before geminates implies that the onset of /a/ occurs sooner after the target of /i/ with geminates than with single consonants. If the relation between the vowel targets is fixed, the earlier onset of the /a/ after the geminate can be modeled only by increasing the settling time of /a/ when it follows a geminate. With the /a/ having a longer settling time, its onset must be earlier if its target is fixed. So, for speaker I1's i-a utterances, the /a/ following a geminate was modeled as having a lower stiffness (longer settling time) than /a/ following a single consonant. To maximize similarity across vowel patterns, the target of vowel 2 was also phased with respect to a late point in vowel 1 for a-i utterances.

4.2.2.1.2. Consonant-vowel organization

For both vowel patterns, the consonant target occurs earlier with respect to vowel 1 with the geminate than with the single consonant. For the a-i utterances, this can be modeled by phasing the target of a geminate consonant earlier in the /i/ than the target of a single consonant. The model for speaker I1's a-i utterances was constructed in this way: no difference in settling time or phasing of vowels[5], but a phasing difference between the consonant and /i/ that accounts for the observed acoustic shortening and the longer interval in the articulatory measures between the targets of the consonant and the second vowel. The parameter values are shown in Table 4.9.

parameters for a-i utterances for speaker I1	utterances with single C	utterances with geminate C
vowel settling time	110.03 ms	
consonant settling time	104.23 ms	
consonant deactivation phase	300°	370°
phase angles: consonant with following /a/	240°, 40°	
consonant with following /i/, 2nd syllable	240°, 120°	240°, 0°
/a/ with following /i/	840°, 240°	

Table 4.9. Parameter values for a-i utterances for speaker I1.

For i-a utterances, because the onset of the /a/ is earlier with a geminate, all phases of /a/ up to the target (240°) are earlier compared to the single consonant case. The consonant target is phased with an angle in /a/ less than 240°, since the target of the consonant occurs before the target of the /a/. Hence the target of the consonant occurs earlier relative to the preceding vowel when the consonant is a geminate. Thus even if the consonant target is phased with the same angle of the /a/ in both single and geminate

[5]This fails to account for the small increase in duration of the vowel 1 target interval, observed only in the Horizontal factor.

utterances, the settling time difference in /a/ causes the target of the geminate to occur earlier relative to the target of the preceding /i/. One result of this is acoustic shortening of that /i/ in the context of a geminate. Speaker I1's i-a utterances were modeled in this way, using a difference in settling time in the second vowel to account for the first vowel being shorter in both acoustic and articulatory (target interval) measures. The parameter values are listed below. Note that while all vowels following single consonants had the same settling time, the /a/ following a geminate consonant had a longer settling time. The values used were the means of the settling times for both /i/ and /a/.

parameters for i-a utterances for speaker I1	utterances with single C	utterances with geminate C
vowel settling time	106.44 ms	106.44 ms (1st syll) 117.22 ms (2nd syll)
consonant settling time	104.23 ms	
consonant deactivation phase	300°	370°
phase angles:		
consonant with following /i/, 1st syllable	240°, 40°	
consonant with following /a/	240°, 40°	
/i/ with following /a/	680°, 240°	

Table 4.10. Parameter values for i-a utterances for speaker I1.

These models were tested on speaker I1's data in the same way as had been done for the Japanese models. The r^2 between the actual durational differences between single and geminate a-i utterances, and the differences predicted by the model in Table 4.9 was .86. The r^2 between the actual differences in i-a utterances and the differences predicted by the model in Table 4.10 was .93.

In fact, while they were developed for different sets of utterances, these two models have much in common. In both, the consonant settling time was the same for singles and geminates, and in both, the same difference in consonant deactivation phase was used. In both models, it was the target of the consonant that was phased with following vowels, and for the first syllable it was 40° in either /i/ or /a/ that was phased with the consonant target. The difference between the models is that for the a-i utterances the single/geminate differences in consonant-vowel coordination were modeled by a phasing difference, but for the i-a utterances the single/geminate differences were modeled by a difference in vowel settling time.

In order to investigate further the contribution of the difference in settling time to the two models, the a-i and i-a utterances were both modeled with and without a difference in vowel settling time. That is, additional tests were made, using the model in Table 4.9 with the different settling times shown in the first row of Table 4.10, and the model in Table 4.10 with the same vowel settling time with singles and geminates, as shown in the first row of Table 4.9. The r^2 between the actual differences in the a-i utterances and the differences predicted by the a-i model using different vowel settling times was .75 (compared to .86 using the same settling times). The r^2 between the actual differences in the i-a utterances and the differences predicted by the i-a model with the same vowel settling times was .44 (compared to .93 using different settling times). Note that in the i-a model with the same vowel settling times, the only difference between utterances with single and geminate consonants is in the deactivation phase of the consonant. The low correlation is presumably due to the absence of any differences in the parameter values that would contribute to modelling the durational differences that were observed in the intervals between vowels and consonant. For the a-i model, introducing a difference in vowel settling times would decrease the duration of the vowel 1 target interval with geminates, when its duration was actually about the same with both consonant lengths. Thus, incorporating this additional difference between singles and geminates made the model worse.

The models for a-i and i-a utterances for speaker I1 are combined in Table 4.11. Both hypotheses about vowel settling time are listed, the single value that fit the a-i data, and the different values for vowels after singles and geminates that fit the i-a data.

parameter values for speaker I1	utterances with single C	utterances with geminate C
vowel settling time	110.03 ms or 106.44 ms	110.03 ms or 106.44 ms (1st syll) 117.22 ms (2nd syll)
consonant settling time	104.23 ms	104.23 ms
consonant deactivation phase	300°	370°
phase angles:		
consonant with following /i/, 1st syllable	240°, 40°	240°, 40°
consonant with following /i/, 2nd syllable	240°, 120°	240°, 0°
consonant with following /a/	240°, 40°	240°, 40°
/a/ with following /i/	840°, 240°	840°, 240°
/i/ with following /a/	680°, 240°	680°, 240°

Table 4.11. Parameter values for models for speaker I1 ("model #I1"), showing two possibilities for values of vowel settling time.

In both the a-i and i-a utterances, the parameters of the model must represent that the achievement of target of a geminate consonant occurs earlier relative to the preceding vowel than does a single consonant. This pattern was modeled in different ways in the two sets of utterances, showing that to some extent a similar result can be achieved by manipulation of different model parameters, settling time and phasing.

4.2.2.2. Modelling Italian speakers I2 and I3

The model for speaker I1 reflects the constant interval between vowel targets that was found for that speaker's i-a utterances. The interval between vowel targets in the a-i utterances was also modeled as being constant, although the closest available measure (/m/ target to vowel 2 target) was in fact somewhat longer with geminates for speaker I1. For a-i utterances produced by speaker I2, the target to target interval (/m/ to vowel 2) was not affected by Consonant Length. Therefore, these utterances could be modeled in the same way as speaker I1's a-i utterances, with constant vowel stiffness, the vowel target of the second vowel fixed relative to the first vowel, and a phasing difference between single and geminate consonants.

The parameter values for the complete set of models for speaker I2 are listed in Table 4.12. For vowel settling time, the same two hypotheses tested with speaker I1 are both listed here. For the a-i utterances, the same value (127.78 ms) for vowels with single and geminate consonants was found to give better results, with consonant-related differences resulting from differences in phasing. The difference in phasing between singles and geminates for a consonant and following /a/, which was not used in the models for speaker I1, is discussed below, with reference to the i-a utterances.

parameter values for speaker I2	utterances with single C	utterances with geminate C
vowel settling time	127.78 ms (both) or 115.83 ms	127.78 ms (both) or 115.83 ms (1st syll) 151.67 ms (2nd syll)
consonant settling time	95.43 ms	95.43 ms
consonant deactivation phase	320°	440°
phase angles:		
consonant with following /i/, 1st syllable	240°, 40°	240°, 40°
consonant with following /i/, 2nd syllable	240°, 120°	240°, 0°
consonant with following /a/	240°, 40°	240°, 60°
/a/ with following /i/	840°, 240°	840°, 240°
/i/ with following /a/	810°, 360°	810°, 360°

Table 4.12. Parameter values for models for speaker I2, showing two possibilities for vowel settling time.

The r^2 between the actual durational differences between single and geminate a-i utterances, and the differences predicted by the model in Table 4.12 with the same vowel settling times was .98. The r^2 for the model with different vowel settling times was .90.

The a-i utterances produced by speaker I3 showed somewhat different patterns from speakers I1 and I2. The interval from /m/ target to vowel 2 target was significantly longer with geminates, as was the movement into the second vowel, which was not generally true for a-i utterances for speakers I1 and I2 (see Table 3.2). The target interval for the first vowel was not affected by the length of the consonant, so the delay in vowel 2 target is due to the longer movement time. These effects can be modeled by phasing the onset of the second vowel (/i/) with the first vowel, and increasing the settling time of /i/ following a geminate. The change in settling time between singles and geminates will not affect the duration of the first vowel, but will increase the duration of the movement into the second vowel and the interval between the targets of /m/ and the second vowel.

The parameters for the complete model for speaker I3 are listed in Table 4.13 below. For the a-i utterances, the model with a difference in vowel settling time following single and geminate consonants was superior.

parameter values for speaker I3	utterances with single C	utterances with geminate C
vowel settling time	174.61 ms or	
	156.47 ms	156.47 ms (1st syll) 210.89 ms (2nd syll)
consonant settling time	120.28 ms	
consonant deactivation phase	280°	380°
phase angles:		
consonant with following /i/, 1st syllable	240°, 40°	
consonant with following /i/, 2nd syllable	240°, 40°	240°, 20°
consonant with following /a/	240°, 40°	240°, 60°
/a/ with following /i/	500°, 0°	
/i/ with following /a/	810°, 360°	

Table 4.13. Parameter values for models for speaker I3, showing two possibilities for vowel settling time.

The r^2 between the actual durational differences between single and geminate a-i utterances, and the differences predicted by the model in Table 4.13, using different settling times, was .94, as opposed to the model with the same settling time, which had an r^2 of .33.

Speaker I2 and I3's i-a utterances showed patterns somewhat different from their a-i utterances. For speaker I2, and for some measures for speaker I3, the interval between vowel targets was significantly shorter with geminates. In order to model this pattern, the target of the second vowel could not be fixed relative to the first vowel, as was done in the models for speaker I1. For both speakers I2 and I3, the target interval of the first vowel was shorter, but the movement into the second vowel was longer, when the consonant was a geminate. This pattern is reminiscent of the pattern observed in speaker

I1's i-a utterances, where the shorter first vowel target interval, coupled with a longer movement into the second vowel, was modeled by increasing the settling time of /a/ when it followed a geminate. For speakers I2 and I3, this pattern was also modeled by increasing the settling time of /a/ following a geminate, and by phasing /i/ with a point (360°) in the second vowel /a/ later than its target, which results in the interval between vowel targets being shorter with a geminate consonant. With this phasing late in the second vowel, because the movements into that vowel were very long, its onset was much earlier with geminates. If the consonant target were phased to the same point in the vowel with single or geminate consonants, it would be too early in the geminate utterances. (The interval from the consonant target to the vowel 2 target would be too long.) Therefore, a difference in the phasing of the consonant with vowel 2 is needed, as well as the difference in vowel settling times.

For speaker I2, the r^2 between the actual durational differences between single and geminate i-a utterances, and the differences predicted by the model in Table 4.13, using different settling times, was .88, as opposed to the model with the same settling time, which had an r^2 of .11. For speaker I3, the r^2 between the actual durational differences between single and geminate i-a utterances, and the differences predicted by the model using different settling times, was .96, as opposed to the model with the same settling time, which had an r^2 of .08.

Thus, for the i-a utterances, the patterns observed in the three speakers could be modeled by very similar strategies, although the values for the phase angles differ among speakers. That constant intervals between the vowels were found to some extent in all speakers, but not everywhere, suggests that while the relation between the vowel gestures may be approximately "maintain a constant interval", speakers vary as to how they produce this effect, or in whether they control the targets or some other part of the vowel gestures.

As was done for the Japanese models, each of the Italian models was tested on all the Italian speakers. Each model was tested using the same vowel settling time throughout, and using different vowel settling times for vowels following single and geminate consonants. The settling times and consonant deactivation phases calculated for each speaker were used with all models tested on that speaker's data.

The r^2 between the differences predicted by the models and the actual differences in the durations for the different speakers are shown in Table 4.14. The models are labeled according to the speaker that they best fit, e.g. model #I1 is the model developed for speaker I1. Values in boldface are the r^2 values for the model developed for that speaker. Note that for the a-i utterances, models #I1 and #I2 were the same, and for the i-a utterances, models #I2 and #I3 were the same.

	same vowel settling time with single and geminate consonants			different settling times after single and geminate consonants		
a-i utterances	#I1	#I2	#I3	#I1	#I2	#I3
speaker I1	**.86**	**.86**	.27	.75	.75	.45
speaker I2	**.98**	**.98**	.15	.90	.90	.50
speaker I3	.47	.47	.33	.62	.62	**.94**
i-a utterances	#I1	#I2	#I3	#I1	#I2	#I3
speaker I1	.44	.23	.23	**.93**	.80	.80
speaker I2	.13	.11	.11	.66	**.88**	**.88**
speaker I3	.17	.08	.08	.83	**.96**	**.96**

Table 4.14. r^2 values for testing 3 models on 3 Italian speakers.

Although speaker I2 was best fit by the same model as I3 for i-a utterances, the results for speaker I2 were in some ways more like the results for speaker I1. Using different vowel settling times with singles and geminates was important for speaker I3 for utterances with both vowel patterns, whereas for speakers I1 and I2 the a-i utterances did not require different vowel settling times even though the i-a utterances did. However, overall the models with different vowel settling times tended to have higher r^2 values for both vowel patterns and all speakers. This suggests that in general, some temporal characteristic of the vowels is affected by the length of the consonant.

4.2.3. Testing the models on speakers of the other language

All of the Japanese models were tested on the Italian speakers, and the Italian models on the Japanese speakers. For every speaker, the values appropriate to that speaker were used for consonant deactivation phase, and vowel and consonant settling times. However, the way in which the values were varied between single and geminate was determined by the model being tested. For example, in testing Japanese model #J1 on Italian speaker I1, the values derived for model #I1 were used for the consonant deactivation phases (300° for singles and 370° for geminates). The overall mean vowel settling time (110.03 ms) and the mean consonant settling times for single and geminate consonants (93.62 ms and 104.23 ms)were used. The consonant settling times for singles and geminates were calculated for the purpose of testing the Japanese models as these values had not been used in the Italian models.

As had been done with the Italian speakers, the Italian models were tested on the Japanese speakers in two ways: using the mean vowel settling time for all vowels, and varying the settling time of the second vowel between utterances with single and geminate consonants. The results of the modelling with mismatched languages for speakers and models are listed in Tables 4.15 and 4.16.

a-i utterances	models #J1	#J2	#J3
speaker I1	.62	.10	.01
speaker I2	.41	.10	.01
speaker I3	.01	.00	.00
i-a utterances	**#J1**	**#J2**	**#J3**
speaker I1	.02	.00	.03
speaker I2	.15	.00	.23
speaker I3	.20	.24	.16

Table 4.15. r^2 values for testing 3 Japanese models on 3 Italian speakers.

	same vowel settling time with single and geminate consonants			different settling times after single and geminate consonants		
a-i utterances	#I1	#I2	#I3	#I1	#I2	#I3
speaker J1	.35	.35	.80	.40	.40	.79
speaker J2	.00	.00	.59	.01	.0I	.61
speaker J3	.10	.10	.25	.17	.17	.17
i-a utterances	#I1	#I2	#I3	#I1	#I2	#I3
speaker J1	.26	.18	.18	.31	.26	.26
speaker J2	.67	.66	.66	.74	.73	.73
speaker J3	.12	.05	.05	.02	.01	.01

Table 4.16. r^2 values for testing 3 Italian models, with two possibilities for vowel settling time, on 3 Japanese speakers.

In some cases, surprisingly high r^2 values were reached with a model that did not match the speaker's language, for example the a-i utterances for speaker J1 with Italian model #I3. The a-i utterances of speaker I3 (modeled by model #I3) were, in fact, somewhat Japanese-like, in that the target-to-target interval increases between singles and geminates. In the a-i utterances in both languages, many intervals were slightly longer with geminates, making the measured durations in the two languages look more similar than they did in the i-a utterances. Intervals over which the two languages appear to contrast the most in the i-a utterances included intervals involving the target of the first vowel, so in the model of the a-i utterances which did not include these intervals, some of the between-language differences were missing. It is less clear why speaker J2's i-a utterances should be fairly well fit by the Italian models. These models predict the same duration with single and geminate consonants for the interval between vowel targets, whereas for speaker J2 this interval was approximately 37 ms longer with geminates. However, some other intervals, for instance those measuring the time between events in the consonant and the second vowel, patterned similarly for speaker J2 and for the Italian speakers, giving rise to a high r^2 for the Italian models in predicting the durations for speaker J2.

Despite these cases in which fairly high correlations were found for mismatched models, never were all three speakers of a language well fit by a model for the other language. The r^2 between the models' predictions and speakers' productions for mismatched models were usually substantially lower than the r^2 values for the speakers with any of the models for their own languages. That more than one model with a given structure fits a particular speaker better than the models with a different structure suggests that it is not just the particular values chosen for phase angles that account for the inaccuracy of the mismatched models. Rather, the different structures of the Italian and Japanese models seem to reflect genuine differences in the patterns of the two languages.

The models show that by making these assumptions about what is controlled, it is possible to generate a good approximation to the observed data with limited differences needed to represent the single/geminate contrast. Most importantly, the models provide evidence that control of intergestural relations within the structures assumed for the different languages can closely imitate the pattern of differences that was observed between utterances with single and geminate consonants.

5. Interpretation of the phase angles in the model

5.1. Duration of activation of a gesture

The Italian models use phase angles in vowel gestures that are greater than the 360° that make up a single cycle, in order to coordinate the vowels to each other yet allow an appropriate delay between them. This requires that the cycle be interpreted as an abstract description of timing rather than as a unit whose total duration is necessarily 360°. If the movement to the target of a gesture takes 240°, then for a gesture to continue for 700° or 800°, its activation would have to continue for a very long time after the achievement of target. Once the articulators associated with the gesture have reached their target position, this position is maintained as long as the gesture is active, subject to interactions with other gestures. Yet the vocal tract does not remain in a fixed position for this entire time. Later gestures become active, and overlap some portion of the preceding gesture, contributing to control of the shape of the vocal tract.

That vowel gestures might continue long after other gestures have become activated is supported by findings of coarticulation between quite distant vowels: Magen (1989) reported acoustic effects of the first full vowel on the last in /bVbəbVb/ sequences produced by English speakers. The first vowel would have to be active for a long time, if these effects are the consequence of overlap of vowel gestures.

A problem arises if more than one gesture is active simultaneously with different targets defined for the same tract variable: only one target can be met at a given time. The consequence of simultaneous activation of multiple gestures with similar degrees of constriction, for example, two vowels, could be a blending of the two gestures (Saltzman & Munhall 1989), resulting in a compromise between their targets. In the modelling described here, gestures are either wholly active or inactive. During the period that a gesture is active, the articulators must achieve its target, subject of course to demands from other gestures. Other interpretations of gesture activation are, of course, possible. A model in which gestures become active gradually, and gradually become inactive as they end, could be interpreted so that the later phases of the gesture would exert only partial control over the vocal tract. Such a model might come closer to representing the kinds of context effects that can be measured between different vowels (e.g. Öhman 1966), which become smaller in the more separated parts of the vowels.

An alternative view is that gestures do not actually remain active for as long a time as other gestures may be phased with them. Phasing the target of the second vowel with 800° of the first vowel, for example, could simply be a statement that the second vowel reaches its target a specific amount of time (defined in terms of the settling time of the first vowel) after the onset of the first vowel gesture, with no predictions about the duration of the period of activation of either gesture. The two vowel gestures would not necessarily overlap at all. This interpretation of phasing, however, makes no predictions about how much overlap can occur among gestures, a concept that has provided well-defined hypotheses about coarticulation (e.g. Bell-Berti & Harris 1981, Hardcastle 1985, Fowler & Smith 1986, Whalen 1990, Keating 1990, Farnetani 1990) as well as about the kind of temporal properties of articulatory movement discussed here. Nor does this interpretation make any predictions about how long a vowel gesture might remain active, or how long it could be used for phasing purposes. Because of the quantity of experimental evidence that can be accounted for by the hypothesis of gestural overlap, it seems preferable and more constrained to interpret phasing in the stricter sense as referring to the simultaneous occurrence of particular phases of two active gestures, which implies actual overlap between them.

5.2. Relation between the movement patterns and phases of the abstract gestures

If a gesture can be activated for more than 360°, then the period during which it has primary influence over the shape of the vocal tract is much shorter than its total duration. The target, defined for the purpose of measurement as being where the movement slowed to less than a threshold velocity, is by hypothesis assigned to a phase angle of 240° of the gestural cycle. The onset, where the movement exceeded a threshold velocity, is assigned to 0° of the cycle. The problem with this definition of onset is that a gesture must have become active before its articulatory consequences will show up in the movement trajectory. If gestures can continue to be active for an extended period, perhaps a symmetrical effect might exist with a gesture active long before it is apparent in the articulator movements.

A related problem in interpreting the phase angles used in the modelling is that they represent arbitrary stages in the cycle of a gesture. The only stages in the cycle that have a readily identifiable meaning are the onset and the achievement of target, and possibly also the end of activation, except that this is not associated with the same number of degrees in every gesture. The onset and target were labeled in the movement trajectories because it was possible to identify them consistently. The phases used in the modelling included these events but also many others that do not have any obvious interpretation (e.g. 40°). They were chosen for pragmatic reasons: they were the values that produced the pattern observed in the measured intervals. Since these intervals were themselves based on a somewhat arbitrary choice of events in the trajectories, the values of phase angles used in the modelling may be in part the consequence of this original selection of events to label.

5.3. Vowel-to-vowel vs. vowel-and-consonant timing organization and the modelling results

The modelling procedure started out with the assumption that the different patterns of temporal organization that had been observed in Japanese and Italian could be represented by different structures for the relations among the gestures – for Japanese, coordinating each gesture with adjacent ones, and for Italian, coordinating the vowels with vowels, and the consonants also with vowels. The patterns that were being represented were those differences in timing due to differences in length of the intervocalic consonant. These differences were modeled by varying parameter values within the structures for the two languages. Particularly for Japanese, the differences between singles and geminates could be accounted for by variation in only one or two parameter values. The Italian data seemed to require more changes in parameter values, with different sets of utterances being best modeled by changes in settling time or phasing. In particular for the i-a utterances, accurate modelling of the vocalic movement durations required that vowels following single and geminate consonants have different values for settling time. This implies that the length of the consonant does have some effect on the timing properties of the vowels, even though their phasing does not directly involve the consonant. With the geminates, the movement into the second vowel starts sooner than with single consonants. Thus to some extent the Italian models presented here contradict the strongest form of the vowel-to-vowel timing hypothesis, which is that consonants play no role at all in the temporal organization of the vowels. However, the phasing relations in Italian were well modeled by a structure that does not involve the consonant, unlike the structure of the Japanese model. The higher correlations generally found within speakers of the same language, even when using models developed for different speakers, lends some support to the initial assumption that the two languages require models with different structures.

These models were developed to reflect the effect of the consonant length contrast on a specific set of data. Particularly for the Italian, the complexity of the observed differences due to the single/geminate contrast, and the differences between the two vowel patterns, resulted in the models having rather a large number of parameters for the number of interval durations being modeled. The value of the models lie in their presumed extensibility to other utterances beyond those tested here, and the general statements that they make about the kinds of variation that were found in the two languages.

Chapter V

DISCUSSION

The original goal of this dissertation was to test the hypothesis that the two different models of timing, vowel-to-vowel and combined vowel-and-consonant, underlie the distinction between the traditional categories of mora-timing and syllable-timing. Each of these traditional categories was associated with a language that was expected to exemplify it, and the timing organization of gestures in those languages was compared. This was done by comparing the difference in temporal patterns in the two languages between two contexts that could be supposed to vary only in the time domain, i.e. utterances with single or geminate consonants. The results supported the hypothesis that languages traditionally described as belonging to different categories were best characterized by different models of gestural timing. Japanese, an example of mora-timing, was clearly best modeled by vowel-and-consonant timing. Italian, an example of a syllable-based language, showed very different patterns from Japanese and seemed to behave in accordance with vowel-to-vowel timing, although the results were somewhat less clear than for Japanese.

Using the comparison between single and geminate consonants to reveal the organization of gestural timing raises the question of what geminate consonants might consist of, particularly how they can be described in terms of gestures.

1. Nature of the contrast between single and geminate consonants

In this study, the interest was in the difference between the effect of single vs. geminate consonants on surrounding vowels, not on the consonants themselves. An account of the nature of geminates should describe what the essential articulatory difference is between the two contrasting consonant types, and to what extent the differences between singles and geminates can be described in the same way in different languages.

1.1. Consonantal length contrast in gestural terms

Consider what the contrast between single and geminate consonants might consist of in terms of articulatory gestures. If a single consonant gesture, with stiffness k is taken as the basic unit, what could define a geminate? Two possibilities have been raised for how to define a constriction with longer duration: (1) a geminate could be a single gesture with longer duration, or (2) a geminate could consist of more than one gesture. The modelling in Chapter IV treated geminates as a single gesture (option 1).

If a geminate consists of one gesture with longer duration than a single consonant, it must have either a greater stiffness or a longer period of activation. Both of these differences were used in the modelling. An increase in stiffness alone would not be adequate for representing the single/geminate contrast. A gesture with greater stiffness would result in a movement that moves towards and away from the constriction more slowly, as well as holding the constriction for slightly longer. Geminates in Japanese were characterized by slower movements, with the movement into a geminate averaging about 15-20 ms longer than the movement into a single consonant. Speaker I3 also had a substantial difference (35 ms) between the durations of movement into single and geminate consonants, but speaker I1 had only 10 ms difference and speaker I2 none, suggesting that this is a less crucial difference in Italian than in Japanese. However, the main difference between singles and geminates in both languages was the duration of the held closure, which for Japanese was as much as three times longer for a geminate. A difference in stiffness alone cannot model this large a durational difference. Therefore, in the modelling it was also necessary to specify a longer period of activation for geminates. The duration of this period was specified ad hoc for each speaker whose data were modeled, in order to optimize the fit. Independently setting the period of activation in this model is similar to the description of jaw movements in (short) English vowels as having three parts, suggested by McGarr, Löfqvist and Story (submitted). They describe the movements as consisting of opening, holding and closing portions. The single-gesture account of geminates specifies movement towards the closure (from the stiffness) and holding period (period of activation).

It would be more desirable to be able to predict how the duration of the period of activation should differ between singles and geminates on the basis of some principles. Its value would presumably vary across languages; the consonant target interval (which was assumed to correspond to the time from the target of the gesture to the end of activation) was longer in geminates for the Japanese speakers than the Italian speakers. In the computational model based on Articulatory Phonology (Browman and Goldstein 1990a, 1990b), there are two distinct values specified for the duration of the period of activation, one for vowels and one for (single) consonants. One possible hypothesis for geminates is that their period of activation is the same as for vowels, which is 1.5 times the period for consonants. This would be sufficient to model the duration of the target interval for geminates in Italian, but might not be quite long enough for Japanese. However, treating geminates as having a period of activation equivalent to vowels would coincide well with mora-timing in Japanese. A single vowel can count as a mora, but the only consonants that can are geminates and syllable-final nasals. If a geminate has the same period of activation as a vowel, then a mora could be described as necessarily including a gesture or gestures with that period of activation. (Possibly syllable-final nasals could be accounted for in the same way.) The main advantage of specifying geminates as having the same period of activation as a vowel is that it potentially offers a principled way of specifying the duration of a geminate's activation that ties in with what must already be specified in the model. The period of activation of geminates, and their stiffness, are all that have to be specified to distinguish geminates from single consonants in a model that treats geminates as single gestures.

The other possible model that was suggested, in which geminates consist of two gestures, has different advantages than the single-gesture model. In this model, a geminate is made up of two gestures that are always coordinated in a particular, tightlylinked fashion. Each of the gestures would presumably have, in the simplest model, the same properties as the corresponding single consonant gesture. If geminates consist of two gestures, it might be possible to show that the same phasing relations could hold between the consonant and neighboring vowel regardless of the length of the consonant, provided the vowel is phased to the adjacent consonant. This might permit simplification of, for example, the C-V phasing in the Japanese models, where different phase angles were needed to capture the difference between utterances with single and geminate consonants.

A major appeal of the two-gesture representation is that phonologically geminates often seem to behave like two units (e.g., Clements & Keyser 1983; Schein & Steriade 1986). In multi-tier phonological representations, geminates are usually analyzed as two slots on a rhythmic tier linked to a single set of feature nodes. The two-gesture interpretation of geminates may correspond more closely to the (abstract) rhythmic tier, and the interpretation of geminates as a single, slower gesture may be closer to the information carried by the feature tier(s). The rhythmic tier, or a representation as two gestures, categorically represents the temporal contrast between singles and geminates, perhaps without precisely accounting for their durations. The feature tiers suggest that single and geminate consonants have the same content (feature values, target position), but do not specify the temporal difference that would be represented on the rhythmic tier. The feature and gesture-based representations differ in that the gestural representation of a geminate, whether as one or two gestures, include both spatial and temporal information about the production of the consonants, whereas the separate tiers in a multi-tiered representation carry these two different types of information.

A drawback to the two-gesture hypothesis is that the coordination between the two gestures has to be specified. The two gestures of a geminate would have to be phased so that the second gesture reached its target before the articulators moved away from the target for the first gesture. Since, as soon as a gesture ceases to be active, the articulators relax away from the target towards their neutral position (see Saltzman & Munhall 1989), the second gesture's target would have to occur no later than the end of the activation of the first gesture. However, if it occurred earlier than the end of activation, the two gestures would overlap. The extent of any overlap within a geminate cannot he determined from the data, as only a single held period is apparent. Overlap between adjacent consonantal gestures might be measurable in a heterorganic consonant cluster. This hypothesis is thus somewhat more difficult to relate to the available data than the single-gesture hypothesis. Another difficulty in relating this model of geminates to the data for the Japanese geminates, in particular, is that the measured settling time for geminates was considerably longer than for the corresponding single consonants. The simplest form of the two-gesture model would be to assume that the constituent gestures were identical to single consonant gestures, which would imply that the settling time should be the same for both singles and geminates, contrary to what was observed.

The two options for the specification of the single/geminate contrast in gestural terms suggest different hypotheses about how this contrast is produced. It is difficult to choose which one best represents the apparent behavior of the speakers in this study. In the modelling in Chapter IV, the single-gesture hypothesis was used. It is closer to what was measured in the data than the two-gesture hypothesis, as only a single consonantal movement is apparent in the trajectories for either single or geminate consonants. The single-gesture hypothesis distinguishes singles and geminates by increasing the stiffness and period of activation for geminates. Values for these parameters must be determined that contrast the two consonant lengths. The two-gesture hypothesis distinguishes them by number of gestures. This hypothesis requires specification of the extent of the overlap between the two gestures in a geminate, in order to model the single/geminate contrast.

1.2. Generality of the findings

By using the single/geminate contrast as the basis for comparing timing hypotheses, it is being assumed that the durational differences are general timing effects, not specific to geminates. If these differences were specific to geminates as a category, no predictions would be made for timing in utterances with consonant clusters, which also have greater closure duration. Concluding about general timing organization from the single/geminate contrast would be less valid if the effects of consonant length did not generalize to other categories of greater consonantal duration. However, for both Japanese and Italian, few significant differences in durations of the various intervals were found between utterances with the /mp/ cluster and with the geminates, and where they were found, they were similar in magnitude to the small differences between oral and nasal geminates. For the duration of the consonant target interval itself, this was true especially of the Japanese speakers. The durations of the intervals in utterances with the cluster seemed most influenced by the nasality of the part of the cluster adjacent to the interval: that is, measures relating to the first part of the utterance tended not to differ significantly between the cluster /mp/ and the geminate /mm/, and measures of the second part were more likely to pattern with /pp/. Such behavior suggests that the cluster does not differ from the geminates in any way relating to length; rather, it constitutes a sequence of the two categories of nasality.

For both languages, the results from the measured intervals that supported the different timing hypotheses showed similar patterns with the cluster as with the geminates. Although a direct statistical comparison was not made between the cluster and the single consonants, the similar durauions that were observed for the cluster and for the geminates suggest that an analysis directly comparing single consonants and cluster would also yield results showing the same patterns. If the cluster behaves like the geminates with respect to durational effects, then the differences found between the single and geminate consonants should be the result of the difference in duration that also applies to the consonant cluster, not the consequence of some special geminate-specific behavior. To the extent that the geminates and the cluster behave in the same way, the two-gesture hypothesis for geminates may be better supported. The /mp/ cluster used in this study could be described as consisting of a single labial gesture with coordinated velic gestures, but non-homorganic clusters would have to be specified by more than one gesture. If the results for /mp/ generalize to non-homorganic clusters, then a unified account contrasting single consonants to longer consonants would be possible. This would suggest classing geminates with other, multi-gesture consonant combinations.

2. Connecting the timing differences to other pbonological patterns

Assuming that the different durational changes measured in the two languages are a consequence of timing differences alone, the phasing models presented in Chapter IV support the original hypothesis that Japanese and Italian are characterized by vowel-and-consonant and vowel-to-vowel timing, respectively. The difference in timing organization can contribute to understanding other evidence that the relations between consonants and vowels differ in Japanese and Italian.

2.1. Connecting the timing models to syllables and moras

The phasing relations described in the modelling in Chapter IV define a pattern of coordination at the level of individual gestures, but do not address the question of how the gestural coordination relates to traditional descriptions of phonological organization in terms of syllables and moras. Italian, as well as many other Romance (and other) languages, has traditionally been described as organized around syllables, but Japanese is considered to be organized in moras. One reason for being interested in the relation between a gestural description of timing, and one in terms of syllables or moras is that the languages have been described in terms of these units, and experimental evidence has been found for mora-timing in Japanese (e.g. Port et al 1987), and, less clearly, syllable-timing in Italian (Bertinetto 1988). The idea of describing rhythmic properties in terms of syllables or moras is appealing because there is other evidence for these units, such as phonological rules that are sensitive to syllable structure. For example, Italian is normally described as shortening vowels in closed syllables, that is, word-medially, before geminates and any cluster that cross a syllable boundary.

Syllables as basic phonological units in a language might be expected to co-occur with vowel-to-vowel timing because they are defined in terms of vowels: in Italian, each syllable must include a vowel, and each full vowel constitutes a separate syllable. Italian has little vowel reduction (den Os 1985), in the sense that English does, where unstressed vowels are frequently reduced to schwa. Each syllable has equal weight regardless of the number of consonants. Italian, with simpler syllable structure than English and smaller differences between stressed and unstressed vowels (Vayra, Avesani & Fowler 1984), has a more straightforward relation between vowel and syllable, possibly favoring a timing organization based on vowels. Dauer (1983) suggested that the structure of a language may be as relevant to the perceived rhythm as the variance of inter-stress or inter-syllable durations. The traditional description of Italian as syllable-based captures the centrality of vowels to its structure.

The notion of all syllables being equal, regardless of the number of consonants, coincides with an analysis by Chierchia (1982) that non-prepausal syllables must have branching rimes, of which the coda could be either vowel or consonant. That is, each syllable has the same syllabic "weight", but the coda can be made up of either a long vowel or a short vowel and a consonant. (This analysis has the drawback of analyzing all open syllables as containing long vowels, essentially assigning the same status to the length differences in vowels and consonants. For Italian this is redundant, as there is only a single length contrast which is evidenced acoustically in both vowels and consonants. See Bertinetto and Vivalda (1978) for a discussion of alternate analyses of the length contrast.) Regardless of the presence or absence of a syllable-final consonant, each syllable would have similar structure. This supports the hypothesis that consonants are peripheral to the rhythmic structure of Italian, which is clearly instantiated in the vowel-to-vowel timing model. In that model, the consonant(s) are phased only to the vowel in the same syllable, but each vowel is phased to the vowels preceding and following, making the vowels the base of the timing organization.

In contrast, Japanese consonants and vowels are more closely interrelated. The traditional unit of Japanese timing, the mora, is defined in terms of both consonants and vowels. Normally it consists of a consonant and vowel, but one vowel alone can be a mora, and so can one consonant, if syllable-final. Similarly, the vowel-and-consonant timing that appears to describe the coordination of articulatory gestures in Japanese is specified in terms of both vowels and consonants. Thus, as for Italian, the properties of the traditional phonological unit coincide with the proposals made here about articulatory coordination. The combined vowel-and-consonant timing model suggests what property of a mora makes it the basic unit in Japanese: it is the fact that both vowels and consonants are essential in establishing the rhythm.

2.2. Length contrasts in consonants and vowels

The patterns of coordination that were observed among the consonant and vowel gestures may also relate to the phonological distinctions that a language uses. Although both Japanese and Italian have geminate consonants, only Japanese also has geminate vowels, requiring that length be specified for both consonants and vowels. The addition of either a consonant or a vowel has an equivalent effect on the observed durations. This pattern would not be produced by vowel-to-vowel timing, because in that model consonants do not enter into the coordination between vowels, and the addition of a consonant would not affect the vowel durations in the same way that the addition of a vowel would. This implies that languages with independently contrastive length in both vowels and consonants ought to conform to the combined vowel-and-consonant model. It is languages with these length contrasts that have been described as mora-timed, the timing category expected to co-occur with combined vowel-and-consonant timing. This prediction appears to hold for Japanese, and could be tested on other languages that have these length distinctions, such as Hungarian or Finnish.

2.3. Changes in relative timing between consonants and vowels

Another phonological pattern that may be related to the structure of a language's timing organization is the freedom with which consonants and vowels historically have shifted relative to each other. Some Romance languages have undergone a process known as Dorsey's Law (Steriade 1990), wherein a copy of the tautosyllabic vowel is epenthesized in consonant clusters. Steriade shows how a gestural analysis of this process can easily account for the inserted vowel always being the same as the vowel following the cluster. Assuming the vowel gesture is active during the consonant gestures, if the consonant gestures move apart, the vowel gesture is exposed, and the apparent result is an inserted vowel. This process relies on vowels remaining stable as consonants vary their coordination. In a language in which the vowels are coordinated with each other, re-timing of a consonant relative to them would affect only a single phasing relation, rather than (at least) two in a language in which a consonant gesture is coordinated to the vowels on either side. For this reason, processes like Dorsey's Law might be more frequent in vowel-to-vowel timed languages, such as Italian or possibly other Romance languages (see also Browman 1991). When the phonology operates on gestures that have temporal extent, a language's pattern of timing organization can make predictions about certain aspects of its phonological behavior whose origin could be obscure without reference to temporal information. This kind of process also shows the value of a phonological representation in which consonants and vowels are on separate tiers, as that alone can represent this kind of re-timing.

The proposal that languages can structure their timing organization in more than one way could be seen as a complication compared to a single, universal organization, or it could be seen as a unifying account of a number of phenomena, including cross-linguistically differing rhythmic behaviors, traditional assignment of different basic units (syllable or mora), and greater or lesser likelihood of certain phonological processes. This proposal is also relevant to the question of what is phonetically universal and what must be specified for each language. Keating (1985b) argues for the inclusion of at least some phonetic rules as part of grammar, although she considers that certain common, cross-linguistic tendencies may constitute "default options" that would not be included in an individual language's grammar. The results presented in this dissertation suggest that even characteristics very fundamental to the production of an utterance, such as the form of the coordination among gestures, may be language-specific, not universal, and hence necessarily part of an individual language's grammar. Furthermore, this shows that basic properties of articulatory behavior are relevant even to large-scale phonological patterns.

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APPENDIX 1

For presentation to the speakers, the stimuli were divided into block types as listed below. Note that not all stimuli collected were analyzed here.

JAPANESE

Block type aCV presented 8 times	Block type aGV presented 8 times	Block type iCV presented 8 times	Block type iGV presented 8 times
mapa	mappa	mipa	mippa
mata	matta	mita	mitta
mama	mamma	mima	mimma
mana	manna	mina	minna
mapi	mappi	mipi	mippi
mami	mammi	mimi	mimmi
mani	manni	mini	minni

Block type VCV presented 3 times	Block type VGV presented 3 times	Block type VmpV presented 10 times
mapi	mappi	mampa
mami	mammi	mampi
mani	manni	mimpa
mipa	miopa	mimpi
mita	mitta	
mima	mimma	
mina	minna	

ITALIAN

Block type aCa	Block type aCi	Block type iCa	Block type iCi
Presented to speaker			
I1 5 times	I1 8 times	I1 8 times	I1 5 times
I2 6 times	I2 8 times	I2 7 times	I2 6 times
I3 4 times	I3 7 times	I3 6 times	I3 5 times
mapa	mapi	mipa	mipi
mata	mati	mita	miti
mama	mami	mima	mimi
mana	mani	mina	mini
masa	masi	misa	misi
mara	mari	mira	miri

Block type aGa	Block type aGi	Block type iGa	Block type iGi
Presented to speaker			
I1 6 times	I1 8 times	I1 8 times	I1 6 times
I2 6 times	I2 8 times	I2 8 times	I2 6 times
I3 5 times	I3 7 times	I3 5 times	I3 5 times
mappa	mappi	mippa	mippi
matta	matti	mitta	mitti
mamma	mammi	mimma	mimmi
manna	manni	minna	minni

Block type aCCa	Block type aCCi	Block type iCCa	Block type iCCi
Presented to speaker			
I1 5 times	I1 8 times	I1 8 times	I1 5 times
I2 6 times	I2 8 times	I2 8 times	I2 6 times
I3 5 times	I3 6 times	I3 5 times	I3 5 times
maspa	maspi	mispa	mispi
mapra	mapri	mipra	mipri
matpa	matpi	mitpa	mitpi
marpa	marpi	mirpa	mirpi
maspra	maspri	mispra	mispri
mampa*	mampi*	mimpa*	mimpi*

* Presented only to speaker I1.

APPENDIX 2

ANOVA Tables

Tables A2.1 to A2.4 show the analyses of variance for the acoustic durations. Tables A2.5 to A2.8 show the analyses of variance for the articulatory measures of the utterances with bilabial consonants. In these tables, the column entitled "SME sig." shows the results of simple main effects for the effect of Length, when there was an interaction of Length × Nasal. A "p" in this column means that the main effect of Length was significant for oral consonants (p vs. pp). An "m" means it was significant for nasal consonants (m vs. mm).

Table A2.1. Analysis of variance for acoustic measures of utterances with single and geminate consonants produced by Italian speakers.

speaker Effect	utterances	acoustic segment	F	df	p
I1					
Length					
	a-initial bilabials	vowel 1	68.76	1, 33	0.0000
		consonant closure	247.27	1, 33	0.0000
		total consonant	254.51	1, 33	0.0000
		vowel 2	19.44	1, 33	0.0001
	i-initial bilabials	vowel 1	100.90	1, 37	0.0000
		consonant closure	296.64	1, 37	0.0000
		total consonant	293.35	1, 37	0.0000
		vowel 2	43.56	1, 37	0.0000
	a-initial alveolars	vowel 1	233.87	1, 38	0.0000
		consonant closure	186.20	1, 38	0.0000
		total consonant	202.31	1, 38	0.0000
		vowel 2	3.55	1, 38	0.0671
	i-initial alveolars	vowel 1	129.13	1, 36	0.0000
		consonant closure	275.47	1, 36	0.0000
		total consonant	270.41	1, 36	0.0000
		vowel 2	46.18	1, 36	0.0000
Nasal					
	a-initial bilabials	vowel 1	3.92	1, 33	0.0562
		consonant closure	17.77	1, 33	0.0002
		total consonant	33.46	1, 33	0.0000
		vowel 2	18.46	1, 33	0.0001
	i-initial bilabials	vowel 1	18.33	1, 37	0.0001
		consonant closure	7.02	1, 37	0.0118
		total consonant	26.92	1, 37	0.0000
		vowel 2	5.07	1, 37	0.0304
	a-initial alveolars	vowel 1	54.69	1, 38	0.0000
		consonant closure	36.92	1, 38	0.0000
		total consonant	53.08	1, 38	0.0000
		vowel 2	33.32	1, 38	0.0000
	i-initial alveolars	vowel 1	44.62	1, 36	0.0000
		consonant closure	13.70	1, 36	0.0007
		total consonant	60.20	1, 36	0.0000
		vowel 2	28.41	1, 36	0.0000
Length X Nasal					
	a-initial bilabials	vowel 1	0.06	1, 33	0.8126
		consonant closure	0.04	1, 33	0.8519
		total consonant	0.13	1, 33	0.7157
		vowel 2	2.98	1, 33	0.0935
	i-initial bilabials	vowel 1	0.09	1, 37	0.7631
		consonant closure	0.01	1, 37	0.9127
		total consonant	0.03	1, 37	0.8680
		vowel 2	3.86	1, 37	0.0571
	a-initial alveolars	vowel 1	0.28	1, 38	0.5983

		consonant closure	1.40	1, 38	0.2440
		total consonant	0.00	1, 38	0.9488
		vowel 2	0.04	1, 38	0.8424
	i-initial alveolars	vowel 1	7.12	1, 36	0.0114
		consonant closure	1.53	1, 36	0.2248
		total consonant	2.07	1, 36	0.1590
		vowel 2	4.26	1, 36	0.0464

I2

Length					
	a-initial bilabials	vowel 1	205.60	1, 14	0.0000
		consonant closure	58.23	1, 14	0.0000
		total consonant	41.01	1, 14	0.0000
		vowel 2	2.63	1, 14	0.1272
	i-initial bilabials	vowel 1	75.81	1, 12	0.0000
		consonant closure	131.75	1, 12	0.0000
		total consonant	205.32	1, 12	0.0000
		vowel 2	5.05	1, 12	0.0443
	a-initial alveolars	vowel 1	348.05	1, 20	0.0000
		consonant closure	90.37	1, 20	0.0000
		total consonant	84.71	1, 20	0.0000
		vowel 2	0.64	1, 20	0.4321
	i-initial alveolars	vowel 1	111.80	1, 13	0.0000
		consonant closure	236.37	1, 13	0.0000
		total consonant	291.79	1, 13	0.0000
		vowel 2	0.25	1, 13	0.6282
Nasal					
	a-initial bilabials	vowel 1	13.59	1, 14	0.0024
		consonant closure	4.38	1, 14	0.0550
		total consonant	16.70	1, 14	0.0011
		vowel 2	3.56	1, 14	0.0803
	i-initial bilabials	vowel 1	4.36	1, 12	0.0589
		consonant closure	3.62	1, 12	0.0813
		total consonant	34.40	1, 12	0.0001
		vowel 2	6.34	1, 12	0.0270
	a-initial alveolars	vowel 1	9.61	1, 20	0.0056
		consonant closure	2.89	1, 20	0.1046
		total consonant	18.87	1, 20	0.0003
		vowel 2	7.85	1, 20	0.0110
	i-initial alveolars	vowel 1	5.72	1, 13	0.0326
		consonant closure	9.81	1, 13	0.0079
		total consonant	53.71	1, 13	0.0000
		vowel 2	7.90	1, 13	0.0147
Length X Nasal					
	a-initial bilabials	vowel 1	1.47	1, 14	0.2450
		consonant closure	7.30	1, 14	0.0172
		total consonant	3.13	1, 14	0.0986
		vowel 2	1.47	1, 14	0.2458
	i-initial bilabials	vowel 1	0.06	1, 12	0.8155
		consonant closure	0.18	1, 12	0.6751
		total consonant	0.01	1, 12	0.9420
		vowel 2	0.38	1, 12	0.5516

a-initial alveolars	vowel 1	1.90	1, 20	0.1831
	consonant closure	3.33	1, 20	0.0832
	total consonant	4.66	1, 20	0.0432
	vowel 2	0.34	1, 20	0.5655
i-initial alveolars	vowel 1	0.43	1, 13	0.5221
	consonant closure	0.06	1, 13	0.8050
	total consonant	1.12	1, 13	0.3089
	vowel 2	0.68	1, 13	0.4234

I3

Length

a-initial bilabials	vowel 1	141.42	1, 19	0.0000
	consonant closure	344.18	1, 19	0.0000
	total consonant	349.95	1, 19	0.0000
	vowel 2	2.27	1, 19	0.1481
i-initial bilabials	vowel 1	89.26	1, 11	0.0000
	consonant closure	112.02	1, 11	0.0000
	total consonant	95.88	1, 11	0.0000
	vowel 2	6.40	1, 11	0.0280
a-initial alveolars	vowel 1	94.95	1, 16	0.0000
	consonant closure	159.56	1, 16	0.0000
	total consonant	141.97	1, 16	0.0000
	vowel 2	0.00	1, 16	0.9578
i-initial alveolars	vowel 1	26.13	1, 11	0.0003
	consonant closure	53.90	1, 11	0.0000
	total consonant	84.23	1, 11	0.0000
	vowel 2	3.33	1, 11	0.0952

Nasal

a-initial bilabials	vowel 1	3.94	1, 19	0.0619
	consonant closure	0.42	1, 19	0.5261
	total consonant	24.63	1, 19	0.0001
	vowel 2	0.17	1, 19	0.6827
i-initial bilabials	vowel 1	0.09	1, 11	0.7697
	consonant closure	6.60	1, 11	0.0261
	total consonant	32.23	1, 11	0.0001
	vowel 2	0.02	1, 11	0.8965
a-initial alveolars	vowel 1	17.01	1, 16	0.0008
	consonant closure	0.10	1, 16	0.7519
	total consonant	28.95	1, 16	0.0001
	vowel 2	22.43	1, 16	0.0002
i-initial alveolars	vowel 1	2.94	1, 11	0.1143
	consonant closure	0.29	1, 11	0.5993
	total consonant	5.35	1, 11	0.0410
	vowel 2	1.00	1, 11	0.3391

Length X Nasal

a-initial bilabials	vowel 1	0.11	1, 19	0.7462
	consonant closure	3.31	1, 19	0.0848
	total consonant	1.79	1, 19	0.1973
	vowel 2	0.40	1, 19	0.5338
i-initial bilabials	vowel 1	0.27	1, 11	0.6159
	consonant closure	3.21	1, 11	0.1006
	total consonant	2.25	1, 11	0.1620

	vowel 2	0.33	1, 11	0.5757
a-initial alveolars	vowel 1	0.11	1, 16	0.7467
	consonant closure	1.34	1, 16	0.2646
	total consonant	0.01	1, 16	0.9228
	vowel 2	3.77	1, 16	0.0700
i-initial alveolars	vowel 1	0.89	1, 11	0.3648
	consonant closure	2.47	1, 11	0.1444
	total consonant	5.35	1, 11	0.0410
	vowel 2	0.07	1, 11	0.8027

Table A2.2. Analysis of variance for acoustic measures of utterances with geminate and cluster consonants produced by Italian speaker I1.

utterances	acoustic segment	F	df	p
speaker I1				
Long Consonant Type				
a-initial bilabials	vowel 1	3.80	2, 23	0.0376
	consonant closure	13.25	2, 23	0.0001
	total consonant	25.65	2, 23	0.0000
	vowel 2	10.62	2, 23	0.0005
i-initial bilabials	vowel 1	6.00	2, 24	0.0077
	consonant closure	3.60	2, 24	0.0428
	total consonant	8.53	2, 24	0.0016
	vowel 2	10.02	2. 24	0.0007

Table A2.3. Analysis of variance for acoustic measures of utterances with single and geminate consonants produced by Japanese speakers.

speaker / Effect	utterances	acoustic segment	F	df	p
J1					
Length					
	a-initial bilabials	vowel 1	13.56	1, 61	0.0005
		consonant closure	219.36	1, 61	0.0000
		total consonant	301.81	1, 61	0.0000
		vowel 2	0.19	1, 61	0.6684
	i-initial bilabials	vowel 1	11.96	1, 67	0.0009
		consonant closure	445.35	1, 67	0.0000
		total consonant	471.98	1, 67	0.0000
		vowel 2	23.69	1, 67	0.0000
	a-initial alveolars	vowel 1	40.66	1, 31	0.0000
		consonant closure	149.15	1, 31	0.0000
		total consonant	149.15	1, 31	0.0000
		vowel 2	6.28	1, 31	0.0177
	i-initial alveolars	vowel 1	11.64	1, 66	0.0011
		consonant closure	282.43	1, 66	0.0000
		total consonant	282.43	1, 66	0.0000
		vowel 2	13.82	1, 66	0.0004
Nasal					
	a-initial bilabials	vowel 1	44.10	1, 61	0.0000
		consonant closure	0.35	1, 61	0.5556
		total consonant	9.74	1, 61	0.0028
		vowel 2	9.04	1, 61	0.0038
	i-initial bilabials	vowel 1	29.08	1, 67	0.0000
		consonant closure	5.21	1, 67	0.0257
		total consonant	14.72	1, 67	0.0003
		vowel 2	16.14	1, 67	0.0002
	i-initial alveolars	vowel 1	3.77	1, 66	0.0564
		consonant closure	0.00	1, 66	0.9959
		total consonant	5.10	1, 66	0.0272
		vowel 2	95.96	1, 66	0.0000
Length X Nasal					
	a-initial bilabials	vowel 1	12.15	1, 61	0.0009
		consonant closure	1.63	1, 61	0.2070
		total consonant	0.92	1, 61	0.3407
		vowel 2	0.01	1, 61	0.9070
	i-initial bilabials	vowel 1	9.07	1, 67	0.0037
		consonant closure	0.96	1, 67	0.3307
		total consonant	0.40	1, 67	0.5272
		vowel 2	1.39	1, 67	0.2429
	i-initial alveolars	vowel 1	7.02	1, 66	0.0101
		consonant closure	0.53	1, 66	0.4677
		total consonant	0.20	1, 66	0.6560
		vowel 2	7.18	1, 66	0.0093

J2

Length					
	a-initial bilabials	vowel 1	14.48	1, 74	0.0003
		consonant closure	767.79	1, 74	0.0000
		total consonant	706.61	1, 74	0.0000
		vowel 2	23.41	1, 74	0.0000
	i-initial bilabials	vowel 1	23.63	1, 75	0.0000
		consonant closure	898.42	1, 75	0.0000
		total consonant	846.77	1, 75	0.0000
		vowel 2	12.25	1, 75	0.0008
	a-initial alveolars	vowel 1	17.17	1, 36	0.0002
		consonant closure	362.89	1, 36	0.0000
		total consonant	362.89	1, 36	0.0000
		vowel 2	0.03	1, 36	0.8624
Nasal					
	a-initial bilabials	vowel 1	26.80	1, 74	0.0000
		consonant closure	76.43	1, 74	0.0000
		total consonant	90.51	1, 74	0.0000
		vowel 2	24.89	1, 74	0.0000
	i-initial bilabials	vowel 1	10.82	1, 75	0.0015
		consonant closure	1.48	1, 75	0.2283
		total consonant	6.79	1, 75	0.0110
		vowel 2	16.33	1, 75	0.0001
Length X Nasal					
	a-initial bilabials	vowel 1	1.26	1, 74	0.2655
		consonant closure	0.00	1, 74	0.9909
		total consonant	0.00	1, 74	0.9864
		vowel 2	2.53	1, 74	0.1158
	i-initial bilabials	vowel 1	0.03	1, 75	0.8559
		consonant closure	0.23	1, 75	0.6317
		total consonant	1.48	1, 75	0.2269
		vowel 2	16.72	1, 75	0.0001

J3

Length					
	a-initial bilabials	vowel 1	205.36	1, 50	0.0000
		consonant closure	230.62	1, 50	0.0000
		vowel 2	3.89	1, 50	0.0541
	i-initial bilabials	vowel 1	172.99	1, 51	0.0000
		consonant closure	478.44	1, 51	0.0000
		vowel 2	2.09	1, 51	0.1543
	a-initial alveolars	vowel 1	22.43	1, 24	0.0001
		consonant closure	102.33	1, 24	0.0000
		vowel 2	2.69	1, 24	0.1142
	i-initial alveolars	vowel 1	87.19	1, 47	0.0000
		consonant closure	759.78	1, 47	0.0000
		vowel 2	3.03	1, 47	0.0881
Nasal					
	a-initial bilabials	vowel 1	36.17	1, 50	0.0000
		consonant closure	90.09	1, 50	0.0000
		vowel 2	11.26	1, 50	0.0015

i-initial bilabials	vowel 1	44.13	1, 51	0.0000
	consonant closure	135.80	1, 51	0.0000
	vowel 2	29.22	1, 51	0.0000
i-initial alveolars	vowel 1	0.12	1, 47	0.7296
	consonant closure	139.78	1, 47	0.0000
	vowel 2	38.01	1, 47	0.0000
Length X Nasal				
a-initial bilabials	vowel 1	23.70	1, 50	0.0000
	consonant closure	0.57	1, 50	0.4546
	vowel 2	0.01	1, 50	0.9375
i-initial bilabials	vowel 1	7.00	1, 51	0.0108
	consonant closure	6.88	1, 51	0.0115
	vowel 2	0.02	1, 51	0.8820
i-initial alveolars	vowel 1	21.80	1, 47	0.0000
	consonant closure	38.74	1, 47	0.0000
	vowel 2	0.02	1, 47	0.8838

Table A2.4. Analysis of variance for acoustic measures of utterances with geminate and cluster consonants produced by Japanese speakers.

utterances	acoustic segment	F	df	p
speaker J1				
Long Consonant Type				
a-initial bilabials	vowel 1	39.53	2, 44	0.0000
	consonant closure	1.01	2, 44	0.3739
	total consonant	7.44	2, 44	0.0016
	vowel 2	11.08	2, 44	0.0001
i-initial bilabials	vowel 1	10.32	2, 47	0.0002
	consonant closure	2.58	2, 47	0.0866
	total consonant	6.08	2, 47	0.0045
	vowel 2	9.25	2, 47	0.0004
speaker J2				
Long Consonant Type				
a-initial bilabials	vowel 1	25.94	2, 53	0.0000
	consonant closure	16.06	2, 53	0.0000
	total consonant	19.45	2, 53	0.0000
	vowel 2	10.23	2, 53	0.0002
i-initial bilabials	vowel 1	5.56	2, 55	0.0063
	consonant closure	0.41	2, 55	0.6634
	total consonant	0.89	2, 55	0.4156
	vowel 2	16.12	2, 55	0.0000
speaker J3				
Long Consonant Type				
a-initial bilabials	vowel 1	27.86	2, 36	0.0000
	consonant closure	21.23	2, 36	0.0000
	vowel 2	5.25	2, 36	0.0100
i-initial bilabials	vowel 1	19.48	2, 35	0.0000
	consonant closure	33.18	2, 35	0.0000
	vowel 2	14.74	2, 35	0.0000

Table A2.5. Analysis of variance for articulatory measures of utterances with single and geminate bilabial consonants for Italian speakers.

speaker effect	utterances measure	measured interval	F	df	p	SME sig?
I1						
Length						
	a-i bilabials					
	LA	Consonant target interval	35.34	1, 33	0.0000	
	Horiz	/m/ target to vowel 2 target	6.94	1, 33	0.0127	
	Vert	/m/ target to vowel 2 target	0.01	1, 32	0.9125	
	TB2y	/m/ target to vowel 2 target	8.28	1, 33	0.0070	
	TDx	/m/ target to vowel 2 target	7.17	1, 33	0.0115	
	Horiz	/m/ target to vowel 2 onset	5.68	1, 33	0.0230	
	Ven	/m/ target to vowel 2 onset	0.47	1, 32	0.4980	
	TB2y	/m/ target to vowel 2 onset	1.15	1, 33	0.2918	
	TDx	/m/ target to vowel 2 onset	0.90	1, 33	0.3485	
	Horiz	movement into vowel 2	0.10	1, 33	0.7486	
	Vert	movement into vowel 2	0.33	1, 32	0.5698	
	TB2y	movement into vowel 2	3.89	1, 33	0.0571	
	TDx	movement into vowel 2	4.55	1, 33	0.0405	
	Horiz	Vowel 2 target interval	0.04	1, 33	0.8507	
	Vert	Vowel 2 target interval	0.45	1, 32	0.5054	
	TB2y	Vowel 2 target interval	0.00	1, 33	0.9741	
	TDx	Vowel 2 target interval	0.54	1, 33	0.4677	
	Horiz	cons target to vowel 2 target	29.96	1, 33	0.0000	
	Vert	cons target to vowel 2 target	2.56	1, 32	0.1196	
	TB2y	cons target to vowel 2 target	30.34	1, 33	0.0000	
	TDx	cons target to vowel 2 target	30.46	1, 33	0.0000	
	i-a bilabials					
	LA	Consonant target interval	106.95	1, 37	0.0000	p,m
	Horiz	vowel 1 target to vowel 2 target	1.69	1, 37	0.2016	
	Vert	vowel 1 target to vowel 2 target	1.51	1, 35	0.2276	
	TB2y	vowel 1 target to vowel 2 target	0.74	1, 37	0.3963	
	TDx	vowel 1 target to vowel 2 target	0.30	1, 37	0.5869	
	Horiz	/m/ target to vowel 2 target	0.74	1, 37	0.3967	
	Vert	/m/ target to vowel 2 target	1.64	1, 35	0.2083	
	TB2y	/m/ target to vowel 2 target	0.79	1, 37	0.3812	
	TDx	/m/ target to vowel 2 target	0.20	1, 37	0.6555	
	Horiz	Vowel 1 target interval	10.92	1, 37	0.0021	
	Vert	Vowel 1 target interval	1.16	1, 35	0.2893	
	TB2y	Vowel 1 target interval	13.75	1, 37	0.0007	p
	TDx	Vowel 1 target interval	8.14	1, 37	0.0071	p
	Horiz	/m/ target to vowel 2 onset	11.13	1, 37	0.0019	
	Vert	/m/ target to vowel 2 onset	0.87	1, 35	0.3579	
	TB2y	/m/ target to vowel 2 onset	14.52	1, 37	0.0005	p
	TDx	/m/ target to vowel 2 onset	10.19	1, 37	0.0029	
	Horiz	movement into vowel 2	9.80	1, 37	0.0034	
	Ven	movement into vowel 2	0.08	1, 35	0.7773	
	TB2y	movement into vowel 2	18.13	1, 37	0.0001	p

TDx	movement into vowel 2	9.97	1, 37	0.0032	
Horiz	movement into vowel 1	0.04	1, 37	0.8441	
Vert	movement into vowel 1	5.26	1, 35	0.0279	
TB2y	movement into vowel 1	1.78	1, 37	0.1900	
TDx	movement into vowel 1	0.00	1, 37	0.9499	
Horiz	Vowel 2 target interval	7.97	1, 37	0.0076	
Vert	Vowel 2 target interval	2.96	1, 35	0.0941	
TB2y	Vowel 2 target interval	1.99	1, 37	0.1664	
TDx	Vowel 2 target interval	12.31	1, 37	0.0012	
Horiz	vowel 1 target to cons target	16.04	1, 37	0.0003	p
Vert	vowel 1 target to cons target	12.14	1, 35	0.0013	
TB2y	vowel 1 target to cons target	11.85	1, 37	0.0014	
TDx	vowel 1 target to cons target	15.20	1, 37	0.0004	p
Horiz	cons target to vowel 2 target	9.36	1, 37	0.0041	
Vert	cons target to vowel 2 target	4.13	1, 35	0.0498	
TB2y	cons target to vowel 2 target	10.71	1, 37	0.0023	
TDx	cons target to vowel 2 target	14.28	1, 37	0.0006	
Nasal					
a-i bilabials					
LA	Consonant target interval	0.22	1, 33	0.6397	
Horiz	/m/ target to vowel 2 target	5.47	1, 33	0.0256	
Vert	/m/ target to vowel 2 target	7.84	1, 32	0.0086	
TB2y	/m/ target to vowel 2 target	20.06	1, 33	0.0001	
TDx	/m/ target to vowel 2 target	10.42	1, 33	0.0028	
Horiz	/m/ target to vowel 2 onset	10.64	1, 33	0.0026	
Vert	/m/ target to vowel 2 onset	0.04	1, 32	0.8343	
TB2y	/m/ target to vowel 2 onset	9.78	1, 33	0.0037	
TDx	/m/ target to vowel 2 onset	19.21	1, 33	0.0001	
Horiz	movement into vowel 2	1.28	1, 33	0.2657	
Vert	movement into vowel 2	5.28	1, 32	0.0282	
TB2y	movement into vowel 2	1.53	1, 33	0.2244	
TDx	movement into vowel 2	7.28	1, 33	0.0109	
Horiz	Vowel 2 target interval	1.07	1, 33	0.3074	
Vert	Vowel 2 target interval	1.10	1, 32	0.3017	
TB2y	Vowel 2 target interval	7.78	1, 33	0.0087	
TDx	Vowel 2 target interval	8.68	1, 33	0.0059	
Horiz	cons target to vowel 2 target	6.74	1, 33	0.0140	
Vert	cons target to vowel 2 target	6.57	1, 32	0.0153	
TB2y	cons target to vowel 2 target	23.03	1, 33	0.0000	
TDx	cons target to vowel 2 target	14.00	1, 33	0.0007	
i-a bilabials					
LA	Consonant target interval	15.00	1, 37	0.0004	
Horiz	vowel 1 target to vowel 2 target	26.58	1, 37	0.0000	
Vert	vowel 1 target to vowel 2 target	12.85	1, 35	0.0010	
TB2y	vowel 1 target to vowel 2 target	21.04	1, 37	0.0001	
TDx	vowel 1 target to vowel 2 target	17.54	1, 37	0.0002	
Horiz	/m/ target to vowel 2 target	58.94	1, 37	0.0000	
Vert	/m/ target to vowel 2 target	20.63	1, 35	0.0001	
TB2y	/m/ target to vowel 2 target	38.79	1, 37	0.0000	
TDx	/m/ target to vowel 2 target	28.23	1, 37	0.0000	
Horiz	Vowel 1 target interval	10.54	1, 37	0.0025	

Vert	Vowel 1 target interval	48.04	1, 35	0.0000
TB2y	Vowel 1 target interval	19.30	1, 37	0.0001
TDx	Vowel 1 target interval	23.93	1, 37	0.0000
Horiz	/m/ target to vowel 2 onset	22.63	1, 37	0.0000
Vert	/m/ target to vowel 2 onset	55.64	1, 35	0.0000
TB2y	/m/ target to vowel 2 onset	32.46	1, 37	0.0000
TDx	/m/ target to vowel 2 onset	37.50	1, 37	0.0000
Horiz	movement into vowel 2	1.68	1, 37	0.2025
Vert	movement into vowel 2	13.20	1, 35	0.0009
TB2y	movement into vowel 2	0.74	1, 37	0.3960
TDx	movement into vowel 2	2.37	1, 37	0.1321
Horiz	movement into vowel 1	0.20	1, 37	0.6548
Vert	movement into vowel 1	3.13	1, 35	0.0858
TB2y	movement into vowel 1	7.54	1, 37	0.0093
TDx	movement into vowel 1	0.00	1, 37	0.9499
Horiz	Vowel 2 target interval	48.53	1, 37	0.0000
Vert	Vowel 2 target interval	2.32	1, 35	0.1369
TB2y	Vowel 2 target interval	0.29	1, 37	0.5955
TDx	Vowel 2 target interval	37.73	1, 37	0.0000
Horiz	vowel 1 target to cons target	5.08	1, 37	0.0302
Vert	vowel 1 target to cons target	9.96	1, 35	0.0033
TB2y	vowel 1 target to cons target	5.81	1, 37	0.0210
TDx	vowel 1 target to cons target	11.12	1, 37	0.0020
Horiz	cons target to vowel 2 target	23.25	1, 37	0.0000
Vert	cons target to vowel 2 target	3.01	1, 35	0.0913
TB2y	cons target to vowel 2 target	11.11	1, 37	0.0020
TDx	cons target to vowel 2 target	6.71	1, 37	0.0136
Length X Nasal				
a-i bilabials				
LA	Consonant target interval	0.00	1, 33	0.9615
Horiz	/m/ target to vowel 2 target	0.02	1, 33	0.8926
Vert	/m/ target to vowel 2 target	0.17	1, 32	0.6844
TB2y	/m/ target to vowel 2 target	0.30	1, 33	0.5906
TDx	/m/ target to vowel 2 target	0.66	1, 33	0.4224
Horiz	/m/ target to vowel 2 onset	0.04	1, 33	0.8512
Vert	/m/ target to vowel 2 onset	0.47	1, 32	0.4980
TB2y	/m/ target to vowel 2 onset	3.67	1, 33	0.0640
TDx	/m/ target to vowel 2 onset	1.63	1, 33	0.2105
Horiz	movement into vowel 2	0.00	1, 33	0.9486
Vert	movement into vowel 2	0.09	1, 32	0.7613
TB2y	movement into vowel 2	3.15	1, 33	0.0850
TDx	movement into vowel 2	0.93	1, 33	0.3429
Horiz	Vowel 2 target interval	0.08	1, 33	0.7750
Vert	Vowel 2 target interval	0.01	1, 32	0.9067
TB2y	Vowel 2 target interval	1.41	1, 33	0.2442
TDx	Vowel 2 target interval	1.02	1, 33	0.3207
Horiz	cons target to vowel 2 target	0.00	1, 33	0.9776
Vert	cons target to vowel 2 target	0.31	1, 32	0.5833
TB2y	cons target to vowel 2 target	0.52	1, 33	0.4779
TDx	cons target to vowel 2 target	1.18	1, 33	0.2846
i-a bilabials				

LA	Consonant target interval	7.39	1, 37	0.0099
Horiz	vowel 1 target to vowel 2 target	4.56	1, 37	0.0394
Vert	vowel 1 target to vowel 2 target	0.34	1, 35	0.5619
TB2y	vowel 1 target to vowel 2 target	0.65	1, 37	0.4244
TDx	vowel 1 target to vowel 2 target	2.54	1, 37	0.1197
Horiz	/m/ target to vowel 2 target	2.63	1, 37	0.1132
Vert	/m/ target to vowel 2 target	0.98	1, 35	0.3278
TB2y	/m/ target to vowel 2 target	0.80	1, 37	0.3769
TDx	/m/ target to vowel 2 target	0.95	1, 37	0.3355
Horiz	Vowel 1 target interval	0.92	1, 37	0.3441
Vert	Vowel 1 target interval	7.84	1, 35	0.0083
TB2y	Vowel 1 target interval	4.86	1, 37	0.0338
TDx	Vowel 1 target interval	4.22	1, 37	0.0471
Horiz	/m/ target to vowel 2 onset	0.10	1, 37	0.7508
Vert	/m/ target to vowel 2 onset	10.30	1, 35	0.0028
TB2y	/m/ target to vowel 2 onset	5.29	1, 37	0.0272
TDx	/m/ target to vowel 2 onset	2.62	1, 37	0.1138
Horiz	movement into vowel 2	1.15	1, 37	0.2895
Vert	movement into vowel 2	6.54	1, 35	0.0150
TB2y	movement into vowel 2	4.16	1, 37	0.0486
TDx	movement into vowel 2	0.71	1, 37	0.4044
Horiz	movement into vowel 1	2.16	1, 37	0.1499
Vert	movement into vowel 1	0.01	1, 35	0.9433
TB2y	movement into vowel 1	0.51	1, 37	0.4778
TDx	movement into vowel 1	2.11	1, 37	0.1544
Horiz	Vowel 2 target interval	0.04	1, 37	0.8454
Vert	Vowel 2 target interval	3.83	1, 35	0.0584
TB2y	Vowel 2 target interval	0.09	1, 37	0.7684
TDx	Vowel 2 target interval	0.65	1, 37	0.4252
Horiz	vowel 1 target to cons target	4.68	1, 37	0.0371
Vert	vowel 1 target to cons target	0.75	1, 35	0.3927
TB2y	vowel 1 target to cons target	1.44	1, 37	0.2380
TDx	vowel 1 target to cons target	5.30	1, 37	0.0271
Horiz	cons target to vowel 2 target	0.22	1, 37	0.6435
Vert	cons target to vowel 2 target	0.01	1, 35	0.9218
TB2y	cons target to vowel 2 target	0.18	1, 37	0.6752
TDx	cons target to vowel 2 target	0.06	1, 37	0.8087

speaker effect	utterances measure	measured interval	F	df	p	SME sig?
I2						
Length						
	a-i bilabials					
	LA	Consonant target interval	19.59	1, 14	0.0006	
	Horiz	/m/ target to vowel 2 target	0.58	1, 13	0.4603	
	TB2y	/m/ target to vowel 2 target	0.12	1, 14	0.7304	
	Horiz	/m/ target to vowel 2 onset	0.15	1, 13	0.7085	
	TB2y	/m/ target to vowel 2 onset	2.22	1, 14	0.1583	
	Horiz	movement into vowel 2	0.01	1, 13	0.9227	
	TB2y	movement into vowel 2	0.91	1, 14	0.3571	
	Horiz	Vowel 2 target interval	0.02	1, 13	0.8808	
	TB2y	Vowel 2 target interval	0.06	1, 14	0.8101	
	Horiz	cons target to vowel 2 target	50.33	1, 13	0.0000	p,m
	TB2y	cons target to vowel 2 target	49.81	1, 14	0.0000	
	i-a bilabials					
	LA	Consonant target interval	190.35	1, 12	0.0000	
	Horiz	vowel 1 target to vowel 2 target	20.29	1, 12	0.0007	
	TB2y	vowel 1 target to vowel 2 target	11.18	1, 12	0.0059	
	TDx	vowel 1 target to vowel 2 target	39.47	1, 12	0.0000	
	Horiz	/m/ target to vowel 2 target	36.93	1, 12	0.0001	
	TB2y	/m/ target to vowel 2 target	11.54	1, 12	0.0053	
	TDx	/m/ target to vowel 2 target	30.15	1, 12	0.0001	
	Horiz	Vowel 1 target interval	37.98	1, 12	0.0000	
	TB2y	Vowel 1 target interval	91.97	1, 12	0.0000	
	TDx	Vowel 1 target interval	47.95	1, 12	0.0000	
	Horiz	/m/ target to vowel 2 onset	53.62	1, 12	0.0000	
	TB2y	/m/ target to vowel 2 onset	49.53	1, 12	0.0000	
	TDx	/m/ target to vowel 2 onset	34.62	1, 12	0.0001	
	Horiz	movement into vowel 2	30.74	1, 12	0.0001	
	TB2y	movement into vowel 2	7.33	1, 12	0.0190	
	TDx	movement into vowel 2	10.72	1, 12	0.0067	
	Horiz	movement into vowel 1	0.04	1, 12	0.8370	
	TB2y	movement into vowel 1	2.84	1, 12	0.1177	
	TDx	movement into vowel 1	0.02	1, 12	0.9005	
	Horiz	Vowel 2 target interval	2.05	1, 12	0.1776	
	TB2y	Vowel 2 target interval	0.10	1, 12	0.7619	
	TDx	Vowel 2 target interval	1.93	1, 12	0.1896	
	Horiz	vowel 1 target to cons target	18.35	1, 12	0.0011	
	TB2y	vowel 1 target to cons target	48.09	1, 12	0.0000	
	TDx	vowel 1 target to cons target	24.87	1, 12	0.0003	
	Horiz	cons target to vowel 2 target	1.74	1, 12	0.2117	
	TB2y	cons target to vowel 2 target	0.18	1, 12	0.6765	
	TDx	cons target to vowel 2 target	1.00	1, 12	0.3373	
Nasal						
	a-i bilabials					
	LA	Consonant target interval	2.51	1, 14	0.1352	
	Horiz	/m/ target to vowel 2 target	5.92	1, 13	0.0301	
	TB2y	/m/ target to vowel 2 target	3.77	1, 14	0.0725	

Horiz	/m/ target to vowel 2 onset	1.99	1, 13	0.1817
TB2y	/m/ target to vowel 2 onset	1.21	1, 14	0.2908
Horiz	movement into vowel 2	0.29	1, 13	0.6020
TB2y	movement into vowel 2	0.03	1, 14	0.8712
Horiz	Vowel 2 target interval	0.01	1, 13	0.9187
TB2y	Vowel 2 target interval	0.11	1, 14	0.7446
Horiz	cons target to vowel 2 target	4.68	1, 13	0.0497
TB2y	cons target to vowel 2 target	2.47	1, 14	0.1384
i-a bilabials				
LA	Consonant target interval	190.35	1, 12	0.0000
Horiz	vowel 1 target to vowel 2 target	0.05	1, 12	0.8186
TB2y	vowel 1 target to vowel 2 target	0.55	1, 12	0.4711
TDx	vowel 1 target to vowel 2 target	0.21	1, 12	0.6517
Horiz	/m/ target to vowel 2 target	0.49	1, 12	0.4969
TB2y	/m/ target to vowel 2 target	1.37	1, 12	0.2645
TDx	/m/ target to vowel 2 target	0.06	1, 12	0.8066
Horiz	Vowel 1 target interval	0.01	1, 12	0.9065
TB2y	Vowel 1 target interval	0.63	1, 12	0.4436
TDx	Vowel 1 target interval	3.73	1, 12	0.0776
Horiz	/m/ target to vowel 2 onset	1.02	1, 12	0.3324
TB2y	/m/ target to vowel 2 onset	0.06	1, 12	0.8102
TDx	/m/ target to vowel 2 onset	3.15	1, 12	0.1013
Horiz	movement into vowel 2	1.16	1, 12	0.3017
TB2y	movement into vowel 2	3.20	1, 12	0.0990
TDx	movement into vowel 2	10.06	1, 12	0.0080
Horiz	movement into vowel 1	0.47	1, 12	0.5075
TB2y	movement into vowel 1	0.63	1, 12	0.4442
TDx	movement into vowel 1	0.52	1, 12	0.4859
Horiz	Vowel 2 target interval	9.56	1, 12	0.0093
TB2y	Vowel 2 target interval	2.13	1, 12	0.1700
TDx	Vowel 2 target interval	11.17	1, 12	0.0059
Horiz	vowel 1 target to cons target	0.91	1, 12	0.3592
TB2y	vowel 1 target to cons target	2.77	1, 12	0.1221
TDx	vowel 1 target to cons target	0.09	1, 12	0.7703
Horiz	cons target to vowel 2 target	2.22	1, 12	0.1617
TB2y	cons target to vowel 2 target	3.54	1, 12	0.0844
TDx	cons target to vowel 2 target	0.03	1, 12	0.8649
Length X Nasal				
a-i bilabials				
LA	Consonant target interval	1.61	1, 14	0.2255
Horiz	/m/ target to vowel 2 target	19.65	1, 13	0.0007
TB2y	/m/ target to vowel 2 target	8.96	1, 14	0.0097
Horiz	/m/ target to vowel 2 onset	0.85	1, 13	0.3737
TB2y	/m/ target to vowel 2 onset	1.16	1, 14	0.3000
Horiz	movement into vowel 2	0.87	1, 13	0.3691
TB2y	movement into vowel 2	0.52	1, 14	0.4817
Horiz	Vowel 2 target interval	0.20	1, 13	0.6625
TB2y	Vowel 2 target interval	0.02	1, 14	0.8940
Horiz	cons target to vowel 2 target	6.36	1, 13	0.0255
TB2y	cons target to vowel 2 target	0.92	1, 14	0.3541
i-a bilabials				

LA	Consonant target interval	2.71	1, 12	0.1258
Horiz	vowel 1 target to vowel 2 target	1.10	1, 12	0.3149
TB2y	vowel 1 target to vowel 2 target	0.04	1, 12	0.8364
TDx	vowel 1 target to vowel 2 target	0.00	1, 12	0.9484
Horiz	/m/ target to vowel 2 target	0.49	1, 12	0.4969
TB2y	/m/ target to vowel 2 target	0.07	1, 12	0.8016
TDx	/m/ target to vowel 2 target	0.21	1, 12	0.6563
Horiz	Vowel 1 target interval	1.74	1, 12	0.2118
TB2y	Vowel 1 target interval	0.70	1, 12	0.4206
TDx	Vowel 1 target interval	0.56	1, 12	0.4689
Horiz	/m/ target to vowel 2 onset	0.06	1, 12	0.8049
TB2y	/m/ target to vowel 2 onset	0.43	1, 12	0.5250
TDx	/m/ target to vowel 2 onset	0.08	1, 12	0.7841
Horiz	movement into vowel 2	0.87	1, 12	0.3706
TB2y	movement into vowel 2	0.13	1, 12	0.7268
TDx	movement into vowel 2	0.96	1, 12	0.3470
Horiz	movement into vowel 1	2.65	1, 12	0.1292
TB2y	movement into vowel 1	0.01	1, 12	0.9195
TDx	movement into vowel 1	0.54	1, 12	0.4780
Horiz	Vowel 2 target interval	11.24	1, 12	0.0058
TB2y	Vowel 2 target interval	0.30	1, 12	0.5924
TDx	Vowel 2 target interval	13.21	1, 12	0.0034
Horiz	vowel 1 target to cons target	1.63	1, 12	0.2262
TB2y	vowel 1 target to cons target	0.41	1, 12	0.5344
TDx	vowel 1 target to cons target	0.00	1, 12	0.9767
Horiz	cons target to vowel 2 target	0.08	1, 12	0.7792
TB2y	cons target to vowel 2 target	0.01	1, 12	0.9332
TDx	cons target to vowel 2 target	0.00	1, 12	0.9661

speaker effect	utterances measure	measured interval	F	df	p	SME sig?
I3						
Length						
	a-i bilabials					
	LA	Consonant target interval	45.09	1, 19	0.0000	
	Horiz	/m/ target to vowel 2 target	28.38	1, 19	0.0000	
	TBy	/m/ target to vowel 2 target	29.41	1, 19	0.0000	p,m
	TBx	/m/ target to vowel 2 target	11.47	1, 19	0.0031	
	Horiz	/m/ target to vowel 2 onset	0.11	1, 19	0.7492	
	TBy	/m/ target to vowel 2 onset	0.13	1, 19	0.7181	
	TBx	/m/ target to vowel 2 onset	0.00	1, 19	0.9605	
	Horiz	movement into vowel 2	8.82	1, 20	0.0076	
	TBy	movement into vowel 2	11.67	1, 20	0.0027	
	TBx	movement into vowel 2	4.96	1, 20	0.0377	
	Horiz	Vowel 2 target interval	0.85	1, 20	0.3664	
	TBy	Vowel 2 target interval	0.64	1, 20	0.4329	
	TBx	Vowel 2 target interval	2.62	1, 20	0.1210	
	Horiz	cons target to vowel 2 target	67.58	1, 20	0.0000	p,m
	TBy	cons target to vowel 2 target	97.03	1, 20	0.0000	p,m
	TBx	cons target to vowel 2 target	26.15	1, 20	0.0001	
	i-a bilabials					
	LA	Consonant target interval	21.60	1, 11	0.0007	
	Horiz	vowel 1 target to vowel 2 target	6.39	1, 11	0.0281	
	TBy	vowel 1 target to vowel 2 target	2.57	1, 11	0.1371	
	TBx	vowel 1 target to vowel 2 target	7.63	1, 11	0.0185	
	Horiz	/m/ target to vowel 2 target	3.52	1, 11	0.0872	
	TBy	/m/ target to vowel 2 target	1.28	1, 11	0.2816	
	TBx	/m/ target to vowel 2 target	3.01	1, 11	0.1106	
	Horiz	Vowel 1 target interval	46.18	1, 11	0.0000	
	TBy	Vowel 1 target interval	38.43	1, 11	0.0001	
	TBx	Vowel 1 target interval	31.39	1, 11	0.0002	
	Horiz	/m/ target to vowel 2 onset	76.52	1, 11	0.0000	
	TBy	/m/ target to vowel 2 onset	61.58	1, 11	0.0000	
	TBx	/m/ target to vowel 2 onset	46.42	1, 11	0.0000	
	Horiz	movement into vowel 2	27.39	1, 11	0.0003	
	TBy	movement into vowel 2	48.56	1, 11	0.0000	
	TBx	movement into vowel 2	7.77	1, 11	0.0176	
	Horiz	movement into vowel 1	0.01	1, 11	0.9052	
	TBy	movement into vowel 1	0.04	1, 11	0.8385	
	TBx	movement into vowel 1	4.90	1, 11	0.0707	
	Horiz	Vowel 2 target interval	1.76	1, 11	0.2119	
	TBy	Vowel 2 target interval	0.02	1, 11	0.8924	
	TBx	Vowel 2 target interval	1.08	1, 11	0.3200	
	Horiz	vowel 1 target to cons target	17.89	1, 11	0.0014	
	TBy	vowel 1 target to cons target	20.61	1, 11	0.0008	
	TBx	vowel 1 target to cons target	17.33	1, 11	0.0016	
	Horiz	cons target to vowel 2 target	6.73	1, 11	0.0250	
	TBy	cons target to vowel 2 target	16.83	1, 11	0.0018	
	TBx	cons target to vowel 2 target	2.00	1, 11	0.1851	

Nasal				
a-i bilabials				
LA	Consonant target interval	1.90	1, 19	0.1844
Horiz	/m/ target to vowel 2 target	0.52	1, 19	0.4786
TBy	/m/ target to vowel 2 target	1.18	1, 19	0.2906
TBx	/m/ target to vowel 2 target	0.07	1, 19	0.7936
Horiz	/m/ target to vowel 2 onset	0.43	1, 19	0.5213
TBy	/m/ target to vowel 2 onset	0.28	1, 19	0.6004
TBx	/m/ target to vowel 2 onset	0.81	1, 19	0.3801
Horiz	movement into vowel 2	0.21	1, 20	0.6505
TBy	movement into vowel 2	0.02	1, 20	0.8880
TBx	movement into vowel 2	0.85	1, 20	0.3666
Horiz	Vowel 2 target interval	0.87	1, 20	0.3617
TBy	Vowel 2 target interval	0.92	1, 20	0.3492
TBx	Vowel 2 target interval	0.25	1, 20	0.6221
Horiz	cons target to vowel 2 target	18.58	1, 20	0.0003
TBy	cons target to vowel 2 target	33.94	1, 20	0.0000
TBx	cons target to vowel 2 target	7.58	1, 20	0.0123
i-a bilabials				
LA	Consonant target interval	4.08	1, 11	0.0684
Horiz	vowel 1 target to vowel 2 target	0.36	1, 11	0.5610
TBy	vowel 1 target to vowel 2 target	0.17	1, 11	0.6891
TBx	vowel 1 target to vowel 2 target	0.14	1, 11	0.7191
Horiz	/m/ target to vowel 2 target	0.59	1, 11	0.4573
TBy	/m/ target to vowel 2 target	0.82	1, 11	0.3844
TBx	/m/ target to vowel 2 target	0.00	1, 11	0.9550
Horiz	Vowel 1 target interval	1.78	1, 11	0.2092
TBy	Vowel 1 target interval	1.81	1, 11	0.2057
TBx	Vowel 1 target interval	2.01	1, 11	0.1841
Horiz	/m/ target to vowel 2 onset	4.73	1, 11	0.0524
TBy	/m/ target to vowel 2 onset	5.92	1, 11	0.0332
TBx	/m/ target to vowel 2 onset	3.04	1, 11	0.1093
Horiz	movement into vowel 2	0.73	1, 11	0.4100
TBy	movement into vowel 2	1.92	1, 11	0.1930
TBx	movement into vowel 2	1.39	1, 11	0.2630
Horiz	movement into vowel 1	0.05	1, 11	0.8333
TBy	movement into vowel 1	0.21	1, 11	0.6538
TBx	movement into vowel 1	0.20	1, 11	0.6663
Horiz	Vowel 2 target interval	5.53	1, 11	0.0384
TBy	Vowel 2 target interval	0.00	1, 11	0.9532
TBx	Vowel 2 target interval	2.24	1, 11	0.1630
Horiz	vowel 1 target to cons target	0.17	1, 11	0.6847
TBy	vowel 1 target to cons target	0.39	1, 11	0.5433
TBx	vowel 1 target to cons target	0.01	1, 11	0.9396
Horiz	cons target to vowel 2 target	2.78	1, 11	0.1235
TBy	cons target to vowel 2 target	3.11	1, 11	0.1056
TBx	cons target to vowel 2 target	0.16	1, 11	0.6940
Length X Nasal				
a-i bilabials				
LA	Consonant target interval	1.36	1, 19	0.2579
Horiz	/m/ target to vowel 2 target	3.67	1, 19	0.0705

TBy	/m/ target to vowel 2 target	5.79	1, 19	0.0264
TBx	/m/ target to vowel 2 target	0.44	1, 19	0.5174
Horiz	/m/ target to vowel 2 onset	1.81	1, 19	0.1946
TBy	/m/ target to vowel 2 onset	2.36	1, 19	0.1406
TBx	/m/ target to vowel 2 onset	1.84	1, 19	0.1912
Horiz	movement into vowel 2	0.44	1, 20	0.5140
TBy	movement into vowel 2	0.01	1, 20	0.9158
TBx	movement into vowel 2	1.36	1, 20	0.2573
Horiz	Vowel 2 target interval	3.59	1, 20	0.0727
TBy	Vowel 2 target interval	5.59	1, 20	0.0283
TBx	Vowel 2 target interval	0.47	1, 20	0.4991
Horiz	cons target to vowel 2 target	13.10	1, 20	0.0017
TBy	cons target to vowel 2 target	24.47	1, 20	0.0001
TBx	cons target to vowel 2 target	2.98	1, 20	0.0996
i-a bilabials				
LA	Consonant target interval	1.25	1, 11	0.2882
Horiz	vowel 1 target to vowel 2 target	0.03	1, 11	0.8624
TBy	vowel 1 target to vowel 2 target	0.15	1, 11	0.7080
TBx	vowel 1 target to vowel 2 target	0.07	1, 11	0.8018
Horiz	/m/ target to vowel 2 target	0.02	1, 11	0.8904
TBy	/m/ target to vowel 2 target	0.14	1, 11	0.7130
TBx	/m/ target to vowel 2 target	0.12	1, 11	0.7325
Horiz	Vowel 1 target interval	0.23	1, 11	0.6440
TBy	Vowel 1 target interval	0.08	1, 11	0.7817
TBx	Vowel 1 target interval	0.05	1, 11	0.8316
Horiz	/m/ target to vowel 2 onset	0.67	1, 11	0.4311
TBy	/m/ target to vowel 2 onset	0.04	1, 11	0.8379
TBx	/m/ target to vowel 2 onset	0.19	1, 11	0.6676
Horiz	movement into vowel 2	0.91	1, 11	0.3618
TBy	movement into vowel 2	0.09	1, 11	0.7710
TBx	movement into vowel 2	0.01	1, 11	0.9165
Horiz	movement into vowel 1	0.12	1, 11	0.7354
TBy	movement into vowel 1	0.30	1, 11	0.5944
TBx	movement into vowel 1	0.87	1, 11	0.3714
Horiz	Vowel 2 target interval	0.11	1, 11	0.7503
TBy	Vowel 2 target interval	2.82	1, 11	0.1212
TBx	Vowel 2 target interval	0.27	1, 11	0.6148
Horiz	vowel 1 target to cons target	0.70	1, 11	0.4220
TBy	vowel 1 target to cons target	1.20	1, 11	0.2969
TBx	vowel 1 target to cons target	0.47	1, 11	0.5050
Horiz	cons target to vowel 2 target	2.68	1, 11	0.1301
TBy	cons target to vowel 2 target	0.99	1, 11	0.3415
TBx	cons target to vowel 2 target	0.25	1, 11	0.6236

Table A2.6. Analysis of variance for articulatory measures of utterances with geminate and cluster bilabial consonants for Italian speaker I1.

speaker effect	utterances measure	measured interval	F	df	p
I1					
Long Consonant Type					
a-i bilabials					
	LA	Consonant target interval	23.39	2, 23	0.0000
	Horiz	/m/ target to vowel 2 target	1.72	2, 23	0.2014
	Vert	/m/ target to vowel 2 target	1.54	2, 21	0.2383
	TB2y	/m/ target to vowel 2 target	5.12	2, 23	0.0145
	TDx	/m/ target to vowel 2 target	8.94	2, 23	0.0013
	Horiz	/m/ target to vowel 2 onset	1.36	2, 23	0.2761
	Vert	/m/ target to vowel 2 onset	0.93	2, 21	0.4104
	TB2y	/m/ target to vowel 2 onset	10.96	2, 23	0.0005
	TDx	/m/ target to vowel 2 onset	2.26	2, 23	0.1267
	Horiz	movement into vowel 2	0.12	2, 23	0.8912
	Vert	movement into vowel 2	0.80	2, 21	0.4625
	TB2y	movement into vowel 2	12.08	2, 23	0.0003
	TDx	movement into vowel 2	1.20	2, 23	0.3184
	Horiz	Vowel 2 target interval	0.68	2, 23	0.5167
	Vert	Vowel 2 target interval	3.66	2, 21	0.0434
	TB2y	Vowel 2 target interval	2.20	2, 23	0.1331
	TDx	Vowel 2 target interval	3.01	2, 23	0.0689
	Horiz	cons target to vowel 2 target	3.15	2, 23	0.0619
	Vert	cons target to vowel 2 target	1.34	2, 21	0.2844
	TB2y	cons target to vowel 2 target	6.67	2, 23	0.0052
	TDx	cons target to vowel 2 target	13.57	2, 23	0.0001
i-a bilabials					
	LA	Consonant target interval	7.69	2, 24	0.0026
	Horiz	vowel 1 target to vowel 2 target	6.62	2, 24	0.0051
	Vert	vowel 1 target to vowel 2 target	6.50	2, 22	0.0061
	TB2y	vowel 1 target to vowel 2 target	14.02	2, 24	0.0001
	TDx	vowel 1 target to vowel 2 target	4.34	2, 24	0.0247
	Horiz	/m/ target to vowel 2 target	9.44	2, 24	0.0009
	Vert	/m/ target to vowel 2 target	18.74	2, 22	0.0000
	TB2y	/m/ target to vowel 2 target	28.48	2, 24	0.0000
	TDx	/m/ target to vowel 2 target	4.79	2, 24	0.0177
	Horiz	Vowel 1 target interval	2.91	2, 24	0.0740
	Vert	Vowel 1 target interval	21.09	2, 22	0.0000
	TB2y	Vowel 1 target interval	11.83	2, 24	0.0003
	TDx	Vowel 1 target interval	5.76	2, 24	0.0090
	Horiz	/m/ target to vowel 2 onset	3.98	2, 24	0.0322
	Vert	/m/ target to vowel 2 onset	38.15	2, 22	0.0000
	TB2y	/m/ target to vowel 2 onset	20.42	2, 24	0.0000
	TDx	/m/ target to vowel 2 onset	7.43	2, 24	0.0031
	Horiz	movement into vowel 2	1.92	2, 24	0.1691
	Vert	movement into vowel 2	5.01	2, 22	0.0161
	TB2y	movement into vowel 2	0.16	2, 24	0.8562

TDx	movement into vowel 2	0.91	2, 24	0.4178
Horiz	movement into vowel 1	1.97	2, 24	0.1609
Vert	movement into vowel 1	3.68	2, 22	0.0417
TB2y	movement into vowel 1	3.57	2, 24	0.0440
TDx	movement into vowel 1	1.00	2, 24	0.3816
Horiz	Vowel 2 target interval	11.09	2, 24	0.0004
Vert	Vowel 2 target interval	0.68	2, 22	0.5151
TB2y	Vowel 2 target interval	1.36	2, 24	0.2750
TDx	Vowel 2 target interval	3.90	2, 24	0.0342
Horiz	vowel 1 target to cons target	4.70	2, 24	0.0189
Vert	vowel 1 target to cons target	3.52	2, 22	0.0470
TB2y	vowel 1 target to cons target	3.34	2, 24	0.0527
TDx	vowel 1 target to cons target	6.35	2, 24	0.0061
Horiz	cons target to vowel 2 target	2.99	2, 24	0.0691
Vert	cons target to vowel 2 target	12.92	2, 22	0.0002
TB2y	cons target to vowel 2 target	13.55	2, 24	0.0001
TDx	cons target to vowel 2 target	1.45	2, 24	0.2543

Table A2.7. Analysis of variance for articulatory measures of utterances with single and geminate bilabial consonants for Japanese speakers.

speaker effect	utterances measure	measured interval	F	df	p	SME sig?
J1						
Length						
	a-i bilabials					
	LLy	Consonant target interval	172.91	1, 60	0.0000	
	Horiz	/m/ target to vowel 2 target	40.42	1, 60	0.0000	p,m
	Vert	/m/ target to vowel 2 target	35.77	1, 60	0.0000	p,m
	TB2y	/m/ target to vowel 2 target	44.89	1, 60	0.0000	p,m
	TDx	/m/ target to vowel 2 target	52.25	1, 60	0.0000	p,m
	Horiz	/m/ target to vowel 2 onset	47.54	1, 60	0.0000	p,m
	Vert	/m/ target to vowel 2 onset	13.92	1, 60	0.0004	m
	TB2y	/m/ target to vowel 2 onset	15.58	1, 60	0.0002	m
	TDx	/m/ target to vowel 2 onset	41.50	1, 60	0.0000	
	Horiz	movement into vowel 2	1.47	1, 61	0.2295	
	Vert	movement into vowel 2	4.64	1, 61	0.0351	
	TB2y	movement into vowel 2	20.46	1, 61	0.0000	
	TDx	movement into vowel 2	6.47	1, 61	0.0135	
	Horiz	Vowel 2 target interval	48.70	1, 61	0.0000	
	Vert	Vowel 2 target interval	33.26	1, 61	0.0000	
	TB2y	Vowel 2 target interval	37.40	1, 61	0.0000	
	TDx	Vowel 2 target interval	44.36	1, 61	0.0000	
	Horiz	cons target to vowel 2 target	14.11	1, 61	0.0004	
	Vert	cons target to vowel 2 target	9.10	1, 61	0.0037	m
	TB2y	cons target to vowel 2 target	21.50	1, 61	0.0000	
	TDx	cons target to vowel 2 target	23.32	1, 61	0.0000	
	i-a bilabials					
	LLy	Consonant target interval	243.57	1, 65	0.0000	
	Horiz	vowel 1 target to vowel 2 target	111.16	1, 66	0.0000	
	Vert	vowel 1 target to vowel 2 target	52.95	1, 67	0.0000	
	TB2y	vowel 1 target to vowel 2 target	69.10	1, 64	0.0000	
	TDx	vowel 1 target to vowel 2 target	94.98	1, 59	0.0000	
	Horiz	/m/ target to vowel 2 target	154.08	1, 65	0.0000	
	Vert	/m/ target to vowel 2 target	96.68	1, 65	0.0000	
	TB2y	/m/ target to vowel 2 target	96.61	1, 65	0.0000	
	TDx	/m/ target to vowel 2 target	160.22	1, 65	0.0000	
	Horiz	Vowel 1 target interval	114.37	1, 66	0.0000	
	Vert	Vowel 1 target interval	18.51	1, 67	0.0001	
	TB2y	Vowel 1 target interval	26.18	1, 64	0.0000	p,m
	TDx	Vowel 1 target interval	77.30	1, 59	0.0000	p,m
	Horiz	/m/ target to vowel 2 onset	146.11	1, 65	0.0000	
	Vert	/m/ target to vowel 2 onset	44.68	1, 65	0.0000	
	TB2y	/m/ target to vowel 2 onset	57.33	1, 65	0.0000	p,m
	TDx	/m/ target to vowel 2 onset	146.13	1, 65	0.0000	p,m
	Horiz	movement into vowel 2	2.69	1, 66	0.1059	
	Vert	movement into vowel 2	31.71	1, 67	0.0000	
	TB2y	movement into vowel 2	50.38	1, 64	0.0000	

TDx	movement into vowel 2	1.34	1, 59	0.2514	
Horiz	movement into vowel 1	4.29	1, 68	0.0421	
Vert	movement into vowel 1	2.17	1, 68	0.1451	
TB2y	movement into vowel 1	5.73	1, 68	0.0195	
TDx	movement into vowel 1	3.67	1, 68	0.0596	
Horiz	Vowel 2 target interval	5.85	1, 66	0.0183	
Vert	Vowel 2 target interval	3.41	1, 67	0.0690	
TB2y	Vowel 2 target interval	0.33	1, 64	0.5701	
TDx	Vowel 2 target interval	2.41	1, 59	0.1257	
Horiz	vowel 1 target to cons target	4.04	1, 68	0.0484	
Vert	vowel 1 target to cons target	1.31	1, 68	0.2555	
TB2y	vowel 1 target to cons target	3.11	1, 68	0.0823	
TDx	vowel 1 target to cons target	4.53	1, 68	0.0369	m
Horiz	cons target to vowel 2 target	153.49	1, 66	0.0000	
Vert	cons target to vowel 2 target	73.06	1, 67	0.0000	
TB2y	cons target to vowel 2 target	87.96	1, 64	0.0000	
TDx	cons target to vowel 2 target	121.55	1, 59	0.0000	
Nasal					
a-i bilabials					
LLy	Consonant target interval	0.45	1, 60	0.5068	
Horiz	/m/ target to vowel 2 target	6.80	1, 60	0.0115	
Vert	/m/ target to vowel 2 target	11.16	1, 60	0.0014	
TB2y	/m/ target to vowel 2 target	11.17	1, 60	0.0014	
TDx	/m/ target to vowel 2 target	9.44	1, 60	0.0032	
Horiz	/m/ target to vowel 2 onset	6.45	1, 60	0.0137	
Vert	/m/ target to vowel 2 onset	10.53	1, 60	0.0019	
TB2y	/m/ target to vowel 2 onset	9.53	1, 60	0.0031	
TDx	/m/ target to vowel 2 onset	6.93	1, 60	0.0108	
Horiz	movement into vowel 2	0.58	1, 61	0.4489	
Vert	movement into vowel 2	0.05	1, 61	0.8324	
TB2y	movement into vowel 2	0.77	1, 61	0.3845	
TDx	movement into vowel 2	1.47	1, 61	0.2298	
Horiz	Vowel 2 target interval	4.84	1, 61	0.0316	
Vert	Vowel 2 target interval	1.44	1, 61	0.2340	
TB2y	Vowel 2 target interval	6.39	1, 61	0.0141	
TDx	Vowel 2 target interval	9.30	1, 61	0.0034	
Horiz	cons target to vowel 2 target	0.05	1, 61	0.8298	
Vert	cons target to vowel 2 target	0.18	1, 61	0.6702	
TB2y	cons target to vowel 2 target	0.70	1, 61	0.4055	
TDx	cons target to vowel 2 target	0.13	1, 61	0.7146	
i-a bilabials					
LLy	Consonant target interval	3.39	1, 65	0.0702	
Horiz	vowel 1 target to vowel 2 target	1.13	1, 66	0.2922	
Vert	vowel 1 target to vowel 2 target	5.62	1, 67	0.0206	
TB2y	vowel 1 target to vowel 2 target	2.36	1, 64	0.1296	
TDx	vowel 1 target to vowel 2 target	0.88	1, 59	0.3508	
Horiz	/m/ target to vowel 2 target	0.00	1, 65	0.9737	
Vert	/m/ target to vowel 2 target	16.49	1, 65	0.0001	
TB2y	/m/ target to vowel 2 target	3.29	1, 65	0.0744	
TDx	/m/ target to vowel 2 target	0.26	1, 65	0.6117	
Horiz	Vowel 1 target interval	17.91	1, 66	0.0001	

Vert	Vowel 1 target interval	0.67	1, 67	0.4161
TB2y	Vowel 1 target interval	9.35	1, 64	0.0033
TDx	Vowel 1 target interval	13.13	1, 59	0.0006
Horiz	/m/ target to vowel 2 onset	15.11	1, 65	0.0002
Vert	/m/ target to vowel 2 onset	5.79	1, 65	0.0190
TB2y	/m/ target to vowel 2 onset	16.73	1, 65	0.0001
TDx	/m/ target to vowel 2 onset	16.64	1, 65	0.0001
Horiz	movement into vowel 2	36.15	1, 66	0.0000
Vert	movement into vowel 2	7.38	1, 67	0.0084
TB2y	movement into vowel 2	3.76	1, 64	0.0570
TDx	movement into vowel 2	19.60	1, 59	0.0000
Horiz	movement into vowel 1	0.37	1, 68	0.5443
Vert	movement into vowel 1	2.09	1, 68	0.1526
TB2y	movement into vowel 1	0.53	1, 68	0.4673
TDx	movement into vowel 1	0.10	1, 68	0.7510
Horiz	Vowel 2 target interval	1.36	1, 66	0.2477
Vert	Vowel 2 target interval	5.56	1, 67	0.0213
TB2y	Vowel 2 target interval	2.44	1, 64	0.1234
TDx	Vowel 2 target interval	0.39	1, 59	0.5369
Horiz	vowel 1 target to cons target	14.60	1, 68	0.0003
Vert	vowel 1 target to cons target	1.61	1, 68	0.2094
TB2y	vowel 1 target to cons target	10.69	1, 68	0.0017
TDx	vowel 1 target to cons target	10.35	1, 68	0.0020
Horiz	cons target to vowel 2 target	15.59	1, 66	0.0002
Vert	cons target to vowel 2 target	2.45	1, 67	0.1224
TB2y	cons target to vowel 2 target	1.32	1, 64	0.2553
TDx	cons target to vowel 2 target	4.90	1, 59	0.0307
Length X Nasal				
a-i bilabials				
LLy	Consonant target interval	2.11	1, 65	0.1513
Horiz	/m/ target to vowel 2 target	5.43	1, 60	0.0232
Vert	/m/ target to vowel 2 target	10.37	1, 60	0.0021
TB2y	/m/ target to vowel 2 target	8.44	1, 60	0.0051
TDx	/m/ target to vowel 2 target	8.47	1, 60	0.0050
Horiz	/m/ target to vowel 2 onset	4.66	1, 60	0.0349
Vert	/m/ target to vowel 2 onset	4.11	1, 60	0.0472
TB2y	/m/ target to vowel 2 onset	4.33	1, 60	0.0416
TDx	/m/ target to vowel 2 onset	3.50	1, 60	0.0664
Horiz	movement into vowel 2	0.90	1, 61	0.3457
Vert	movement into vowel 2	2.17	1, 61	0.1455
TB2y	movement into vowel 2	2.37	1, 61	0.1285
TDx	movement into vowel 2	3.89	1, 61	0.0531
Horiz	Vowel 2 target interval	0.37	1, 61	0.5435
Vert	Vowel 2 target interval	1.85	1, 61	0.1789
TB2y	Vowel 2 target interval	2.99	1, 61	0.0889
TDx	Vowel 2 target interval	2.50	1, 61	0.1189
Horiz	cons target to vowel 2 target	0.89	1, 61	0.3498
Vert	cons target to vowel 2 target	4.06	1, 61	0.0483
TB2y	cons target to vowel 2 target	3.24	1, 61	0.0767
TDx	cons target to vowel 2 target	2.53	1, 61	0.1170
i-a bilabials				

LLy	Consonant target interval	2.11	1, 65	0.1513
Horiz	vowel 1 target to vowel 2 target	1.64	1, 66	0.2052
Vert	vowel 1 target to vowel 2 target	1.00	1, 67	0.3216
TB2y	vowel 1 target to vowel 2 target	1.68	1, 64	0.1998
TDx	vowel 1 target to vowel 2 target	3.10	1, 59	0.0837
Horiz	/m/ target to vowel 2 target	3.85	1, 65	0.0541
Vert	/m/ target to vowel 2 target	1.11	1, 65	0.2962
TB2y	/m/ target to vowel 2 target	2.70	1, 65	0.1050
TDx	/m/ target to vowel 2 target	2.90	1, 65	0.0933
Horiz	Vowel 1 target interval	1.83	1, 66	0.1802
Vert	Vowel 1 target interval	1.58	1, 67	0.2134
TB2y	Vowel 1 target interval	4.05	1, 64	0.0483
TDx	Vowel 1 target interval	5.87	1, 59	0.0185
Horiz	/m/ target to vowel 2 onset	3.62	1, 65	0.0614
Vert	/m/ target to vowel 2 onset	2.10	1, 65	0.1518
TB2y	/m/ target to vowel 2 onset	5.66	1, 65	0.0203
TDx	/m/ target to vowel 2 onset	7.74	1, 65	0.0071
Horiz	movement into vowel 2	0.09	1, 66	0.7624
Vert	movement into vowel 2	0.05	1, 67	0.8175
TB2y	movement into vowel 2	0.58	1, 64	0.4473
TDx	movement into vowel 2	1.34	1, 59	0.2514
Horiz	movement into vowel 1	0.01	1, 68	0.9059
Vert	movement into vowel 1	0.69	1, 68	0.4074
TB2y	movement into vowel 1	1.19	1, 68	0.2792
TDx	movement into vowel 1	0.09	1, 68	0.7645
Horiz	Vowel 2 target interval	0.14	1, 66	0.7142
Vert	Vowel 2 target interval	0.02	1, 67	0.8929
TB2y	Vowel 2 target interval	1.52	1, 64	0.2227
TDx	Vowel 2 target interval	0.27	1, 59	0.6073
Horiz	vowel 1 target to cons target	1.08	1, 68	0.3020
Vert	vowel 1 target to cons target	1.56	1, 68	0.2159
TB2y	vowel 1 target to cons target	3.17	1, 68	0.0793
TDx	vowel 1 target to cons target	4.23	1, 68	0.0435
Horiz	cons target to vowel 2 target	0.23	1, 66	0.6328
Vert	cons target to vowel 2 target	0.00	1, 67	0.9584
TB2y	cons target to vowel 2 target	0.02	1, 64	0.8891
TDx	cons target to vowel 2 target	0.49	1, 59	0.4872

speaker effect	utterances measure	measured interval	F	df	p	SME sig?
J2						
Length						
	a-i bilabials					
	LA	Consonant target interval	178.63	1, 72	0.0000	p,m
	Horiz	/m/ target to vowel 2 target	27.74	1, 72	0.0000	
	Vert	/m/ target to vowel 2 target	3.28	1, 72	0.0741	
	TB2y	/m/ target to vowel 2 target	42.35	1, 72	0.0000	
	TDx	/m/ target to vowel 2 target	67.87	1, 72	0.0000	
	Horiz	/m/ target to vowel 2 onset	12.67	1, 72	0.0007	
	Vert	/m/ target to vowel 2 onset	9.65	1, 72	0.0027	
	TB2y	/m/ target to vowel 2 onset	18.56	1, 72	0.0001	
	TDx	/m/ target to vowel 2 onset	22.59	1, 72	0.0000	
	Horiz	movement into vowel 2	0.58	1, 74	0.4505	
	Vert	movement into vowel 2	0.02	1, 74	0.8812	
	TB2y	movement into vowel 2	20.53	1, 74	0.0000	
	TDx	movement into vowel 2	0.94	1, 74	0.3351	
	Horiz	Vowel 2 target interval	167.31	1, 74	0.0000	
	Vert	Vowel 2 target interval	63.26	1, 74	0.0000	
	TB2y	Vowel 2 target interval	117.11	1, 74	0.0000	
	TDx	Vowel 2 target interval	126.01	1, 74	0.0000	
	Horiz	cons target to vowel 2 target	1.70	1, 74	0.1961	
	Vert	cons target to vowel 2 target	4.78	1, 74	0.0320	
	TB2y	cons target to vowel 2 target	0.37	1, 74	0.5422	
	TDx	cons target to vowel 2 target	1.27	1, 74	0.2627	
	i-a bilabials					
	LA	Consonant target interval	256.84	1, 74	0.0000	
	Horiz	vowel 1 target to vowel 2 target	34.58	1, 74	0.0000	
	Vert	vowel 1 target to vowel 2 target	130.48	1, 71	0.0000	
	TB2y	vowel 1 target to vowel 2 target	198.92	1, 70	0.0000	
	TDx	vowel 1 target to vowel 2 target	64.95	1, 67	0.0000	
	Horiz	/m/ target to vowel 2 target	36.27	1, 74	0.0000	
	Vert	/m/ target to vowel 2 target	147.67	1, 72	0.0000	p,m
	TB2y	/m/ target to vowel 2 target	322.69	1, 74	0.0000	p,m
	TDx	/m/ target to vowel 2 target	84.38	1, 73	0.0000	
	Horiz	Vowel 1 target interval	24.58	1, 74	0.0000	
	Vert	Vowel 1 target interval	37.75	1, 71	0.0000	
	TB2y	Vowel 1 target interval	21.53	1, 70	0.0000	
	TDx	Vowel 1 target interval	22.76	1, 67	0.0000	
	Horiz	/m/ target to vowel 2 onset	27.72	1, 74	0.0000	
	Vert	/m/ target to vowel 2 onset	51.07	1, 72	0.0000	
	TB2y	/m/ target to vowel 2 onset	43.84	1, 74	0.0000	
	TDx	/m/ target to vowel 2 onset	31.87	1, 73	0.0000	
	Horiz	movement into vowel 2	1.19	1, 74	0.2790	
	Vert	movement into vowel 2	15.48	1, 71	0.0002	
	TB2y	movement into vowel 2	152.08	1, 70	0.0000	
	TDx	movement into vowel 2	28.33	1, 67	0.0000	
	Horiz	movement into vowel 1	0.38	1, 75	0.5405	
	Vert	movement into vowel 1	2.50	1, 73	0.1185	
	TB2y	movement into vowel 1	4.06	1, 75	0.0475	

TDx	movement into vowel 1	0.06	1, 73	0.8104	
Horiz	Vowel 2 target interval	20.25	1, 74	0.0000	m
Vert	Vowel 2 target interval	0.09	1, 71	0.7677	
TB2y	Vowel 2 target interval	0.14	1, 70	0.7085	
TDx	Vowel 2 target interval	4.55	1, 67	0.0365	
Horiz	vowel 1 target to cons target	36.62	1, 75	0.0000	
Vert	vowel 1 target to cons target	26.35	1, 73	0.0000	
TB2y	vowel 1 target to cons target	24.44	1, 75	0.0000	
TDx	vowel 1 target to cons target	33.27	1, 73	0.0000	
Horiz	cons target to vowel 2 target	6.79	1, 74	0.0111	
Vert	cons target to vowel 2 target	75.35	1, 71	0.0000	
TB2y	cons target to vowel 2 target	208.18	1, 70	0.0000	
TDx	cons target to vowel 2 target	38.92	1, 67	0.0000	
Nasal					
a-i bilabials					
LA	Consonant target interval	8.06	1, 72	0.0059	
Horiz	/m/ target to vowel 2 target	0.00	1, 72	0.9625	
Vert	/m/ target to vowel 2 target	30.36	1, 72	0.0000	
TB2y	/m/ target to vowel 2 target	21.40	1, 72	0.0000	
TDx	/m/ target to vowel 2 target	0.46	1, 72	0.4991	
Horiz	/m/ target to vowel 2 onset	0.36	1, 72	0.5524	
Vert	/m/ target to vowel 2 onset	8.46	1, 72	0.0048	
TB2y	/m/ target to vowel 2 onset	19.58	1, 72	0.0000	
TDx	/m/ target to vowel 2 onset	1.45	1, 72	0.2327	
Horiz	movement into vowel 2	0.75	1, 74	0.3878	
Vert	movement into vowel 2	18.73	1, 74	0.0000	
TB2y	movement into vowel 2	5.68	1, 74	0.0197	
TDx	movement into vowel 2	0.58	1, 74	0.4491	
Horiz	Vowel 2 target interval	1.29	1, 74	0.2601	
Vert	Vowel 2 target interval	23.46	1, 74	0.0000	
TB2y	Vowel 2 target interval	21.61	1, 74	0.0000	
TDx	Vowel 2 target interval	0.02	1, 74	0.8932	
Horiz	cons target to vowel 2 target	14.29	1, 74	0.0003	
Vert	cons target to vowel 2 target	13.42	1, 74	0.0005	
TB2y	cons target to vowel 2 target	3.44	1, 74	0.0678	
TDx	cons target to vowel 2 target	11.22	1, 74	0.0013	
i-a bilabials					
LA	Consonant target interval	0.21	1, 74	0.6484	
Horiz	vowel 1 target to vowel 2 target	2.05	1, 74	0.1568	
Vert	vowel 1 target to vowel 2 target	28.75	1, 71	0.0000	
TB2y	vowel 1 target to vowel 2 target	46.09	1, 70	0.0000	
TDx	vowel 1 target to vowel 2 target	2.67	1, 67	0.1071	
Horiz	/m/ target to vowel 2 target	0.35	1, 74	0.5555	
Vert	/m/ target to vowel 2 target	40.38	1, 72	0.0000	
TB2y	/m/ target to vowel 2 target	78.59	1, 74	0.0000	
TDx	/m/ target to vowel 2 target	1.88	1, 73	0.1750	
Horiz	Vowel 1 target interval	1.22	1, 74	0.2738	
Vert	Vowel 1 target interval	6.32	1, 71	0.0142	
TB2y	Vowel 1 target interval	6.56	1, 70	0.0126	
TDx	Vowel 1 target interval	1.99	1, 67	0.1625	
Horiz	/m/ target to vowel 2 onset	0.19	1, 74	0.6668	

Vert	/m/ target to vowel 2 onset	13.80	1, 72	0.0004
TB2y	/m/ target to vowel 2 onset	15.82	1, 74	0.0002
TDx	/m/ target to vowel 2 onset	1.37	1, 73	0.2454
Horiz	movement into vowel 2	0.17	1, 74	0.6834
Vert	movement into vowel 2	4.56	1, 71	0.0363
TB2y	movement into vowel 2	30.33	1, 70	0.0000
TDx	movement into vowel 2	0.24	1, 67	0.6260
Horiz	movement into vowel 1	5.18	1, 75	0.0256
Vert	movement into vowel 1	6.10	1, 73	0.0159
TB2y	movement into vowel 1	2.59	1, 75	0.1114
TDx	movement into vowel 1	0.59	1, 73	0.4452
Horiz	Vowel 2 target interval	0.44	1, 74	0.5084
Vert	Vowel 2 target interval	9.53	1, 71	0.0029
TB2y	Vowel 2 target interval	0.12	1, 70	0.7284
TDx	Vowel 2 target interval	0.00	1, 67	0.9968
Horiz	vowel 1 target to cons target	19.88	1, 75	0.0000
Vert	vowel 1 target to cons target	1.03	1, 73	0.3142
TB2y	vowel 1 target to cons target	6.16	1, 75	0.0153
TDx	vowel 1 target to cons target	13.32	1, 73	0.0005
Horiz	cons target to vowel 2 target	4.22	1, 74	0.0434
Vert	cons target to vowel 2 target	21.74	1, 71	0.0000
TB2y	cons target to vowel 2 target	49.29	1, 70	0.0000
TDx	cons target to vowel 2 target	0.42	1, 67	0.5216
Length X Nasal				
a-i bilabials				
LA	Consonant target interval	9.09	1, 72	0.0036
Horiz	/m/ target to vowel 2 target	1.46	1, 72	0.2314
Vert	/m/ target to vowel 2 target	3.11	1, 72	0.0819
TB2y	/m/ target to vowel 2 target	2.06	1, 72	0.1554
TDx	/m/ target to vowel 2 target	0.13	1, 72	0.7150
Horiz	/m/ target to vowel 2 onset	2.01	1, 72	0.1606
Vert	/m/ target to vowel 2 onset	0.00	1, 72	0.9747
TB2y	/m/ target to vowel 2 onset	0.80	1, 72	0.3726
TDx	/m/ target to vowel 2 onset	0.00	1, 72	0.9825
Horiz	movement into vowel 2	0.64	1, 74	0.4269
Vert	movement into vowel 2	3.34	1, 74	0.0716
TB2y	movement into vowel 2	1.13	1, 74	0.2922
TDx	movement into vowel 2	0.02	1, 74	0.8985
Horiz	Vowel 2 target interval	2.17	1, 74	0.1452
Vert	Vowel 2 target interval	2.31	1, 74	0.1328
TB2y	Vowel 2 target interval	0.10	1, 74	0.7505
TDx	Vowel 2 target interval	1.34	1, 74	0.2510
Horiz	cons target to vowel 2 target	7.23	1, 74	0.0089
Vert	cons target to vowel 2 target	0.82	1, 74	0.3691
TB2y	cons target to vowel 2 target	0.13	1, 74	0.7167
TDx	cons target to vowel 2 target	3.30	1, 74	0.0734
i-a bilabials				
LA	Consonant target interval	0.03	1, 74	0.8665
Horiz	vowel 1 target to vowel 2 target	0.41	1, 74	0.5228
Vert	vowel 1 target to vowel 2 target	3.96	1, 71	0.0503
TB2y	vowel 1 target to vowel 2 target	2.01	1, 70	0.1605

TDx	vowel 1 target to vowel 2 target	0.05	1, 67	0.8229
Horiz	/m/ target to vowel 2 target	0.02	1, 74	0.9011
Vert	/m/ target to vowel 2 target	5.09	1, 72	0.0271
TB2y	/m/ target to vowel 2 target	4.22	1, 74	0.0435
TDx	/m/ target to vowel 2 target	0.18	1, 73	0.6706
Horiz	Vowel 1 target interval	1.48	1, 74	0.2270
Vert	Vowel 1 target interval	0.36	1, 71	0.5480
TB2y	Vowel 1 target interval	0.15	1, 70	0.6955
TDx	Vowel 1 target interval	1.23	1, 67	0.2709
Horiz	/m/ target to vowel 2 onset	0.47	1, 74	0.4946
Vert	/m/ target to vowel 2 onset	1.01	1, 72	0.3173
TB2y	/m/ target to vowel 2 onset	0.48	1, 74	0.4906
TDx	/m/ target to vowel 2 onset	0.95	1, 73	0.3330
Horiz	movement into vowel 2	0.68	1, 74	0.4114
Vert	movement into vowel 2	1.10	1, 71	0.2975
TB2y	movement into vowel 2	1.79	1, 70	0.1856
TDx	movement into vowel 2	3.21	1, 67	0.0776
Horiz	movement into vowel 1	0.01	1, 75	0.9288
Vert	movement into vowel 1	1.70	1, 73	0.1959
TB2y	movement into vowel 1	2.25	1, 75	0.1378
TDx	movement into vowel 1	0.02	1, 73	0.8871
Horiz	Vowel 2 target interval	4.47	1, 74	0.0379
Vert	Vowel 2 target interval	2.63	1, 71	0.1094
TB2y	Vowel 2 target interval	1.01	1, 70	0.3189
TDx	Vowel 2 target interval	1.95	1, 67	0.1676
Horiz	vowel 1 target to cons target	0.45	1, 75	0.5024
Vert	vowel 1 target to cons target	0.22	1, 73	0.6438
TB2y	vowel 1 target to cons target	0.94	1, 75	0.3349
TDx	vowel 1 target to cons target	1.02	1, 73	0.3164
Horiz	cons target to vowel 2 target	2.18	1, 74	0.1438
Vert	cons target to vowel 2 target	2.93	1, 71	0.0914
TB2y	cons target to vowel 2 target	0.59	1, 70	0.4432
TDx	cons target to vowel 2 target	0.14	1, 67	0.7115

speaker effect	utterances measure	measured interval	F	df	p	SME sig?
J3						
Length						
	a-i bilabials					
	LA	Consonant target interval	90.13	1, 49	0.0000	
	Horiz (ex TT)	/m/ target to vowel 2 target	126.94	1, 49	0.0000	p,m
	Horiz (in TT)	/m/ target to vowel 2 target	33.59	1, 49	0.0000	p,m
	Vert	/m/ target to vowel 2 target	175.56	1, 49	0.0000	
	TB2y	/m/ target to vowel 2 target	99.85	1, 49	0.0000	
	TDx	/m/ target to vowel 2 target	86.65	1, 49	0.0000	p,m
	Horiz (ex TT)	/m/ target to vowel 2 onset	131.08	1, 49	0.0000	p,m
	Horiz (in TT)	/m/ target to vowel 2 onset	64.66	1, 49	0.0000	
	Vert	/m/ target to vowel 2 onset	56.03	1, 49	0.0000	
	TB2y	/m/ target to vowel 2 onset	91.09	1, 49	0.0000	
	TDx	/m/ target to vowel 2 onset	131.80	1, 49	0.0000	
	Horiz (ex TT)	movement into vowel 2	33.74	1, 51	0.0000	p,m
	Horiz (in TT)	movement into vowel 2	0.18	1, 51	0.6741	
	Vert	movement into vowel 2	51.51	1, 51	0.0000	
	TB2y	movement into vowel 2	22.43	1, 51	0.0000	
	TDx	movement into vowel 2	10.44	1, 51	0.0022	m
	Horiz (ex TT)	Vowel 2 target interval	43.07	1, 51	0.0000	
	Horiz (in TT)	Vowel 2 target interval	36.06	1, 51	0.0000	
	Vert	Vowel 2 target interval	26.65	1, 51	0.0000	p,m
	TB2y	Vowel 2 target interval	8.54	1, 51	0.0052	
	TDx	Vowel 2 target interval	35.38	1, 51	0.0000	
	Horiz (ex TT)	cons target to vowel 2 target	1.36	1, 51	0.2494	
	Horiz (in TT)	cons target to vowel 2 target	1.31	1, 51	0.2573	
	Vert	cons target to vowel 2 target	5.60	1, 51	0.0218	p
	TB2y	cons target to vowel 2 target	6.77	1, 51	0.0121	
	TDx	cons target to vowel 2 target	1.33	1, 51	0.2542	
	i-a bilabials					
	LA	Consonant target interval	287.48	1, 51	0.0000	p,m
	Horiz (ex TT)	vowel 1 target to vowel 2 target	482.29	1, 51	0.0000	
	Horiz (in TT)	vowel 1 target to vowel 2 target	274.58	1, 51	0.0000	
	Vert	vowel 1 target to vowel 2 target	298.94	1, 50	0.0000	
	TB2y	vowel 1 target to vowel 2 target	174.93	1, 51	0.0000	
	TDx	vowel 1 target to vowel 2 target	396.25	1, 51	0.0000	

Horiz (ex TT)	/m/ target to vowel 2 target	1249.29	1, 51	0.0000	
Horiz (in TT)	/m/ target to vowel 2 target	956.02	1, 51	0.0000	
Vert	/m/ target to vowel 2 target	374.69	1, 50	0.0000	
TB2y	/m/ target to vowel 2 target	622.06	1, 51	0.0000	p,m
TDx	/m/ target to vowel 2 target	998.35	1, 51	0.0000	
Horiz (ex TT)	Vowel 1 target interval	349.53	1, 51	0.0000	
Horiz (in TT)	Vowel 1 target interval	201.53	1, 51	0.0000	
Vert	Vowel 1 target interval	93.46	1, 50	0.0000	
TB2y	Vowel 1 target interval	64.41	1, 51	0.0000	
TDx	Vowel 1 target interval	266.21	1, 51	0.0000	
Horiz (ex TT)	/m/ target to vowel 2 onset	743.36	1, 51	0.0000	p,m
Horiz (in TT)	/m/ target to vowel 2 onset	644.80	1, 51	0.0000	p,m
Vert	/m/ target to vowel 2 onset	105.96	1, 50	0.0000	
TB2y	/m/ target to vowel 2 onset	167.93	1, 51	0.0000	
TDx	/m/ target to vowel 2 onset	544.02	1, 51	0.0000	p,m
Horiz (ex TT)	movement into vowel 2	62.16	1, 51	0.0000	p,m
Horiz (in TT)	movement into vowel 2	33.61	1, 51	0.0000	p,m
Vert	movement into vowel 2	9.09	1, 50	0.0040	
TB2y	movement into vowel 2	12.57	1, 51	0.0008	
TDx	movement into vowel 2	44.23	1, 51	0.0000	p,m
Horiz (ex TT)	movement into vowel 1	3.44	1, 51	0.0695	
Horiz (in TT)	movement into vowel 1	1.92	1, 51	0.1720	
Vert	movement into vowel 1	8.99	1, 50	0.0042	
TB2y	movement into vowel 1	6.07	1, 51	0.0171	
TDx	movement into vowel 1	0.55	1, 51	0.4598	
Horiz (ex TT)	Vowel 2 target interval	9.39	1, 51	0.0035	
Horiz (in TT)	Vowel 2 target interval	0.59	1, 51	0.4453	
Vert	Vowel 2 target interval	8.07	1, 50	0.0065	
TB2y	Vowel 2 target interval	8.03	1, 51	0.0066	
TDx	Vowel 2 target interval	28.27	1, 51	0.0000	
Horiz (ex TT)	vowel 1 target to cons target	44.85	1, 51	0.0000	
Horiz (in TT)	vowel 1 target to cons target	33.68	1, 51	0.0000	
Vert	vowel 1 target to cons target	75.51	1, 50	0.0000	p,m
TB2y	vowel 1 target to cons target	15.74	1, 51	0.0002	
TDx	vowel 1 target to cons target	46.53	1, 51	0.0000	
Horiz (ex TT)	cons target to vowel 2 target	336.22	1, 51	0.0000	
Horiz (in TT)	cons target to vowel 2 target	302.47	1, 51	0.0000	

Vert	cons target to vowel 2 target	110.67	1, 50	0.0000
TB2y	cons target to vowel 2 target	127.24	1, 51	0.0000
TDx	cons target to vowel 2 target	276.74	1, 51	0.0000
Nasal				
a-i bilabials				
LA	Consonant target interval	6.04	1, 49	0.0176
Horiz (ex TT)	/m/ target to vowel 2 target	1.46	1, 49	0.2327
Horiz (in TT)	/m/ target to vowel 2 target	0.02	1, 49	0.8846
Vert	/m/ target to vowel 2 target	0.97	1, 49	0.3291
TB2y	/m/ target to vowel 2 target	13.32	1, 49	0.0006
TDx	/m/ target to vowel 2 target	1.58	1, 49	0.2151
Horiz (ex TT)	/m/ target to vowel 2 onset	0.62	1, 49	0.4338
Horiz (in TT)	/m/ target to vowel 2 onset	0.07	1, 49	0.7969
Vert	/m/ target to vowel 2 onset	3.84	1, 49	0.0557
TB2y	/m/ target to vowel 2 onset	0.54	1, 49	0.4640
TDx	/m/ target to vowel 2 onset	0.38	1, 49	0.5404
Horiz (ex TT)	movement into vowel 2	0.72	1, 51	0.4007
Horiz (in TT)	movement into vowel 2	0.01	1, 51	0.9408
Vert	movement into vowel 2	0.09	1, 51	0.7668
TB2y	movement into vowel 2	15.47	1, 51	0.0003
TDx	movement into vowel 2	0.99	1, 51	0.3239
Horiz (ex TT)	Vowel 2 target interval	9.34	1, 51	0.0036
Horiz (in TT)	Vowel 2 target interval	2.24	1, 51	0.1404
Vert	Vowel 2 target interval	9.90	1, 51	0.0028
TB2y	Vowel 2 target interval	1.87	1, 51	0.1778
TDx	Vowel 2 target interval	12.73	1, 51	0.0008
Horiz (ex TT)	cons target to vowel 2 target	2.88	1, 51	0.0960
Horiz (in TT)	cons target to vowel 2 target	3.06	1, 51	0.0862
Vert	cons target to vowel 2 target	5.06	1, 51	0.0289
TB2y	cons target to vowel 2 target	30.16	1, 51	0.0000
TDx	cons target to vowel 2 target	0.93	1, 51	0.3400
i-a bilabials				
LA	Consonant target interval	25.10	1, 51	0.0000
Horiz (ex TT)	vowel 1 target to vowel 2 target	0.21	1, 51	0.6486
Horiz (in TT)	vowel 1 target to vowel 2 target	0.01	1, 51	0.9420
Vert	vowel 1 target to vowel 2 target	4.89	1, 50	0.0316
TB2y	vowel 1 target to vowel 2 target	0.86	1, 51	0.3574
TDx	vowel 1 target to vowel 2 target	0.23	1, 51	0.6301
Horiz (ex TT)	/m/ target to vowel 2 target	0.68	1, 51	0.4138

Horiz (in TT)	/m/ target to vowel 2 target	0.00	1, 51	0.9814
Vert	/m/ target to vowel 2 target	1.02	1, 50	0.3182
TB2y	/m/ target to vowel 2 target	9.50	1, 51	0.0033
TDx	/m/ target to vowel 2 target	2.21	1, 51	0.1433
Horiz (ex TT)	Vowel 1 target interval	2.57	1, 51	0.1154
Horiz (in TT)	Vowel 1 target interval	0.67	1, 51	0.4186
Vert	Vowel 1 target interval	2.63	1, 50	0.1111
TB2y	Vowel 1 target interval	8.69	1, 51	0.0048
TDx	Vowel 1 target interval	2.69	1, 51	0.1073
Horiz (ex TT)	/m/ target to vowel 2 onset	6.02	1, 51	0.0176
Horiz (in TT)	/m/ target to vowel 2 onset	2.77	1, 51	0.1024
Vert	/m/ target to vowel 2 onset	0.47	1, 50	0.4967
TB2y	/m/ target to vowel 2 onset	26.57	1, 51	0.0000
TDx	/m/ target to vowel 2 onset	9.57	1, 51	0.0032
Horiz (ex TT)	movement into vowel 2	2.29	1, 51	0.1367
Horiz (in TT)	movement into vowel 2	2.10	1, 51	0.1534
Vert	movement into vowel 2	0.00	1, 50	0.9862
TB2y	movement into vowel 2	7.06	1, 51	0.0105
TDx	movement into vowel 2	3.68	1, 51	0.0605
Horiz (ex TT)	movement into vowel 1	1.58	1, 51	0.2140
Horiz (in TT)	movement into vowel 1	0.03	1, 51	0.8718
Vert	movement into vowel 1	6.31	1, 50	0.0153
TB2y	movement into vowel 1	0.07	1, 51	0.7896
TDx	movement into vowel 1	0.07	1, 51	0.7909
Horiz (ex TT)	Vowel 2 target interval	0.73	1, 51	0.3954
Horiz (in TT)	Vowel 2 target interval	1.45	1, 51	0.2338
Vert	Vowel 2 target interval	4.13	1, 50	0.0474
TB2y	Vowel 2 target interval	1.14	1, 51	0.2905
TDx	Vowel 2 target interval	0.39	1, 51	0.5372
Horiz (ex TT)	vowel 1 target to cons target	0.00	1, 51	0.9717
Horiz (in TT)	vowel 1 target to cons target	0.01	1, 51	0.9342
Vert	vowel 1 target to cons target	18.87	1, 50	0.0001
TB2y	vowel 1 target to cons target	0.48	1, 51	0.4902
TDx	vowel 1 target to cons target	1.82	1, 51	0.1829
Horiz (ex TT)	cons target to vowel 2 target	4.13	1, 51	0.0474
Horiz (in TT)	cons target to vowel 2 target	6.23	1, 51	0.0158
Vert	cons target to vowel 2 target	0.81	1, 50	0.3728
TB2y	cons target to vowel 2 target	0.04	1, 51	0.8418

TDx	cons target to vowel 2 target	1.74	1, 51	0.1925
Length X Nasal				
a-i bilabials				
LA	Consonant target interval	1.78	1, 49	0.1884
Horiz (ex TT)	/m/ target to vowel 2 target	12.43	1, 49	0.0009
Horiz (in TT)	/m/ target to vowel 2 target	4.61	1, 49	0.0368
Vert	/m/ target to vowel 2 target	0.05	1, 49	0.8274
TB2y	/m/ target to vowel 2 target	0.41	1, 49	0.5266
TDx	/m/ target to vowel 2 target	9.75	1, 49	0.0030
Horiz (ex TT)	/m/ target to vowel 2 onset	4.65	1, 49	0.0360
Horiz (in TT)	/m/ target to vowel 2 onset	1.84	1, 49	0.1817
Vert	/m/ target to vowel 2 onset	0.02	1, 49	0.8789
TB2y	/m/ target to vowel 2 onset	0.01	1, 49	0.9033
TDx	/m/ target to vowel 2 onset	2.69	1, 49	0.1075
Horiz (ex TT)	movement into vowel 2	7.61	1, 51	0.0080
Horiz (in TT)	movement into vowel 2	1.66	1, 51	0.2028
Vert	movement into vowel 2	0.02	1, 51	0.8858
TB2y	movement into vowel 2	0.25	1, 51	0.6194
TDx	movement into vowel 2	5.89	1, 51	0.0188
Horiz (ex TT)	Vowel 2 target interval	2.59	1, 51	0.1137
Horiz (in TT)	Vowel 2 target interval	0.39	1, 51	0.5370
Vert	Vowel 2 target interval	5.08	1, 51	0.0285
TB2y	Vowel 2 target interval	2.51	1, 51	0.1195
TDx	Vowel 2 target interval	2.47	1, 51	0.1220
Horiz (ex TT)	cons target to vowel 2 target	3.65	1, 51	0.0616
Horiz (in TT)	cons target to vowel 2 target	0.91	1, 51	0.3448
Vert	cons target to vowel 2 target	4.33	1, 51	0.0425
TB2y	cons target to vowel 2 target	2.83	1, 51	0.0984
TDx	cons target to vowel 2 target	2.91	1, 51	0.0943
i-a bilabials				
LA	Consonant target interval	12.61	1, 51	0.0008
Horiz (ex TT)	vowel 1 target to vowel 2 target	2.18	1, 51	0.1459
Horiz (in TT)	vowel 1 target to vowel 2 target	0.87	1, 51	0.3554
Vert	vowel 1 target to vowel 2 target	2.07	1, 50	0.1562
TB2y	vowel 1 target to vowel 2 target	0.00	1, 51	0.9837
TDx	vowel 1 target to vowel 2 target	0.69	1, 51	0.4117
Horiz (ex TT)	/m/ target to vowel 2 target	0.03	1, 51	0.8620
Horiz (in TT)	/m/ target to vowel 2 target	0.03	1, 51	0.8583

Vert	/m/ target to vowel 2 target	1.73	1, 50	0.1940
TB2y	/m/ target to vowel 2 target	4.75	1, 51	0.0340
TDx	/m/ target to vowel 2 target	0.32	1, 51	0.5728
Horiz (ex TT)	Vowel 1 target interval	0.74	1, 51	0.3947
Horiz (in TT)	Vowel 1 target interval	0.12	1, 51	0.7348
Vert	Vowel 1 target interval	0.73	1, 50	0.3968
TB2y	Vowel 1 target interval	0.00	1, 51	0.9876
TDx	Vowel 1 target interval	1.01	1, 51	0.3200
Horiz (ex TT)	/m/ target to vowel 2 onset	15.10	1, 51	0.0003
Horiz (in TT)	/m/ target to vowel 2 onset	7.39	1, 51	0.0090
Vert	/m/ target to vowel 2 onset	1.07	1, 50	0.3057
TB2y	/m/ target to vowel 2 onset	2.21	1, 51	0.1436
TDx	/m/ target to vowel 2 onset	10.85	1, 51	0.0018
Horiz (ex TT)	movement into vowel 2	11.96	1, 51	0.0011
Horiz (in TT)	movement into vowel 2	4.73	1, 51	0.0344
Vert	movement into vowel 2	3.37	1, 50	0.0723
TB2y	movement into vowel 2	0.00	1, 51	0.9987
TDx	movement into vowel 2	9.58	1, 51	0.0032
Horiz (ex TT)	movement into vowel 1	1.58	1, 51	0.2140
Horiz (in TT)	movement into vowel 1	0.03	1, 51	0.8718
Vert	movement into vowel 1	2.15	1, 50	0.1489
TB2y	movement into vowel 1	0.02	1, 51	0.8767
TDx	movement into vowel 1	0.94	1, 51	0.3369
Horiz (ex TT)	Vowel 2 target interval	0.23	1, 51	0.6302
Horiz (in TT)	Vowel 2 target interval	0.85	1, 51	0.3602
Vert	Vowel 2 target interval	1.38	1, 50	0.2449
TB2y	Vowel 2 target interval	0.05	1, 51	0.8194
TDx	Vowel 2 target interval	2.01	1, 51	0.1618
Horiz (ex TT)	vowel 1 target to cons target	0.00	1, 51	0.9717
Horiz (in TT)	vowel 1 target to cons target	0.01	1, 51	0.9342
Vert	vowel 1 target to cons target	4.81	1, 50	0.0330
TB2y	vowel 1 target to cons target	0.00	1, 51	0.9746
TDx	vowel 1 target to cons target	0.04	1, 51	0.8360
Horiz (ex TT)	cons target to vowel 2 target	3.41	1, 51	0.0707
Horiz (in TT)	cons target to vowel 2 target	2.82	1, 51	0.0990
Vert	cons target to vowel 2 target	0.02	1, 50	0.8859
TB2y	cons target to vowel 2 target	0.01	1, 51	0.9432
TDx	cons target to vowel 2 target	1.98	1, 51	0.1651

Table A2.8. Analysis of variance for articulatory measures of utterances with geminate and cluster bilabial consonants for Japanese speakers.

speaker effect	utterances measure	measured interval	F	df	p
J1					
Long Consonant Type					
	a-i bilabials				
	LLy	Consonant target interval	0.67	2, 44	0.5179
	Horiz	/m/ target to vowel 2 target	5.32	2, 44	0.0085
	Vert	/m/ target to vowel 2 target	9.48	2, 44	0.0004
	TB2y	/m/ target to vowel 2 target	9.69	2, 44	0.0003
	TDx	/m/ target to vowel 2 target	9.39	2, 44	0.0004
	Horiz	/m/ target to vowel 2 onset	6.08	2, 44	0.0047
	Vert	/m/ target to vowel 2 onset	5.98	2, 44	0.0050
	TB2y	/m/ target to vowel 2 onset	6.12	2, 44	0.0045
	TDx	/m/ target to vowel 2 onset	4.99	2, 44	0.0112
	Horiz	movement into vowel 2	0.84	2, 44	0.4372
	Vert	movement into vowel 2	1.59	2, 44	0.2148
	TB2y	movement into vowel 2	3.02	2, 44	0.0588
	TDx	movement into vowel 2	4.06	2, 44	0.0240
	Horiz	Vowel 2 target interval	4.12	2, 44	0.0229
	Vert	Vowel 2 target interval	1.87	2, 44	0.1656
	TB2y	Vowel 2 target interval	5.24	2, 44	0.0091
	TDx	Vowel 2 target interval	5.10	2, 44	0.0102
	Horiz	cons target to vowel 2 target	0.31	2, 44	0.7343
	Vert	cons target to vowel 2 target	1.68	2, 44	0.1986
	TB2y	cons target to vowel 2 target	1.50	2, 44	0.2352
	TDx	cons target to vowel 2 target	0.81	2, 44	0.4528
	i-a bilabials				
	LLy	Consonant target interval	2.11	2, 47	0.1324
	Horiz	vowel 1 target to vowel 2 target	5.16	2, 47	0.0094
	Vert	vowel 1 target to vowel 2 target	2.90	2, 47	0.0650
	TB2y	vowel 1 target to vowel 2 target	2.39	2, 44	0.1030
	TDx	vowel 1 target to vowel 2 target	3.66	2, 39	0.0348
	Horiz	/m/ target to vowel 2 target	6.33	2, 47	0.0037
	Vert	/m/ target to vowel 2 target	7.22	2, 47	0.0018
	TB2y	/m/ target to vowel 2 target	2.51	2, 44	0.0931
	TDx	/m/ target to vowel 2 target	4.40	2, 39	0.0190
	Horiz	Vowel 1 target interval	11.48	2, 47	0.0001
	Vert	Vowel 1 target interval	1.69	2, 47	0.1964
	TB2y	Vowel 1 target interval	8.78	2, 44	0.0006
	TDx	Vowel 1 target interval	16.02	2, 39	0.0000
	Horiz	/m/ target to vowel 2 onset	12.72	2, 47	0.0000
	Vert	/m/ target to vowel 2 onset	5.75	2, 47	0.0058
	TB2y	/m/ target to vowel 2 onset	14.39	2, 44	0.0000
	TDx	/m/ target to vowel 2 onset	18.39	2, 39	0.0000
	Horiz	movement into vowel 2	16.42	2, 47	0.0000
	Vert	movement into vowel 2	1.71	2, 47	0.1920
	TB2y	movement into vowel 2	5.47	2, 44	0.0075

TDx	movement into vowel 2	14.33	2, 39	0.0000
Horiz	movement into vowel 1	0.20	2, 47	0.8178
Vert	movement into vowel 1	0.42	2, 47	0.6576
TB2y	movement into vowel 1	0.15	2, 47	0.8625
TDx	movement into vowel 1	0.10	2, 47	0.9019
Horiz	Vowel 2 target interval	0.17	2, 47	0.8482
Vert	Vowel 2 target interval	2.11	2, 47	0.1331
TB2y	Vowel 2 target interval	0.74	2, 44	0.4849
TDx	Vowel 2 target interval	0.90	2, 39	0.4165
Horiz	vowel 1 target to cons target	7.02	2, 47	0.0022
Vert	vowel 1 target to cons target	1.41	2, 47	0.2531
TB2y	vowel 1 target to cons target	6.00	2, 47	0.0048
TDx	vowel 1 target to cons target	7.22	2, 47	0.0018
Horiz	cons target to vowel 2 target	5.17	2, 47	0.0093
Vert	cons target to vowel 2 target	0.57	2, 47	0.5681
TB2y	cons target to vowel 2 target	0.22	2, 44	0.8030
TDx	cons target to vowel 2 target	2.04	2, 39	0.1432

speaker effect	utterances measure	measured interval	F	df	p
J2					
Long Consonant Type					
	a-i bilabials				
	LA	Consonant target interval	8.03	2, 52	0.0009
	Horiz	/m/ target to vowel 2 target	0.50	2, 53	0.6111
	Vert	/m/ target to vowel 2 target	10.47	2, 53	0.0001
	TB2y	/m/ target to vowel 2 target	6.53	2, 53	0.0029
	TDx	/m/ target to vowel 2 target	0.44	2, 53	0.6472
	Horiz	/m/ target to vowel 2 onset	0.09	2, 53	0.9112
	Vert	/m/ target to vowel 2 onset	2.97	2, 53	0.0600
	TB2y	/m/ target to vowel 2 onset	10.77	2, 53	0.0001
	TDx	/m/ target to vowel 2 onset	1.21	2, 53	0.3051
	Horiz	movement into vowel 2	0.04	2, 53	0.9567
	Vert	movement into vowel 2	5.47	2, 53	0.0069
	TB2y	movement into vowel 2	2.27	2, 53	0.1130
	TDx	movement into vowel 2	2.02	2, 53	0.1429
	Horiz	Vowel 2 target interval	4.82	2, 53	0.0120
	Vert	Vowel 2 target interval	10.26	2, 53	0.0002
	TB2y	Vowel 2 target interval	8.16	2, 53	0.0008
	TDx	Vowel 2 target interval	0.96	2, 53	0.3888
	Horiz	cons target to vowel 2 target	7.12	2, 53	0.0018
	Vert	cons target to vowel 2 target	3.51	2, 53	0.0371
	TB2y	cons target to vowel 2 target	2.43	2, 53	0.0980
	TDx	cons target to vowel 2 target	2.54	2, 53	0.0888
	i-a bilabials				
	LA	Consonant target interval	0.51	2, 54	0.6017
	Horiz	vowel 1 target to vowel 2 target	4.07	2, 53	0.0227
	Vert	vowel 1 target to vowel 2 target	12.56	2, 52	0.0000
	TB2y	vowel 1 target to vowel 2 target	15.84	2, 53	0.0000
	TDx	vowel 1 target to vowel 2 target	5.20	2, 47	0.0091
	Horiz	/m/ target to vowel 2 target	4.29	2, 53	0.0187
	Vert	/m/ target to vowel 2 target	16.53	2, 52	0.0000
	TB2y	/m/ target to vowel 2 target	24.56	2, 53	0.0000
	TDx	/m/ target to vowel 2 target	3.53	2, 47	0.0373
	Horiz	Vowel 1 target interval	1.70	2, 53	0.1933
	Vert	Vowel 1 target interval	2.85	2, 52	0.0669
	TB2y	Vowel 1 target interval	4.09	2, 53	0.0223
	TDx	Vowel 1 target interval	2.20	2, 47	0.1223
	Horiz	/m/ target to vowel 2 onset	1.74	2, 53	0.1854
	Vert	/m/ target to vowel 2 onset	7.22	2, 52	0.0017
	TB2y	/m/ target to vowel 2 onset	8.77	2, 53	0.0005
	TDx	/m/ target to vowel 2 onset	0.98	2, 47	0.3840
	Horiz	movement into vowel 2	0.82	2, 53	0.4459
	Vert	movement into vowel 2	2.52	2, 52	0.0902
	TB2y	movement into vowel 2	22.93	2, 53	0.0000
	TDx	movement into vowel 2	1.50	2, 47	0.2340
	Horiz	movement into vowel 1	1.14	2, 54	0.3263
	Vert	movement into vowel 1	1.47	2, 53	0.2398
	TB2y	movement into vowel 1	0.16	2, 54	0.8511

TDx	movement into vowel 1	0.37	2, 53	0.6920
Horiz	Vowel 2 target interval	1.93	2, 53	0.1548
Vert	Vowel 2 target interval	7.20	2, 52	0.0017
TB2y	Vowel 2 target interval	0.92	2, 53	0.4030
TDx	Vowel 2 target interval	1.89	2, 47	0.1628
Horiz	vowel 1 target to cons target	6.68	2, 54	0.0026
Vert	vowel 1 target to cons target	1.91	2, 53	0.1578
TB2y	vowel 1 target to cons target	2.40	2, 54	0.1001
TDx	vowel 1 target to cons target	6.92	2, 53	0.0021
Horiz	cons target to vowel 2 target	6.97	2, 53	0.0020
Vert	cons target to vowel 2 target	9.00	2, 52	0.0004
TB2y	cons target to vowel 2 target	15.82	2, 53	0.0000
TDx	cons target to vowel 2 target	2.68	2, 47	0.0792

speaker effect	utterances measure	measured interval	F	df	p
J3					
Long Consonant Type					
	a-i bilabials				
	LA	Consonant target interval	3.02	2, 36	0.0614
	Horiz (ex TT)	/m/ target to vowel 2 target	7.60	2, 36	0.0018
	Horiz (in TT)	/m/ target to vowel 2 target	2.01	2, 36	0.1481
	Vert	/m/ target to vowel 2 target	0.29	2, 36	0.7485
	TB2y	/m/ target to vowel 2 target	18.33	2, 36	0.0000
	TDx	/m/ target to vowel 2 target	7.26	2, 36	0.0022
	Horiz (ex TT)	/m/ target to vowel 2 onset	1.81	2, 36	0.1782
	Horiz (in TT)	/m/ target to vowel 2 onset	1.59	2, 36	0.2174
	Vert	/m/ target to vowel 2 onset	1.42	2, 36	0.2550
	TB2y	/m/ target to vowel 2 onset	0.13	2, 36	0.8800
	TDx	/m/ target to vowel 2 onset	3.17	2, 36	0.0539
	Horiz (ex TT)	movement into vowel 2	6.48	2, 36	0.0040
	Horiz (in TT)	movement into vowel 2	0.41	2, 36	0.6674
	Vert	movement into vowel 2	0.10	2, 36	0.9022
	TB2y	movement into vowel 2	15.32	2, 36	0.0000
	TDx	movement into vowel 2	3.33	2, 36	0.0470
	Horiz (ex TT)	Vowel 2 target interval	7.05	2, 36	0.0026
	Horiz (in TT)	Vowel 2 target interval	1.69	2, 36	0.1994
	Vert	Vowel 2 target interval	0.62	2, 36	0.5438
	TB2y	Vowel 2 target interval	16.15	2, 36	0.0000
	TDx	Vowel 2 target interval	8.32	2, 36	0.0011
	Horiz (ex TT)	cons target to vowel 2 target	3.39	2, 36	0.0448
	Horiz (in TT)	cons target to vowel 2 target	1.00	2, 36	0.3763
	Vert	cons target to vowel 2 target	4.31	2, 36	0.0210
	TB2y	cons target to vowel 2 target	23.52	2, 36	0.0000
	TDx	cons target to vowel 2 target	2.66	2, 36	0.0833
	i-a bilabials				
	LA	Consonant target interval	11.08	2, 34	0.0002
	Horiz (ex TT)	vowel 1 target to vowel 2 target	0.27	2, 35	0.7657
	Horiz (in TT)	vowel 1 target to vowel 2 target	0.85	2, 35	0.4373
	Vert	vowel 1 target to vowel 2 target	4.69	2, 34	0.0159
	TB2y	vowel 1 target to vowel 2 target	0.48	2, 35	0.6244
	TDx	vowel 1 target to vowel 2 target	0.11	2, 35	0.8967

Horiz (ex TT)	/m/ target to vowel 2 target	0.41	2, 34	0.6655
Horiz (in TT)	/m/ target to vowel 2 target	0.86	2, 34	0.4317
Vert	/m/ target to vowel 2 target	1.86	2, 33	0.1724
TB2y	/m/ target to vowel 2 target	6.73	2, 34	0.0035
TDx	/m/ target to vowel 2 target	1.43	2, 34	0.2536
Horiz (ex TT)	Vowel 1 target interval	8.33	2, 35	0.0011
Horiz (in TT)	Vowel 1 target interval	4.19	2, 35	0.0233
Vert	Vowel 1 target interval	7.30	2, 34	0.0023
TB2y	Vowel 1 target interval	4.92	2, 35	0.0131
TDx	Vowel 1 target interval	4.95	2, 35	0.0128
Horiz (ex TT)	/m/ target to vowel 2 onset	22.75	2, 34	0.0000
Horiz (in TT)	/m/ target to vowel 2 onset	13.49	2, 34	0.0000
Vert	/m/ target to vowel 2 onset	5.37	2, 33	0.0096
TB2y	/m/ target to vowel 2 onset	17.17	2, 34	0.0000
TDx	/m/ target to vowel 2 onset	15.23	2, 34	0.0000
Horiz (ex TT)	movement into vowel 2	15.70	2, 35	0.0000
Horiz (in TT)	movement into vowel 2	5.33	2, 35	0.0095
Vert	movement into vowel 2	3.04	2, 34	0.0610
TB2y	movement into vowel 2	4.35	2, 35	0.0206
TDx	movement into vowel 2	13.33	2, 35	0.0000
Horiz (ex TT)	movement into vowel 1	0.20	2, 35	0.8176
Horiz (in TT)	movement into vowel 1	0.45	2, 35	0.6395
Vert	movement into vowel 1	2.62	2, 34	0.0872
TB2y	movement into vowel 1	0.04	2, 35	0.9611
TDx	movement into vowel 1	0.12	2, 35	0.8831
Horiz (ex TT)	Vowel 2 target interval	1.42	2, 35	0.2554
Horiz (in TT)	Vowel 2 target interval	1.26	2, 35	0.2957
Vert	Vowel 2 target interval	2.09	2, 34	0.1393
TB2y	Vowel 2 target interval	1.31	2, 35	0.2829
TDx	Vowel 2 target interval	4.21	2, 35	0.0230
Horiz (ex TT)	vowel 1 target to cons target	2.49	2, 35	0.0971
Horiz (in TT)	vowel 1 target to cons target	2.71	2, 35	0.0808
Vert	vowel 1 target to cons target	14.58	2, 34	0.0000
TB2y	vowel 1 target to cons target	0.84	2, 35	0.4404
TDx	vowel 1 target to cons target	1.86	2, 35	0.1705
Horiz (ex TT)	cons target to vowel 2 target	5.24	2, 35	0.0102
Horiz (in TT)	cons target to vowel 2 target	3.91	2, 35	0.0294

Vert	cons target to vowel 2 target	0.35	2, 34	0.7049
TB2y	cons target to vowel 2 target	0.28	2, 35	0.7588
TDx	cons target to vowel 2 target	2.85	2, 35	0.0712