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**Functional organization of velar movements following jaw
perturbation**

Kollia, Haralambia, Ph.D.

City University of New York, 1994

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FUNCTIONAL ORGANIZATION OF VELAR MOVEMENTS
FOLLOWING JAW PERTURBATION

by

HARALAMBIA KOLLIA

A dissertation submitted to the Graduate Faculty in Speech and Hearing Sciences
in partial fulfillment of the requirements for the degree of Doctor of Philosophy,
The City University of New York

1994

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This manuscript has been read and accepted for the Graduate Faculty in Speech and Hearing Sciences in satisfaction of the dissertation requirement for the degree of Doctor of Philosophy.

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ABSTRACT

FUNCTIONAL ORGANIZATION OF VELAR MOVEMENTS FOLLOWING
JAW PERTURBATION

by

Haralambia Kollia

Adviser: Professor Katherine Safford Harris

One approach to understanding the control of speech motor actions is to identify the manner in which individual articulators are coordinated. Previous investigations of relative timing indicate that jaw, lips, and larynx are functionally constrained during bilabial closing. Similar coordination has been observed linking the jaw and lips with the tongue, and, recently, with the velum, providing evidence of temporal stability among functionally related articulators. The interpretation is that speech movements are not controlled independently, but rather globally, reflecting large scale vocal tract actions.

Mechanical perturbation of the articulators has been used to examine motor control principles underlying speech production. One common observation has been that if one member of a group of functionally related articulators is perturbed during articulation, the other members compensate. These response patterns reflect

sensorimotor organization for speech, having implications for speech production theories. The present study examines functional organization in speech motor control as indexed by the relationships between the spatiotemporal responses of both anatomically remote and linked articulators, namely in velum, upper lip, and lower lip kinematics following jaw perturbation.

Subjects were fitted with mandibular prostheses allowing delivery of jaw-lowering, random perturbations during productions of the utterance /mabnab/, around the first vowel onset. Jaw, lip, and velar kinematics were recorded optoelectronically, simultaneously with the acoustic signal.

Consistent with previous results, perturbed utterances differed from control utterances in the spatiotemporal characteristics of articulatory kinematics. Generally, articulatory displacements and velocities increased with jaw perturbation. These changes often depended on the time of perturbation, in that they tended to increase with loads occurring closer to the acoustic vowel onset. Additionally, temporal intervals between articulatory events within and across articulators were affected significantly by the perturbations. Coordinative timing among lips, jaw, and velum was generally maintained following the perturbation. Variations in timing frequently depended on the temporal relations between the onset of the perturbation and that of the component speech event.

These findings suggest that, when functionally coordinated, the jaw, lips, and velum exhibit comparable sensorimotor organization. Velar responses to jaw perturbation were analogous to lip and jaw responses, indicating a rather global speech motor control mechanism.

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CHAPTER ONE

INTRODUCTION

1.1 THEORETICAL ANTECEDENTS TO SPEECH MOTOR CONTROL

Skilled motor activity involves the coordination in time and space of multiple muscles and joints, and their trajectories. Each of these elements represents –at a different level– a degree of freedom for the system. When implicated in a particular task, all such degrees of freedom have to be controlled during the realization of the task. Controlling a multitude of degrees of freedom poses a complex problem. To simplify this problem of control, the number of degrees of freedom must be reduced. Bernstein (1967), considered coordinated activity in biological systems to be ultimately a problem of regulation of the elements to be controlled –the degrees of freedom– in a given movement. In other words, the problem of understanding the coordination of multiple muscles, joints, and trajectories during skilled action can be reduced to finding a mechanism that can explain how the multiple degrees of freedom are governed during motor activity. In that sense, the control of motor activity should not be assigned to a single system, rather it may be more efficient if distributed among several systems, with the degrees of freedom to be controlled by each system reduced.

One way to reduce the degrees of freedom in a system is to group members of the system into functional linkages, or coordinative structures (Turvey, 1977, 1980). In this view, a number of independent muscles can become linked in a functional, task-specific manner, thereby acting as a unit. Because musculature is inherently organized into functionally and anatomically linked groups (e.g., oral musculature, brachial

musculature, etc.), such functionally based muscle groupings (i.e., coordinative structures) provide classes of motorically equivalent acts that can be regulated by relatively autonomous and adaptive muscle systems (Fowler et al., 1980). In this way, the individual degrees of freedom of each muscle and joint in the group are reduced to those of the new unit. The internal degrees of freedom, that is, those within the functionally-coupled muscle aggregation, are controlled in a relatively autonomous manner during the coordinated activity of that unit, even in situations of varying kinematic parameters such as speed. The task-specific synergies are flexible; they adjust to external variations so that the task is realized and the coordination maintained. Furthermore, the organization of control in the coordinative structures can be conceptualized as hierarchical, with multiple coordinative structures being organized into larger systems (Turvey, 1977).

Approximately 70 muscles contribute to speech production, and the control of their coordinated action presents an instance of the problem of regulation of the degrees of freedom, comparable to that problem for other motor acts. One of the major tasks in speech is the formation and release of constrictions in various regions of the vocal tract, for example, bilabial constriction and release gestures that require the synergistic actions of the upper lip, lower lip, and jaw. The articulators involved in the formation and release of a vocal tract constriction have been viewed as organized into a coordinative structure (Fowler et al., 1980; Kelso et al., 1984; Saltzman, 1986). According to Fowler and her colleagues (1980), when these coordinative structures, or groups of coordinative structures, operate as a unit, the parameters characterizing properties of the individual muscles or of the individual coordinative structures (that form a collective) may covary. This covariation of the parameters seems to give rise to a relatively stable relationship within the collective that is maintained despite changes in the individual parameters. From that standpoint, the issue of the multiple degrees of freedom during

coordinated action can be conceived of as a set of constraints for a specific *collective*, rather than a set of commands to be issued to *each element* in the motor system (Fowler et al., 1980).

Accordingly, albeit at a different level, Lee (1984) suggests that neuromotor synergies may be one of the contributors to the coordination of intentional action. The neuromotor synergies hypothesis postulates that intentional actions are constrained by low-level neurally based patterns, implying that a wide range of coordinated intentional actions can be generated by recruiting, suppressing, or modulating sets of neuromotor synergies, or networks subserving neuromotor synergies. Neuromotor synergies differ from biomechanical, task, and cognitive constraints even though these constraints often overlap. Lee defines neuromotor synergies for intentional (and automatic) actions in terms of neurally-based synergistic patterns, such as those observed in the classical flexor-withdrawal reflexes. This definition is distinct from the definitions of coordinative structures that stress the biomechanical similarities among movements, such as those discussed above, in that it attempts references to the possible neural bases for those similarities. These neuromotor synergies (or action units) are morphologically defined rather than functionally defined or goal-directed, despite the known limitations of this approach, mainly because neural constraints on intentional acts might be easier to detect morphologically. This interpretation of synergy requires spatial, temporal, and scaling stability: the same set of muscles should always be activated; synchronization, fixed temporal order, or fixed phase relationships should hold over a range of movement parameters (cf. Kelso, Holt, Rubin, & Kugler, 1981), and, finally, the properties of a synergy or the relations among its components should exhibit scaling after suprathreshold activation of these components.

Scaling is not essential to goal-directed synergies, such as the coordinative structure construct, since it is the overall goal of the intended action that needs to be achieved. As

an example of how coordinative structures may provide answers to the problem of degrees of freedom in speech, Fowler et al. (1980) examined the regulation of speaking rate. They suggest that since coordinative structures of coarser definition can be superimposed on coordinative structures of finer definition, the same coordinative structures may govern an utterance over varying production amplitudes, maintaining, for instance, relatively constant timing relations among articulators over a significant increase in rate.

This view of speech production also takes into account the inherent physical properties of the structures that comprise the flexible coordinative structures. Coordinative structures for speech may be modeled as a vibratory system using a mass-spring model whose kinematics are determined by the system's dynamic properties and by its initial conditions. The spatial goal of such a system is intrinsic to the system itself and may be attained from any given starting point, thus accounting for the rapid changes in the configuration of the speech muscles required during speech production (Fowler et al., 1980). Temporal goals are also postulated to be intrinsic to the speech production system. In fact, Bell-Berti and Harris (1981) have proposed a model of speech production in which articulatory timing relationships are considered intrinsic to speech motor organization, rather than a result of the articulatory events, and in which the fundamental units of speech production are dynamic gestures. Such gestures have been hypothesized to obey task dynamic constraints such as those implemented in the Saltzman and Munhall (1989) model thereby reducing substantially the degrees of freedom that need to be controlled.

In the coordination of speech movements, the functional units have been defined in terms of sets of primitive (fundamental, irreducible) tasks to be performed during speech production. One definition of functional units in speech production was proposed by Saltzman (1986), and is based on related work on motor control of the

limbs (Saltzman and Kelso, 1987). For Saltzman and Munhall (1989), a gesture is “a member of a family of functionally equivalent articulatory movement patterns that are actively controlled with reference to a speech-relevant goal (e.g., bilabial closure)” (p. 334). This definition distinguishes between gestures and movements, in that while gestures are composed of movements, only movements that have an active function in the realization of a gesture can be considered gestures or components of gestures. Saltzman and Munhall consider inter-gestural subgroups to be dynamically coupled, exhibiting patterns of covariation that reflect the existence of functional linkages. Accordingly, speech production is achieved through the implementation of higher order, multigesture units. The dynamical coupling observed in the intra-gestural subgroups provides for a temporal cohesion that is stable for short durations (i.e., the duration for the formation of the constriction) within an utterance. Cohesiveness is also evident in the observed stability of intergestural phasing. Similarly, Browman and Goldstein (1986) specify such intergestural cohesion in terms of the stability of the spatiotemporal relations among gestures.

From a slightly different standpoint, Mattingly and Liberman (Liberman & Mattingly, 1985; Mattingly, 1990) also consider phonetic gestures as the primitives in a speaker’s phonological representation. However, Mattingly (1990) posits that phonetic gestures as organizing principles have a global, not simply a local effect on the vocal tract. In particular, the aerodynamic and geometric properties of the vocal tract are pertinent to the definition of phonetic tasks as suggested by Saltzman and Munhall (1989). Further, gestures are organized functionally rather than anatomically. Specifically, the so-called “task dynamic” approach of Saltzman and Munhall (1989) defines gesture-specific dynamics in a set of goal-space coordinates called tract variables. The tract-variable coordinates are constriction-specific. These gesture-specific dynamics are then utilized to shape the movement patterns of the associated set

of articulators. The resultant movement patterns are sensitive both to the segmental composition of the utterance, and to the structure of imposed (simulated) mechanical perturbations. A tract variable is associated with specific articulators (e.g., the tract variable of lip aperture involves the upper lip, lower lip and jaw) that are employed to form constrictions, and the parameter values of the dynamic equation of its movement: target (rest position), stiffness, and damping. What is characterized dynamically is the movement of tract variables rather than the movement of individual articulators. These proposals remove a strictly anatomical aspect from the tiers of Browman and Goldstein's (1987) articulatory phonology, and admit a functional organization in the definition of phonetic gestures, in agreement with the Saltzman and Munhall (1989) definition. The results of the present study will point to the necessity for consideration of a global aspect in the speech motor control mechanism, even if this aspect is as yet not very well understood.

The document that ensues focuses on movement characteristics of specific articulators, namely the jaw, the lips, and the velum, and the temporal and spatial coordination of the movements displayed during the attainment of a specific linguistic goal. As was discussed in general terms earlier (and in detail below), articulators involved in the production of an utterance have been shown to exhibit task-specific, goal-oriented organization. Specifically, functional linkages have been shown to exist temporarily among the articulator sets during production of the utterance's component gestures. For example, the upper lip, lower lip, and jaw are linked in a task-specific manner during production of the bilabial gesture /p/ in /paf/, while for production of /f/, the upper lip is no longer necessarily –but may be– linked to the lower lip and the jaw. These functional linkages, or coordinative constraints, are transient in character: as soon as the task is realized their task-specific coupling dissolves (Turvey, 1990).

For theories of motor control in speech production the coordinative structure paradigm is very attractive, given the extraordinary complexity of the problem at hand. One of the empirical methods employed to demonstrate evidence of such connections involves introducing mechanical perturbations to an articulator, and observing the responses of the articulators to the new requirements brought about by the disturbance. One common observation is that if one member of a group of functionally linked articulators is perturbed during speaking, the other members show compensatory adjustments. The compensatory response patterns are considered to reflect sensorimotor organization for speech, in that they suggest an immediate gesture-specific interaction between afferent and efferent signals. Mechanisms of motor control for speech are hence thought to employ on-line sensory and motor information to and from the periphery in the regulation of the movements of the articulators.

The question that arises then, is whether it is reasonable to assume that the collective function of these articulators will result in an action that overrides the variability of each member of the articulatory group. Gracco and Abbs (1986) examined the movement patterns of the upper lip, the lower lip, and the jaw during speech production. They observed that the combined action of these articulators was significantly less variable than the action of each of the components of the group. Specifically, the composite action had significantly less variable profiles of peak displacement and peak velocity than did each of its components.

Furthermore, in an electromyographic and kinematic study of the coordination of lip and jaw movements during speech, Gracco (1988) observed a consistent timing relation in the peak velocities of the three articulators for oral closure. That was not the case for the oral opening movements and their associated velocities. The time of the peak amplitude of the EMG signal that was associated with a movement and the time of the onset of the muscle activity, were closely related to the time of the peak velocity for that

movement, and were dependent on the requirements of the task. These adjustments seemed to be specified for the articulatory group, rather than independently for the individual articulators. Given these findings then, it is reasonable to view articulators that are grouped for a task as a unit whose kinematic parameters are adjusted in a goal-specific manner.

Gracco and Abbs (1987) described motor programming as an algorithm, a procedure for the implementation of commands to the motor system, which may include the necessary regulation and channeling of information through the appropriate sensorimotor pathways. These motor control processes are considered to be distributed, non centralized, thus accounting for a hierarchical organization of the neural subsystems. Such sensorimotor mechanisms of afferent and efferent information exchange should only operate for on-line adjustments if their operation results in a modification necessary to the achievement of the intended goal, linguistic or otherwise. Such mechanisms produce not generalized, but task specific and goal-oriented modifications. Sensorimotor mechanisms are, then, considered to be functionally specific. The task-dynamic model proposed by Saltzman and Munhall (1989) is one example of an algorithm that holds some promise in producing patterns of articulator movements such as those described above.

It is perhaps worth mentioning that much of the necessary information regarding coordination of multiple degree-of-freedom biological systems has been provided by studying rhythmic movements (Stone, 1981; Turvey, 1990). In that sense, theories that use first approximation analogies of the speech motor action to an oscillator model might be improved by considering neurophysiological afferent and efferent contributions. Indeed, most of the studies that are discussed below have designed and used speech tasks in an attempt to simulate quasi-rhythmical movement patterns in the articulator movements that are produced. Accordingly, in the present study, the stimulus utterance

was designed in such a way as to provide a nearly sinusoidal type of rhythmic movement of the articulators involved (lips, jaw, and velum). Given that speech production is not rhythmical in the same sense that chewing or walking are, a number of objections have been voiced about the use of reiterant speech in studies of speech motor control. However, by using utterances that require quasi-rhythmical articulator movements, such as the one used in this study, non-random, speech movements may be studied and compared to other known motor tasks without using reiterant speech.

1.2 STATIC PERTURBATION STUDIES

As mentioned earlier, one of the methods for examining functional organization in speech movements involves introducing transient mechanical perturbations to the speech motor system, and observing the reorganizing responses of the articulators to the altered requirements. These perturbations may be static or dynamic. Static perturbations commonly involve placing a small bite-block between the teeth, thus fixing the jaw in a specifically open position, thus impeding further jaw movement during the experiment. Dynamic perturbations involve a temporary disturbance of movement of the lip or the jaw, by applying a small loading force to the lip or the jaw along or against the direction of its movement. The load is sizeable enough to alter the movement without, however, completely disrupting it.

A number of static perturbation studies have been conducted to examine the degree of compensation evidenced in response to the altered speaking conditions. These studies have shown that normal speakers compensate for the effects of a bite-block. That is, the lips and the tongue seem to provide the necessary adjustments to overcome the effects of the fixed jaw position. Specifically, Lindblom, Lubker, and Gay (1979) found that twelve Swedish vowels produced in isolation by six speakers each of whose jaw had been fixed with a bite-block, had formant frequency patterns that were "close to

perfect” in that “they fell within normal ranges of F-pattern variation” (p. 157). These compensations were immediate, in that no practice was necessary to achieve normal sounding vowel productions. These results were used to support a predictive central programming model of speech production, according to which speech motor programming is able to handle novel contexts and to display high plasticity by “learning” from an error simulator at the central level, *before* the motor commands are issued to the peripheral system. The authors then postulate that a vowel target is coded as a sensory goal, specified at a neurophysiological level, and that the simulator issues commands that generate corresponding simulated sensory consequences. These simulated sensory consequences are then compared to the sensory consequences of the intended act. The motor commands from the simulator to the periphery are subsequently adjusted –based on the previous comparison– so that the intended targets are actualized. This model uses contextual information and invokes an adaptive peripheral control mechanism, along with a predictive central control mechanism. By using the information from the simulator, the system has access to more information than it would have if it relied on a peripheral closed loop model, and thus selects the appropriate motor plan flexibly, and is able to produce responses to perturbations.

Later, Gay, Lindblom, and Lubker (1981) extended their earlier results by examining the specific compensatory patterns produced in various parts of the vocal tract for different vowels and correlating them with x-ray images of articulator position during steady state vowel production in normal and bite-block conditions. They found that the resultant compensatory adjustments were maximal at those locations in the vocal tract where the constrictions were maximal. In other words, the deviations of the “supershapes” (the vocal tract shapes that resulted from the placement of the bite-block) from the normal (non-bite-block) vocal tract shapes were minimal at the points of maximum constriction of the vocal tract, especially for the vowels /i/ and /u/. By

contrast, the deviations were maximal in regions of large vocal tract areas, indicating that compensation for the effects of perturbation is evidently context-sensitive (i.e., vowel- or gesture-specific).

It is also important to address the issue of the time interval required by the speech production system to compensate for the changes brought on by the perturbation. In a reaction time study, Lubker (1979) found that when the jaw is fixed in a very open, low position with a bite-block, the organization and production times necessary to produce high vowels, which require high jaw positions, are longer than the times seen in the normal (non-bite-block) condition. These longer reaction times were taken as evidence for a system working at the extremes of its normal ranges, at least until habituation occurs. This interpretation takes into account the Lindblom et al. (1979) model of the inherently compensatory, context-sensitive, and predictive nature of the speech production mechanism that is reported earlier. There have, however, been some differing views to that model.

Fowler and Turvey (1980) looked in detail at the reaction times and the quality of vowels produced normally and in two bite-block conditions: under time pressure and with no time pressure. They found no difference in the response initiation latency, or in the acoustic measures of the vowels in the normal and bite-block conditions. Neither practice nor time pressure affected vowel production in the bite-block condition to a discernible degree. Fowler and Turvey (1980) found it preferable to view their results through the prism of the coordinative structure model proposed by Fowler et al. (1980), rather than through the Lindblom et al. (1979) model, on grounds of parsimony and of compatibility of the former with non speech theories of motor control. Unlike Lindblom et al. (1979), Fowler et al. (1980) propose no simulated central program that adjusts its commands to the periphery in novel speaking contexts. In fact, they suggest removing the simulator loop since it cannot anticipate perturbations, unlike a closed-loop system

with a non simulated feedback loop. Instead, they suggest that the speech musculature is organized within a set of constraints that are provided by a coordinative structure. These constraints delimit and circumscribe the actions of the vocal tract. The coordinative structure then (or the speech musculature organization), generates the speech motor commands; it does not generate the procedures (or programs) for selecting a speech motor plan or an organization.

An electromyographic study (Folkins & Zimmermann, 1981) of bite-block speech provided further evidence against a model of speech production that employs a central simulation, error adjusting system. This study showed that during bite-block speech, the jaw muscles produced activity bursts similar to those of unperturbed, non-bite-block, speech. The authors see these results as providing evidence favoring the involvement of peripheral neuromotor control processes in speech motor organization. Further, these results are consistent with a task-dynamic account, in which the central specifications for articulatory motor control take into account information about the on-going state of the periphery (Kelso, Saltzman, Tuller, 1986).

While experiments using static perturbations provide information regarding the compensatory abilities of the system by eliminating one of its degrees of freedom (jaw movement), dynamic perturbations –discussed below– provide information regarding the on-line compensatory abilities of the system during speech production with all of its degrees of freedom present.

1.3 DYNAMIC PERTURBATION STUDIES

As mentioned earlier, dynamic perturbations involve a temporary disturbance of the movement of an articulator, by applying a small load to it along or against the direction of its movement. The load is sizeable enough to perturb the movement without, however, causing its total interruption. Again, one purpose is to test the idea that the

articulators are grouped together for a specific function. If it is true that articulators work toward a common goal, then if the movement of one is disturbed, the others will compensate for the disturbance and the goal will be attained.

1.3.1 Local articulators

Folkins and Abbs (1975) explored the characteristics of speech motor sequences using a dynamic perturbation paradigm. If the kinematic relations among the lips and the jaw are relatively stable in normal speech production, and these relationships are maintained following perturbations of jaw movement for the achievement of the intended goal, then this would provide further evidence for goal-specific coordinative structures in speech. In other words, such a finding would provide support for the notion of speech motor control being organized according to goal-specific coordinative structures. In their experiment, Folkins and Abbs perturbed the jaw during closure for the first /p/ in “a /hæpæp/ again”. They observed that lip closure was achieved in all cases, through movement modifications that involved increased displacement and velocity of the labial closing gesture, that were chiefly seen in the upper lip.

Gracco and Abbs (1988) used methodology similar in principle to the Folkins and Abbs (1975), to deliver perturbations to the lower lip during its closing movement. They found that the pattern of temporal relations of movement velocities remained stable despite lip perturbations. In fact, the ordering of the peak velocities and the durations of the movements of the perturbed utterances did not vary as a result of the perturbation, despite increases in movement displacement and muscle activity of the jaw, and upper and lower lips. These findings were comparable to the results of earlier studies of the same investigators (Gracco & Abbs 1985, and Abbs & Gracco 1984), in which the upper lip and the lower lip showed corrective displacement adjustments to perturbations delivered to the lower lip. In a later study (Gracco & Abbs, 1989), subjects received lower lip perturbations with different offset times during productions of the utterance

“sapapple,” an utterance that involves two successive bilabial closing movements. Comparisons of the EMG signal with the kinematic data for the upper and lower lips during the second oral closure of the sequence indicated that the two structures were affected by the addition of the load in differing degrees. In particular, both the upper and the lower lips exhibited similar temporal adjustments to the load, whereas for the movement displacement and the EMG activity the adjustments were not symmetrical between the upper lip and the lower lip. Furthermore, the varying load conditions resulted in different effects on the timing of the EMG and movement onsets for the second oral closing movement. These results were taken to reflect the different contributions of the upper and lower lip to the changed movement requirements. Therefore, the non-symmetrical contribution of the upper and lower lips for the attainment of lip closure indicates that the closing action is achieved in a reciprocal manner which, however, may not necessarily be equally divided among the two structures but, rather, are distributed in a relatively “weighted” fashion.

Given the findings of the above studies, it becomes clear that local (intra-gestural) compensation is an established response to perturbations of articulator movements during speech production, and thereby provides evidence supporting the existence of coordinative structures among articulators.

1.3.2 Functional specificity

It is reasonable to assume, therefore, that articulators are grouped in functionally-organized, task-specific aggregates, and that if one member of the group is perturbed during speech production, the other members will compensate so that the acoustic output, or constriction goal, of the system remain relatively stable. If we accept this concept of functional coupling, then if remote compensation were shown to exist, it would provide greater insight into the organization of coordinative structures, by probing the extent of the functional unit in speech motor control. A number of studies

have sought evidence of remote compensation in experiments involving more anatomically remote articulators than the upper lip and the lower lip, looking, for example, at such articulator pairs as the of jaw and upper lip, jaw and tongue, and lip and larynx.

Considering that the lip-larynx coordination experiment (Munhall et al., submitted) discussed later has a somewhat different theoretical basis than the following jaw-upper lip (Shaiman 1988, 1989) and the jaw-tongue studies (Kelso et al., 1984; Shaiman 1988, 1989), it should be clarified here that the term “remote” has been used to refer not only to coordination within gestures (e.g., bilabial, that is, lip closure), but also to coordination between gestures (e.g., in the articulator system that includes the lip and the larynx, or, as in the present study, the jaw and the velum). Further, the term “remote” has been used in the past to refer to the upper lip as it relates to the jaw, or as it relates to the lower lip in perturbation studies. It seems though that, while the upper lip is arguably more remote to the jaw than is the lower lip, it is by no means “remote” to the lower lip.

The above definitional disagreements notwithstanding, Kelso et al. (1984) looked at upper lip, lower lip, and tongue EMG responses to jaw perturbation in two phonetic contexts: one that required labial action for oral constriction (/bæb/), and one that required tongue action for oral constriction (/bæz/). For /bæb/, they observed upper and lower lip compensation to perturbation of jaw raising toward the final /b/, but no compensatory tongue activity. For /bæz/, on the other hand, only lingual compensation was seen for the production of /z/. In a subsequent manipulation, the jaw was perturbed during both its closing and its opening movement, while upper lip activity was monitored. The rationale for these perturbations was that if these articulators are functionally coupled, then compensation should occur only when necessitated by the phonetic target. Indeed, upper lip reactions were observed only when the jaw was

perturbed in its closing movement. When perturbations were delivered to the jaw during its opening movement the upper lip showed no such responses, that is, they were task-specific. These observations were taken as support for the conjecture that compensatory activity should occur only when it aids completion of the ongoing target action, in this case, lip closure. Therefore, these results provided additional support for a theory of functional and task-specific articulatory organization in speech.

In a more detailed experiment focusing on the same question, Shaiman (1988) looked at lower lip responses to upper lip perturbations during /æpæ/ and /æfæ/, while at the same time restricting jaw movement with the use of a bite-block. It was expected that for /æpæ/, an utterance that requires bilabial action for lip closure, a perturbation of the upper lip closing movement would induce a corrective lower lip response. In the case of /æfæ/, an utterance that requires no upper lip participation for the production of the labiodental /f/, a perturbation in the upper lip should not affect lower lip movement. As hypothesized, Shaiman found lower lip compensation in the form of increased movement displacement and EMG activity for /æpæ/, but not for /æfæ/. Given that the lower lip was active both in /p/ and /f/ production, its compensation only to perturbations during /æpæ/ was attributed to task-specific motor control mechanisms.

In a second perturbation experiment examining bilabial and alveolar closure, Shaiman (1988, 1989) looked at tongue EMG activity and also at jaw, upper lip and lower lip kinematic and EMG responses to jaw perturbations before and during tongue elevation for /ædæ/ as compared with /æbæ/. Here, also, the underlying premise was that unless an articulator is functionally implicated in an utterance—even if structurally linked to the articulators that participate in the production of the utterance—that articulator will not show compensatory responses to perturbations of neighboring articulators. For /æbæ/ the oral constriction is formed at the lips and the tongue plays no active role in the constriction formation, whereas for /ædæ/ the tongue forms the

constriction and the lips do not participate. Shaiman did, indeed, observe compensatory responses in the lips and the jaw for /æbæ/, but not for /ædæ/, when jaw movement was perturbed. However, three of her six subjects exhibited only upper lip and lower lip responses to jaw perturbation (non-autogenic responses), and no jaw responses to jaw perturbation (autogenic responses), even though jaw mobility was not restricted as in the preceding study and the jaw was free to respond to the perturbation along with the lips. Exclusively non-autogenic responses have been observed in previous studies as well (e.g., Folkins & Abbs, 1975; Folkins & Zimmermann, 1982). In fact, one of the six subjects demonstrated exclusively jaw responses, while two subjects exhibited a combination of jaw and lip compensatory responses to the load. Shaiman (1988) noted that subjects may differ in the way they responded to a perturbation, although their response pattern remained constant across experimental conditions.

This last observation directs our attention to the problem of individual differences and their role in physiological research. For certain types of physiological problems it is perhaps preferable not to group subjects, but, rather, to view each subject separately and to attempt to find those unifying patterns that transcend variation across subjects. Inter-subject variability reflects the complexity, flexibility, and plasticity of the nervous system and is an issue whose implications for the conclusions of these studies must be addressed. Nonetheless, the results from the two experiments discussed above indicate that compensatory responses to perturbations during speech are organized in a functional manner, specific to the task in progress, and only the movements of those articulators involved in the production show compensatory adjustments.

A final point that should be addressed refers to a methodological issue. For the articulators manipulated in Shaiman's experiments (1988, 1989), EMG responses were not consistently associated with kinematic changes. Moreover, inconsistent EMG findings were observed in all six subjects in this study, suggesting that EMG area

measurements could not be used to assess compensatory activity. Similar conclusions were drawn by Folkins and Abbs (1975), who found EMG information from the orbicularis oris superior muscle to be an inadequate indicator of compensatory activity. However, a methodological problem arises as a result of this, since earlier studies have relied heavily on electromyographic information. Ideally, EMG and kinematic data should be used in conjunction in those circumstances in which EMG activity can be obtained from only one muscle per articulator.

1.3.3 Remote articulators

The Shaiman (1988, 1989), and Kelso et al.(1984) studies focused on functional linkages among the articulatory components of a given speech gesture (e.g., the coordination of upper lip, lower lip, and jaw during production of bilabial gestures). Munhall, Löfqvist, and Kelso (submitted) extended the perturbation paradigm to investigate the functional linkages that might exist among articulators that are not mechanically coupled. Munhall et al. considered as “remote” those articulators implicated in the production of a specific target at different locations in the vocal tract. For their experiment they chose the lips, the jaw, and the larynx as they are coupled during the production of a voiceless stop. These articulators form the necessary constrictions at different locations: the lips and jaw (oral closure), and the glottis (vocal fold –glottal– closure). In particular, they examined possible compensatory responses of the larynx following perturbation of the anatomically remote lower lip during the closing movement for the first bilabial voiceless stop in /ipíp/. The hypothesis was that the larynx would exhibit compensatory responses in order to maintain the relative phasing between the laryngeal and the oral articulatory movements necessary for the production of the stop consonant. They found that laryngeal movements were soon –if not immediately– altered following loading of the lip during /p/ production. Specifically, in the perturbed trials, the duration of the laryngeal adduction gesture was

lengthened, resulting in an increase in the total duration of the glottal cycle. In addition, the onsets of movements were delayed for the glottal abduction and the closing of the jaw and the upper lip. At the same time, the duration of the oral closure itself was shortened. However, subjects showed variable reactions to the perturbation. For the closing movement the jaw, upper lip, and lower lip kinematics were modified in two of the three subjects, whereas for the opening movement, all three subjects showed kinematic changes such as increased velocity and displacement.

Despite the observed response patterns, a disruption was observed in the proper phasing of oral and laryngeal gestures at the /p/ release. The delayed onset of the laryngeal abduction and increased duration of the laryngeal adduction after early oral release resulted in an increased VOT in the perturbed productions. Thus, Munhall et al. concluded that, even though their findings extended the perturbation paradigm to intergestural coordinative patterns and provided further support for interarticulator coupling during speech, the data were less clear as to the exact nature of the response patterns induced in the larynx by the perturbation. Further, Munhall et al. considered the data as pointing to certain limitations of the functional compensatory abilities of these remote articulators in preserving their coordinative timing following mechanical perturbations. That is, the goal of compensation in this study was temporal (the maintenance of the relative phasing between movements), while in the previous perturbation studies it was spatial (the achievement of a specific constriction goal within gestures).

The perturbation studies reviewed above lend support to a theory of functional specificity and to goal-directed action in the coupling of the articulatory structures in speech, both within, and between gestures. In the present study, the notion of flexible, functionally specific, task-oriented organization in speech motor control is explored further using a perturbation paradigm and examining the effect of the perturbation on a

remote articulator. This experiment provides further insight into the issue of intergestural cohesion by examining the relationship among the spatial and temporal response patterns of both anatomically linked and remote articulators: the jaw, the upper lip, the lower lip, and the velum. The velum was judged to be well-suited for this study because of its anatomical separation from the lips–jaw complex, and because of the importance of its temporally accurate function for the production of contiguous oral and nasal sounds. However, relatively little is known about the velum and its function in an articulatory aggregate.

1.4 VELUM STUDIES

1.4.1 Studies of velar position

The position of the velum for the production of a given sound has been found to depend on the phonetic environment. For example, (Bell-Berti and Hirose, 1975; Bell-Berti et al., 1979) velar height has been found to be directly proportional to the degree of constriction in the oral cavity, so that low vowels were associated with lower velar positions than high vowels, while obstruents require effective closure of the velopharyngeal port and a concomitantly high velum position. For nasal consonants, the velum is low, as the oral cavity is sealed and airflow is directed through the nasopharynx and the nasal cavity. These results were consistent with results from earlier studies (e.g., Moll 1962), and have found support in a number of other studies. For example, Clumeck (1976) also found that velar position depended on vowel height. Such vowel effects were examined in more detail by Bell-Berti et al. (1979), who found velar position to be influenced by vowel quality during adjacent nasal and obstruent consonants in utterances such as /fipmip/ or /fapmap/ and /fimpip/ or /fampap/. Again, velar position was found to be lower in the environment of the low, open vowel /a/, than in that of the high, closed vowel /i/.

1.4.2 Studies of velum lowering as part of an articulatory organization

Relatively little is known about the function of the velum as part of an articulatory aggregate. McClean (1973), in a cinefluorographic study of the coarticulatory characteristics of velar lowering movements in three subjects, found that velar and lingual movements were coordinated for CVVN production (/riæn/, as in: “three answers”), so that the time of onset of velar movement from /r/ to /n/ was highly correlated with the time of onset of lingual movement from /i/ to /æ/. Specifically, he observed that the velar lowering onset was related to lingual movement toward attainment of steady state /æ/ in either of two ways: in one velar lowering onset occurred before, and in the other it occurred after the tongue reached its steady state /æ/ position. The second type of velar lowering onset was attributed to the longer duration of pauses seen in the marked junctural boundaries between the two vowels of the sequence studied.

Clumeck (1976), studying patterns of velar movement in six languages, found that the velum lowers more and earlier for a low vowel than for a high one when the vowel either follows or precedes a nasal consonant. He also observed velar opening amplitude to be greater for a low vowel than for a high one. In his study, speakers of American English, but not of other languages, showed consistent velar lowering (a dip in the velar movement trace) for low vowels in oral contexts, although Henderson (1984) reported velar lowering for vowels in oral contexts in Hindi.

The temporal relationship between the velum and the lower lip was probed in a study of articulatory organization of syllable structure, in which Krakow (1989) examined the patterns of activity of lower lip raising and velum lowering for /m/ in varying syllable positions and with different word affiliations. She observed strong effects of syllable structure on the velum, but not on the lower lip, with velar lowering movements reflecting consistent effects of syllable affiliation that were generally

amplified in syllable-final position. Krakow also observed interactions across articulators: for syllable-initial /m/ the end of the velar lowering followed the end of the lower lip raising, whereas for syllable-final nasals, it followed the beginning of that movement. The general finding was, then, that the end of the velar lowering movement was temporally correlated with peak low or peak high lower lip positions. Krakow's results showed a similar difference in coordination between word-initial and word-final nasals. Word-initially, lip raising and velum lowering were phased to be almost synchronous. Word-finally, the two movements were not coincident, rather, velum lowering preceded lip raising so much that it coincided with the beginning of the lower lip raising movement. It becomes clear, then, that velar movements are shown to exhibit temporal specificity in a given phonetic context, such as syllable position, with respect to other articulators.

Stress effects on velar lowering movements have also been studied. Krakow (1987) found small but inconsistent differences in the spatial minima attained in velar lowering as a function of stress in bisyllables. However, temporal differences were more robust, with stressed syllables having low position plateaus, indicating a delay between the end of the velar lowering and the onset of velar raising movement. A relatively low velar position plateau was seen for both low (/a/) and high (/i/) vowels in the syllable that received primary stress, even though velar position was higher overall for /i/ than it was for /a/.

As discussed earlier, McClean (1973) found evidence of durational influences on the onset of the velar lowering with respect to the onset of the lingual movement. Effects of differences in vowel duration were examined more systematically by Bell-Berti and Krakow (1991), who, in a study of velar lowering, found that velar lowering before a nasal or oral consonant occurred earlier as the preceding oral vowel sequence duration increased with added segments. Further, there was a consistent observation that the

velar lowering movement consisted of multiple lowering steps, which became increasingly evident with longer sequences of vocalic segments preceding the nasal. These separate velar lowering steps were associated with the specific vowel and consonant movements in the utterance. Given that the number of discrete velar movements in a movement trajectory varied with speaking rate and number of segments per utterance, it was suggested that the timing of the velar lowering movement is stable across speaking rates, and so is the timing relation between the onset of velar lowering movement and that of the concordant oral movement.

1.4.3 Studies of velum raising as part of an articulatory organization

Velar raising movements have been studied in substantially less detail than velar lowering movements. Bell-Berti (1973, 1976), in an electromyographic study of the function of the velopharyngeal muscles, found that the levator palatini muscle was primarily responsible for velar elevation, and it was the only muscle whose EMG activity pattern was consistent across the three subjects in the study. In particular, production of oral consonants was always preceded by a peak in levator palatini muscle activity, while production of nasals was always preceded by a suppression of muscle activity.

Bell-Berti and Hirose (1975) further observed that the pattern of velar raising was highly correlated with EMG bursts of the levator palatini muscle, even though these two activities were not coincident, occurring 60 msec apart. In a cinefluorographic study of two speakers' lingual, labial, and velar movements Kent et al. (1974) found that in VC_nC contexts velar raising began before or sometimes during the oral closure for the nasal consonant, usually well before bilabial closure for the nasal consonant target was attained. Regarding effects of phonetic context on velar raising, Bell-Berti et al. (1979) found that after a nasal consonant, the velum rises earlier and faster for a high vowel than for a low one in utterances such as /fipmip/ or /fapmap/.

Recently, Kollia, Gracco and Harris (1992b, submitted) conducted a comprehensive study of the kinematic characteristics of the velum examining the raising and lowering movements of the velum as well as those of the jaw and the upper lip, within and across two contiguous syllables in six subjects. The two syllables of the utterance /mabnab/ differed in terms of stress, with the first syllable receiving the primary stress. The effects of the presence vs. absence of primary stress on the extent of interarticulator coordination between velum, jaw, and upper lip during the closing movements in the two syllables were also examined.

Looking at the kinematic parameters (displacement, duration, and peak velocity) of the three articulators, Kollia et al. found that the upper lip and the jaw had similar peak velocity-displacement scaling relations for the two /b/ closing movements in the utterance, regardless of stress prominence. For the velum, the peak velocity-displacement correlation in the first raising (i.e., the /b/ closing movement of the syllable that had primary stress) was significant, but it was not as high as those for the jaw or the upper lip. In the second raising movement, the correlation between peak velocity and peak displacement for the velum was greater, and almost as high as for the jaw or the upper lip. It is possible that the difference in the tightness of these relations may be due to the different raising patterns in the two movements. That is, Kollia et al. found that the velum raising was achieved in a multi-step pattern that was seen in many of the individual tokens of all six subjects. Specifically, in the utterance /mabnab/, two distinct raising movements of the velum from the /m/ to /b/ in /mab/ were seen; one from /m/ to /a/, and a subsequent raising from /a/ to /b/. For some subjects an intervening plateau was seen between the two raising movements. These observations of the stepwise raising of the velum are comparable with the findings by Bell-Berti and Krakow (1991) mentioned earlier, regarding the stepwise lowering of the velum with longer durations. Thus, whereas in the first syllable the raising was often achieved in

multiple steps (two raising movements with often an intervening plateau), in the second there was always a single, smooth raising movement. Kollia et al. proposed that these two raising patterns were a consequence of the different durations of the two syllables. The longer duration associated with primary stress afforded uncovering of the multiple raising steps of the velum, one for /m/ to /a/ raising and one for /a/ to /b/.

Also consistent with previous findings, the difference in stress between the two syllables was additionally reflected in the greater movement displacements and greater peak closing velocities for all articulators in syllables receiving primary stress. However, the peak closing velocity differences were not as consistent for the velum; unlike the jaw and the upper lip, the velum showed a tendency for unchanged or higher raising velocity in the syllable with secondary stress. Further, syllable durations measured kinematically differed between the first and the second syllables (/mab/ and /nab/) for all three articulators. Jaw, upper lip, and velum movement durations were shorter in the first syllable (/mab/) than in the second (/nab/), despite the fact that the first syllable was the one containing the primary stress, with the second syllable apparently exhibiting a phrase final lengthening effect.

To assess the degree of interarticulator cohesion across articulator pairs, Kollia et al. measured the correlation between the times of arrival at peak position and the correlation between the times of arrival at peak velocity. In the unstressed syllable, the velum–jaw and the velum–upper lip pairs showed equal cohesion for the opening and the closing movements. The upper lip–jaw pair, however, showed greater interarticulator cohesion for the second closing than for the preceding opening movement.

Analyses of interarticulator relative timing patterns revealed that closing events for the velum and the jaw, and for the velum and the upper lip were related, but not as highly as for the upper lip and the jaw. Further, it became apparent that for the closing movement, the time of peak position rather than the time of peak velocity was a better

index of the interarticulator cohesion between the velum and the jaw, and between the velum and the upper lip. This was apparently due to the fact that during the first velar raising (for /mab/) the movement was often achieved in two distinct steps: one for the raising from /m/ to /a/, and one for the raising from /a / to /b/. Each one of those raising movements had a peak in the velocity trace associated with it. However, the /mab/ raising movement was just as often accomplished in a single step, and that single step had a relevant peak in its corresponding velocity trace. As a result, even though in all cases the peak velocity that was selected for the analyses was the one associated with the second raising movement, the time at which that peak velocity occurred was not as stable as the time at which the peak position occurred. By contrast, for the jaw and the lips /mab/ was always achieved in two distinct movements, each in the opposite direction, and each with its peak position or peak velocity at about the same time. In this way, for the lips and the jaw, peak position and peak velocity were about equally good indices of interarticulator cohesion.

Regarding the effects of stress pattern on the cohesion across articulators (indexed by the relative timing relations among the times of attainment of peak position and peak velocity), Kollia et al. found that these indices were maintained for the two closing movements across stress patterns for all articulator pairs (velum–jaw, upper lip–jaw and velum–upper lip). Moreover, the temporal coupling between velum–jaw was less affected than that between upper lip–jaw by differences in primary vs. non-primary stress. The relative timing relationships were tighter –less variable– for the second closure than for the first closure for all three articulators.

1.5 HYPOTHESES ADVANCED IN THE PRESENT STUDY

The present experiment focuses on the issues of intergestural and intragestural coordination during speech production, particularly on the degree of cohesion that

exists among bilabial and velar gestures during productions of the utterance /mabnab/. While findings from previous experiments lead us to expect that a high degree of (intra-gestural) cohesion exists among anatomically linked articulators, there has been little research on the patterns of (inter-gestural) cohesion among anatomically remote articulators. It is possible that anatomically linked articulators such as the lips-and-jaw or the tongue-and-jaw, reflect the smallest functional unit of motor organization. Alternatively, the organization of motor control may involve larger aggregates of articulators, linked together according to sound-specific configurations. The case with inter- and intra-gestural cohesion is somewhat similar: a number of studies point to coordination of the articulatory movement characteristics within a gesture, while there is less evidence from perturbation studies pointing to such coordination among gestures being preserved after a perturbation.

Intergestural cohesion was probed by applying mechanical perturbations to the jaw during productions of the stimulus utterance, and by analyzing the resultant patterns of spatial and temporal responses of the jaw, the upper lip, the lower lip, and the velum. The general question addressed in the present investigation, then, is the following: what is the extent of the functional motor organization for speech? That is, in functionally linked articulators, does motor control operate only over local groups of articulators, or does it also extend to non-local groups? The specific hypothesis is that the velum adheres to a functional articulatory synergy that links the lips, the jaw, and the velum for the production of a bilabial oral stop, so that jaw perturbations that result in lip compensations will have an effect on the timing or the extent of velum movements.

One prediction of this hypothesis is that, during the production of an utterance that contains a bilabial closure, perturbations of the closing movement of the jaw will result in compensatory responses of the lips and, possibly, the jaw in terms of faster and/or more extensive movements, and also in concomitant modifications of the spatial and

temporal parameters of the velar kinematics necessary for the production of the target utterance. If, however, this hypothesis is not true, and the velum does not adhere to that functionally organized articulatory aggregate, then perturbations of the jaw movement that effect compensatory changes of lip and jaw kinematics, will not affect the spatial and durational characteristics of *velum* kinematics.

The former outcome would support the notion of flexible, functionally-specific, task-oriented articulatory group formations, with coordinative structures having global vocal tract control, whereas the latter outcome would suggest that coordinative structures are limited in scope, being gesture-specific rather than segment-specific (e.g., lip closure rather than /b/ production). It is also important to distinguish between anatomical linkage and goal-oriented functional linkage as a basis for speech motor control. Linkage can be considered to exist in two levels: a structural level, at which articulators are anatomically connected to each other (in the way the lower lip is structurally linked to the jaw), and a neural level, at which the structures are considered to share common neural substrates. In the formulation explored here, goal-oriented control is hypothesized to override the existence of anatomical linkage, at least within the vocal tract.

In addition to examining the functionally specific coupling of the velum to the lips-jaw complex, this perturbation study will provide further insight into the inferred interactions between the sensory and motor processes underlying the control of speech motor behavior. One of the interesting aspects of loading a structure is the potential for differential effects depending on the time of the application of the load. In fact, detailed examination of the results of previous perturbation studies (Gracco, 1984) suggests that the onset of the loading relative to the onset of the movement cycle might result in different compensatory responses. Gracco and Abbs (1982), in an early perturbation study, noticed a trend for differential EMG activity of the orbicularis oris inferior muscle

depending on the time of the application of the load relative to the onset of the EMG activity. Therefore, one of the purposes of this experiment is to determine if this hypothesis is true, and to assess systematically the possibility of variable effects of the load on the movement characteristics not only of the velum, but also of the jaw, the upper lip, and the lower lip.

CHAPTER TWO

METHOD AND RESEARCH DESIGN

2.1 SUBJECTS

The subjects were six females with no history of neurologic, hearing, or speech disorder, ranging in age from 25 to 50 years. Except for BK –the experimenter and a native speaker of Greek– all subjects were native speakers of English and naive to the exact purposes of the experiment. The subjects were told that the purpose of the experiment was to view the movements of their articulators during conditions of jaw loading and non loading. AH, BK, CB, JP, and FE had had formal phonetic training, while LW had no formal phonetic training, but is a fluent speaker of a foreign language. All the speech sounds required for production of the stimulus utterance were within the subjects' native phonological repertoire. Moreover, for the native speakers of English, the stimulus utterance obeys English phonotactic constraints. BK is a fluent speaker of English, and her productions were judged appropriate by phonetically trained native speakers of English.

2.2 SPEECH STIMULI

The utterance for the purposes of this experiment was /mabnab/, one for which the velum moves quickly and maximally. The utterance was selected because for its production the velum is expected to reach extremes of its range of movement for speech (Bell-Berti 1973, 1976; Krakow 1989). Figure 2.1 presents an example of the acoustic waveform and the corresponding kinematic trace of the velar movement for /mabnab/.

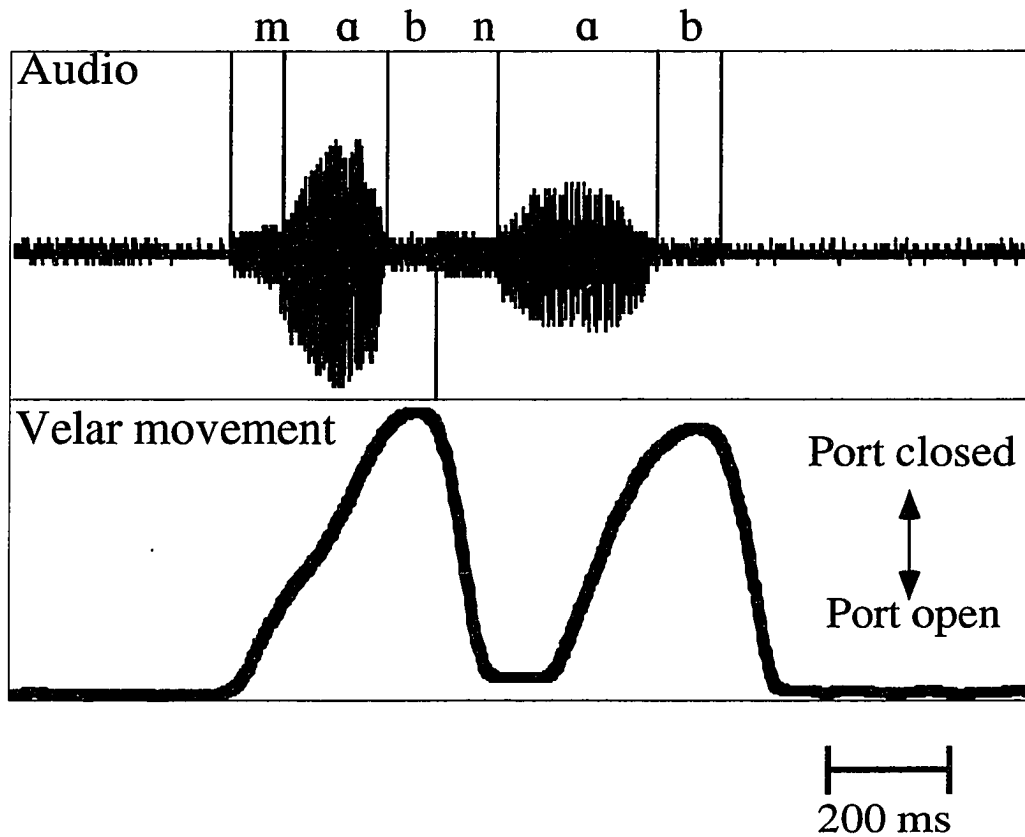


Figure 2.1 Acoustic waveform for /mabnab/, with the corresponding velar movement trajectory. The velopharyngeal port is open during production of the nasal consonants /m/ and /n/, and is closed during production of the bilabial stop /b/. For nasal sounds the velum is at a low position, while for oral sounds it is elevated.

The velum begins rising from a lowered position for /m/ toward a high position for /b/, followed by rapid velar lowering for /n/, and a final rise for /b/. The vowel /a/ was selected for maximal jaw and lip movements, as well as for maximal velar lowering. The coarticulatory effects of /a/ on the nasal consonant result in a lower velar position than do the coarticulatory effects of other vowels (that is, the velum is at a lower position for /m/ in /ma/ than it is for /m/ in /mi/ Bell-Berti et al. 1979). The stress was always on the first syllable and was maintained constant to avoid variability due to changes in stress, such as those reported by Krakow (1987). The utterance was spoken in isolation, at a self-selected conversational rate.

2.3 INSTRUMENTATION

2.3.1 The Velotrace

Velar movements were tracked using the Velotrace, a device developed for this purpose by Horiguchi and Bell-Berti (1987). The Velotrace, shown in Figure 2.2, consists of an internal lever connected to an external lever via a push rod, which rides on a support rod, and is encased in a stainless steel tube. Part of the support rod rests on the floor of the nose, and part extends outside the nose. The tip of the curved internal lever rides on the nasal surface of the velum, moving with it; the movements of the internal lever are transmitted to the external lever through the push rod. The external lever is twice as long as the internal lever, and therefore the movements traced from the external lever are about twice as large as the actual velar movements that they reflect (Horiguchi and Bell-Berti, 1987). In the analysis that follows velar movements are expressed as the movements of the external lever of the Velotrace. The absolute magnitude of the Velotrace movements may vary across speakers, both because anatomical differences among subjects may result in differentially optimal positioning of the internal lever of the Velotrace, and consequently in different absolute displacements

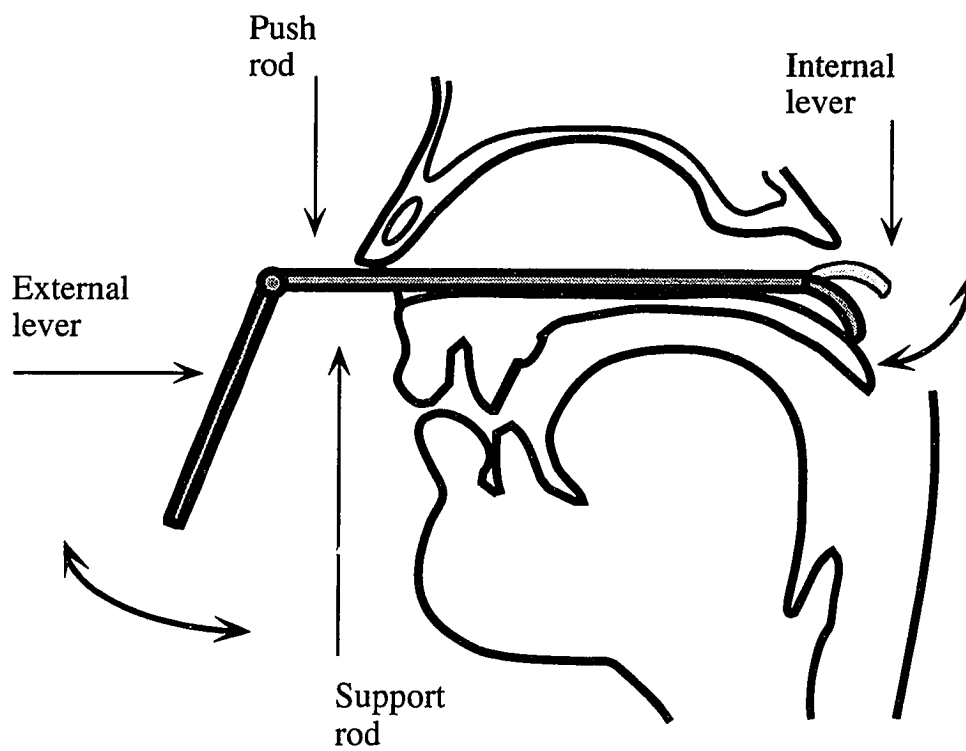


Figure 2.2 Schematic representation of the Velotrace positioned in the nasal cavity (midsagittal view). The structural components of the Velotrace and their movement directions are indicated on the graph by arrows.

of the external lever, and because speakers may also differ in the absolute extent of velar movement. The Velotrace has been shown to be sensitive to even the very rapid velar movements of consecutive oral-nasal sequences (Horiguchi and Bell-Berti, 1987). The Velotrace provides midsagittal indices of the vertical positions of the velum as a function of time, in an analog signal that can be sampled at a high enough frequency to allow accurate representations of velar movement, as well as accurate calculations of the velocity function. The Velotrace does not measure the size of the velopharyngeal port per se. However, it is well known that the size of the velopharyngeal port is reflected in the position of the velum. The levator veli palatini (the muscle primarily responsible for velar elevation) has been found to raise the velum even *after* velopharyngeal port closure has been achieved. Therefore, the range of vertical positions of the velum during its port-opening and closing action provides a continuous signal of velar movement that has two properties: first, it is indicative of motor control mechanisms of the velum during speech, and second, it is free of the discontinuity limitations that appear in measures of port size once closure is accomplished (Horiguchi and Bell-Berti, 1987; Bell-Berti, 1980).

2.3.2 The Jaw Splint

A custom made jaw splint, shown in Figure 2.3, was produced for each subject. A mandibular dental impression was taken, and a plaster cast of the subject's mandibular dentition was made and used to mold the jaw splint. The dental impression was made with Bosworth Supergel Fast Type I Alginate Impression Material, and the cast was made using Modern Materials' White Dentstone. An acrylic resin (Lang Dental Mfg. Co.'s Jet Acrylic Self Curing Resin powder, and Jet Liquid Acrylic) casing for the lower teeth was made, reinforced with a total of six wires curved over the teeth (Austenal Dental Inc. stainless steel wire 19 gauge, item no.0810-19). The acrylic casing had two wide, stainless steel wires (Gibbs Instrument labs, stainless steel wires

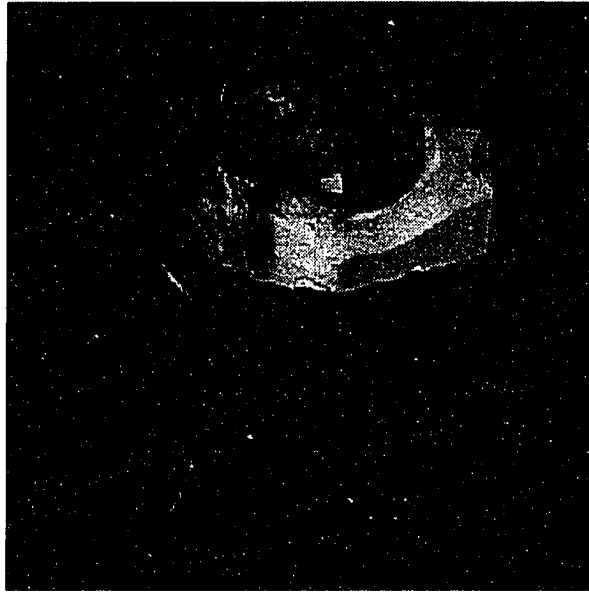


Figure 2.3 Picture of a jaw splint positioned on a mandibular impression.

of .0625" thickness) embedded in its outer sides. The wires exited the acrylic casing upward, at approximately 45 degree angles, at the level of the cuspids, so as to minimize interference with bilabial closure. One of the wires was then bent to the midsagittal plane in a Z-shape, and the other one was bent horizontally and cut at the length of about 1" from the lips. Two holes were then punched in the horizontal part of the wires, as close to the mouth as possible, and nylon coated steel leader wire (manufactured by South Bend, 24", 30 lbs) was threaded through, and joined into a loop through which the hook of a torque motor connector wire was placed. The jaw splint was kept in place with the help of a dental adhesive (Dentco inc.'s Super Poli-Grip Denture Adhesive Cream). The shorter steel wire of the jaw splint was bent so as to not obscure the LED on the center of the vermilion border of the subject's upper lip, thus allowing for recording of upper lip movements.

2.3.3 The movement tracking system

Infrared light emitting diodes (LED's) were attached to the bridge of the subject's nose (as a reference), lips, jaw splint, and the external lever (stable reference and movable lever) of the Velotrace. The trajectories of interest derived from the LED's were those of the vertical displacements of the lips, the jaw, and the nose reference, and those of the horizontal displacements of the Velotrace LED's. The light modulations from the LED's were obtained using an optoelectronic tracking device. The device consisted of an infrared-sensitive camera with a Schottky planar photodiode in its focal plane that received the light modulations and transduced the generated potentials into pairs of x and y coordinates to a series of preamplifiers and amplifiers, and finally to a frequency-modulation (FM) tape for recording. FM recording equipment was used because movement signals contain spectral components as low as 0 Hz, that might not be captured by amplitude modulation equipment (Kelso et al., 1985; Kay et al., 1985).

2.3.4 The chair, the Cephalostat, and the Torque Motor

The experimental setup consisted of an adjustable dental chair, enclosed in an aluminum tubular beam framework, onto which a cephalostat and a DC Brushless torque motor were fixed. The torque motor was placed directly below the subject's jaw, and thus the force applied to the jaw was in the vertical direction. A load cell was connected in series to the wire joining the jaw splint to the torque motor, allowing monitoring and control of the load. The tracking load on the jaw splint was measured using a calibrated transducer to be 30 grams. The cephalostat was comprised of a padded headband that extended forward from a wooden, helmet-shaped box permanently attached to the set of beams encasing the dental chair. The cephalostat could be adjusted to fit securely around the subject's head. The Velotrace was then fastened to the stable parts of the cephalostat. (For a more detailed description of this setup see Kelso et al., 1984, pp. 814-815).

A highly directional microphone was used for audio recording during the experiment.

2.4 PROCEDURE

2.4.1 Subject Preparation

The Velotrace was coated with 2% Xylocaine (Lidocaine HCl) gel, and the subject's nasal cavity was sprayed with 4% Xylocaine spray. Following anaesthetization, the subject was positioned in the experimental chair, her head was secured with the cephalostat, she was fitted with her custom jaw splint, and, finally, with the Velotrace. Infrared LED's were then attached to the subject. The LED's were placed on the subject at the bridge of the nose (stable reference LED to monitor head movement), the center of the vermilion border of the upper lip (upper lip LED) and of the lower lip (lower lip LED), the tip of the external lever of the Velotrace (Velotrace LED), the external, stable

part of the support rod of the Velotrace (Velotrace reference LED to monitor Velotrace movement), and the point on the arm of the jaw splint closest to the subject's jaw (jaw LED). For one subject, BK, the LED that was placed on the center of the vermilion border of the upper lip could not be recorded, because it was obscured by one of the outer steel wires of the jaw splint. As a result no upper lip kinematics were obtained for this subject. This problem was remedied for the other subjects by bending the outer wire of the jaw splint at an angle that did not obscure the upper lip LED. A schematic representation of a subject positioned for the experiment is shown in Figure 2.4. The stimulus utterance was printed on an 8 1/2" by 11" card, and was placed before the subject. The subject was instructed to produce the stimulus utterance, in isolation, at a self-selected, comfortable speech rate, as soon as she heard the cueing tone. Unanticipated perturbations were randomly delivered near the onset of the first vowel of the utterance.

At the end of the experiment, sustained /s/ and /m/ productions were obtained for every subject to view the maximum range of the velar displacement. In addition, for two of the subjects, a number of perturbations were delivered to the jaw while the subject was at rest, to assess the degree to which the jaw and the velum are mechanically coupled (the data is presented in section 2.4.3).

2.4.2 Perturbation presentation

The subject was instructed to produce the stimulus utterance as soon as she heard the cueing tone. The perturbations were presented randomly on no more than 20% of the trials. The load that was applied to the jaw was approximately 430 to 500 grams, and was roughly adjusted depending on the subjects' physical tolerance. The load for each subject was as follows: AH: 450 grams, BK: 500 grams, CB: 500 grams, FE: 500 grams, JP: 500 grams, and LW: 430 grams. The rise time of the load was 35 msec, and its fall time was 15 msec. The 35 msec rise time was long enough to avoid elicitation of

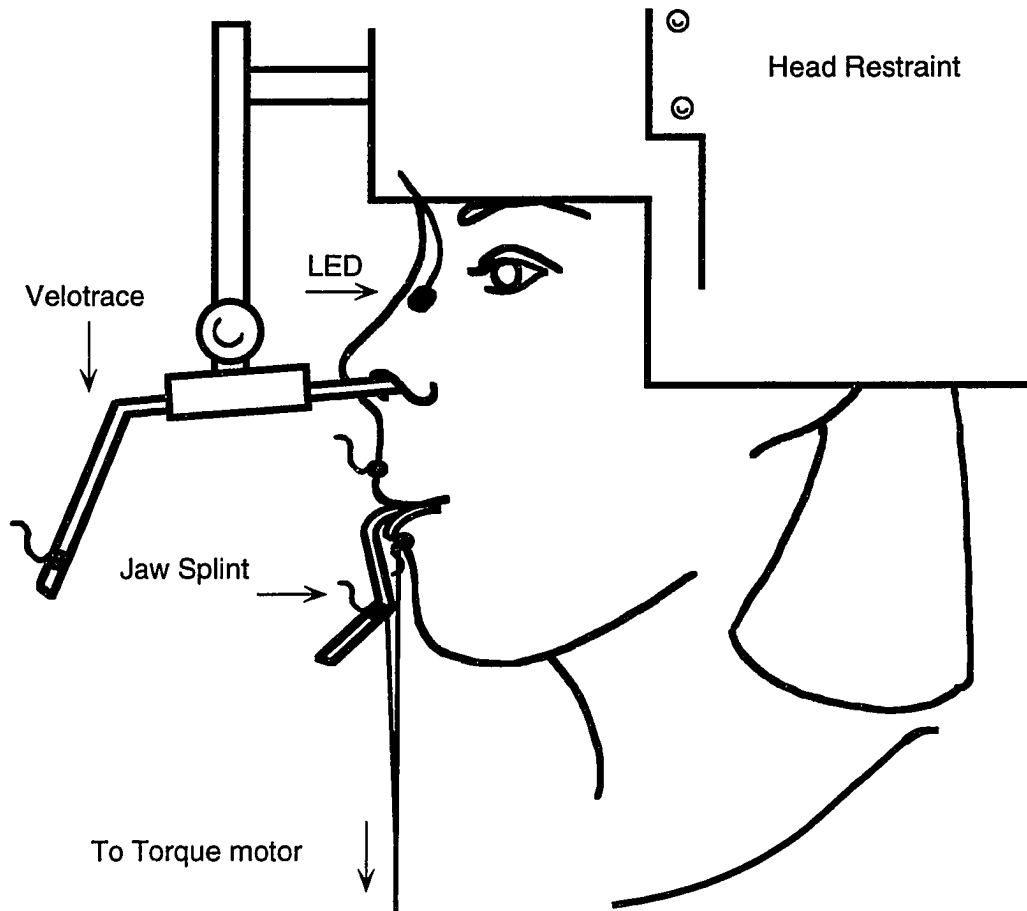


Figure 2.4 Schematic representation of the experimental apparatus, with the subject positioned for the experiment. LED's can be seen on the nose (reference LED), the upper lip, the lower lip, the arm of the jaw splint and the external lever of the Velotrace.

a reflex response, given that reflexes generally have a latency period of about 6 msec (Dubner et al., 1978). The load was applied to the jaw, in general, for approximately 1000 msec (total duration of 1050 msec), in order to include the entire duration of the utterance, so that there were no load-offset signal effects. The load duration necessary to cover the utterance was adjusted for each subject's speaking rate. The exact duration of the load application was calculated for each subject prior to the initiation of the experiment, based on a sample of 10-15 tokens spoken by the subject in their chosen "comfortable" speech rate. The average duration of the nasal was calculated from the waveform, so that the interval in which the load could be applied was obtained. The subject was cued with a short tone presented by the experimenter, she then began to speak, and after a variable delay the load was applied, perturbing her jaw movement. Approximately 20% of the tokens were perturbed to minimize anticipation of the load or adaptation to it (Abbs & Gracco, 1984). A computer program was used to control the triggering and delivery of the perturbations with the following constraints:

1. the first trial was never a perturbation, and
2. there were at least 2 trials without perturbation between trials with perturbation.

The reason for these deviations from a completely randomized perturbation delivery program was to allow comparison of each perturbed token with the non-perturbed token immediately preceding it, to minimize variability attributable to serial and long term effects of the motor control system at various levels (Schmidt, 1982). In this way, if, for example, a subject showed signs of fatigue toward the end of the experiment, e.g., producing tokens at a slower rate, these tokens would have as controls tokens occurring immediately prior to them, rather than tokens occurring in the beginning of the experiment.

Given that initial and successive perturbations have no immediately preceding unperturbed token, they do not allow for such a comparison. Also, the non-perturbed

token that follows a perturbed one is often changed due to carryover effects from the compensatory adjustments of the preceding perturbation (cf. Schmidt, 1982). Therefore, the control token appropriate for comparison was the one preceding the perturbed token, and it could not be one immediately following a perturbed token.

2.4.3 Jaw loading with structures at rest and while sustaining /a/

As a precursor to the present investigation, it was necessary to determine whether jaw loading would result in either an obligatory reflex response in the velum, or a concomitant mechanical response of the velum to the jaw movement. The question was whether a downward displacement of the jaw would cause the velum to lower as would a structure that has a tight mechanical connection to the jaw, such as the lower lip or the tongue. A reflex response of the velum to imposed jaw lowering was a second matter of inquiry. The question in this case was whether the load would result in an overall reflex reaction in the oral musculature. In order to study such potential reflexive coupling of the velum to the jaw and degree of mechanical coupling between the two articulators, two experimental manipulations were carried out for two of the subjects.

The first experiment examined the possibility of a mechanical effect of jaw perturbation on the velum, while both structures are at rest; a load was applied to the subject's jaw and she was instructed to not resist the load. The second experiment examined the possibility of a reflex response of the velum to jaw perturbation, while both structures are functionally active for /a/ production. Again, a load was applied to the subject's jaw while she sustained phonation of /a/, and was instructed to not resist the load, but rather, to maintain phonation and allow passive displacement.

Shown in Figure 2.5 are representative results from the first experiment for one of the subjects. The top trace shows the load onset, the load duration of about 1 second, and the load offset. The middle traces show the positions of the jaw at rest (black line) and after application of the load (grey line). The bottom traces show the positions of the

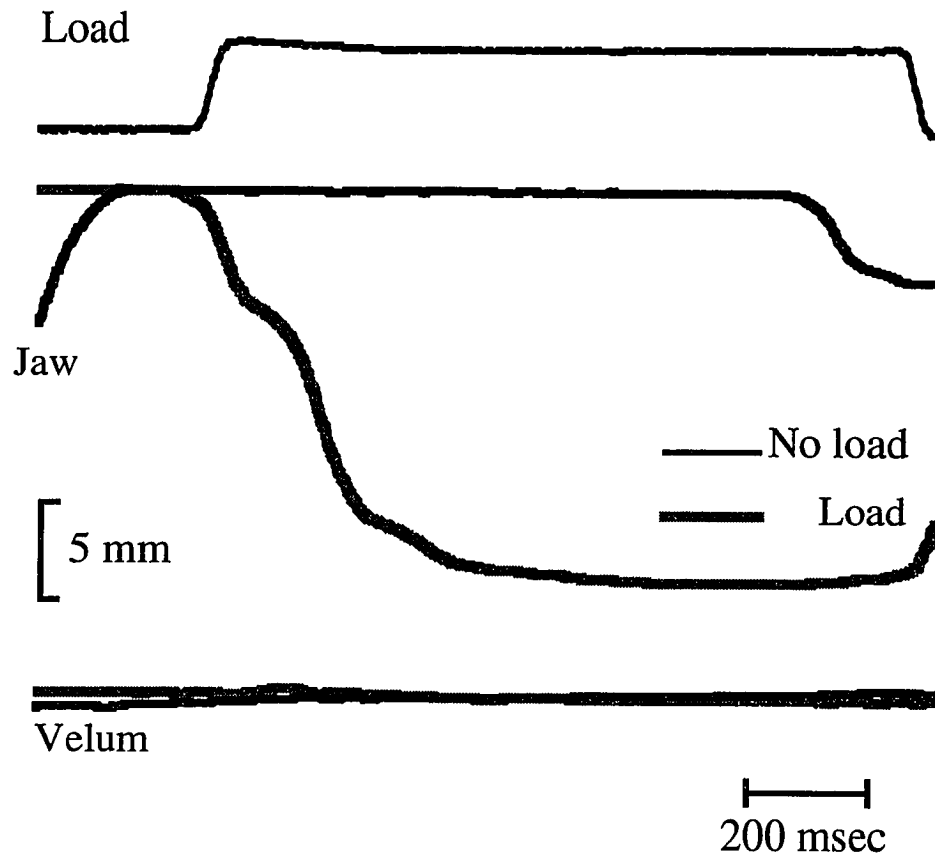


Figure 2.5 Jaw, velum and load trajectories during jaw loading, while the subject is at rest. Shown are averaged traces from one subject. The top trace shows the load being applied, lasting about 1 sec, and coming off. The middle traces show the jaw displacements in conditions of loading and non-loading. The bottom traces show the corresponding displacements of the velum; these displacements did not differ in the two conditions.

velum at rest (black line) and after application of the load (grey line). It is clear that, while the jaw was significantly lowered, the position of the velum did not differ in the two conditions. Figure 2.6 shows the results from both experiments for the two subjects in bar-graph form: the top graph shows the position of the jaw in the two conditions (loads and controls) while the subjects were at rest and during /a/ phonation. On the left side are the results from subject CB and on the right are the results from subjects LW. It is clear that the load produced a significant lowering of the position of the jaw, relative to the control condition in each case (at rest and during phonation) for both subjects. The significant differences are indicated with a dot placed over the appropriate load bars.

In both cases the resultant velar positions did not differ in the load vs. non-load conditions. For subject CB the analysis of variance (repeated measures, pairwise) showed significant differences in the jaw positions in the load condition compared with the control condition, both at rest ($p < .0001$) and while phonating ($p < .0004$). The positions of the jaw in the load vs. the control condition were lower by an average of 1.39 mm at rest, and by an average of 21.68 mm during phonation. For the velum, however, in the two conditions –loads vs. controls– no difference was found in position at rest ($p > .25$, NS; mean difference = 0.43 mm), or while phonating ($p > .15$, NS; mean difference = 0.87 mm). The position was measured before (control) and during (load) the load application, for each token.

Similarly, for subject LW the analysis of variance showed significant differences in the jaw positions in the load condition compared with the control condition, both at rest and while phonating (for both $p < .0001$). The positions of the jaw in the load vs. the control condition were lower by an average of 6.76 mm at rest, and by an average of 3.41 mm during phonation. Again, no difference was found in velum position in the two load conditions while phonating ($p > .64$, NS; mean difference = 0.16 mm).

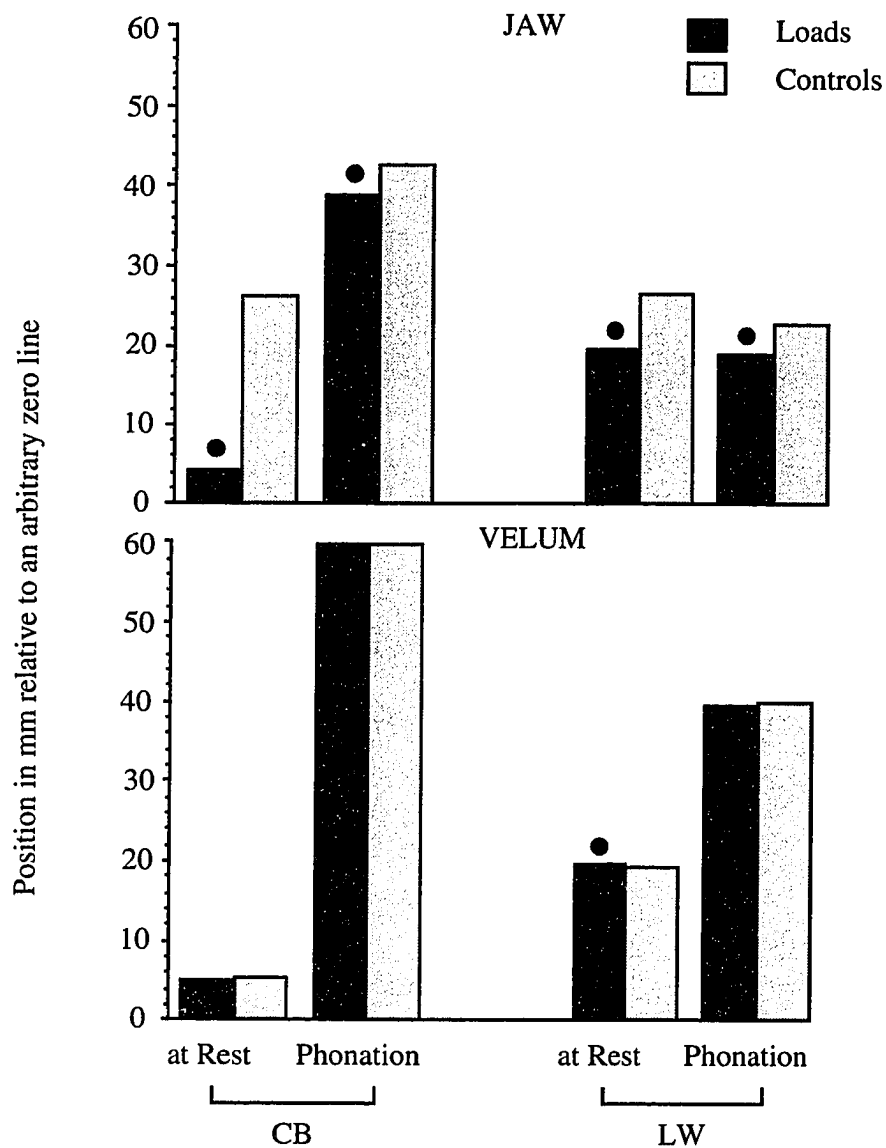


Figure 2.6 Mean Jaw and Velum positions in conditions of jaw loading and non loading, with the subjects (CB, LW) at rest and also while sustaining /a/ phonation. Significant differences ($p < .05$) between loads and their controls are marked with a dot above the appropriate load bars.

However, a significant difference was seen in the position of the velum at rest ($p < .024$). The difference in position between loads and controls with the velum at rest was 0.21 mm, with the load tokens being higher in position than the controls. The importance of this difference for the purposes of this study is difficult to interpret.

These results provided evidence that any mechanical linkage between the jaw and the velum is at best limited. Further, there was no evidence of a reflex response of the velum to jaw perturbation. We have, therefore, ruled out both an obligatory mechanical and a stereotypic reflex reaction of the velum to imposed jaw lowering.

2.5 DATA COLLECTION AND RECORDING

2.5.1 Data Acquisition

The movement and acoustic data were recorded using FM recording instrumentation on a multichannel magnetic tape at a speed of $3\frac{3}{4}$ inches per second, for storage and subsequent analysis. A calibration signal was obtained for later analysis. The procedure involved displacing an LED a known distance (2cm) and recording the two known LED positions.

In summary, six (five for subject BK) LED positions were recorded into six (five for subject BK) channels on the tape, resulting in an equal number of movement signals: the y-axis movement of the nose and x-axis movement of the Velotrace reference signals, the x-axis movement of the velum, and the y-axis movements of the upper lip (no upper lip recording for subject BK), lower lip, and jaw movement signals. The load cell signal from the torque motor and the voice signal were recorded simultaneously with the movement signals.

2.5.2 Data Extraction

These eight signals were subsequently digitized using an 1104 processor with 12-bit resolution at a rate of 500 Hz (for the movement signals) and 10K Hz (for the speech

signal) without further filtering, and input to a VAX 4000-500 computer for analysis. The individual tokens were extracted from the calibrated signal files and labeled for each type of utterance (load and control utterances). For each token, the speech signal was marked at the acoustic onset of the first vowel (that is, the lineup point), and each extracted token was comprised of a 1500 msec window around that marker (300 msec before and 1200 msec after the marker, or, 6000 and 24000 samples before and after the marker respectively). To mark the lineup point of each token on the waveform display, the cursor was placed at the vicinity of the vowel onset, the signal was then magnified at that position, the cursor was placed at the acoustic onset of the first vowel, and the token was given the appropriate label.

2.5.3 Signal Processing

The movement files were smoothed using a 42 msec triangular window that eliminated most of the signal energy above 24 Hz, so that frequencies higher than the frequencies of the articulator movements (about 10-15 Hz) were low pass filtered. The reference channels were subtracted from the appropriate kinematic channels to correct for any horizontal or vertical head shift during the experiment. Specifically, the nose reference LED signal was subtracted from the upper lip, the lower lip, and the jaw LED signal. The Velotrace reference LED signal was subtracted from the Velotrace movement LED signal. Further, the subtracted jaw LED signal was subtracted from the subtracted lower lip LED signal, so that the resultant lower lip signal reflected the movement of the lower lip only. For the remainder of the text "lower lip" is used to refer exclusively to that resultant lower lip (i.e., lower lip – jaw) signal.

In addition, the lip aperture signal was calculated by subtracting the upper lip LED signal from the combined lower lip and jaw LED signals. The resulting signal indicated the instantaneous distance between upper and lower lip as a function of time. For

subject BK the lip aperture signal could not be calculated since no usable upper lip data were obtained.

The signals in the new set of movement files were then differentiated using a central difference algorithm to obtain the corresponding velocities. The velocity files were then smoothed using a 42-msec triangular window, and each individual token was extracted from the movement and velocity channels (cf. Kay et al., 1985, for a detailed description of the digitization and filtering procedure used at Haskins Laboratories). For subject FE the lip aperture velocity signal could not be used for statistical analyses due to a malfunction in the software processing routine.

2.5.4 Event Marking

The local maxima and minima of the movement and velocity signals for each token were marked automatically and subsequently inspected individually. The peak positions of the movement channels were marked based on the zero-crossing values of the corresponding velocity signals, with specific noise criteria determined for each signal. That is, the points at which the velocity traces crossed the zero line were taken to indicate onset and offset of movement, i.e. local maxima and minima on the corresponding movement traces. As an example, Figure 2.7 shows the acoustic waveform for /mabnab/, marked at the vowel onset, and the corresponding smoothed and averaged kinematic traces of the movements of the velum, upper lip, lower lip, and jaw, marked at the position maxima and minima for one subject (AH). The figure shows the velum raising from /m/ to /b/, while at the same time the jaw, the lower lip, and the upper lip open for /a/, and close to produce the /b/. The time and amplitude values were output into label files, and shipped to a Macintosh personal computer for statistical analyses. (For greater detail on the data manipulation see Appendix 1.)

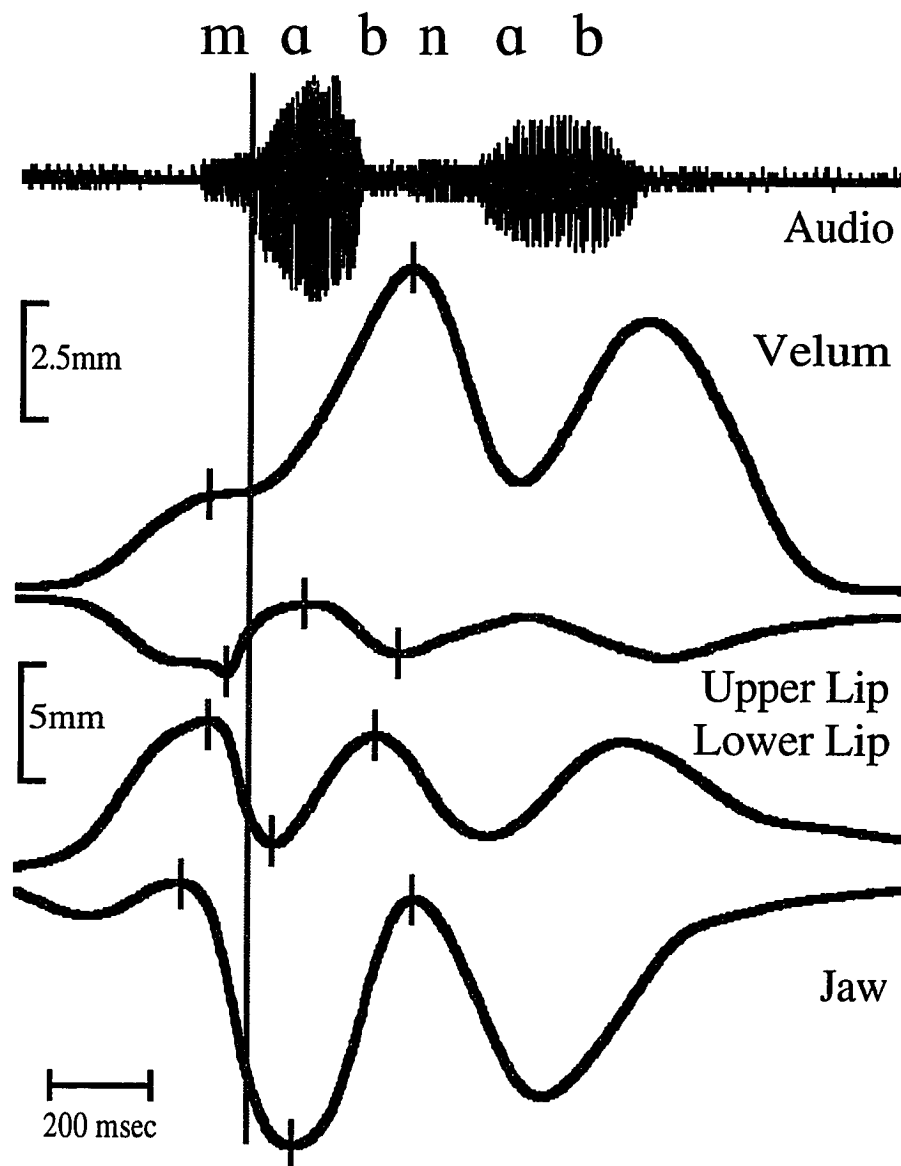


Figure 2.7 Shown are an acoustic waveform for /mabnab/ with the first vowel onset marked (long vertical line), and the corresponding averaged kinematic traces of the velum, the upper lip, the lower lip and the jaw for control (non-perturbed) tokens from subject AH. The short vertical lines on the movement trajectories mark movement onsets for /mab/ landmarks, defined by zero crossings of the corresponding velocity signals.

2.5.5 Data Calculation

All temporal measures were referenced to the time of the acoustic vowel onset. The time of the acoustic vowel onset was subtracted from all other measures of time. The movement durations were then calculated by subtracting the movement offset times from the movement onset times. For the movement displacements, the values of the peak position at movement offset were subtracted from the values of peak position at movement onset. This difference gave a measure of the movement's amplitude (or displacement). The absolute value of that difference was used as the amplitude value for all displacements. For the peak velocity values of the movements, the values from the signal files were used without further processing. Therefore, the peak velocities of the closing movements of the jaw, the lower lip, and the velum have a positive sign, whereas the peak velocity of the closing movement of the upper lip has a negative sign.

2.6 LOAD ONSET CHARACTERISTICS

As mentioned earlier, one of the purposes of this experiment was to determine the potential for differential effects depending on the time of the application of the load on the movement characteristics not only of the velum, but also of the jaw, the upper lip, and the lower lip. Therefore, the load onsets were distributed within an approximately 300 msec window before the acoustic vowel onset. The overall load application interval was divided into three 100 msec bands. Loads applied during the interval 0 to 100 msec prior to the vowel onset were grouped into the "late loads" category. Loads applied during the interval 100 to 200 msec prior to the vowel onset were grouped into the "mid loads", and loads applied more than 200 msec before the vowel onset were grouped into the "early loads" category.

The load onsets were distributed randomly, using a computer program developed at Haskins Laboratories (cf. section 2.4.2). One of the program variables was the time

delay between the onset of the cueing tone and the load onset time, and that interval was specified by the experimenter. Since each subject's response was initiated after the cueing tone, and since the subject's average reaction time was factored in the load onset interval specified in the program, then, to a large extent the load onset times relative to the utterance were dependent on the subject's reaction time. Even though a serious effort was made to account for individual variation by adjusting the load onset interval for each subject's mean reaction time, the temporal distribution of the loads within subjects was still not homogeneous as subjects displayed great within-subject variability during the course of the experiment. In one of the subjects (FE) all loads fell in the "early" category, and in another subject (JP) they fell in the "early and "mid" categories. In two other subjects (AH, CB) some of the loads occurred after the vowel onset ("Post-VO" category).

2.7 STATISTICAL ANALYSIS

An equal number of perturbed tokens and unperturbed control tokens were analyzed. The number of pairs varied for each subject, and was: AH: 85, BK: 69, CB: 78, FE: 78, JP: 138, and LW: 53. The control tokens obtained were those unperturbed tokens occurring immediately prior to the perturbed tokens, or as temporally proximal to them as possible, so as to minimize any variability that could be attributed to serial effects.

A one factor within, one factor between repeated measures analysis of variance was performed on the data. The within factor was "load presence," that is, load condition vs. non-load (control) condition; the between factor was "load onset time relative to vowel onset," which for the load tokens represented the early- vs. mid- vs. late-load application onset times relative to the vowel onset.

Despite the large number of comparisons in the data that follows, a Bonferroni correction was not deemed necessary, since each subject's data was analyzed separately,

thus reducing the actual comparisons by a factor of about six. Moreover, within each subject, the data pertaining to each articulator (i.e., jaw, lower lip, upper lip, and velum) was analyzed independently also, further reducing the number of effective comparisons and, thus, the possibility of Type I error rate due to repeated testing. Therefore, no adjustments for Type I error were made. Had the comparisons been performed across all subjects and articulators, a Bonferroni correction would have been necessary.

CHAPTER THREE

RESULTS

3.1 RESULTS FOR THE /ma/ OPENING AND /b/ CLOSING MOVEMENTS IN /mab/ OF /mabnab/

As discussed in the previous chapter (2.4.3), examination of the velar movements during jaw loading at rest and during sustained phonation indicated no significant mechanical coupling between the jaw and the velum, since successive passive jaw lowerings resulted in no significant change of velar position (Figures 2.5, 2.6). Therefore the results discussed below do not reflect reflex responses or mechanical coupling effects, rather they reflect the articulatory organization for speech of the velum and the jaw-lips complex.

The movement of interest in this study is the closing movement toward the first /b/ in /mabnab/. The closing movement for the jaw, the lower lip and the velum is an upward –raising– movement; rather, for the upper lip it is a downward –lowering– movement. The results reported below are for this particular gesture.

Consistent with results from previous experiments that have shown compensatory responses of the lips to jaw loading, perturbed utterances differed from control utterances in both the spatial and temporal characteristics of articulatory movement. Lip, jaw, and velar movements exhibited response patterns indicative of compensation, such as increased movement displacement and increased oral closing velocity, as well as changes in the durations of the movements. However, each subject dealt with the load

application idiosyncratically. For example, for some subjects (e.g. FE, LW) movement duration was minimally changed, while movement displacement and velocity changed considerably. By contrast, for others (e.g. subject AH) duration varied substantially, while jaw, lower lip and velum closing velocities remained relatively stable. These load specific changes in the movement parameters (displacement, velocity and duration) are discussed below for the six subjects, for each of the articulators (jaw, lower lip, upper lip and velum) and also for lip aperture. Lip aperture was used as a global indicator of oral closure, as it reflects the goal-directed combined effects of displacement of the upper lip, the lower lip and the jaw for achieving /b/ closure. Following is a summary presentation of the results across subjects for the different articulators, followed by presentation of the results for each subject separately.

Section 3.1 begins with a brief description of the effects of the perturbation on the opening movement of the jaw (the direct recipient of the perturbation) and on the lip aperture (a function of the upper lip, lower lip, and jaw activity, 3.1.1). The section continues with the description of the effects of the perturbation on the closing movements of the oral articulators' collective activity as reflected in the lip aperture (3.1.2), and on each articulator separately: jaw, lower lip, upper lip and velum (3.1.3–6). These results are presented in Tables 3.1 (for /a/ opening) and 3.2 (/b/ closure). Table 3.3 presents the means, standard deviations, F-values and p levels for the analyses of variance on the *initial positions* of the jaw and lower lip in all conditions for the six subjects. Table 3.4 lists the degrees of freedom per subject and condition from the statistical analyses, as those varied across subjects.

3.1.1 Opening movement for /ma/ in /mab/ (Jaw and Lip Aperture)

The load did indeed affect the jaw; its movement characteristics changed as a result of the application of the load. Table 3.1 presents the results from the analyses of variance on the load specific changes for the jaw and the lip aperture measures

Table 3.1: F-values, df's, and p values for load-control analyses of variance for the /a/ opening movement.

Subj.	Measure	JAW	LIP APERTURE
AH	Displ. Veloc. Dur'n.	F[1, 81]= 38.23 , p=.0001 F[1, 81]= 27.86, p=.0001 F[1, 81]= 1.83, NS	F[1, 81]= 26.05, p=.0001 F[1, 81]= 1.39, p=NS F[1, 81]= .78, NS
BK	Displ. Veloc. Dur'n.	F[1, 66]= 504.76, p=.0001 F[1, 66]= 550.43, p=.0001 F[1, 66]= 18.78 , p=.0001	No data
CB	Displ. Veloc. Dur'n.	F[1, 74]= 24.58, p=.0001 F[1, 74]= 14.54, p=.0003 F[1, 74]= .0001, NS	F[1, 74]= .10 , NS F[1, 74]= .31 , NS F[1, 74]= .40, NS
FE	Displ. Veloc. Dur'n.	F[1, 77]= 28.27, p=.0001 F[1, 77]= 4.44, p=.038 F[1, 77]= .500, NS	F[1, 77]= 5.52 , p=.021 No data F[1, 77]= .57, NS
JP	Displ. Veloc. Dur'n.	F[1, 135]= 12.96, p=.0004 F[1, 135]= 1.30, NS F[1, 135]= 7.61, p=.007	F[1, 135]= .98, NS F[1, 135]= 1.03, NS F[1, 135]= 2.25, NS
LW	Displ. Veloc. Dur'n.	F[1, 47]= 59.74, p=.0001 F[1, 47]= 10.11, p=.0026 F[1, 47]= 28.33, p=.0001	F[1, 47]= 9.77, p=.003 F[1, 47]= 8.36, p=.006 F[1, 47]= .0001, NS

Table 3.2: F-values, df's, and p values for load-control analyses of variance for the /b/ closing movement.

Subj-Meas.	VELUM /mab/	JAW /ab/	LOWER LIP /ab/	UPPER LIP /ab/	LIP APERTURE /ab/
AH					
Displ.	F[1, 81]= 8.31, p=.0050	F[1, 81]= 36.66, p=.0001	F[1, 81]= 5.32, p=.024	F[1, 81]= 1.41, NS	F[1, 81]= 33.41, p=.0001
Veloc.	F[1, 81]= 1.73, NS	F[1, 81]= 1.98, NS	F[1, 81]= .66, NS	F[1, 81]= 6.97, p=.001	F[1, 81]= .14, NS (int)
Dur'	F[1, 81]= 11.02, p=.0014	F[1, 81]= 63.41, p=.0001	F[1, 81]= 10.17, p=.0020	F[1, 81]= .27, NS	F[1, 81]= 30.05, p=.0001
BK					
Displ.	F[1, 66]= 80.44, p=.0001	F[1, 66]= 138.35, p=.0001	F[1, 66]= .28, NS	No data	No data
Veloc.	F[1, 66]= 90.63, p=.0001	F[1, 66]= 146.77, p=.0001	F[1, 66]= 52.77, p=.0001	No data	No data
Dur'	F[1, 66]= .62, NS (int)	F[1, 66]= 71.80, p=.0001	F[1, 66]= 142.55, p=.0001	No data	No data
CB					
Displ.	F[1, 74]= 6.93, p=.010	F[1, 74]= 6.40, p=.014	F[1, 74]= 1.89, NS (int)	F[1, 74]= 71.24, p=.0001	F[1, 74]= .27, NS (int)
Veloc.	F[1, 74]= 3.87, p=.053	F[1, 74]= 25.84, p=.0001	F[1, 74]= 14.71, p=.0001	F[1, 74]= 21.69, p=.0001	F[1, 74]= 5.22, p=.025
Dur.	F[1, 74]= 3.25, p=.076	F[1, 74]= 58.65, p=.0001	F[1, 74]= 4.52, p=.037	F[1, 74]= 10.66, p=.002	F[1, 74]= 42.19, p=.0001
FE					
Displ.	F[1, 77]= .68, NS	F[1, 77]= 5.19, p=.025	F[1, 77]= 54.16, p=.0001	F[1, 77]= 64.95, p=.0001	F[1, 77]= .75, NS
Veloc.	F[1, 77]= .001, NS	F[1, 77]= 2.22, NS	F[1, 77]= .92, NS	F[1, 77]= 29.48, p=.0001	No data
Dur.	F[1, 77]= 3.61, p=.061	F[1, 77]= 2.54, NS	F[1, 77]= .22, NS	F[1, 77]= 3.25, p=.075	F[1, 77]= 3.62, NS
JP					
Displ.	F[1, 135]= 1.47, NS(int)	F[1, 135]= 2.71, NS	F[1, 135]= 2.05, NS(int)	F[1, 135]= 11.64, p=.0009	F[1, 135]= 3.22, NS (int)
Veloc.	F[1, 135]= 1.27, NS(int)	F[1, 135]= 3.47, p=.065	F[1, 135]= .51, NS (int)	F[1, 135]= 17.11, p=.0001	F[1, 135]= 1.65, NS (int)
Dur'	F[1, 135]= .89, NS (int)	F[1, 135]= 10.97, p=.001	F[1, 135]= 8.55, p=.0041	F[1, 135]= 7.16, p=.0084	F[1, 135]= .001, NS (int)
LW					
Displ.	F[1, 47]= .004, NS	F[1, 47]= 44.28, p=.0001	F[1, 47]= 39.45, p=.0001	F[1, 47]= 7.59, p=.008	F[1, 47]= 8.25, p=.0061
Veloc.	F[1, 47]= .58, NS (int)	F[1, 47]= 12.47, p=.0009	F[1, 47]= 20.25, p=.0001	F[1, 47]= 1.71, NS (int)	F[1, 47]= 16.14, p=.0002
Dur.	F[1, 47]= .35, NS	F[1, 47]= .35, p=.074	F[1, 47]= .23, NS	F[1, 47]= 11.31, p=.0015	F[1, 47]= 61.42, p=.0001

Table 3.3: Means, standard deviations, F-values and p values for load vs. control repeated measures analyses of variance performed on the initial position of the first opening and closing movements of jaw and lower lip for each subject. * indicates significant differences.

Jaw Positions				Lower Lip Positions			
AH							
Measure	1 /m/	2 /a/	3 /b/		1 /m/	2 /a/	3 /b/
F-value	10.977	72.753	10.475		79.549	49.897	56.703
p	.0014	.0001	.0018		.0001	.0001	.0001
Loads mean	9.61	-4.688	9.994		-2.243	-7.866	-2.936
Std dev	3.003	2.62	1.833		1.919	1.986	1.312
Controls mean	10.974	-1.346	10.929		-3.896	-9.868	-4.283
Std dev	1.758	3.1	1.717		1.276	2.255	1.154
Early L mean	6.504 *	-3.465*	9.717		-.747*	-7.506*	-2.960*
Std dev	2.004	2.835	1.892		1.389	1.713	1.351
Mid L mean	10.329	-5.019*	10.132*		-1.405*	-7.323*	-3.215*
Std dev	1.867	2.545	2.100		1.353	1.689	1.261
Late L mean	11.777*	-5.600*	10.313		-3.214*	-7.677*	-3.257*
Std dev	1.642	2.370	1.774		1.335	1.977	1.082
Post VO L mean	11.568	-5.330*	9.911*		-4.192	-9.280	-2.160*
Std dev	1.686	1.792	1.680		1.261	2.218	1.408
Early C mean	10.818*	-1.515*	10.842*		-3.571*	-9.744*	-4.049*
Std dev	1.914	3.665	1.958		1.531	2.337	1.235
Mid C mean	11.121	-1.385*	11.139*		-3.963*	-10.173*	-4.448*
Std dev	1.590	2.720	1.389		1.033	2.044	.925
Late C mean	10.932*	-1.219*	10.868		-4.145*	-9.734*	-4.297*
Std dev	1.671	3.120	1.365		1.169	2.230	1.112
Post VO C mean	11.234	-1.196*	11.041*		-4.072	-10.096	-4.590
Std dev	1.823	2.292	2.062		1.007	2.454	1.215
BK							
F-value	20.798	632.484	95.757		145.593	61.805	294.171
p	.0001	.0001	.0001		.0001	.0001	.0001
Loads mean	5.853	-6.692	2.777		-.730	-10.801	-2.810
Std dev	.792	2.664	2.484		.862	1.613	.809
Controls mean	6.134	1.328	5.799		-.057	-8.966	-.913
Std dev	.471	1.070	.468		-.390	1.052	.472
Early L mean	5.246*	-5.052*	5.217*		-1.976*	-10.255*	-2.330*
Std dev	1.397	2.180	2.247		1.067	1.220	.748
Mid L mean	5.987	-6.475*	2.718*		-.601*	-10.777*	-3.115*
Std dev	.470	2.467	2.296		.431	1.669	-.627
Late L mean	6.001	-7.762*	1.624*		-.255	-11.100*	-2.699*
Std dev	.526	2.705	1.834		.443	1.697	.900
Early C mean	6.368*	1.040*	6.070*		.189*	-9.069*	-.632*
Std dev	.296	1.047	.328		.194	.819	.374
Mid C mean	6.102	1.235*	5.659*		-.115*	-9.127*	-1.046*
Std dev	.506	1.198	.498		.404	1.165	.457
Late C mean	6.055	1.558*	5.824*		-.112	-8.730*	-.900*
Std dev	.478	.906	.440		.410	1.009	.483

Table 3.3 (ct'd)

CB							
F-value	36.300	57.923	202.969		68.656	18.286	148.020
p	.0001	.0001	.0001		.0001	.0001	.0001
Loads mean	6.634	-6.466	6.441		7.598	1.622	6.029
Std dev	1.148	1.929	.582		1.002	1.170	.642
Controls mean	6.667	-4.021	7.451		6.626	.614	4.968
Std dev	.569	1.601	.531		.609	.987	.621
Early L mean	3.621*	-5.451	6.541*		8.016*	1.970*	5.615*
Std dev	1.529	1.687	.387		.520	.645	.568
Mid L mean	6.803*	-6.432*	6.504*		8.538*	1.207*	5.818*
Std dev	.445	1.365	.395		.453	.904	.470
Late L mean	7.004*	-6.838*	6.554*		7.193*	1.960*	6.030*
Std dev	.515	2.088	.468		.917	1.316	.533
Post VO L mean	6.952	-5.469	5.477*		6.666	.772	7.157*
Std dev	.581	2.485	.985		.346	.572	.516
Early C mean	6.476*	-4.817	7.364*		6.537*	.472*	5.017*
Std dev	.736	1.906	.564		.715	1.057*	.848
Mid C mean	6.491*	-3.964*	7.399*		6.730*	.350*	4.799*
Std dev	.498	1.433	.512		.409	.799	.635
Late C mean	6.782*	-3.894*	7.486*		6.574*	.792*	5.048*
Std dev	.566	1.694	.553		.716	1.125	.538
Post VO C mean	6.807	-4.145	7.517*		6.614	.643	5.038*
Std dev	.547	1.355	.522		.459	.446	.803
FE							
F-value	902.384	465.153	414.067		429.707	280.210	322.279
p	.0001	.0001	.0001		.0001	.0001	.0001
Loads mean	6.134	2.673	8.598		9.895	-1.868	8.792
Std dev	1.142	1.349	1.333		.602	1.070	.752
Controls mean	10.944	6.625	12.131		7.284	-5.170	6.636
Std dev	1.304	1.618	1.138		.938	1.345	.791
JP							
F-value	374.9	42.919	101.103		313.353	122.241	331.092
p	.0001	.0001	.0001		.0001	.0001	.0001
Loads mean	-10.076	-19.361	-7.338		7.091	-2.617	4.693
Std dev	4.820	5.065	4.869		4.357	3.957	4.126
Controls mean	-6.730	-16.654	-5.640		4.217	-3.980	2.586
Std dev	5.273	6.081	4.955		4.879	4.668	4.530
Early L mean	-10.260*	-19.723*	-7.595*		7.290*	-2.240*	4.888*
Std dev	4.743	4.939	4.735		4.277	3.927	4.035
Mid L mean	-8.159*	-15.586	-4.655		5.011*	-1.407*	2.708*
Std dev	5.412	6.738	5.640		4.828	4.374	4.713
Early C mean	-6.993*	-16.959*	-5.907*		4.459*	-3.805*	2.845*
Std dev	5.119	5.940	4.823		4.774	4.168	4.396
Mid C mean	-3.984*	-13.475*	-2.857*		1.687*	-5.180*	-.110*
Std dev	6.269	7.551	5.655		5.452	5.219	5.210

Table 3.3 (ct'd)

LW						
F-value	54.043	85.796	71.882	6.054	64.298	83.533
p	.0001	.0001	.0001	.0176	.0001	.0001
Loads mean	6.339	-6.389	5.177	-4.666	-10.508	-4.743
Std dev	.792	2.239	.620	1.121	2.922	.887
Controls mean	6.632	-2.700	6.284	-5.137	-15.743	-5.995
Std dev	.282	2.320	.581	1.159	3.143	1.006
Early L mean	4.804*	-7.045*	5.180*	-4.129*	-10.368*	-4.948*
Std dev	1.215	2.335	.742	.998	2.039	.605
Mid L mean	6.538	-6.775*	5.111*	-4.592*	-9.725*	-4.637*
Std dev	.449	2.213	.645	1.244	2.439	.888
Late L mean	6.570*	-5.282*	5.318*	-5.055	-12.246	-4.882*
Std dev	.334	2.003	.528	.767	3.553	.998
Early C mean	6.497*	-2.916*	6.176*	-5.082*	-15.823*	-6.375*
Std dev	.406	2.885	.411	.910	3.642	1.150
Mid C mean	6.603	-2.661*	6.275*	-5.153*	-15.973*	-5.969*
Std dev	.215	2.256	.548	1.290	3.247	1.039
Late C mean	6.752*	-2.691*	6.349*	-5.126	-15.217*	-5.889*
Std dev	.327	2.389	7.27	1.013	2.860	.904

Table 3.4 Degrees of Freedom per subject and group.

SUBJECT	GROUP	Df's
AH	All tokens	81
	Early	30
	Mid	11
	Late	25
	Post-VO	15
BK	All tokens	66
	Early	12
	Mid	29
	Late	25
CB	All tokens	74
	Early	6
	Mid	23
	Late	39
	Post-VO	6
FE	All tokens	77
	Early	77
JP	All tokens	135
	Early	124
	Mid	11
LW	All tokens	47
	Early	5
	Mid	29
	Late	13

–discussed below– for the oral opening (displacement, velocity and duration) for the six subjects. Jaw opening movements for /ma/ of /mabnab/ were of significantly greater displacement and velocity in the load condition. This was true for 4 of the 6 subjects (AH, BK, CB, LW). For the other two (FE and JP) the jaw opening displacements showed a significant decrease in the load condition. Interestingly however, a significant DC-shift occurred in the initial position of the jaw in the load condition in *all six* subjects, so that the load tokens' initial position was lower than the initial position of their controls (cf. Table 3.3, earlier). In addition, in the load condition the jaw opening duration increased in 2 subjects (BK, LW) and decreased in a third subject (JP). For the remaining 3 subjects the duration of the jaw opening movement did not change in the load condition.

The load also affected the lip aperture measure. The lip aperture represents the composite action of the upper lip, the lower lip and the jaw, as they form the necessary constriction for the /b/ closure. For the opening movement in the load condition the lip aperture –used as an approximation of interlabial distance– significantly increased for three subjects (AH, CB, JP). For two subjects the lip aperture for the /ma/ opening decreased significantly (FE, LW) in the load tokens. For subject BK, since no upper lip data were obtained, it was not possible to infer with any degree of certainty the potential change in lip aperture in the load condition. Even though both lower lip and jaw opening displacements increased in the load tokens, a decrease in upper lip displacement might have resulted in either a reduction, an increase, or in no change in the lip aperture.

The duration of the lip aperture in the opening movement did not change in the load condition.

3.1.2 Closing movement for /b/ in /mab/: Lip Aperture

As a result of the load, the lip aperture displacement for the closing movement was modified. The lip aperture displacement for the closing movement from the open

position for /a/ to the closed position for /b/ significantly increased in the load condition for one subject (AH) and significantly decreased in a second (LW), while for the remaining subjects it did not change significantly. Figure 3.1 shows the lip aperture opening displacement plotted against the closing displacement for two subjects. It is clear that the lip aperture displacement for the closure correlated very highly with the lip aperture displacement for the preceding opening. For the subjects shown on Figure 3.1 the slopes of the regression lines increased in the load condition compared to the control. In that sense, the disturbance that was brought about by the perturbation in the opening phase was corrected during the closing phase. The correlation coefficients between the opening and closing displacements for the lip aperture load and control tokens are shown on Table 3.5, below. Note that subject BK is not shown, since upper lip measures were not obtained for that subject, rendering estimation of the lip aperture measures not feasible.

Table 3.5: Correlation coefficients between the opening and closing displacements for the lip aperture load and control tokens for all subjects except BK.

SUBJECT	AH	CB	FE	JP	LW
Controls	.87	.96	.88	.97	.96
Loads	.85	.96	.94	.95	.93

Figure 3.2 presents the lip aperture closing displacements in bar graph form. It is shown that the lip aperture velocity for /b/ closure significantly decreased in the load condition in two of the subjects (CB, LW), and remained the same in the other subjects. Recall that subject FE had no statistically usable lip aperture velocity information. For

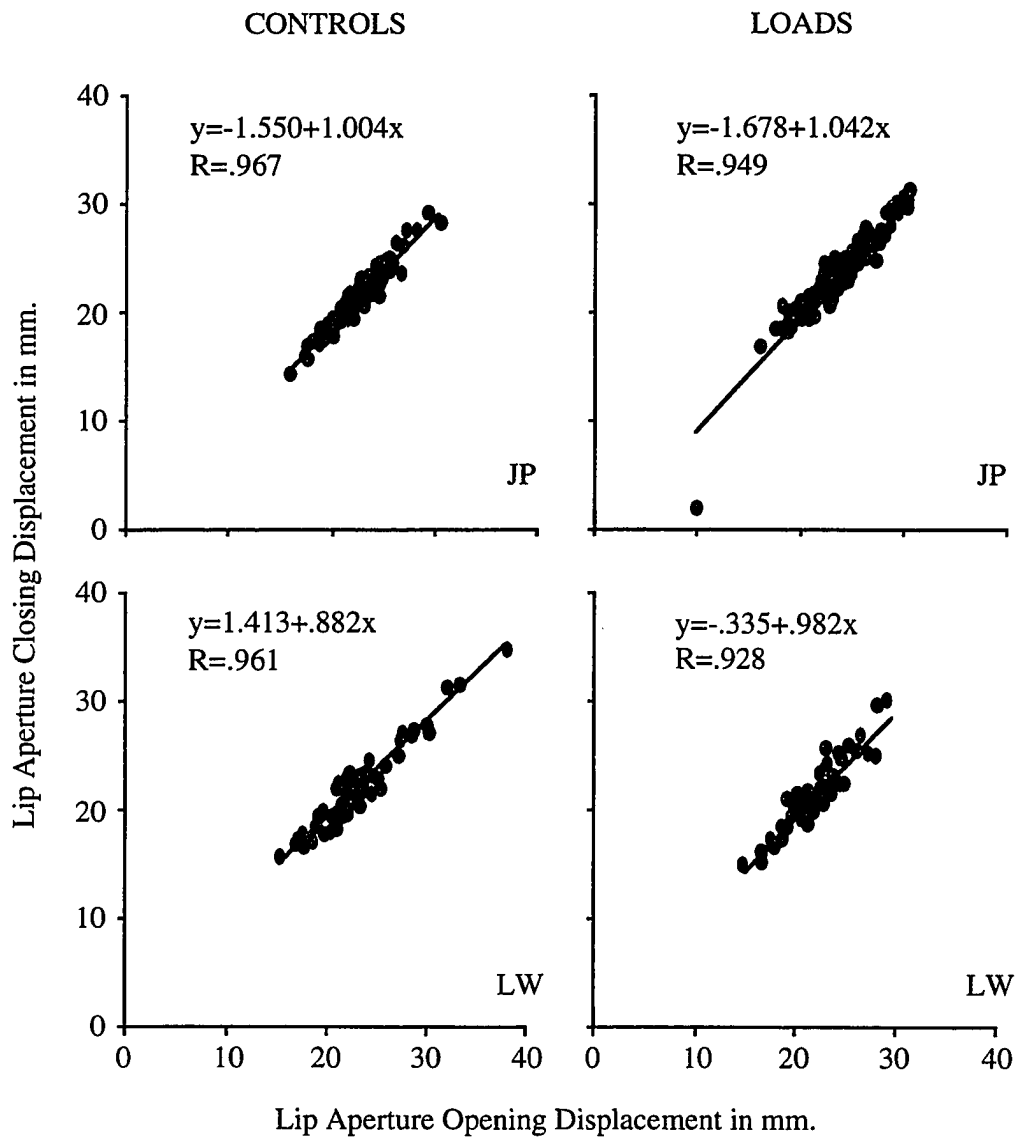


Figure 3.1 Correlations between the opening and closing displacements for the Lip Aperture measure (the sum of lip and jaw displacements) in mm, in the control and load conditions for two of the subjects (JP and LW).

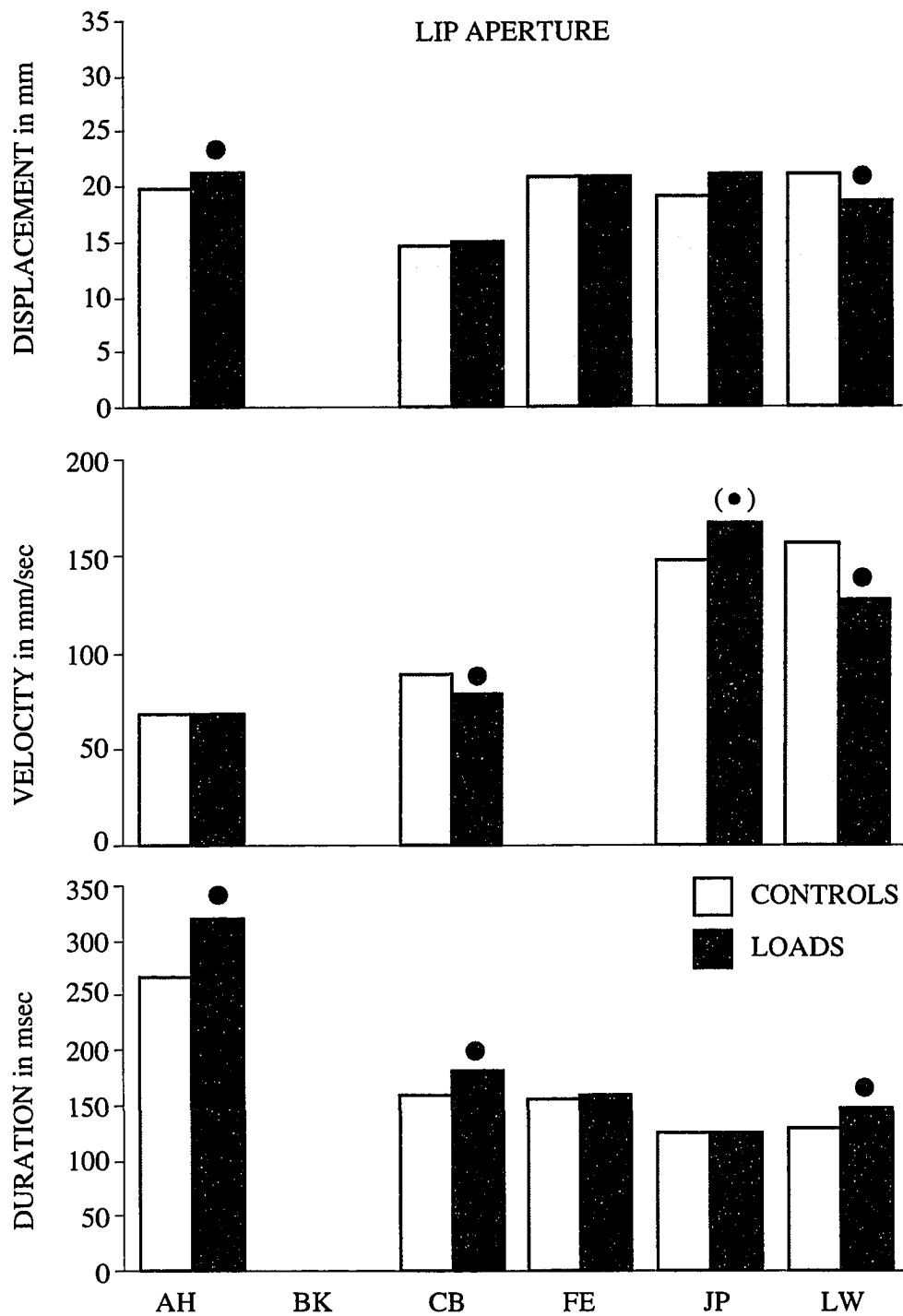


Figure 3.2 Load specific changes in displacement, velocity, and duration for the lip aperture, for all subjects for the closing movement. The significant changes are marked with a dot above the appropriate load bars.

subject JP even though the lip aperture closing velocity was significantly different in the early loads –125 of the 137 tokens–, the overall velocity was statistically the same in load and control tokens. Given that the early tokens represent 91% of her tokens, the relevant bar in Figure 3.2 is marked with a small dot in parentheses, indicating a *trend* toward such change.

The duration of the formation of the lip closure was also adjusted with respect to the duration of the jaw movement for most subjects. The oral closing duration increased in every subject, with that increase being significant in three of the subjects. These load specific differences for the lip aperture measures (displacement, velocity and duration) for the subjects are presented on Table 3.2, and are also shown in bar-graph form in Figure 3.2, with the significant differences marked with a dot above the appropriate load bars.

The changes observed in the characteristics of the lip aperture, suggest a relative invariance of the lip aperture measure in terms of displacement. It appears then that a compensatory response to the load was seen in the collective functioning of the oral articulators. Given the above evidence of compensatory changes in the oral closing system, as reflected by the lip aperture, it is reasonable to continue with the presentation of the results of the individual articulators and subjects.

As an overview, a synoptic tabulation of the mean values for each measure (velocity, displacement, and duration) per articulator (jaw, lower lip, upper lip, and velum) in the control and load conditions is presented in Table 3.6 for each subject. The table also includes the difference between loads and controls (L-C), and the percentage of the control measure that the difference represents $((L-C/C)*100)$. For example, AH's jaw displacement in the load condition increased by 2.4 mm, representing a 19.5% increase. Similarly, AH's lower lip displacement decreased in the load condition

Subj.	Measure	Controls mean	Loads mean	L-C difference	% change from C
AH	Jaw-veloc.	116.3	110	-6.3	-5.42
	Jaw-displ.	12.3	14.7	2.4	19.51
	Jaw-dur.	264.3	340.2	75.9	28.72
	LL-veloc.	47.8	44.6	-3.2	-6.69
	LL-displ.	5.6	4.9	-0.7	-12.5
	LL-dur.	214.5	235.8	21.3	9.93
	UL-veloc.	-41.1	-38.1	3	-7.3
	UL-displ.	2.8	2.9	0.1	3.57
	UL-dur.	149.9	153.6	3.7	2.47
	Velum-veloc.	64.1	61.9	-2.2	-3.43
	Velum-displ.	11.7	13.1	1.4	11.97
	Velum-dur.	334.9	373	38.1	11.38
BK	Jaw-veloc.	51.5	117.3	65.8	127.77
	Jaw-displ.	4.5	9.5	5	111.11
	Jaw-dur.	153.7	230.5	76.8	49.97
	LL-veloc.	111.9	91.7	-20.2	-18.05
	LL-displ.	8.1	8	-0.1	-1.23
	LL-dur.	131.9	160.1	28.2	21.38
	UL-veloc.				
	UL-displ.				
	UL-dur.				
	Velum-veloc.	117.1	151.4	34.3	29.29
	Velum-displ.	18.9	21	2.1	11.11
	Velum-dur.	341.8	338.4	-3.4	-0.99
CB	Jaw-veloc.	105.1	97.2	-7.9	-7.52
	Jaw-displ.	11.5	12.9	1.4	12.17
	Jaw-dur.	216.3	241.3	25	11.56
	LL-veloc.	90.5	98	7.5	8.29
	LL-displ.	4.4	4.4	0	0
	LL-dur.	135.2	116.4	-18.8	-13.91
	UL-veloc.	-14.5	-16.7	-2.2	15.17
	UL-displ.	0.9	1.1	0.2	22.22
	UL-dur.	116	119.3	3.3	2.84
	Velum-veloc.	63.2	71	7.8	12.34
	Velum-displ.	17.8	18.9	1.1	6.18
	Velum-dur.	497.9	479.8	-18.1	-3.64

Subj.	Measure	Controls mean	Loads mean	L-C difference	% change from C
FE	Jaw-veloc.	69.4	72.8	3.4	4.9
	Jaw-displ.	5.5	5.9	0.4	7.27
	Jaw-dur.	180	174.9	-5.1	-2.83
	LL-veloc.	192.4	196	3.6	1.87
	LL-displ.	11.8	10.7	-1.1	-9.32
	LL-dur.	130.1	128.9	-1.2	-0.92
	UL-veloc.	-59.4	-67.1	-7.7	12.96
	UL-displ.	4.7	5.3	0.6	12.77
	UL-dur.	139.1	142.6	3.5	2.52
	Velum-veloc.	18.3	18.3	0	0
	Velum-displ.	11.1	11.4	0.3	2.7
	Velum-dur.	687	673.9	-13.1	-1.91
JP	Jaw-veloc.	142.6	139.4	-3.2	-2.24
	Jaw-displ.	11	12	1	9.09
	Jaw-dur.	192.7	201.2	8.5	4.41
	LL-veloc.	135.3	146	10.7	7.91
	LL-displ.	6.6	6.9	0.3	4.55
	LL-dur.	83.9	81.9	-2	-2.38
	UL-veloc.	-74.1	-89	-14.9	20.11
	UL-displ.	3.9	4.6	0.7	17.95
	UL-dur.	94.6	94	-0.6	-0.63
	Velum-veloc.	64.5	66.1	1.6	2.48
	Velum-displ.	27.5	27.5	0	0
	Velum-dur.	551	549.3	-1.7	-0.31
LW	Jaw-veloc.	116.6	133.5	16.9	14.49
	Jaw-displ.	9	11.6	2.6	28.89
	Jaw-dur.	156.7	161.8	5.1	3.25
	LL-veloc.	158.8	111.2	-47.6	-29.97
	LL-displ.	9.8	5.8	-4	-40.82
	LL-dur.	112.3	107.8	-4.5	-4.01
	UL-veloc.	-50.9	-46.6	4.3	-8.45
	UL-displ.	3.4	3.6	0.2	5.88
	UL-dur.	111.5	124.1	12.6	11.3
	Velum-veloc.	68.6	63	-5.6	-8.16
	Velum-displ.	33.2	33	-0.2	-0.6
	Velum-dur.	472.4	463	-9.4	-1.99

by an average of 0.7 mm, representing a 12.5% decrease.

3.1.3 Closing movement for /b/ in /mab/: Jaw

The jaw closing movement characteristics showed a greater degree of change than the lips. In specific, jaw raising movements toward closure for the first /b/ in /mabnab/, were of significantly greater amplitude (5 of 6 subjects) and longer duration (4 of 6 subjects). The increase in movement amplitude (displacement) was accompanied by a DC-shift in the initial and final positions that the jaw reached. Thus, not only were the displacements of the jaw greater in the load condition, but they were also spatially lower than in the control condition, for all six subjects. For the subject whose movement amplitude did not change in the load condition (JP), the DC-shift (lowering) of the peak position at movement onset was about the same as the shift of peak position at movement offset (cf. Table 3.3). While the velocity did change, it did not change systematically; movements were significantly faster for 2 of the 6 subjects (i.e., increased velocities), significantly slower (i.e., reduced velocities) for another 2 and were not changed for the remaining 2 of the 6 subjects (i.e., same velocities). The mean control and load values for the jaw movement measures (displacement, velocity and duration) for all six subjects are shown in bar-graph form in Figure 3.3 with the significant differences marked with a dot above the appropriate load bars. Again, for subject JP the jaw closing velocity was significantly different in the early loads –125 of the 137 tokens–, while the overall velocity was statistically the same in load and control tokens. Given that the early tokens represent 91% of her tokens, the relevant bar in Figure 3.3 is marked with a small dot in parentheses, indicating a trend toward such change.

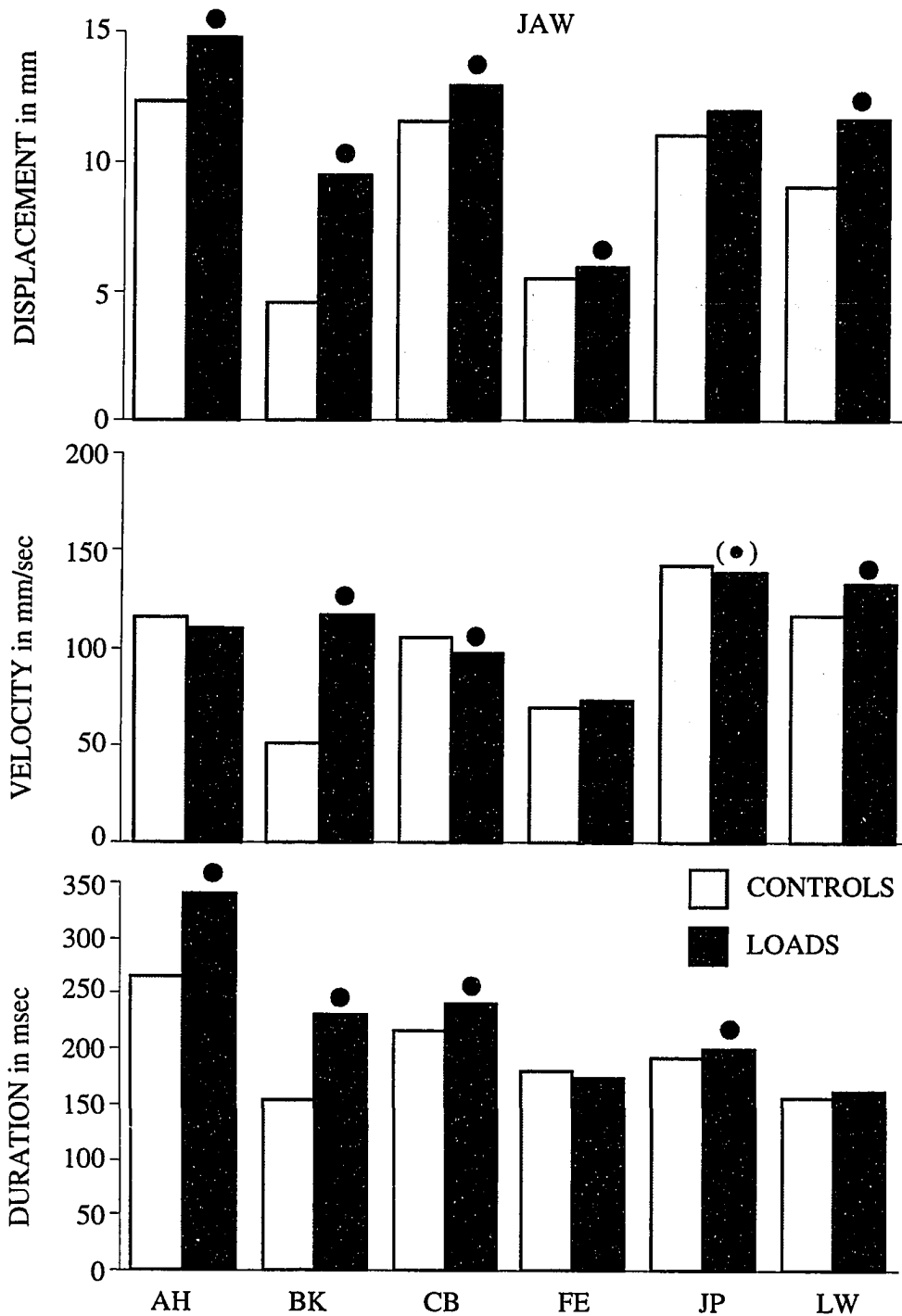


Figure 3.3 Load specific changes in displacement, velocity, and duration for the jaw, for all subjects for the closing movement. The significant changes are marked with a dot above the appropriate load bars.

3.1.4 Closing movement for /b/ in /mab/: Lower Lip

The lower lip displacement showed either no change, or a decrease, presumably because the jaw movement was sufficiently altered to make further displacement adjustments unnecessary. Contrary to the jaw raising movements, lower lip raising movements toward /b/ closure were in general of smaller displacement for five of the six subjects. That decrease was significant for three of the subjects. The decrease in movement amplitude (displacement) was accompanied by a DC-shift in the initial and final positions that the lower lip reached (cf. Table 3.3). That DC-shift was seen in all six subjects. For five of the subjects the peak positions at movement onset and offset were higher in the load condition than in the control. The opposite –lower peak onset and offset positions– was the case with the sixth subject (BK). This means that for those subjects for whom lower lip displacement did not change significantly in the load condition (BK, CB, JP), the DC-shifts observed in the onset and offset of the movement were about equal in magnitude, simply raising or lowering the movement trajectory in the load condition relative to its control. However, for those subjects for whom lower lip displacement significantly decreased in the load condition (AH, FE, LW), the DC-shifts observed in the onset and offset of the movement were of unequal magnitude, and the lower lip movement displacements were reduced compared to their controls .

In the load condition the movements were significantly faster for 1 of the 6 subjects (CB) and significantly slower for 2 (BK, LW). For the subjects whose lower lip closing velocity was significantly different (greater or smaller) in the load tokens (BK, CB, LW), the jaw closing velocity was significantly different in the opposite direction. The lower lip movement duration was significantly longer for 2 of the 6 subjects, and significantly shorter for 2. The load induced changes in the lower lip measures (displacement, velocity and duration) for all six subjects are shown in bar-graph form in

Figure 3.4, with the significant differences marked with a dot above the appropriate load bars.

3.1.5 Closing movement for /b/ in /mab/: Upper Lip

Recall that upper lip data were obtained for five of the six subjects. The load specific differences for the upper lip measures (displacement, velocity and duration) for the six subjects are shown in bar-graph form in Figure 3.5, with the significant differences marked with a dot above the appropriate load bars. Similar to the jaw raising movements, upper lip lowering movements toward closure for the first /b/ in /mabnab/ were of significantly greater displacement for four of the five subjects in the load condition compared to the control. The increase in upper lip displacement was accompanied by a significant decrease in lower lip displacement in two of those subjects (FE, LW). The movements were significantly faster for 3 of the 5 subjects, significantly slower for 1 of the subjects. The changes in velocity were in the same direction (increase or decrease) in the upper lip and lower lip for all five subjects, and for two of the subjects (AH, FE) they were of the same direction in the jaw as well.

The movement duration was significantly longer for the load tokens for 2 subjects, and significantly shorter for 1 of the 5 subjects.

3.1.6 Closing movement for /b/ in /mab/: Velum

Velar raising movements toward closure of the first /b/ in /mabnab/, were of significantly greater amplitude for 3 of the 6 subjects. Of those 3 subjects, 2 showed significantly greater raising velocity (resulting in faster movements), and 1 showed significantly longer raising duration. For the other 3 of the 6 subjects none of these parameters (velocity, displacement, duration) showed changes as a result of the load. Of the 3 subjects that exhibited no load related changes, 2 were those for whom the perturbations occurred very early in the utterance. These apparent load timing effects will be discussed in greater detail below. The load specific differences for the velum

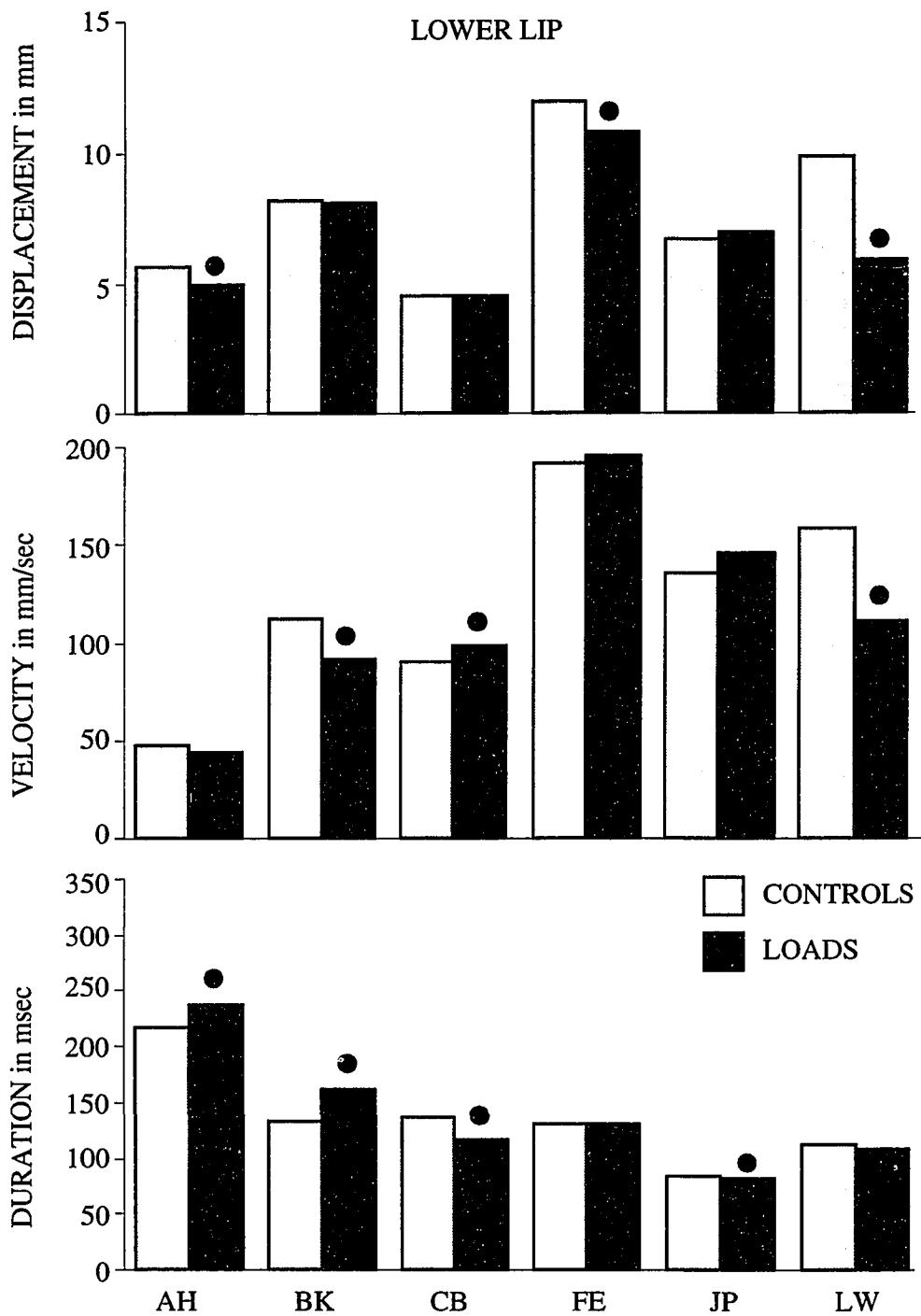


Figure 3.4 Load specific changes in displacement, velocity, and duration for the lower lip, for all subjects for the closing movement. The significant changes are marked with a dot above the appropriate load bars.

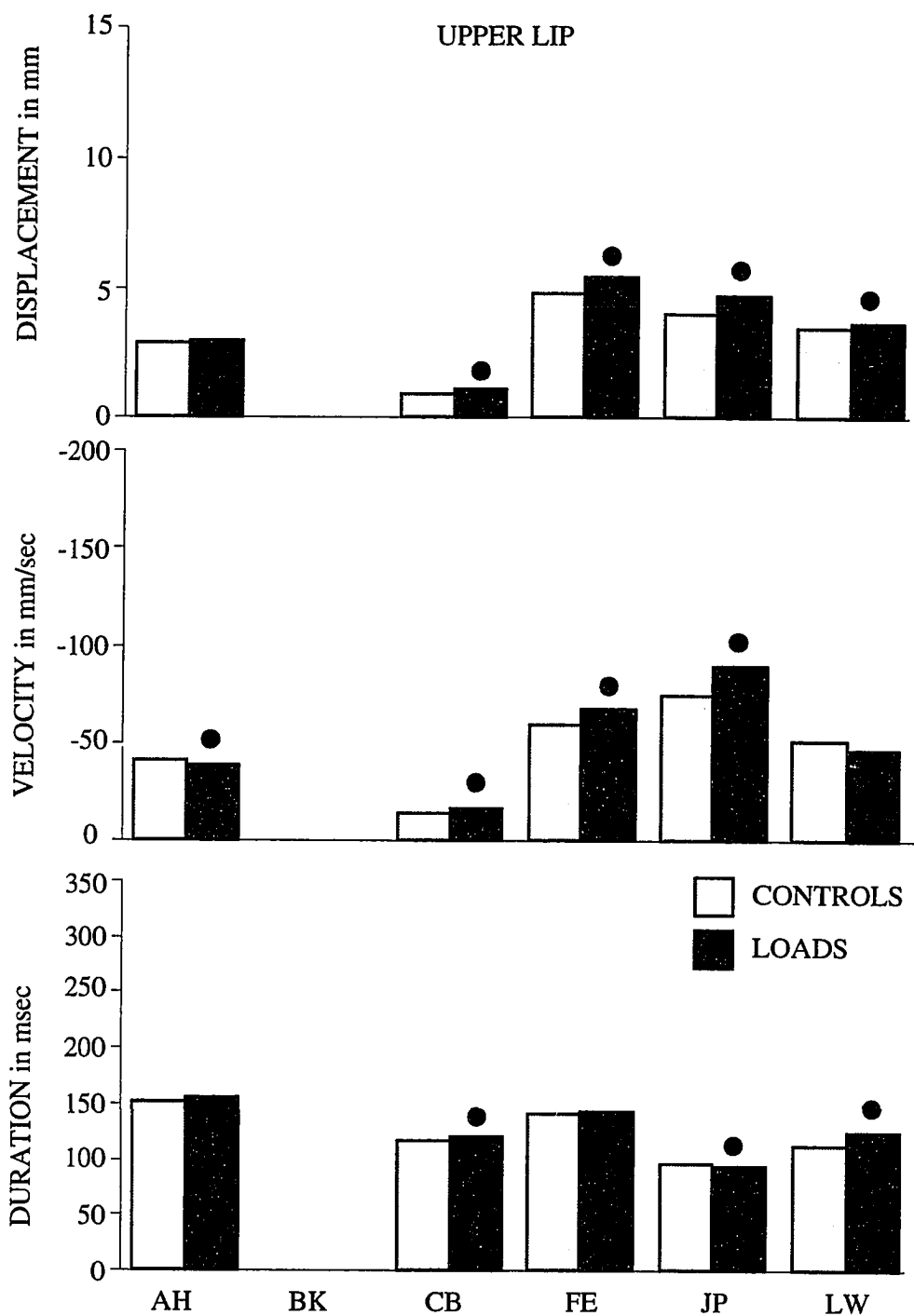


Figure 3.5 Load specific changes in displacement, velocity, and duration for the upper lip, for all subjects for the closing movement. The significant changes are marked with a dot above the appropriate load bars.

measures (displacement, velocity, and duration) for all six subjects are shown in bar-graph form on Figure 3.6, with the significant differences marked with a dot above the appropriate load bars.

It should be noted that a change in the displacement, velocity, or duration of the velum raising movement was accompanied by a like change in the jaw, with the exception of CB whose closing velocities changed in opposite direction for the jaw than for the velum. In other words, an increase in the displacement of the velar movement was accompanied by an increase in the displacement of the jaw movement; likewise, a decrease in the duration of the velar movement was accompanied by a decrease in the duration of the jaw movement.

Overall, the effect of the load was greater in those structures that were anatomically closer to the perturbed structure. For example, of the jaw displacements examined, 76% changed significantly in the load condition. The same was true for 71% of the lower lip displacements, 64% of the upper lip displacements, and 35% of the velum displacements. It can be seen that the effect of the load on the articulators decreased with increasing distance from the site of the perturbation. Similarly gradient effects were seen for the duration of the closing movements of the articulators. 76% of jaw closing durations changed significantly in the load condition, 59% of the lower lip durations, 50% of the upper lip durations and 35% of the velum raising durations. Closing movement velocities did not change with the same systematicity in the load condition as did the displacement and the duration measures. With the exception of the jaw closing velocities, however, that were probably hindered by the load itself, the velocities of the other three articulators decreased with increasing distance, from the lower lip to the velum. Of the jaw closing velocities, 53% changed significantly, compared to 71% of the lower lip velocities, 64% of the upper lip velocities, and 41%

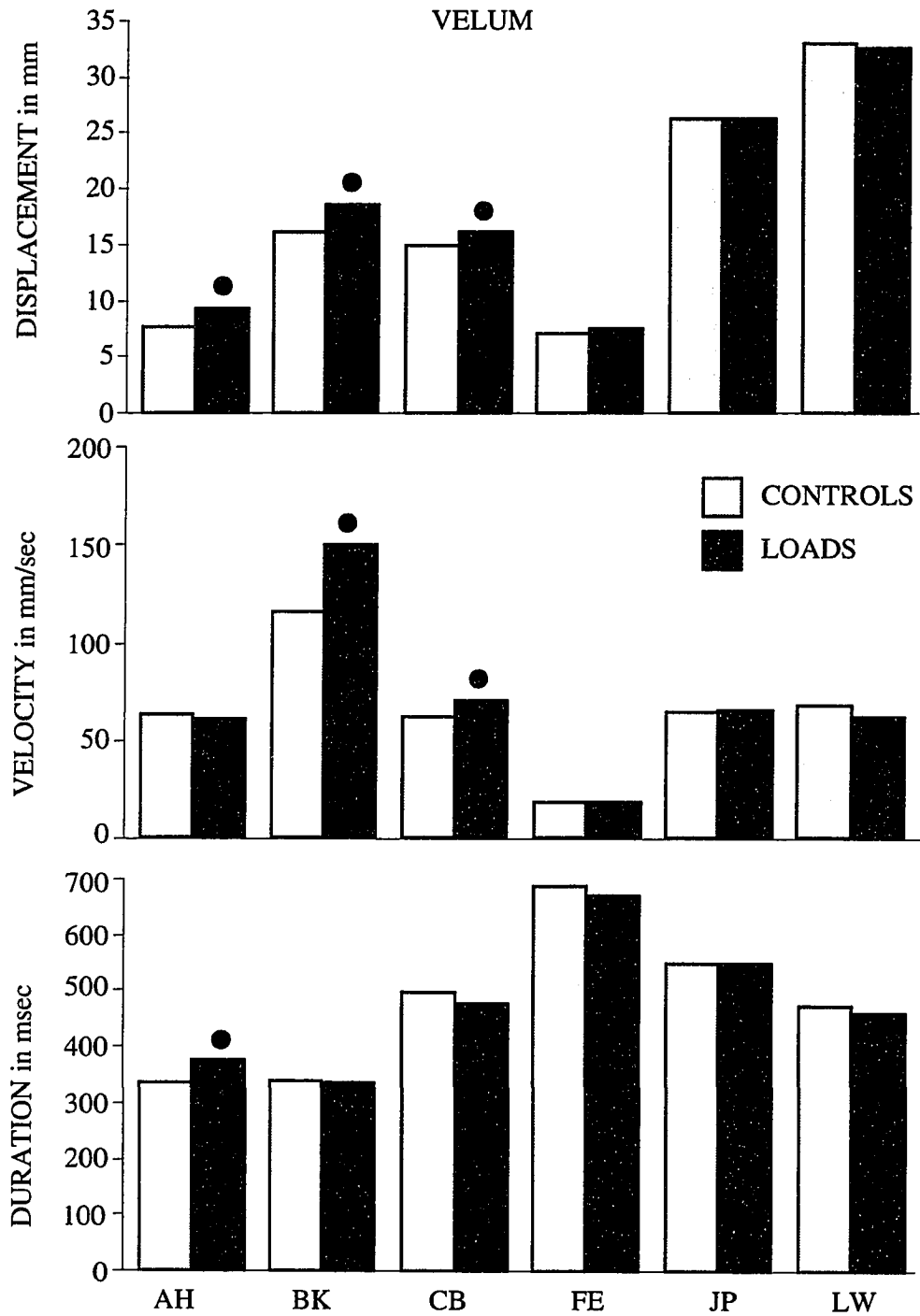


Figure 3.6 Load specific changes in displacement, velocity, and duration for the velum, for all subjects for the closing movement. The significant changes are marked with a dot above the appropriate load bars.

of the velum velocities. These results are presented in Tables 3.7 and 3.8, and Figure 3.7. They are also discussed somewhat differently in a later section (section 3.3 and Figure 3.10).

3.1.7 Duration of the articulatory kinematics for the syllable /mab/

Further, as an overall index of the extended effects of the perturbation on the entire first syllable (/mab/), the differences between loads and controls in the duration of the movements associated with that syllable were examined for the four articulators. The duration was measured from the onset of the movement at /m/ to the peak position for /b/ closure for the jaw, the lower lip, and the upper lip. For the velum, the acoustic vowel onset was used instead of the movement onset, in an effort to reduce variability, as there was great variability between and across subjects in the duration of the prevocalic portion of their velar movement. Figure 3.8 shows these durations for all six subjects, for the four articulators. The significant differences ($p < .05$) between loads and controls are marked with a dot above the appropriate load bars. For one of the subjects (FE) no change in the duration of the articulatory movements associated with the syllable /mab/ occurred between loads and controls. In the jaw, for four of the six subjects (AH, BK, CB, LW) the articulatory movement duration—associated with the syllable—increased significantly in the load condition. The same was true for the upper lip for three subjects (AH, CB, JP), and for the lower lip for two subjects (AH, BK). However, for another three subjects (CB, JP, LW) the lower lip syllable duration in the load condition decreased.

We see that for certain subjects (e.g., CB, JP) there is a reciprocal relationship between the duration changes in one articulator and those in another. For example, for JP, jaw movement duration for /mab/ did not vary in the two conditions, while lower lip movement duration decreased as upper lip syllable duration increased in the load condition. At the same time the velum /mab/ movement duration remained constant for

Table 3.7: Global significant changes per articulator, load group, and subject.					
* Indicates significant (p<.05) differences between loads and controls in all kinematic measures concurrently: displacement, velocity, and duration.					
SUBJECT	Load Group	JAW	LOWER LIP	UPPER LIP	VELUM
AH	Early				
	Mid				
	Late			*	
	Post-VO		*		
CB	Early			*	
	Mid	*			
	Late				
	Post-VO			*	
BK	Early	*		No data	*
	Mid	*			*
	Late	*	*		*
LW	Early				
	Mid	*	*		
	Late		*		
JP	Early				
	Mid				
FE	Early				
Total:		17	17	14	17
		5	4	3	2
		29%	24%	21%	12%
Early=3/22	14%	There are 65 chances for change. There are 14 cases where all parameters change significantly simultaneously (22%)			
Mid=4/18	22%				
Late=5/14	36%				
Post=2/8	25%				
Of these 14 changes, early represent 21%		mid= 29% similarly,		Jaw= 36%	
		late= 35%		Lower Lip= 29%	
		post= 14%		Upper Lip= 21%	
				Velum= 14%	

Table 3.8: Significant changes per load group, articulator, and subject.

* Indicates a significant ($p < .05$) difference between loads and controls in the specified measure: displacement, velocity, or duration.

Subj.	Load Group	JAW			LOWER LIP			UPPER LIP			VELUM		
		Dis	Vel	Dur	Dis	Vel	Dur	Dis	Vel	Dur	Dis	Vel	Dur
AH	Early		*	*	*	*		*			*		*
	Mid	*		*	*	*						*	
	Late	*		*	*		*	*	*	*	*		*
	Post-VO	*		*	*	*	*		*	*			*
CB	Early		*	*		*		*	*	*			*
	Mid	*	*	*			*	*	*		*		
	Late	*		*			*	*	*			*	
	Post-VO		*		*	*		*	*	*			
BK	Early	*	*	*		*	*	No data			*	*	*
	Mid	*	*	*		*	*				*	*	*
	Late	*	*	*	*	*	*				*	*	*
LW	Early	*	*		*	*							
	Mid	*	*	*	*	*	*		*	*		*	*
	Late	*			*	*	*	*		*			
JP	Early	*		*	*	*		*					
	Mid			*	*		*		*	*		*	
FE	Early	*			*			*	*				

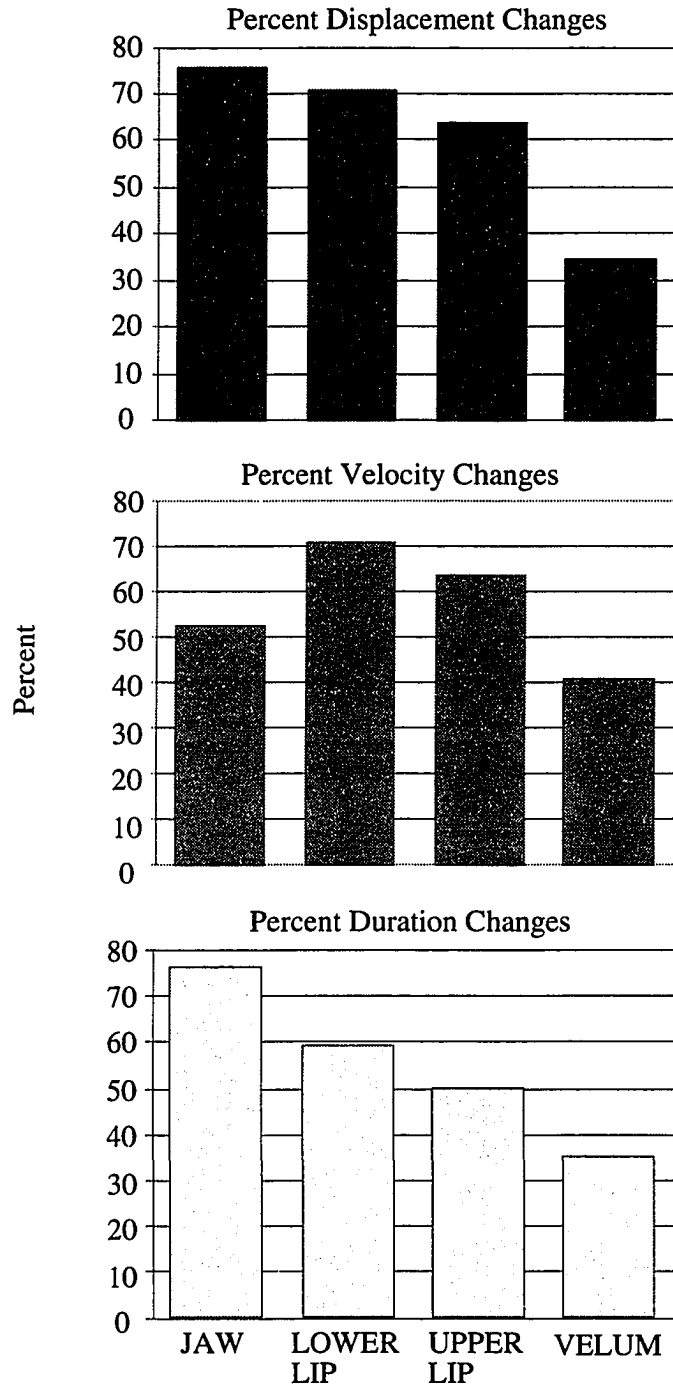


Figure 3.7 Percent of the significant ($p < .05$) number of changes that occurred across subjects in the displacement, velocity, and duration measures for each articulator.

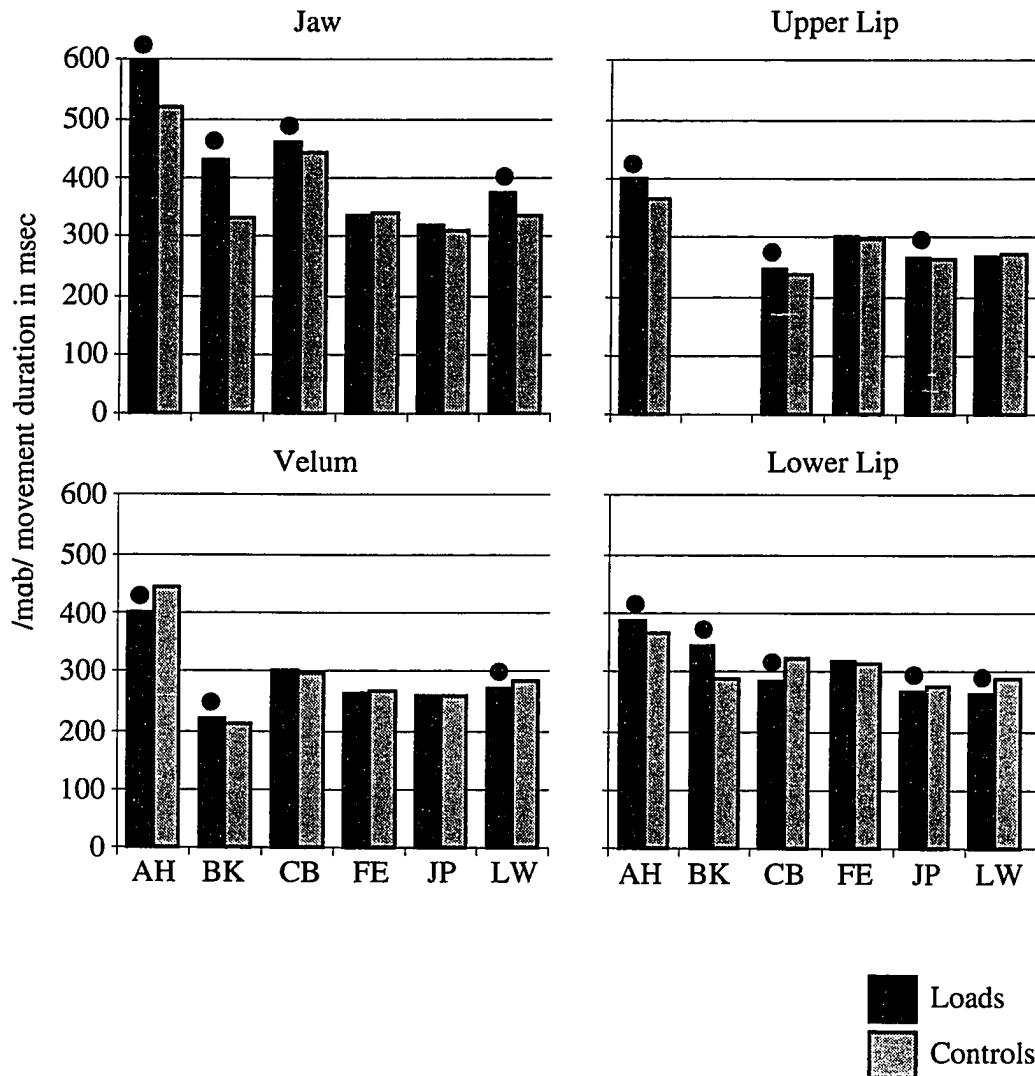


Figure 3.8 Mean duration in msec of the kinematics of the syllable /mab/, for the four articulators, per subject, in the control and load conditions. For the velum the duration is measured from the vowel onset to the peak position for /b/ closure. For the other articulators it is measured from the onset of the opening movement for /ma/, to the peak position for /b/ closure.

JP. Similarly, for CB, the jaw and upper lip /mab/ movement durations showed a small but significant increase, while the lower lip duration showed a greater and significant duration decrease in the load condition. In CB's case also, the velar duration did not vary in the two conditions.

In one case (BK) the changes in duration in the load condition occurred in the same direction (increase) in all measured articulators (jaw, lower lip, and velum).

There are cases where the temporal reciprocity includes the activity of the velum, as in the case of AH and LW. For AH the durations of the jaw, upper lip, and lower lip kinematics for the syllable show a significant increase, yet the duration of the velum shows a significant decrease. For LW the situation is similar: the duration of the jaw movement for the syllable /mab/ showed a significant increase, while the duration of the lower lip movement showed a lesser (but significant) decrease and the upper lip duration remained stable. Again, the duration of the velar movement showed a small but significant decrease as well, as though to counterbalance the increase in duration in the jaw that was not counterbalanced by the lower lip. This is difficult to explain from a coordinative structure, or, for that matter, any point of view: if the duration of all the movements of the oral articulators increases in the load condition, one would expect the duration of the participating velum to show an analogous increase. The velar movement kinematics did not show such an increase in duration. Functionally however, earlier closure of the velopharyngeal port is not problematic, as it does not interfere with the desirable production of either /a/ or /b/, since an oral /a/ is perfectly acceptable in this context.

3.2 LOAD EFFECTS ON THE KINEMATIC PARAMETERS (VELOCITY, DISPLACEMENT, DURATION) OF THE CLOSING MOVEMENTS OF THE FOUR ARTICULATORS PER SUBJECT

As mentioned above, jaw closing velocity increased in one third of the subjects, decreased in another third, and remained the same in the rest. Further, jaw closing movement parameters –velocity, displacement, duration– varied between load and control tokens for all subjects, but not in the same way. This fact suggests that the present findings require a subject–specific description of the results. Accordingly, the kinematic changes observed in the closing movements of the velum, jaw, lower lip and upper lip for each subject are presented –as mentioned earlier– in Table 3.2. Figures 3.3 to 3.6 (jaw, lower lip, upper lip, and velum respectively) presented the same displacement, velocity, duration information in the form of bar graphs, with the significant differences marked with a dot above the appropriate load bars. What follows then, is a description of the general results for each subject separately.

Recall that the general findings described in section 3.1 showed that in the load condition lip, jaw and velar movement responses, such as increased displacement and oral closing velocity, and changes in the movement durations, were indicative of compensation so that the effect of the perturbation is counterbalanced. In addition, for each subject the displacement, velocity and duration generally retained the reciprocal relationships seen in the control condition. It should be stressed again, however, that each subject responded to the perturbation rather idiosyncratically. With the exception of AH, the overall duration of the velum raising movement for /b/ closure was the same in the load tokens as in the controls for all subjects. For the control of the kinematic parameters of their oral articulators, the six subjects appeared to follow –more or less

faithfully-- one of two main emergent strategies. One was a "constrained duration" strategy and the other was a "flexible duration" strategy.

The subjects whose response patterns obeyed a constrained duration strategy were FE and LW. These subjects responded to the perturbation in a way that preserved the temporal aspects of the movement.

FE and LW showed no significant overall changes in the duration of any of their /b/ closing movements. Whenever the closing movement displacements were bigger, the velocity was also greater, and vice versa: whenever the closing movement displacements were smaller, the velocity was also decreased. There was one exception: LW's longer upper lip closing duration was longer in the load tokens than in the controls. In that case, the upper lip closing movement displacement was greater but the velocity was not changed.

The subjects whose response patterns obeyed a flexible duration strategy were AH, BK, CB and JP. These subjects seemed to respond to the perturbation by allowing the durational aspects of the movement to vary. Specifically, two of these subjects (AH and JP) did not modify the overall velocities of their articulator movements in the load condition compared to the control. The other two subjects (BK and CB) modulated all the kinematic parameters of their movements: velocity, duration and displacement. For subject AH jaw, lower lip, and velum movement duration all increased, while the closing velocities of these articulators remained stable as the movement displacements increased (for the jaw and velum). Subject JP showed movement durations that, in the load condition, changed in various directions: the closing movements were longer for the jaw and shorter for the lips. The /b/ closing velocities and displacements remained stable for all articulators, except for the upper lip, whose movements were faster and of bigger displacement. In the load condition BK's jaw and lower lip /b/ closing movements were both of longer duration, while movement velocity and displacement

were also varied. In the load condition, CB's /b/ closing movement durations were allowed to vary, with the durations being the same for the upper lip, longer for the jaw, and shorter for the lower lip. The movement velocities and displacements also varied. Following, then, is an account of the response strategies exhibited by the subjects.

Subjects exhibiting Flexible Duration without changes in velocity (AH, JP)

3.2.1 Subject AH

Overall, AH kept the velocity of the closing movements of the jaw, the lower lip, and the velum constant, while allowing the displacement and the duration of those movements to vary.

In the load condition AH's jaw closing movements retained the same velocity, but jaw closing duration and displacement increased. In the load condition, the lower lip showed generally unaltered closing velocity and increased movement duration, which here were accompanied by a decrease in displacement. It is possible that the reduced lower lip displacement was due to the fact that the jaw displacement was greatly increased rendering any further spatial increases on the part of the lower lip unnecessary. For the upper lip in the load condition, the displacement remained the same, there was a decrease in velocity and the duration of the upper lip closing movement remained the same. It is clear then, that the jaw, the lower lip and the upper lip responded in a spatially compensatory manner to the jaw perturbation. Further, among the three oral articulators, the jaw showed the greater degree of such compensatory behavior.

The behavior of AH's velum showed a similar pattern of response to the jaw perturbation as did the jaw. The closing movements of the velum were of greater displacement and, since they retained the same movement velocity, of longer duration.

3.2.2 Subject JP

In the load condition JP's jaw closing movements showed no change in peak velocity or in displacement, but the duration of these movements was longer. The lower lip closing movement was faster in the early load tokens (125 of the 137 pairs, but overall the same), of no overall different displacement and of a shorter duration. There was however, a differential effect of the load onset on the lower lip closing duration, such that the duration decreased *somewhat* for the early load tokens, but decreased *significantly* for the mid load tokens (12 of the 137 pairs). This effect will be discussed in detail in the following section. The lack of change in displacement in the lower lip might point to the jaw as the main contributor to spatial compensation, yet this does not seem to be the case, since, as mentioned above, the jaw displacement was smaller in the load condition than in the control. The upper lip closing movement showed greater displacement in the load condition than in the control, indicating that the upper lip might be mainly responsible for spatial compensation. The movement velocity was increased, and the overall duration of the upper lip closure was shorter. It seems then that in the load condition the upper lip closing velocity was sufficiently increased to cover the required distance in less time than in the control condition.

JP's velum showed no significant changes in the load condition as compared to the control. Similar to the changes seen in the upper lip and similar to trends observed in the jaw and lower lip, there was a trend toward greater displacement and velocity, but they were not statistically significant. The closing movement duration was the same in the two conditions.

Subjects exhibiting Flexible Duration with changes in velocity (BK, CB)

3.2.3 Subject BK

In the case of BK, velocity, displacement and duration of movement varied a result of the jaw loading. In general, the reciprocal relationship seen in the control condition between these kinematic parameters was maintained in the load condition.

In the load condition BK's jaw closing movements became faster, covered greater distance and their duration was greater than the duration in the control condition. Unfortunately, for this subject the upper lip data could not be obtained due to the obstruction of the upper lip LED by the arm of the jaw splint (cf. 2.4.3). The duration of the lower lip closing movement was longer in the load condition. The lower lip closing velocity was slower in the load tokens than in the controls, while the displacement was the same, and the closing movement duration was longer. However, the peak position attained by both the lower lip and the jaw for /b/ closure was lower (spatially) in the load condition than in the control. Given that bilabial closure was invariably achieved, this result suggests that the upper lip showed compensatory activity, with its closing displacement being greater in the load condition than in the control.

The behavior of BK's velum showed a pattern of response to the jaw perturbation similar to the jaw. Specifically, the closing movements of the velum were of greater displacement and velocity, but, unlike the jaw, the duration of the velar movement was the same in the load and control conditions. The velum, the jaw and the lower lip responded to the jaw perturbation by altering their kinematic parameters.

3.2.4 Subject CB

In general, in the load condition, CB's closing movements showed load related changes, such as increases in movement velocity and displacement.

In the load condition CB's jaw closing movements showed increased displacement, reduced velocity and longer duration. The lower lip closing movements showed increased velocity, the same displacement, and shorter duration. The upper lip closing movements showed increased velocity, displacement and duration. It is possible that the observed increase in upper lip movement velocity in the load condition was not sufficient to maintain the movement duration constant, given the increase in displacement. Alternatively, it is possible that the longer duration of the jaw closure overrode the shorter duration of the lower lip, so that the closure duration of the upper lip was also lengthened. In CB's closing movements, as will be presented later (section 3.3.4), the jaw closing velocity was smaller in the load tokens than in the controls (as the load was applied in the opposite direction from the jaw closing movement), while the lip aperture, upper lip, lower lip and velum closing velocities were greater in the load condition. It is possible that the lips moved faster to overcome the slower jaw closing movement.

The behavior of CB's velum showed a similar pattern of response to the jaw perturbation as did the upper lip. The closing movements of the velum showed greater displacement and were sufficiently faster for the closing movement duration to remain the same in the load condition as in the control (it should be noted however, that early load tokens had a longer duration than their controls –cf. section 3.3.4–).

Subjects exhibiting Constrained Duration (FE, LW)

3.2.5 Subject FE

In general, FE's closing movements maintained the same velocity and duration in the load tokens as in the controls, while the displacement of the movements varied: lower lip movements became smaller, jaw and upper lip movements became bigger and velum movements showed a tendency towards increased displacement.

Specifically, in the load condition FE's jaw closing movements spanned a significantly greater distance with a slightly faster velocity (non-significant) than in the control condition, and the duration was slightly shortened (but this change was again non-significant). For the lower lip, a different pattern of response emerged: the displacement was smaller –possibly the jaw covered most of the necessary distance– the peak velocity and the duration of the closing movement were the same as in the control condition. The upper lip closing movement was bigger, the movement velocity was greater, and therefore the overall closing duration was maintained constant in the two conditions.

FE's velum showed no significant changes in the load condition as compared to the control. The closing movement velocity was the same in the two conditions. There was a trend toward greater displacement and shorter duration, but they were not statistically significant.

3.2.6 Subject LW

LW's closing movements frequently exhibited load dependent variation patterns in the velocity, displacement, and duration of the oral articulators, such that one articulator's parameters varied in one direction (e.g., increase) the parameters of the remaining articulators changed in the opposite direction (e.g., decrease). For the jaw and the lower lip the duration of the /b/ closing movement was overall the same in the load condition as in the control. While the jaw movements were bigger and faster, the lower lip movements were slower and smaller and the upper lip movements were bigger but lasted longer. The velum showed no overall significant changes in any of its parameters, but exhibited similar trends as the other articulators, especially per load group.

In specific, in the load condition LW's jaw closing movements were faster, bigger and of the same duration. The lower lip closing displacement was smaller, the

movement velocity was reduced, and the duration was the same in the load condition as in the control. The upper lip displacement was increased in the load condition, while the closing velocity remained the same, and the closure duration was longer. Again, it seems that the lower lip closing displacement was reduced in the load condition because the jaw and the upper lip presumably provided enough spatial adjustments for closure, so that the lower lip displacement actually had to be reduced.

LW's velum showed no significant changes in the load condition as compared to the control. The closing movement duration, displacement and velocity were similar to the lower lip parameters in that they were slightly reduced in the load condition, but statistically they were the same in the two conditions.

3.3 LOAD TIMING EFFECTS: EARLY, MID, LATE, AND POST-VOWEL ONSET LOAD EFFECTS ON THE VELOCITY, DISPLACEMENT, AND DURATION OF THE OPENING MOVEMENTS OF THE JAW, AND ON THE CLOSING MOVEMENTS OF THE FOUR ARTICULATORS FOR EACH SUBJECT

The general effects of the load on the /b/ closing movement characteristics of each articulator were discussed on the above section (3.2) for each subject (3.2.2 – 3.2.7). In this section, the effects of the time of the application of the load are described. The details of the differential effects of the various load onsets on the same kinematic parameters are discussed for each articulator and each subject below (3.3.1 – 3.3.6).

The load application interval was divided into three 100 msec bands. Loads applied during the interval 0 to 99 msec prior to the acoustic onset of the first vowel were grouped into the "late loads" category. Loads applied during the interval 100 to 199 msec prior to the vowel onset were grouped into the "mid loads"; loads applied more

than 200 msec before the vowel onset were grouped into the “early loads” category. A fourth category included loads that were applied 1 to 200 msec after the acoustic onset of the first vowel (Post-Vowel Onset group). The number of token pairs in each load onset group varied. Figure 3.9 shows the mean load onset times per group with respect to the vowel onset (marked as zero), for each of the subjects. All six subjects have early loads, five of them have mid loads, four subjects have late loads, and two have post-vowel onset loads. The mean onset of the early loads for subjects JP and FE occurs about 100-200 msec before the mean onset in the other subjects. For subject AH the mean onset of the early loads occurs about 50 msec before that onset in the other three subjects.

The same data for each subject will be presented in sections 3.3.2 to 3.3.7 and in Figures 3.10, 3.11, and 3.12 (two subjects per figure) in bar graph form. Even though the data discussed below refer to pairwise comparisons, the figures indicate the pooled control data and the grouped load data (1 control bar plus the appropriate number of load bars per measure per subject), instead of the control bars that correspond to each load group (about 3 load bars plus an equal number of their control bars per measure). The reason for such a presentation was simplicity, and it was based on the fact that the control groups are not significantly different from each other on the same measure. Furthermore, any variability observed in the control tokens groups is mentioned in the text for each subject, and is entirely spurious, since the load onsets were randomly distributed throughout the duration of each experiment.

The effects of the different load groups, from early to mid to late, were frequently gradient, so that there was often a linear increase or decrease of the load-related change from the earlier group to the later. On some occasions such gradient effects were observed in all parameters –displacement, velocity and duration– of all articulators: jaw,

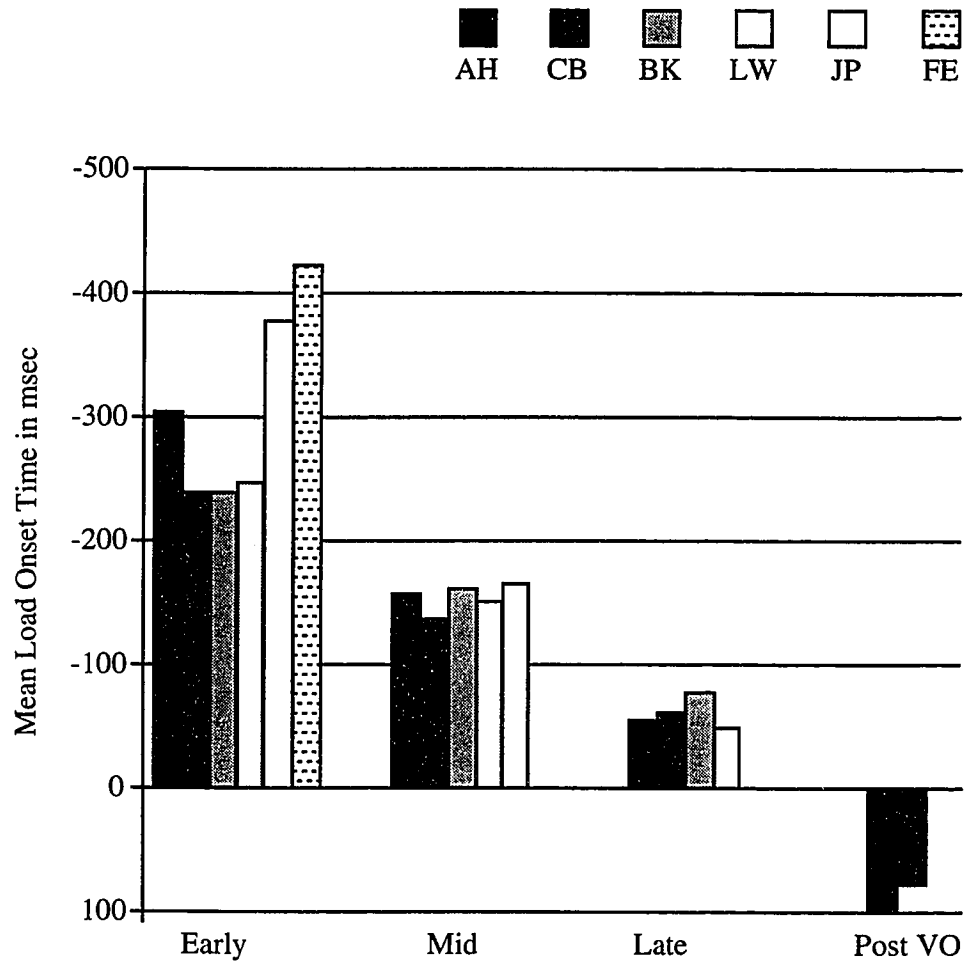


Figure 3.9 Mean Load onset time per load group, in msec, for each subject. Zero is the acoustic onset of the first vowel.

velum, upper lip and lower lip. On other occasions the load group effect varied depending on the parameter, the articulator and the subject. Instances where load tokens differed significantly from each other depending on group are noted in the text. The effects of perturbations occurring post-Vowel Onset (post-VO) were studied in the two subjects in which they occurred (AH, CB) and the results indicated a frequent discontinuity from the preceding pattern. For example, the duration of the upper lip closure in subject AH decreased progressively from early, to mid, to late load tokens, but it increased significantly in the post-VO load tokens.

Overall, collapsing across all subjects and across all articulators, there were a few cases (22%, or 14 of 65, that is, 4 articulators * 6 subjects * load groups per subject; see also Table 3.7, earlier), in which *all* the parameters within a given articulator changed *significantly*. For example, all of CB's jaw parameters (displacement, velocity, duration) changed significantly in the mid group in the load condition compared to the control. Of those 14 cases, the early loads produced 21%, the mid loads 29%, the late loads 36% and the post-VO loads 14%. It is clear then, that the effect of the load was, in a sense, intensified as load onsets were applied closer to the vowel onset. Looking at the sites at which these 14 "global" changes occurred, 36% occurred in the jaw, 29% occurred in the lower lip, 21% occurred in the upper lip and 14% occurred in the velum. It can be seen then, that the effect of the load was, in a similar sense, intensified in the structures that were more proximal to the jaw, the articulator that received the perturbation. These results were briefly mentioned earlier (section 3.1.6, and Tables 3.7 and 3.8) and appear in Figure 3.10.

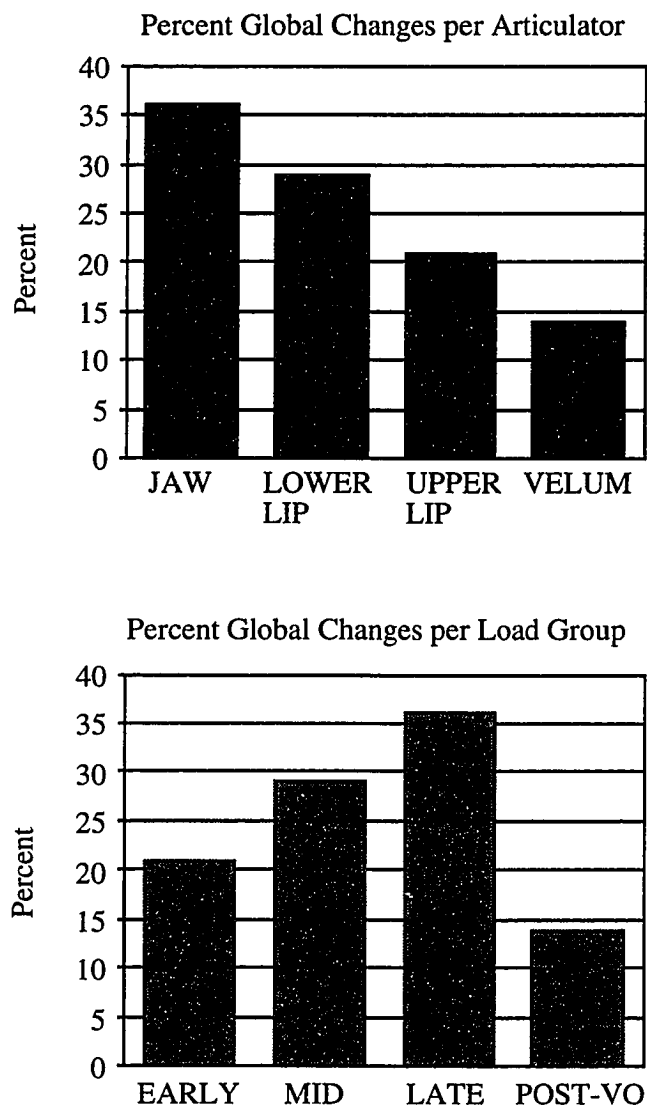


Figure 3.10 Percent of the number of global significant ($p < .05$) changes per articulator (top) and load group (bottom), collapsed across kinematic parameters and subjects.

In general, the following trends were observed for the displacement, velocity and duration of the articulators with different degrees of significance.

The jaw closing **displacements** increased progressively from early to late load tokens in two subjects (AH, CB) and decreased progressively for the other three subjects (BK, JP, LW –for subject FE only early loads were obtained–). It should be noted however, that in both subjects for whom there was a progressive increase in jaw closing displacement (AH, CB), it was followed by a slight drop in the Post-Vowel Onset load tokens. Velum closing displacements increased progressively from early to late load tokens in one subject (BK) and decreased progressively for three other subjects (CB, JP, LW). The upper and lower lip closing displacements did not show similar patterns, with the exception of subject JP, whose early loads always produced greater upper and lower lip closing displacements than the mid loads.

The jaw closing **velocities** increased progressively from early to late loads in two of the subjects (BK, JP) and decreased for another two subjects (CB, LW). The velum raising velocities increased progressively from early to late loads in two subjects (BK, CB), and decreased in a third (JP). Again, the upper and lower lip closing velocities did not show the same amount of regularity. For the upper lip there was a progressive increase in closing velocity in JP and a progressive decrease in CB. For the lower lip there was a progressive increase in closing velocity in BK and a progressive decrease in CB and JP.

The jaw closing **durations** increased progressively from early to late loads in AH while for BK and CB there was an increase from the early to the mid load followed by a decrease in the late loads. The jaw closing durations decreased for two subjects (JP, LW). Velum raising durations decreased progressively from early to late loads in three subjects (BK, CB, JP). In the upper lip there was a progressive increase in closing durations from the early to the late loads in LW and a progressive decrease in AH and

JP. In the lower lip there was a progressive increase in closing durations in AH, CB, LW and a progressive decrease in BK and JP.

Looking at each subject separately, across articulator pairs, it appears that subjects can be divided into groups exhibiting two general tendencies: those for whom load-related effects were mostly *heightened* in the later loads (AH, BK, LW), and those for whom load-related effects were mostly *reduced* in the later loads (CB, JP). Interestingly, all of the subjects in the former group displayed as a secondary, less frequently occurring pattern the pattern of the latter group, and vice versa: all of the subjects in the latter group displayed as a secondary, less frequently occurring pattern the pattern of the former group.

3.3.1 Jaw opening movement for /ma/ in /mab/

The jaw opening movement displacements for /ma/ (in /mabnab/) were affected differentially by the different load onset times. In general, the absolute differences in displacement between loads and controls increased from early, to mid, to late loads for four of the five subjects who had different load groupings (AH, BK, CB, and JP, shown in Figure 3.11; recall that FE had only early load onsets). Subject LW showed increased displacement differences from early to mid loads, but that difference was reduced again in the late loads. For subjects AH and CB, the differences found in the post-VO group were smaller than those found in the preceding (late) load group. Interestingly, for subjects AH and CB the early loads had the effect of actually reducing the jaw opening displacement difference between load and control tokens. In other words, the opening displacements of the tokens in the early load group were in fact smaller than the opening displacements of their controls. This was apparently due to the fact that, for both AH and CB, the jaw movement in the early load condition was initiated at a quite lower position than its control, while the movement's ending position was only slightly lower than its control. In this way, the opening movement

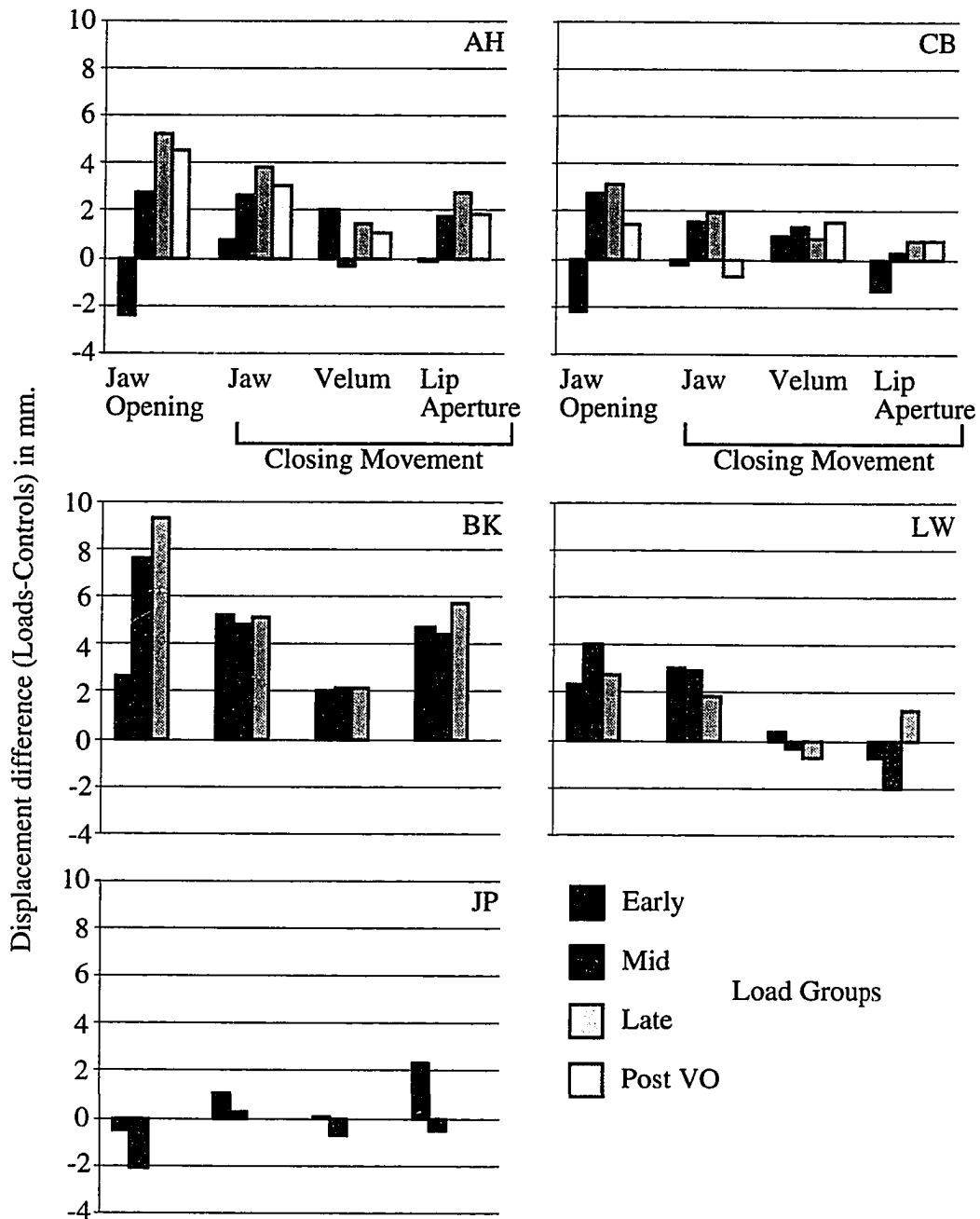


Figure 3.11 Displacement differences between load and control tokens (loads-controls) in mm, as a function of load group. Subject FE is not represented since she has only Early loads. The leftmost set of bars in each graph shows the difference in displacement for the opening movement of the jaw. The other sets of bars show that difference in displacement for the closing movements of the jaw, the velum, and the lip aperture measure.

displacement in the load condition was smaller than in the control. In both cases the difference between the DC-shifts at movement onset and at movement offset was about the same.

3.3.1.1 Effects of the jaw opening movement patterns on the closing movements

The differential load onset time effects on the opening displacements were mirrored in the closing movement displacements in the jaw, the lip aperture, and, at times, the velum. The same was generally true for the lip movements. As can be seen from Tables 3.1 and 3.2, the opening and closing displacements of the lips showed comparable load onset effects. The displacement differences between load and control tokens (loads–controls) are presented in Figure 3.11 for the opening movement of the jaw, and the closing movements of the jaw, the velum, and the lip aperture for the five subjects who had varying load groups (all except FE, who had only early load onsets). For subject LW the jaw and velum closing displacement differences showed similar patterns of graded load onset time effects. Subject JP was somewhat anomalous in these measures, yet certain pattern similarities were seen in the jaw opening and velum closing displacement differences.

Following then, is a detailed description of the patterns of load induced changes as a function of the load group (early, mid, late, post-VO) on each of the parameters (displacement, velocity, duration) for the /b/ closing movement per subject.

Closing movements of the jaw, lower lip, upper lip, and velum

3.3.2 Subject AH (Early, Mid, Late, and Post-Vowel Onset Loads)

A total of 31 pairs of tokens were analyzed in the early load group, 12 pairs in the mid load group, 26 pairs in the late load and 16 in the post–Vowel Onset group. Means and standard deviations are presented in Table 3.9, and are also graphically represented on Figure 3.12.

Table 3.9: Means and standard deviations for Displacement, Velocity, and Duration of the Jaw, Lower Lip, Upper Lip and Velum closing movements, for subject AH. (* indicates significant difference from control)

JAW										
Subject:	EARLY LOADS		MID LOADS		LATE LOADS		POST-V.O.		POOLED	
	mean	std.dev	mean	std.dev	mean	std.dev	mean	std.dev	mean	std.dev
AH										
Number	31		12		26		16		85	
VELOCITY mm/sec										
Controls	117.1	34.9	117.9	18.1	114.7	30.3	116.5	26.0	116.3	29.5
Loads	105.1 *	23.7	117.2	25.4	110.0	23.0	111.8	17.3	110.0	22.6
DISPLACEMENT mm										
Controls	12.4	3.0	12.5	2.3	12.1	2.9	12.2	2.6	12.3	2.8
Loads	13.2	3.1	15.2 *	1.8	15.9 *	3.0	15.2 *	2.8	14.7 *	3.0
DURATION msec										
Controls	269.9	61.5	254.9	35.1	255.3	46.3	275.4	69.7	264.3	55.6
Loads	320.3 *	112.3	328.2 *	73.3	351 *	96.4	370 *	113.0	340.2 *	103.1

Table 3.9: Means and standard deviations for Displacement, Velocity, and Duration of the Jaw, Lower Lip, Upper Lip and Velum closing movements, for subject AH. (ct'd)

Subject:	LOWER LIP						POST-V.O.		POOLED	
	EARLY LOADS		MID LOADS		LATE LOADS		mean	std.dev	mean	std.dev
AH		std.dev		std.dev		std.dev				
Number	31		12		26		16		85	
VELOCITY mm/sec										
Controls	50.3	17.6	50.7	18.3	45.7	13.1	44.2	17.3	47.8	16.3
Loads	42.2 *	17.0	40.9 *	9.6	39.2	19.1	60.7 *	20.9	44.6	19.1
DISPLACEMENT mm										
Controls	5.7	1.8	5.7	1.5	5.4	1.5	5.5	2.0	5.6	1.7
Loads	4.5 *	1.0	4.1 *	0.9	4.4 *	2.0	7.1 *	2.4	4.9 *	2.0
DURATION msec										
Controls	211.4	56.3	207.5	38.7	214.9	48.2	225	51.2	214.5	50.2
Loads	216.6	49.2	226.7	52.9	240.4 *	72.7	272.5 *	79.4	235.8 *	65.9

Table 3.9: Means and standard deviations for Displacement, Velocity, and Duration of the Jaw, Lower Lip, Upper Lip and Velum closing movements, for subject AH. (ct'd)

Subject:	UPPER LIP											
	EARLY LOADS		MID LOADS		LATE LOADS		POST-V.O.		POOLED			
AH	mean	std.dev	mean	std.dev	mean	std.dev	mean	std.dev	mean	std.dev	mean	std.dev
Number	31		12		26		16		85			
VELOCITY mm/sec												
Controls	-39.6	8.0	-41.8	10.2	-41.8	7.9	-42.1	11.5	-41.1		8.9	
Loads	-39.7	6.3	-42.0	9.0	-35.6 *	5.1	-36.4 *	7.0	-38.1 *		6.9	
DISPLACEMENT mm												
Controls	2.7	0.8	2.7	0.8	2.8	0.5	2.8	0.8	2.8		0.7	
Loads	3.0 *	0.5	3.0 *	0.7	2.6	0.3	3.0	0.7	2.9		0.6	
DURATION msec												
Controls	151.4	69.0	153.5	70.9	153.5	45.0	138.3	35.4	149.9		56.7	
Loads	164.6	53.5	143.2	22.6	137.7 *	23.6	166.3 *	30.0	153.6		39.8	

Table 3.9: Means and standard deviations for Displacement, Velocity, and Duration of the Jaw, Lip, Lower Lip, Upper Lip and Velum closing movements, for subject AH. (ct'd)

VELUM										
Subject:	EARLY LOADS		MID LOADS		LATE LOADS		POST-V.O.		POOLED	
	mean	std.dev	mean	std.dev	mean	std.dev	mean	std.dev	mean	std.dev
AH										
Number	31		12		26		16		85	
VELOCITY mm/sec										
Controls	66.9	17.9	70.2	18.4	57.8	15.6	64.2	18.8	64.1	17.7
Loads	67.0	17.7	57.3 *	14.3	53.7	12.3	68.7	23.0	61.9	17.9
DISPLACEMENT mm										
Controls	11.6	3.1	12.7	3.6	10.8	2.7	12.6	2.4	11.7	3.0
Loads	13.6 *	3.9	12.3 *	3.4	12.4	2.8	13.7	2.3	13.1 *	3.2
DURATION msec										
Controls	317.5	67.1	336	79.1	336	72.3	366	50.7	334.9	68.9
Loads	365.3 *	73.2	331.8 *	51.9	389.3	85.5	392.5	80.2	373.0 *	77.5

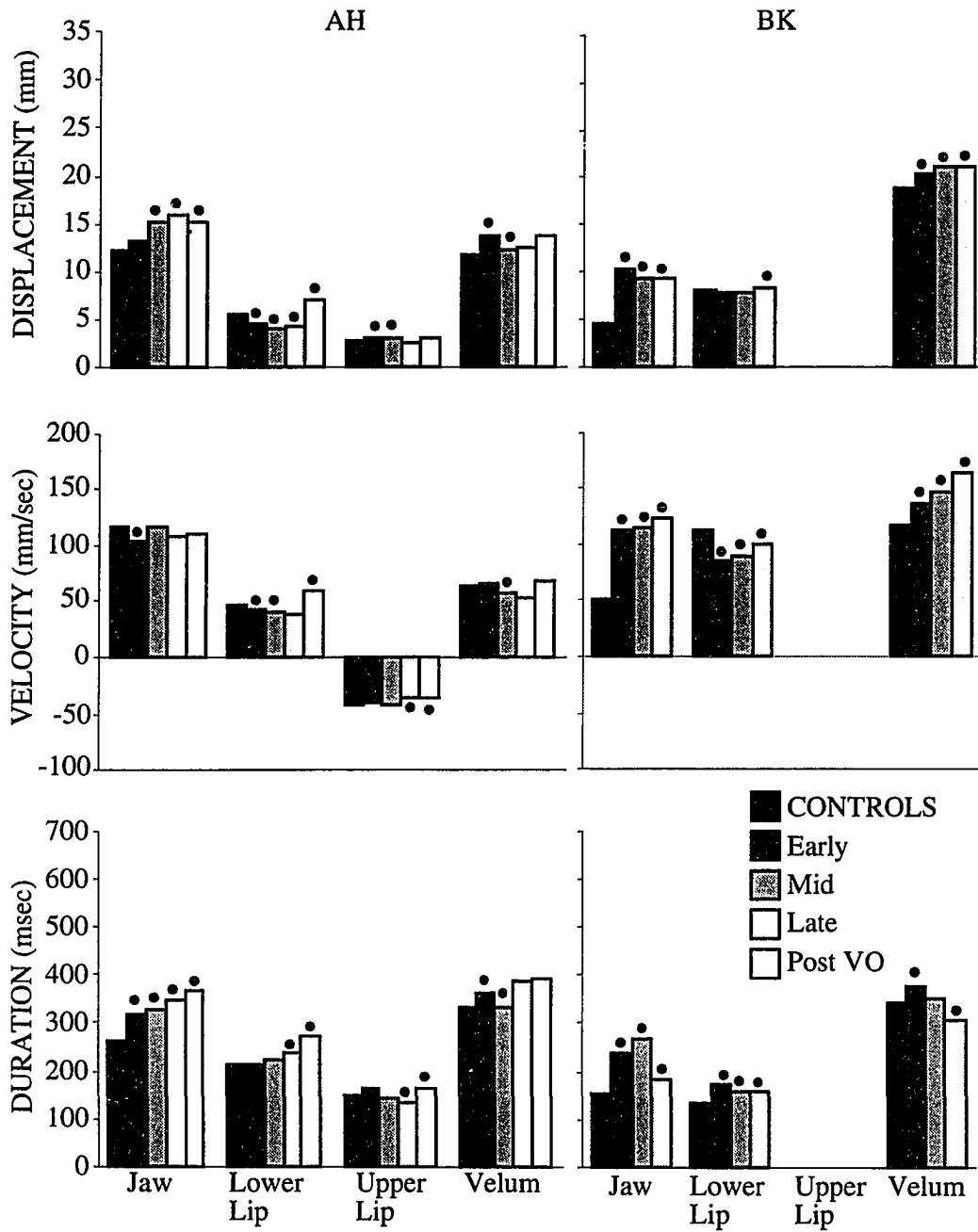


Figure 3.12 Mean displacement, velocity, and duration values for the control and load tokens (per load group) for subjects AH and BK, for all four articulators, for the /b/ closing movement. Significant differences are marked with a dot above the relevant bars. The control bars shown are taken from the entire control group.

JAW

As mentioned previously (section 3.2.1), in the load condition AH's jaw closing movement retained the same velocity, while the displacement and the closing duration increased. For the jaw movement displacement and duration the effects of the load were amplified in the later loads compared to the earlier ones (increases were greater).

The velocity of the load tokens was generally smaller than the velocity of the controls (mean loads= 109.5, mean controls= 116.3 mm/sec) in all groups, but only in the early group was the difference significant (mean loads= 105.1, mean controls= 117.1 mm/sec). In the mid group the velocity was the same in the load tokens as in the controls, while in the late and post-VO groups a decrease in velocity was seen in the load condition. The velocity did not vary significantly across groups. The control tokens in general showed greater variability than did the load tokens.

The displacement of the load tokens was significantly greater than the displacement of the controls (mean loads= 14.7, mean controls= 12.3 mm). The displacements of the early load tokens were only slightly greater than that of their controls, while for the mid, late and post-VO groups, the increases in displacement were statistically significant. In the load tokens, compared to the controls, there was a trend for a progressive increase in displacement from the earlier to the later group creating a significant interaction ($F[3,81]=3.41$, $p<.021$).

The duration of the load tokens was significantly longer than the duration of the controls (mean loads= 340.2, mean controls= 264.3 msec, $F[1,81]= 63.41$, $p<.0001$) for all the groups. The duration of the load tokens showed a trend for an increase in duration from the early group to the late and the post-VO group.

LOWER LIP

Overall, AH's lower lip showed increased closing movement duration and unchanged closing velocity, while the distance it traveled decreased in the load

condition. For all lower lip movement parameters the effects of the load were rather heightened in the later loads compared to the earlier ones (increases and reductions were greater).

The velocity of the early and mid load tokens was significantly lower than the velocity of their controls, and the same was seen in the late load tokens, but it was only marginally significant. In the post-VO group a different pattern was observed: the velocity in the load tokens was significantly greater than that of the controls, creating a significant load group-load condition interaction ($F[3,81]= 5.89, p<.0011$). Additionally, the difference in velocity showed a slight but steady decrease from the early to the late group. Excluding the post-VO load group, the velocity did not vary significantly across groups.

The displacement of the load tokens was significantly smaller than the displacement of the controls (mean loads= 4.9, mean controls= 5.6 mm). In the early, mid and late groups the displacement of the load tokens was significantly smaller than the displacement of the controls. Similar to the change in pattern observed in the velocity of the lower lip closing movement, in the post-VO group the displacement in the load tokens was significantly greater than that of the controls. The greatest differences in displacement were seen in the mid and post-VO groups, but they were in the opposite direction. A steady increase in displacement was observed in the load tokens from the mid to the post-VO groups.

The duration of the load tokens was significantly longer than the duration of the controls (mean loads= 235.8, mean controls= 214.5 msec, $F[1,81]= 10.17, p<.0020$). In the early group the duration of the load tokens was somewhat longer than the duration of the controls and the duration kept increasing until the post-VO group. The increase in duration was significant only in the late and post-VO loads. The difference in duration showed a trend for a steady increase from the early to the post-VO group.

UPPER LIP

In the load condition AH's upper lip showed overall unchanged displacement, decreased velocity and unchanged closing movement duration. Significant changes (reductions) were observed for all measures in the late load group. Further, significant changes were seen in the post-VO group for velocity and duration measures.

The absolute velocity of the load tokens (mean= -38.1 mm/sec) was significantly lower than the velocity of the controls (mean= -41.1 mm/sec). In the load condition the late and post-VO tokens were quite slower than the early or mid tokens, causing a significant interaction ($F[3,81]=2.94, p<.038$). The velocities of the early and mid load tokens were identical to those of their controls. In contrast, the velocities of the late and post-VO load tokens (mean= -35.6 and -36.4 mm/sec respectively) were significantly slower than those of their controls (mean= -41.8 and -42.1 mm/sec respectively).

In the early, mid and post-VO groups, the displacement of the load tokens was overall greater than the displacement of the controls, while the opposite was true for the late group (interaction $F[3,81]=2.55, p<.061$). In the early group, the increase in the displacement in the load tokens was marginally significant, while in the mid and post-VO groups the high variability prohibited significance. The decrease in displacement observed in the late group was statistically significant.

In the early and mid groups the duration of the load tokens was not significantly different from the duration of the controls, due to the great variability associated with these measures in both load and control conditions. The duration was somewhat longer in the early load tokens, and somewhat shorter in the mid load tokens. However, in the late group, the duration of the load tokens was significantly shorter than the duration of the controls, while in the post-VO group the duration of the load tokens was significantly longer than that of the controls. In the load condition, the duration was

progressively shorter from the early to the late group, and increased again in the post-VO group.

VELUM

In general, the kinematics of AH's velum showed a similar pattern of response to the jaw perturbation as did the jaw. Overall, the closing movements of the velum showed increased displacement and duration and maintained the same velocity. Early and late loads produced significant effects on the displacement and duration of the velar closing movements, while the mid loads produced a significant effect on the velocity of the movement. Post-VO loads produced no significant effects. Load effects were heightened in the later loads (greater amounts of increase or decrease).

The velocity of the load tokens (mean loads= 61.9, mean controls= 64.1 mm/sec) was not significantly different from the velocity of the controls. In the mid group the velocity in the load tokens was significantly lower compared to the controls. In the early, late and post-VO groups the changes in velocity in the load condition were not statistically significant. However, the load tokens showed a linear decrease in velocity from the early to the late group, creating a significant effect of group affiliation ($F[3,81]= 3.54, p<.018$). The early load tokens (mean= 67.0 mm/sec) showed a significantly greater velocity than the late load tokens (mean= 53.7 mm/sec). In the post-VO group (mean= 68.7 mm/sec) the velocity increased again, to the level of the early load tokens.

The displacement of the load tokens (mean loads= 13.0, mean controls= 11.7 mm) was significantly greater than the displacement of the controls. This was true for the early and late groups. The difference in displacement between load and control tokens was greater in the early group (2.1 mm) than in the late group (1.6 mm). The post-VO load tokens showed greater displacement than their controls (a difference of 1.1 mm),

but this difference did not reach significance. The mid group showed slightly decreased displacement in the load tokens than in the controls.

The overall duration of the load tokens was significantly longer than the duration of the controls (mean loads= 375.1, mean controls= 335.1 msec). This was true for the early and late groups. The difference in duration between load and control tokens was slightly greater in the early group (50.8 msec) than in the late group (48.2 msec). The post-VO load tokens showed approximately the same duration as the late load tokens, but due to the large variability of the post-VO load group, its duration did not represent a significant increase. The mid group showed the same duration in the load tokens as in the controls.

3.3.3 Subject BK (Early, Mid, and Late Loads)

A total of 13 pairs of tokens were analyzed in the early load group, 30 pairs in the mid load group, and 26 pairs in the late load group. Means and standard deviations are presented in Table 3.10, and are graphically represented on Figure 3.12.

JAW

As mentioned previously (section 3.2.2), in the load condition BK's jaw closing movements showed increased velocity, displacement, and duration in all load groups. While for the displacement the load effects were generally amplified with earlier loads, for the velocity they were amplified with later load onsets.

The velocity of the load tokens (mean loads= 117.3, mean controls= 51.5 mm/sec) was significantly greater than the velocity of the controls in all groups. There was no significant group-dependent difference in the velocity values. There was a trend for the velocity of the load tokens to increase with later load onsets.

The displacement of the load tokens (mean loads= 9.5, mean controls= 4.5 mm) was significantly greater than the displacement of the controls in all groups. As with the

Table 3.10: Means and standard deviations for Displacement, Velocity, and Duration of the Jaw, Lower Lip, Upper Lip and Velum closing movements, for subject BK. (* indicates significant difference from control)

JAW								
Subject:	EARLY LOADS		MID LOADS		LATE LOADS		POOLED	
BK	mean	std.dev	mean	std.dev	mean	std.dev	mean	std.dev
Number	13		30		26		69	
VELOCITY								
Controls	55.7	11.5	51.0	12.9	50.1	9.6	51.5	11.5
Loads	112.0 *	32.6	113.8 *	36.0	123.9 *	43.2	117.3 *	38.1
DISPLACEMENT								
Controls	5.0	0.8	4.4	1.1	4.3	0.9	4.5	1.0
Loads	10.3 *	3.4	9.2 *	2.6	9.4 *	3.5	9.5 *	3.1
DURATION								
Controls	165.1	18.2	151.7	23.0	150.5	14.0	153.7	19.6
Loads	236.8 *	54.8	269.1 *	91.6	182.9 *	29.1	230.5 *	77.1

LOWER LIP								
Subject:	EARLY LOADS		MID LOADS		LATE LOADS		POOLED	
BK	mean	std.dev	mean	std.dev	mean	std.dev	mean	std.dev
Number	13		30		26		69	
VELOCITY								
Controls	112.2	12.8	111.4	14.8	112.2	12.9	111.9	13.6
Loads	84.4 *	11.0	88.3 *	18.2	99.2 *	23.0	91.7 *	19.9
DISPLACEMENT								
Controls	8.4	0.8	8.1	1.1	7.8	0.9	8.1	1.0
Loads	7.9	1.4	7.7	1.5	8.4 *	1.8	8.0	1.6
DURATION								
Controls	138	7.8	132.5	12.2	128.2	9.1	131.9	10.8
Loads	173.5 *	33.7	156.1 *	16.2	158 *	12.1	160.1 *	20.3

Table 3.10: Means and standard deviations for Displacement, Velocity, and Duration of the Jaw, Lower Lip, Upper Lip and Velum closing movements, for subject BK. (ct'd)

VELUM								
Subject:	EARLY LOADS		MID LOADS		LATE LOADS		POOLED	
BK	mean	std.dev	mean	std.dev	mean	std.dev	mean	std.dev
Number	13		30		26		69	
VELOCITY								
Controls	115.6	31.7	118.6	18.1	116.0	18.8	117.1	21.2
Loads	136.2 *	20.5	147.3 *	24.3	163.7 *	23.8	151.4 *	25.3
DISPLACEMENT								
Controls	18.4	3.0	19.1	2.9	19.0	2.6	18.9	2.8
Loads	20.4 *	1.8	21.1 *	2.4	21.1 *	2.4	21.0 *	2.3
DURATION								
Controls	329.1	63.3	354.7	42.2	333.2	32.6	341.8	44.6
Loads	377.1 *	54.0	350.2	43.7	305.5 *	45.7	338.4	53.5

velocity, there was no group-dependent difference in the displacement values. There was a trend for the displacement of the load tokens to decrease with later load onsets.

The duration of the load tokens was significantly greater than the duration of the controls (mean loads= 230.5, mean controls= 153.7 msec). The load tokens showed greater variability than the control tokens. The load tokens showed a decrease in duration from the mid and early groups whose durations were similar, to the late group (mean early loads= 236.8, mean mid loads= 269.1, mean late loads= 182.9 msec), thus causing a significant interaction between group and condition ($F[2,66]= 10.98$, $p<.0001$), and a significant group effect ($F[2,66]= 10.60$, $p<.0001$). The greatest increase in duration was observed in the mid group, while the smallest was seen in the late group.

LOWER LIP

Overall, BK's lower lip closing displacement was the same in the load tokens as in the controls, the movement velocity was slower, and the movement was accomplished in a longer time in the load condition than in the control. Lower lip closing velocities tended to increase with later loads, while durations tended to decrease.

The lower lip closing velocity was significantly smaller in the load tokens (91.7 mm/sec) than in the controls (111.8 mm/sec). This was true for all the groups, with the early load condition showing the greatest reduction in velocity, and the late one showing the smallest. A progressive increase in velocity from the early to the late group was observed. Specifically, the velocity of the early load tokens was slightly slower than that of the mid load tokens, but was significantly slower than that of the late load tokens.

The lower lip closing displacement was overall not significantly different in the load tokens (8.0 mm) than in the controls (8.1 mm). The load group showed greater variability than the control group, possibly accounting for the lack of statistical

significance in either the effect of the load or in the group-condition interaction (interaction $F[2,66]= 2.67, p<.07$). Various changes in displacement were seen in each group. In the early and mid groups, the load tokens showed reduced displacements as compared to the controls, without however those displacements reaching significance. On the contrary, the late load tokens showed significantly increased displacements as compared to the controls. There were no group-dependent differences in the displacement values.

The duration of the load tokens was significantly greater than the duration of the controls (mean loads= 160.1, mean controls= 131.9 msec). The load tokens in general, and the early load tokens in particular showed greater variability than the control tokens. The load tokens showed a slight decrease in duration from the early group, to the mid and late groups whose durations were similar (mean early loads= 173.5, mean mid loads= 156.1, mean late loads= 158.0 msec), causing a significant group effect ($F[2,66]= 5.18, p<.008$). The greatest increase in duration was observed in the early group, while the smallest was seen in the mid group.

UPPER LIP

No upper lip data were obtained for BK. The upper lip movement pattern could, however, be inferred from the combined action of the lower lip and the jaw, at least in terms of movement displacement.

The peak position attained by the lower lip for /b/ closure was significantly lower (spatially, 1.9 mm, $F[1,66]= 294.17, p<.0001$) in the load condition than in the control for all groups, with the mid group showing the greatest separation (2.1 mm) and creating a significant group effect ($F[2,66]= 7.91, p<.0008$). Both control (std. dev.=.5mm) and load tokens (std. dev.=.8 mm) were similarly and minimally variable.

Further, the peak position attained by the jaw for /b/ closure was significantly lower (spatially, 3.0 mm, $F[1,66]= 95.76, p<.0001$) in the load condition than in the control

for all groups. While the control tokens were minimally variable (std. dev.=.5mm), the load tokens were quite more variable (std. dev.= 2.5 mm). There was a progressive lowering of the position of the jaw in the load tokens, with the early load tokens being the closest to the controls (separation=.6 mm) and the late load tokens being the furthest from the controls (separation= 4.2 mm), creating both a significant group-condition interaction ($F[2,66]= 10.86, p<.0001$) and a significant group effect ($F[2,66]= 7.91, p<.0008$).

Therefore, given that the peak positions attained by both the jaw and the lower lip for /b/ closure were spatially lower in the load condition than in the control, and that bilabial closure was invariably achieved, it is reasonable to assume that the upper lip showed compensatory lowering activity, with the upper lip closing position being lower and the displacement being greater in the load condition than in the control. Moreover, from the jaw and lower lip position results, we can speculate that the extent of the compensatory displacement of the upper lip had to be greater in the late load tokens, and smaller in the early load tokens.

VELUM

In general, the kinematics of BK's velum showed a similar pattern of response to the jaw perturbation as the jaw. In the load condition then, the raising movements of the velum were generally faster and bigger than in the control condition, but of the same duration in the load condition as in the control. Velar raising displacements and velocities increased with later loads, while velar raising durations decreased with later load onsets.

The velocity of the load tokens (mean loads= 151.4, mean controls= 117.1 mm/sec, $F[1,66]= 90.63, p<.0001$) was significantly greater than the velocity of the controls in all groups. Given that in the load tokens the velocity increased linearly from the early to the mid to the late group, there was a significant group-condition interaction in the

velocity values ($F[2,66]= 5.75, p<.005$). Specifically, the increase in the velocity of the load tokens was greatest for the late group, and smallest for the early group.

The displacement of the load tokens (mean loads= 21.0, mean controls= 18.9 mm) was significantly greater than the displacement of the controls in all groups. The increase in the displacement of the load tokens was the about the same for all groups, with a trend for increase from the early to the late group. (Further, the peak position attained by the velum for /b/ closure was spatially higher in the load condition than in the control (mean loads= 19.7, mean controls= 17.8 mm, $F[1,66]= 183.66, p<.0001$) for all groups.)

The duration of the load tokens was not significantly different from the duration of the controls (mean loads= 338.4, mean controls= 341.8 msec). Both load and control tokens showed great amount of variability. The load tokens showed a linear decrease in duration from the early to the late group (mean early loads= 377.1, mean mid loads= 350.2, mean late loads= 305.5 msec), causing a significant interaction between group and condition ($F[2,66]= 9.12, p<.0003$), and a significant group effect ($F[2,66]= 6.62, p<.002$). In the early group then, there is a significant increase in duration in the load tokens compared to the controls, in the mid group there is a slight decrease, and in the late group there is a significant decrease in duration in the load tokens compared to the controls. The early load and control tokens showed the greatest amount of variability.

3.3.4 Subject CB (Early, Mid, Late, and Post-Vowel Onset Loads)

A total of 78 pairs of tokens were analyzed; 7 in the early load group, 24 in the mid load group, and 40 pairs in the late load group. Additionally, there was a fourth group of 7 tokens whose load onset occurred shortly after (28 msec – 118 msec) the vowel onset. Means and standard deviations are presented in Table 3.11, and graphically on Figure 3.13.

Table 3.11: Means and standard deviations for Displacement, Velocity, and Duration of the Jaw, Lower Lip, Upper Lip and Velum closing movements, for subject CB. (* indicates significant difference from control)

JAW										
Subject:	EARLY LOADS		MID LOADS		LATE LOADS		POST-V.O.		POOLED	
	mean	std.dev	mean	std.dev	mean	std.dev	mean	std.dev	mean	std.dev
CB										
Number	7		24		40		7		78	
VELOCITY mm/sec										
Controls	117.7	19.6	103.9	14.1	102.8	13.3	109.2	13.8	105.1	14.6
Loads	95.2 *	14.8	92.9 *	10.4	101.7	18.3	87.7 *	31.1	97.2 *	17.9
DISPLACEMENT mm										
Controls	12.2	2.2	11.4	1.7	11.4	1.8	11.7	1.7	11.5	1.8
Loads	12.0	1.6	12.9 *	1.5	13.4 *	2.0	10.9	3.3	12.9 *	2.1
DURATION msec										
Controls	205.4	14.7	218.3	24.1	217.8	30.1	212.0	19.4	216.3	26.3
Loads	243.4 *	18.1	245.9 *	27.4	240.8 *	25.8	225.7	30.1	241.3 *	26.2

Table 3.1.1: Means and standard deviations for Displacement, Velocity, and Duration of the Jaw, Lower Lip, Upper Lip and Velum closing movements, for subject CB. (ct'd)

Subject:	LOWER LIP						POOLED	
	EARLY LOADS		MID LOADS		LATE LOADS		POST-V.O.	
CB	mean	std.dev	mean	std.dev	mean	std.dev	mean	std.dev
Number	7		24		40		78	
VELOCITY mm/sec								
Controls	87.5	14.1	94.0	13.6	90.8	13.5	80.2	18.8
Loads	104.0 *	17.0	98.1	15.0	95.8	19.1	104.1 *	11.1
DISPLACEMENT mm								
Controls	4.5	1.3	4.4	0.8	4.3	1.0	4.4	0.7
Loads	3.6	1.1	4.6	0.9	4.1	1.1	6.4 *	0.8
DURATION msec								
Controls	136.3	35.1	138.4	18.2	133.1	30.5	135.1	13.5
Loads	128.6	28.3	100.7 *	32.0	117.8 *	36.9	150.3	29.6
							135.2	26.2
							116.4 *	36.4

Table 3.11: Means and standard deviations for Displacement, Velocity, and Duration of the Jaw, Lower Lip, Upper Lip and Velum closing movements, for subject CB. (ct'd)

Subject:	UPPER LIP						POST-V.O.		POOLED	
	EARLY LOADS		MID LOADS		LATE LOADS		mean	std.dev	mean	std.dev
CB	mean	std.dev	mean	std.dev	mean	std.dev	mean	std.dev	mean	std.dev
Number	7		24		40		7		78	
VELOCITY mm/sec										
Controls	-14.9	3.5	-13.3	2.9	-14.5	3.0	-17.6	4.9	-14.5	3.3
Loads	-17.9 *	3.1	-16.5 *	4.2	-15.9 *	3.7	-20.8 *	2.5	-16.7 *	3.9
DISPLACEMENT mm										
Controls	0.9	0.3	0.8	0.2	0.9	0.3	1.0	0.3	0.9	0.2
Loads	1.2 *	0.3	1.1 *	0.3	1.1 *	0.3	1.6 *	0.4	1.1 *	0.4
DURATION msec										
Controls	108	19.5	120.3	27.1	114.6	28.3	118	18.8	116.0	26.4
Loads	124.6 *	16.5	113.3	20.7	115.2	21.2	158.6 *	26.8	119.3 *	24.4

Table 3.11: Means and standard deviations for Displacement, Velocity, and Duration of the Jaw, Lower Lip, Upper Lip and Velum closing movements, for subject CB. (ct'd)

Subject:	VELUM									
	EARLY LOADS		MID LOADS		LATE LOADS		POST-V.O.		POOLED	
CB	mean	std.dev	mean	std.dev	mean	std.dev	mean	std.dev	mean	std.dev
Number	7		24		40		7		78	
VELOCITY mm/sec										
Controls	57.8	11.0	63.2	12.9	63.9	15.9	64.9	18.0	63.2	14.7
Loads	61.3	16.5	69.0	17.4	74.1 *	17.2	69.3	5.6	71.0 *	16.7
DISPLACEMENT mm										
Controls	16.2	3.8	18.0	3.3	18.1	3.8	17.1	1.4	17.8	3.5
Loads	17.2	3.4	19.4 *	2.4	19.0	3.4	18.7	2.6	18.9 *	3.1
DURATION msec										
Controls	461.4	51.5	520.9	58.9	489.2	66.9	505.4	53.5	497.9	63.7
Loads	545.1 *	91.1	503	54.3	484.3	56.2	509.4	45.7	479.8	60.1

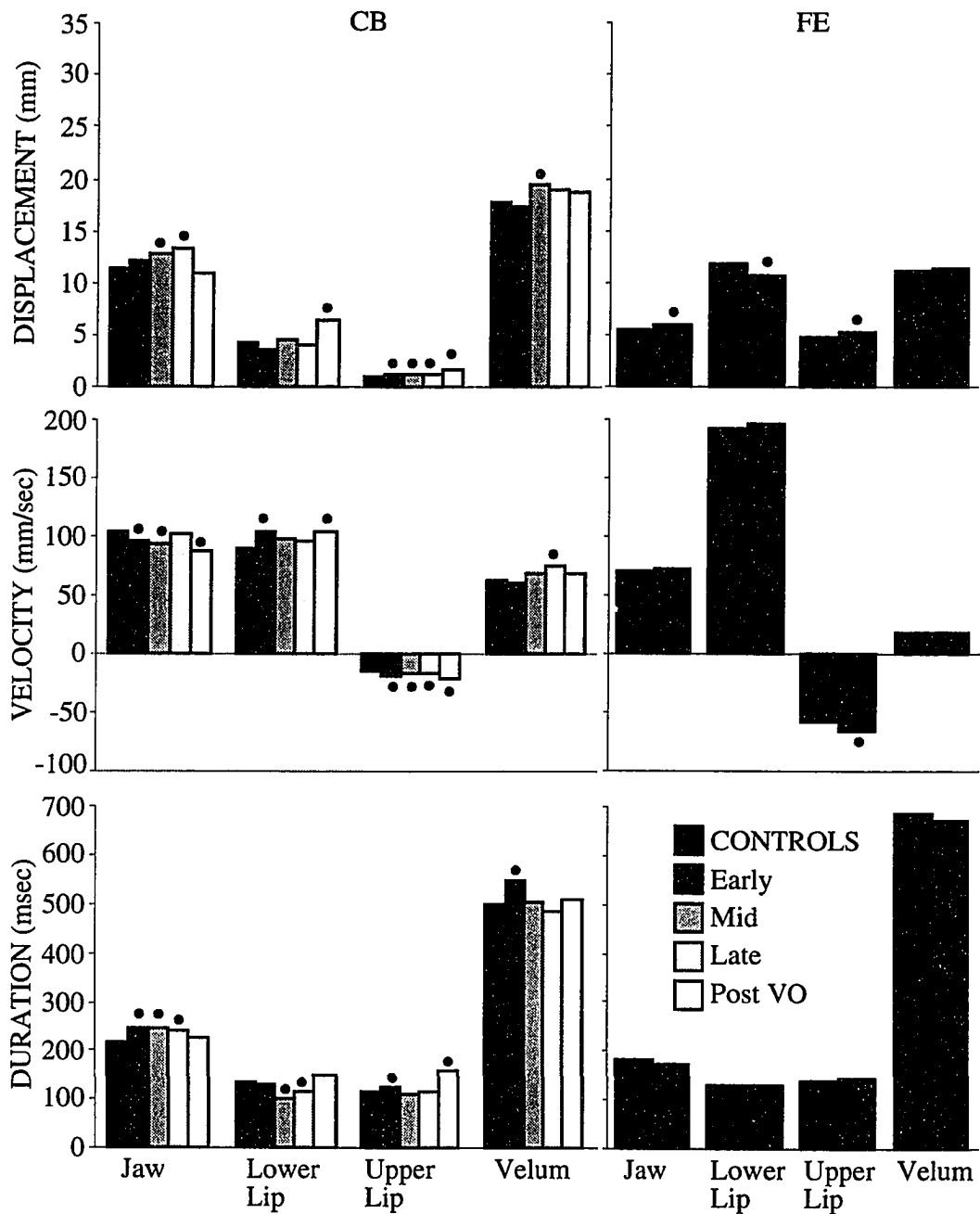


Figure 3.13 Mean displacement, velocity, and duration values for the control and load tokens (per load group) for subjects CB and FE, for all four articulators, for the /b/ closing movement. Significant differences are marked with a dot above the relevant bars. The control bars shown are taken from the entire control group.

JAW

As mentioned previously (section 3.2.3), in the load condition CB's jaw closing movements showed increased displacement and duration, and reduced velocity. Load onset effects were such that the jaw closing displacement showed increased magnitudes in the load condition from the early to the late load group. Further, in the load condition, velocity, displacement and duration showed decreased values in the post-VO group compared to the other load groups. For all three parameters, the mid loads produced consistently significant differences in the load condition.

The velocity of the load tokens was significantly smaller than the velocity of the controls (mean loads= 97.2, mean controls= 105.1 mm/sec, $F[3,74]= 25.84$, $p<.0001$). In the early, mid and post-VO groups a significant decrease in velocity in the load condition was observed. In the late group however, the load and control velocities were the same. This difference created a significant interaction between load group and load condition ($F[3,74]= 4.68$, $p<.005$). The velocity was most variable in the post-VO group in the load condition. Overall, the velocity did not vary significantly for each group, either in the control or in the load tokens.

The displacement of the load tokens was generally significantly greater than the displacement of the controls, for all groups (mean loads= 12.9, mean controls= 11.5 mm, $F[1,74]= 6.40$, $p<.013$). In specific, the load tokens in the mid and late groups showed a significant increase in the displacement, while the early and post-VO groups showed a slight decrease. Moreover, there was a significant interaction between load group and load condition ($F[3,74]= 6.77$, $p<.0004$). The interaction was further evidenced in the fact that the load tokens showed a trend for a progressive increase in displacement compared to their controls from the early group to the late one, followed by a drop in displacement in the post-VO group.

The duration of the load tokens was significantly greater than the duration of the controls (mean loads= 241.3, mean controls= 216.3 msec, $F[1,74]= 58.65$, $p<.0001$). The increase in the duration of the load tokens was significant for the early, mid and late groups, but not for the post-VO group. The difference in the duration between load tokens and controls decreased progressively from the early to the late group, until it became non-significant in the post-VO group.

LOWER LIP

Overall, CB's lower lip movements were faster in traversing the same distance, thereby achieving closure in a shorter time in the load condition.

The lower lip closing velocity was significantly greater in the load tokens (98.0 mm/sec) than in the controls (90.5 mm/sec). This was true for the early and post-VO groups, with the increase in the post-VO group being somewhat greater than that of the early group. In the mid and late groups, the increases in the velocity of the load tokens did not reach significance.

The changes in the lower lip closing displacement were qualitatively comparable to those in the velocity, in that no significant differences were seen in the mid and late groups. Even though the load tokens were not overall different from the controls, there was a significant group-condition interaction ($F[3,74]= 6.86$, $p<.0004$). In the early and post-VO groups the displacement in the load tokens was significantly different from the displacement in the controls, but in different directions. In the early group, the load tokens had smaller displacements than the controls. In the mid and late groups, the displacement was the same in the load tokens as in the controls. Finally, in the post-VO group the load tokens had significantly greater displacements than the controls. Moreover, the displacement of the post-VO load tokens was significantly greater than that of the other load groups. The tokens in the early group in both conditions showed increased variability compared to the other groups.

The duration of the load tokens was overall shorter than that of the control tokens (loads= 116.4, controls= 135.2 msec, $F[1,74]= 4.52$, $p<.037$). However, there was a significant interaction between load group and load condition ($F[3,74]= 4.61$, $p<.005$). First, the duration in the load condition decreased from the early to the mid group, and increased from the mid group to the post-VO one. In addition, the durations of the early, mid and late load tokens were shorter than the durations of their controls (this difference was significant in the mid and late groups), while the post-VO load tokens were longer than their controls (the difference however, did not reach significance).

UPPER LIP

CB's upper lip closing movements were faster, larger and lasted a longer amount of time in the load condition. The absolute velocity of the load tokens (mean= -16.7 mm/sec) was significantly greater than the velocity of the controls (mean= -14.5 mm/sec, $F[1,74]= 21.69$, $p<.0001$) for all groups. In both conditions there was substantial variability in the velocity of the four groups. The greatest increase in velocity in the load condition was seen in the mid group, while the smallest was seen in the late group. The post-VO group showed the highest velocities in both load and control tokens.

The displacement of the load tokens (mean loads= 1.1, mean controls= 0.9 mm, $F[1,74]= 71.24$, $p<.0001$) was significantly greater than the displacement of the controls. All groups showed increased displacement values in the load tokens compared to the controls. There were no group differences in the displacements of the control tokens, while in the load tokens the displacement showed a tendency to decrease from the early group to the late group, and to increase significantly in the post-VO group. In fact, the displacements of post-VO group were significantly greater than the displacements of all other load (and control) groups. The greatest increase in

displacement in the load condition was seen in the post-VO group, followed by the increase in the early group after which it decreased gradually in the mid and late groups.

The duration of the load tokens was significantly longer from the duration of the controls (mean loads= 119.3, mean controls= 116.0 msec, $F[1,74]= 10.66$, $p<.002$). However this significant increase in the duration in the load condition was seen in the early and post-VO groups only. In the post-VO load group the duration (158.6 msec) was significantly longer than in any other group, causing both a significant interaction ($F[3,74]= 6.67$, $p<.0005$) and a significant group effect ($F[3,74]= 2.72$, $p<.05$). In the late group the duration of the load tokens was the same as that of the controls, while in the mid group, the duration of the load tokens was slightly shorter than the duration of the controls.

VELUM

The behavior of CB's velum showed a similar pattern of response to the jaw perturbation as did the upper lip. The closing movements of the velum showed greater displacement and velocity, and maintained the same duration in the load condition as in the control.

The velocity of the load tokens (mean loads= 71.0, mean controls= 63.2 mm/sec, $F[1,74]= 3.87$, $p<.05$) was significantly greater than the velocity of the controls. All groups had increased velocity values. There was no difference in the velocities of the control tokens, while in the load tokens the velocity showed a tendency to increase from the early group to the late group, and to drop again slightly at the post-VO group. The same tendency was observed in the difference in the velocities between the load tokens and the controls. The difference showed a gradual increase from the early group to the late group, and a slight drop at the post-VO group. Only in the late group however, was the increase in velocity in the load condition significant (mean loads= 69.9, mean controls= 73.3 mm/sec).

The displacement of the load tokens (mean loads= 18.9, mean controls= 17.8 mm, $F[1,74]= 6.93$, $p<.01$) was significantly greater than the displacement of the controls. Again, was the increase in the displacement of the load tokens was significant only in one group, this time the mid group (mean loads= 19.4, mean controls= 18.0 mm/sec), while it was borderline significant in the post-VO group. All load groups showed decreased displacement values.

The duration of the load tokens was not significantly different from the duration of the controls (mean loads= 497.8, mean controls= 497.9 msec, $F[1,74]= 3.25$, $p<.07$). In the late and post-VO groups, the duration of the load tokens was about the same as that of the controls. In the mid group the duration of the load tokens was slightly shorter than the duration of the controls. In the early group the duration of the load tokens was significantly greater than the duration of the controls, creating a significant interaction between group and condition ($F[3,74]= 5.23$, $p<.002$).

3.3.5 Subject FE (Early Loads)

The loads applied during the experimental session for FE fell into the early load category. However, as mentioned earlier, they did produce compensatory reactions to the jaw and the lips, the details of which will be discussed below. The load onset range relative to the vowel onset (V1 /a/ in /mabnab/) was 238 – 650 msec. A total of 78 pairs of tokens were analyzed. Means and standard deviations are presented in Table 3.12, and in a graphic representation on Figure 3.13.

JAW

In the early load condition FE's jaw closing movements were greater ($F[1,77]= 5.19$, $p<.025$), the velocity was the same ($F[1,77]= 2.22$, NS) as in the control condition, yet the duration remained unchanged ($F[1,77]= 2.54$, NS). There was however a trend for the velocity to increase, and the duration to decrease, even if they did not reach a level of statistical significance. For example, in the load tokens the mean

Table 3.12: Means and standard deviations for Displacement, Velocity, and Duration of the Jaw, Lower Lip, Upper Lip and Velum closing movements, for subject FE. (* indicates significant difference from control)

JAW								
Subject:	EARLY LOADS		MID LOADS		LATE LOADS		POOLED	
FE	mean	std.dev	mean	std.dev	mean	std.dev	mean	std.dev
Number	78							
VELOCITY mm/sec								
Controls	69.4	15.4						
Loads	72.8	14.3						
DISPLACEMENT mm								
Controls	5.5	1.3						
Loads	5.9 *	1.3						
DURATION msec								
Controls	180.0	18.3						
Loads	174.9	22.3						

LOWER LIP								
Subject:	EARLY LOADS		MID LOADS		LATE LOADS		POOLED	
FE	mean	std.dev	mean	std.dev	mean	std.dev	mean	std.dev
Number	78							
VELOCITY mm/sec								
Controls	192.4	26.7						
Loads	196.0	22.2						
DISPLACEMENT mm								
Controls	11.8	1.2						
Loads	10.7 *	1.1						
DURATION msec								
Controls	130.1	14.1						
Loads	128.9	20.5						

Table 3.12: Means and standard deviations for Displacement, Velocity, and Duration of the Jaw, Lower Lip, Upper Lip and Velum closing movements, for subject FE. (ct'd)

UPPER LIP								
Subject:	EARLY LOADS		MID LOADS		LATE LOADS		POOLED	
FE	mean	std.dev	mean	std.dev	mean	std.dev	mean	std.dev
Number	78							
VELOCITY mm/sec								
Controls	-59.4	8.6						
Loads	-67.1 *	10.2						
DISPLACEMENT mm								
Controls	4.7	0.7						
Loads	5.3 *	0.8						
DURATION msec								
Controls	139.1	14.4						
Loads	142.6	15.9						

VELUM								
Subject:	EARLY LOADS		MID LOADS		LATE LOADS		POOLED	
FE	mean	std.dev	mean	std.dev	mean	std.dev	mean	std.dev
Number	78							
VELOCITY vva2 mm/sec								
Controls	18.3	6.6						
Loads	18.3	6.4						
DISPLACEMENT mm								
Controls	11.1	2.5						
Loads	11.4	2.0						
DURATION msec								
Controls	687	54.7						
Loads	673.9	50.0						

closing velocity was 72.8 mm/sec, while in the controls it was 69.4 mm/sec. Similarly, in the load tokens the mean closing duration was 174.9 msec, while in the controls it was 178.0 msec.

LOWER LIP

In the early load condition FE's lower lip closing movement was smaller ($F[1,77]=54.16$, $p<.0001$), the velocity of the movement was the same ($F[1,77]=.92$, NS), yet the duration of the closing movement was also the same ($F[1,77]=.22$, NS) as in the control condition. A tendency for the lower lip closing velocity to increase, (e.g. mean load tokens velocity was 196.0 mm/sec, mean controls velocity was 192.4 mm/sec) and for the duration to decrease (e.g. mean load tokens velocity was 128.9 msec, mean controls velocity was 130.1 msec) was observed in the load condition, and might explain the results mentioned above. That is, the small increase in velocity, however statistically non-significant, might have been sufficient –combined with the decrease in displacement– to allow for the non significant decrease in duration.

UPPER LIP

In the early load condition FE's upper lip closing movements were bigger ($F[1,77]=64.95$, $p<.0001$), faster ($F[1,77]=29.48$, $p<.0001$), and the overall closing duration was maintained constant in the two conditions ($F[1,77]=3.25$, $p<.075$).

Therefore, the upper lip, the lower lip and the jaw seem to adjust their kinematic parameters as a result of the perturbation in the jaw movement.

VELUM

In the early load condition FE's velum closing movements showed no significant changes as compared to the control condition. The closing movement velocity ($F[1,77]=.001$, NS) was the same in the two conditions. There was a trend toward greater displacement ($F[1,77]=.68$, NS) and shorter duration ($F[1,77]=3.61$, $p<.061$), but given the large variability associated with these measures, they were not statistically

significant. For example, in the load tokens the mean closing duration was 673.9 msec, while in the controls it was 687.0 msec. The standard deviation however, was in the order of 52 msec. Even though the closing movement displacement was unchanged in the two conditions, the peak position of the velum at the moment of closure was significantly lower in the load condition than in the control ($F[1,77]= 15.58, p<.0002$). However, the physical significance of the difference in the two positions (loads mean= 8.65 mm, controls mean= 8.96 mm, difference= .31 mm), is difficult to evaluate.

It appears then that when the load was applied on the jaw well before the acoustic onset of the first vowel (238 – 650 msec), the jaw was indeed perturbed, and the movements of the oral articulators did involve compensatory adjustments due to the load

3.3.6 Subject JP (Early and Mid Loads)

The loads applied during this experimental session fell into two categories: the mid load category, but mostly into the early load category. A total of 137 pairs of tokens were analyzed. Of those, 125 pairs of tokens were in the early load group and 12 pairs in the mid load group. However, as mentioned earlier, the early loads did produce compensatory reactions to the jaw and the lips, the details of which will be discussed below. The range of onsets in the early loads group relative to the onset of the first vowel in /mabnab/ was 202 – 704 msec. Means and standard deviations are presented in Table 3.13, and in a graphic representation on Figure 3.14.

JAW

As mentioned earlier (section 3.2.5), in the early load condition JP's jaw closing movements showed no significant change in velocity ($F[1,135]= 3.47, p<.065$), or in displacement ($F[1,135]= 2.71, NS$), while the closing movement duration was longer ($F[1,135]= 10.97, p<.0012$). The velocity of the load tokens was smaller than the velocity of the control tokens. In specific, the velocity of the early load tokens was the same as the velocity of the mid loads, and they both were smaller than their controls

Table 3.13: Means and standard deviations for Displacement, Velocity, and Duration of the Jaw, Lower Lip, Upper Lip and Velum closing movements, for subject JP. (* indicates significant difference from control)

JAW								
Subject:	EARLY LOADS		MID LOADS		LATE LOADS		POOLED	
JP	mean	std.dev	mean	std.dev	mean	std.dev	mean	std.dev
Number	125		12				137	
VELOCITY mm/sec								
Controls	141.4	21.2	155.3	32.9			142.6	22.6
Loads	139.2	24.3	140.8	22.3			139.4	24.1
DISPLACEMENT mm								
Controls	11.1	2.0	10.6	2.1			11.0	2.0
Loads	12.1 *	2.7	10.9	1.5			12.0	2.6
DURATION msec								
Controls	194.9	25.1	170.2	14.5			192.7	25.3
Loads	202.0 *	22.6	192.8 *	18.2			201.2 *	22.3

LOWER LIP								
Subject:	EARLY LOADS		MID LOADS		LATE LOADS		POOLED	
JP	mean	std.dev	mean	std.dev	mean	std.dev	mean	std.dev
Number	125		12				137	
VELOCITY mm/sec								
Controls	137.9	19.5	108.2	13.5			135.3	20.8
Loads	150.4 *	20.3	100.6	21.7			146.0	24.8
DISPLACEMENT mm								
Controls	6.7	1.0	5.1	0.7			6.6	1.1
Loads	7.1 *	1.4	4.1 *	1.1			6.9	1.6
DURATION msec								
Controls	84.0	7.8	83.3	13.4			83.9	8.4
Loads	82.7	9.8	73.7 *	13.0			81.9 *	10.4

Table 3.13: Means and standard deviations for Displacement, Velocity, and Duration of the Jaw, Lower Lip, Upper Lip and Velum closing movements, for subject JP. (c't'd)

UPPER LIP								
Subject:	EARLY LOADS		MID LOADS		LATE LOADS		POOLED	
JP	mean	std.dev	mean	std.dev	mean	std.dev	mean	std.dev
Number	125		12				137	
VELOCITY mm/sec								
Controls	-73.2	15.2	-83.6	15.5			-74.1	15.4
Loads	-88.8	15.2	-91.4 *	22.1			-89.0 *	15.9
DISPLACEMENT mm								
Controls	3.8	0.7	4.2	0.8			3.9	0.7
Loads	4.7 *	0.7	4.4	1.0			4.6 *	0.7
DURATION msec								
Controls	94.9	9.8	91.8	7.8			94.6	9.7
Loads	95.0	6.7	83.8 *	7.0			94.0 *	7.4

VELUM								
Subject:	EARLY LOADS		MID LOADS		LATE LOADS		POOLED	
JP	mean	std.dev	mean	std.dev	mean	std.dev	mean	std.dev
Number	125		12				137	
VELOCITY mm/sec								
Controls	65.0	25.8	59.2	14.5			64.5	25.0
Loads	67.8	28.1	47.6 *	17.4			66.1	27.9
DISPLACEMENT mm								
Controls	27.8	4.2	25.0	1.5			27.5	4.1
Loads	27.9	4.6	24.3	1.9			27.5	4.5
DURATION msec								
Controls	555.9	45.6	504.3	36.8			551.0	47.2
Loads	552.8	49.0	515.5	26.6			549.3	48.4

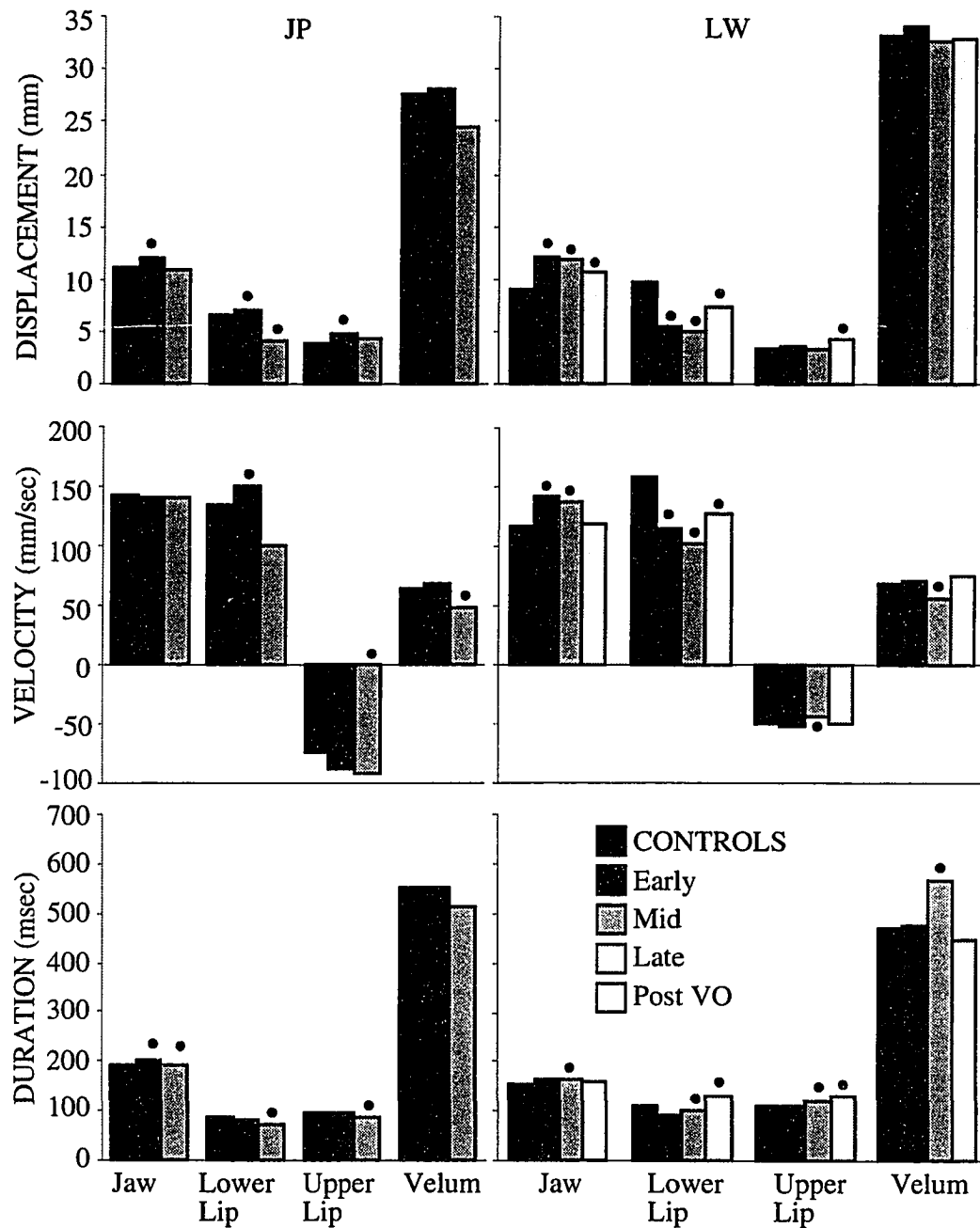


Figure 3.14 Mean displacement, velocity, and duration values for the control and load tokens (per load group) for subjects JP and LW, for all four articulators, for the /b/ closing movement. Significant differences are marked with a dot above the relevant bars. The control bars shown are taken from the entire control group.

(mean early controls duration was 141.4 mm/sec – loads 139.2, mean mid controls duration was 155.3 – loads 140.8 mm/sec).

The displacement of the mid load tokens was somewhat smaller than the displacement of the early loads, and they both were greater than their controls. However, the mid load condition resulted in only a slight increase in displacement, while the early load condition resulted in a quite greater increase in displacement.

The duration of the mid load tokens was somewhat shorter than the duration of the early loads, and they both were significantly longer than their controls (mean early load tokens duration was 202.0 msec – controls 194.9, mean mid load tokens duration was 192.8 – controls 170.2 msec). In the control tokens the duration and the velocity were as variable as in the load tokens, and there was a great difference between the mid and the early conditions. It is unclear why a such a difference would be observed in the control condition.

LOWER LIP

Even though JP's overall lower lip closing velocity was not statistically different between load tokens (146.1 mm/sec) and controls (135.3 mm/sec), this was due mainly to the mid load group. In the early load condition JP's lower lip closing movements (125 of the 137 pairs) were faster, and there was a significant interaction ($F[1,135]=8.42, p<.004$) between load condition (loads vs. controls) and load group (early vs. mid loads).

The velocity of the mid load tokens (mean= 100.6 mm/sec) was significantly smaller than the velocity of the early load tokens (mean= 150.4 mm/sec) , and they both were shorter than their controls. However, the early load condition resulted in a significantly increased velocity, while the mid load condition resulted in a slight decrease in velocity (mid loads mean difference= 7.6 mm/sec, early loads mean difference= 12.5 mm/sec).

No significant overall differences were seen in the displacement values between load and control tokens, because of a significant interaction between load condition and load group ($F[1,135]=13.40$, $p<.0004$). While both load groups appeared to be significantly different from their controls, they were different in opposite ways. The mid load tokens had smaller displacements than their controls, while the early load tokens had bigger displacements.

The duration of the load tokens was overall significantly smaller than that of the control tokens. Further, the interaction between early and mid load conditions was also significant ($F[1,135]=5.12$, $p<.025$). In particular, the duration of the mid load tokens (mean= 73.7 msec) was significantly shorter than the duration of the early load tokens (mean= 82.7 msec) , and they both were shorter than their controls. However, the early load condition resulted in only a slight decrease in duration, while the mid load condition resulted in a greater decrease in duration (mid loads mean difference= 9.6 msec, early loads mean difference= 1.3 msec).

UPPER LIP

In JP's upper lip, the absolute velocity of the load tokens (mean= -89.1 mm/sec) was significantly greater than the velocity of the controls (mean= -74.1 mm/sec). The velocity of the mid load tokens (mean= -91.4 mm/sec) was significantly greater than the velocity of the early load tokens (mean= -88.8 mm/sec) , and they both were greater than their controls. However, the early load condition resulted in a significantly increased velocity, while the mid load condition resulted in a smaller increase in velocity (mid loads mean difference= 7.8 mm/sec, early loads mean difference= 15.6 mm/sec). This difference seems to be due to the differences in velocity in the control groups, rather than the differences in velocity in the load groups. In other words, the early controls and the mid controls were quite different (mid= -83.6 , early -73.2 mm/sec).

The displacement of the load tokens (mean= 4.6 mm) was overall significantly greater than the displacement of the controls (mean= 3.9 mm). The displacement of the mid load tokens (mean= 4.4 mm) was the same as that of the mid controls (mean= 4.3 mm), while there was a significant difference in the values of the early group: the early load tokens (mean= 4.7 mm) were significantly greater than their controls (mean= 3.8 mm). The displacement of the mid load tokens (mean= 4.4 mm) was significantly smaller than the displacement of the early load tokens (mean= 4.7 mm). The displacement of the mid controls (mean= 4.3 mm) was significantly bigger than the displacement of the early controls (mean= 3.8 mm).

The duration of the load tokens (mean= 94.0 msec) was significantly shorter than the duration of the controls (mean= 94.6 msec), and there was a significant interaction between load group and load condition ($F[1,135]= 7.5, p<.007$). In the early group there were no differences between load and control tokens. In the mid group however, the load tokens (mean= 83.8 msec) had a significantly shorter duration than their controls (mean= 91.8 msec).

VELUM

The velocity of JP's velum raising movements in the load tokens (mean loads= 66.1, mean controls= 64.5 mm/sec) was not significantly different from the velocity of the controls. However, there was a significant interaction between load group and load condition ($F[1,135]= 3.94, p<.049$). In the early group there was a small increase in velocity in the load condition (mean loads= 67.8, mean controls= 65.0 mm/sec). In the mid group however, there was a sizable decrease in velocity in the load condition (mean loads= 47.6, mean controls= 59.2 mm/sec).

The displacement of the load tokens (mean loads= 27.5, mean controls= 27.5 mm) was the same as the displacement of the controls. However, there was a tendency for a

slight decrease in displacement in the mid load condition (mean loads= 24.3, mean controls= 25.0 mm) which did not reach significance.

The situation was similar for the duration of the velar raising. The load tokens were about the same as the controls (mean difference was 1.7 msec). Again in the mid group there was a tendency for the load tokens to have slightly greater duration than their controls, while the opposite trend was seen in the early group; however, neither reached significance.

3.3.7 Subject LW (Early, Mid, and Late Loads)

The loads applied during this experimental session fell into three categories: early loads with 6 pairs of tokens, mid loads with 30 pairs of tokens and early loads with 17 pairs of tokens. A total of 53 pairs of load and control tokens were analyzed. Means and standard deviations are presented in Table 3.14, and graphically on Figure 3.14.

JAW

As mentioned previously (section 3.2.6), in the load condition LW's jaw closing movements were faster in covering greater distance, while maintaining the same closing duration.

The velocity of the load tokens was significantly greater than the velocity of the controls (mean loads= 133.5, mean controls= 116.6 mm/sec). Further, there was an interaction between load group and load condition that did not reach significance level ($F[2,47]= 2.90, p<.06$). In the early group there was a significant increase in velocity in the load condition (mean loads= 141.8, mean controls= 112.3 mm/sec). The same was observed in the mid group (mean loads= 138.2, mean controls= 116.8 mm/sec). In the late group however, the two velocities were essentially the same. The velocity decreased from the early to the late group in the load condition, while no such change was seen in the controls.

Table 3.14: Means and standard deviations for Displacement, Velocity, and Duration of the Jaw, Lower Lip, Upper Lip and Velum closing movements, for subject LW. (* indicates significant difference from control)

JAW								
Subject:	EARLY LOADS		MID LOADS		LATE LOADS		POOLED	
LW	mean	std.dev	mean	std.dev	mean	std.dev	mean	std.dev
Number	6		30		14		50	
VELOCITY mm/sec								
Controls	112.3	38.2	116.8	27.3	118.1	33.3	116.6	29.8
Loads	141.8 *	29.2	138.2 *	26.1	119.9	25.8	133.5 *	27.3
DISPLACEMENT mm								
Controls	9.1	3.1	8.9	2.1	9.0	2.4	9.0	2.3
Loads	12.2 *	2.0	11.9 *	2.1	10.6 *	2.1	11.6 *	2.1
DURATION msec								
Controls	157.7	24.2	155.7	16.3	158.4	20.1	156.7	18.0
Loads	165.7	10.3	162.1 *	12.6	159.7	13.4	161.8	12.5

LOWER LIP								
Subject:	EARLY LOADS		MID LOADS		LATE LOADS		POOLED	
LW	mean	std.dev	mean	std.dev	mean	std.dev	mean	std.dev
Number	6		30		14		50	
VELOCITY mm/sec								
Controls	161.3	69.2	160.9	47.6	153.2	36.6	158.8	46.9
Loads	115.6 *	34.2	103.1 *	35.9	126.8 *	42.7	111.2 *	38.4
DISPLACEMENT mm								
Controls	9.4	2.7	10.0	3.0	9.3	2.4	9.8	2.8
Loads	5.4 *	1.7	5.1 *	2.2	7.4 *	2.8	5.8 *	2.5
DURATION msec								
Controls	102.3	20.6	113.3	18.9	114.3	17.0	112.3	18.6
Loads	92	24.8	101.0 *	29.5	129.3 *	21.0	107.8	29.7

Table 3.14: Means and standard deviations for Displacement, Velocity, and Duration of the Jaw, Lower Lip, Upper Lip and Velum closing movements, for subject LW. (ct'd)

UPPER LIP									
Subject:	EARLY LOADS		MID LOADS		LATE LOADS		POOLED		
LW	mean	std.dev	mean	std.dev	mean	std.dev	mean	std.dev	
Number	6		30		14		50		
VELOCITY mm/sec									
Controls	-50.6	5.0	-50.8	7.3	-51.1	8.6	-50.9	7.3	
Loads	-51.6	5.2	-44.0 *	8.0	-50.0	6.8	-46.6 *	7.9	
DISPLACEMENT mm									
Controls	3.4	0.4	3.3	0.5	3.4	0.5	3.4	0.5	
Loads	3.6	0.5	3.3	0.6	4.2 *	0.5	3.6	0.7	
DURATION msec									
Controls	110.7	9.2	110.1	15.4	114.9	14.9	111.5	14.6	
Loads	113	10.0	123 *	15.4	131.3 *	12.2	124.1 *	14.9	

VELUM									
Subject:	EARLY LOADS		MID LOADS		LATE LOADS		POOLED		
LW	mean	std.dev	mean	std.dev	mean	std.dev	mean	std.dev	
Number	6		30		14		50		
VELOCITY mm/sec									
Controls	73.3	26.5	67.5	24.2	69.0	28.0	68.6	25.1	
Loads	69.9	40.5	56.3 *	21.7	74.5	19.7	63.0	24.9	
DISPLACEMENT mm									
Controls	33.7	4.5	33.0	5.7	33.4	5.6	33.2	5.4	
Loads	34.2	7.9	32.8	7.3	33.0	5.7	33.0	6.8	
DURATION msec									
Controls	475.3	36.8	482.3	35.7	450	49.8	472.4	41.9	
Loads	476.3	51.8	467.9 *	37.1	446.9	30.0	463.0	37.9	

The displacement of the load tokens was significantly greater than the displacement of the controls, for all groups (mean loads= 11.6, mean controls= 9.0 mm). There was a trend for a progressive decrease in displacement in the load tokens from the early group to the late one, with the early group showing a greater amount of variability than the other groups in both load and control tokens.

The duration of the load tokens was not significantly different from the duration of the controls (mean loads= 161.8, mean controls= 156.7 msec, $F[1,47]= 3.34$, $p<.07$). Overall, there was a tendency for the load tokens to be somewhat longer than the controls. In the mid group that lengthening was significant (mean loads= 162.1, mean controls= 155.7 msec). In the early group, even though the difference in displacement was greater than that of the mid group, the great variability in both load and control tokens prohibited significance (mean loads= 165.7, mean controls= 157.7 msec). Again, there was a trend for a progressive decrease in duration in the load tokens from the early group to the late one.

LOWER LIP

Overall, LW's lower lip closing displacement was smaller, the movement velocity was reduced, and the movement was accomplished in the same duration in the load condition as in the control.

The lower lip closing velocity was significantly smaller in the load tokens (111.2 mm/sec) than in the controls (158.8 mm/sec). This was true for all the groups, with the mid load condition showing the greatest reduction in velocity, and the late one showing the smallest. In the early load tokens the reduction was about as big as that of the mid loads, but the variability of the early control tokens was very high, resulting in a smaller separation of velocities between load and control tokens.

The lower lip closing displacement was significantly smaller in the load tokens (5.8 mm) than in the controls (9.7 mm). This was true for all the groups, with the mid and

early load conditions showing the greatest reduction in displacement. Further, there was a significant interaction between load condition and load group ($F[2,47]=3.74$, $p<.031$), because in the load condition there was a progressive decrease in displacement from the late to the early group. Again, the tokens in the early group in both conditions showed increased variability compared to the other groups.

The duration of the load tokens was overall the same as that of the control tokens, and in both conditions the early group was more variable than the others. However, there was a significant interaction between load group and load condition was also significant ($F[2,47]=3.82$, $p<.029$). First, the duration in the load condition increased from the early group to the late one. In addition, the durations of the early and mid load tokens were shorter than the durations of their controls, and this was a significant difference in the mid group. However, the late load tokens were significantly longer than their controls.

UPPER LIP

LW's upper lip displacement and duration for closure were increased in the load condition, while the closing velocity remained the same.

The absolute velocity of the load tokens (mean= -46.6 mm/sec) was statistically the same as the velocity of the controls (mean= -50.9 mm/sec). In the load condition, the mid load tokens were significantly slower than the early or late loads. In turn, the velocities of the mid load tokens (mean= -44.0 mm/sec) were significantly slower than the velocities of their controls (mean= -50.8 mm/sec). While the late load tokens showed a trend toward decreased velocity as compared to their controls, the early load tokens showed the opposite trend.

The displacement of the load tokens (mean= 3.6 mm) was overall significantly greater than the displacement of the controls (mean= 3.4 mm). In the control condition there was no difference in the displacement of the three groups, while in the load

condition, the late load tokens showed significantly greater displacement than the mid or early loads, creating a significant interaction between load group and load condition ($F[2,47]=6.45, p<.003$). The mid load displacements were essentially identical as their controls. The early load tokens had slightly greater displacement than their controls, and the late load tokens had a significantly greater displacement than their controls.

The duration of the load tokens (mean= 124.1 msec) was significantly longer than the duration of the controls (mean= 111.5 msec). In the control condition there was no difference in the duration of the three groups, while in the load condition, the duration was progressively greater from the early to the late group. In the early group the duration was slightly longer in the load tokens than in the controls. In the mid and late groups however, the load tokens had a significantly longer duration than their controls.

VELUM

In general, the kinematics of LW's velum showed no significant changes in the load condition as compared to the control, in that the closing movement duration, displacement and velocity were the same in the two conditions.

The velocity of the load tokens (mean loads= 63.0, mean controls= 68.6 mm/sec) was not significantly different from the velocity of the controls. However, there was an interaction between load group and load condition that did not reach significance level ($F[2,47]= 2.49, p<.09$). In the early group there was a small decrease in velocity in the load condition (mean loads= 69.9, mean controls= 73.3 mm/sec). In the mid group however, the decrease in velocity in the load condition was a significant (mean loads= 56.3, mean controls= 67.5 mm/sec). In the late group, the opposite trend was seen: there was a slight increase in the velocity in the load condition (mean loads= 74.5, mean controls= 69.0 mm/sec).

The displacement of the load tokens (mean loads= 33.0, mean controls= 33.2 mm) was the same as the displacement of the controls, with the early and mid load tokens

showing greater variability than the late load tokens or the control tokens. Incidentally, the position of the velum was significantly lower in the load condition as compared to the control, for all three load onset groups ($F[1,47]= 7.79, p<.007$), and decreased progressively (but not significantly) from the early load group to the late one, with the early group showing a greater amount of variability than the other groups in both load and control tokens.

The duration of the load tokens was not significantly different from the duration of the controls (mean loads= 463.0, mean controls= 472.4 msec). Overall, there was a tendency for the load tokens to be shorter than the controls, but only in the mid load tokens did that tendency reach significance (mean loads= 467.9, mean controls= 482.3 msec).

3.3.8 Load groupings

Given the great variability in the response patterns of the articulators per load group across subjects, the question arose whether the classification into load groups corresponded to approximately the same part of the movement's trajectory, for a specific articulator across subjects.

The /ma/ movement onsets (in /mab/) for the jaw and the velum as well as the load onsets with respect to the vowel onset (marked as zero) for each subject are shown in Figure 3.15. The movement onsets were taken from the control tokens in each group to avoid contamination from load effects on the movements. It can be seen that the onset of the velum movement precedes the onset of the jaw movement. There is more variation in the time of velar movement onset across subjects than in the time of jaw movement onsets, mainly because subject FE's velar movement onsets occurred very early: on average more than 400 msec before the vowel onset. Therefore, it seems that the differences among subjects cannot be accounted for simply by the differences in load onsets relative to movement onsets.

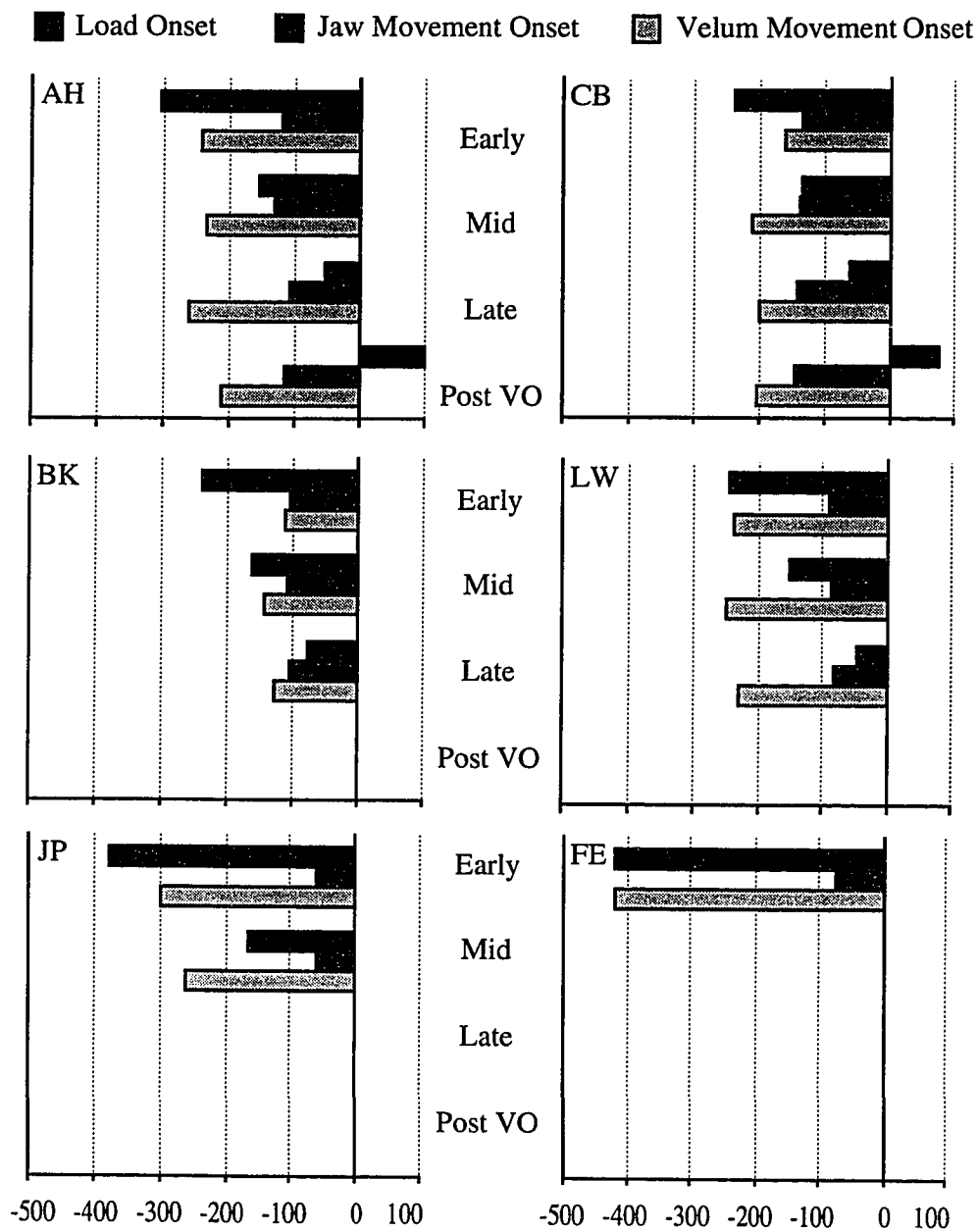


Figure 3.15 Mean times of load, jaw movement, and velum movement onsets with respect to the acoustic vowel onset, per load group, in msec, for each subject. The jaw and velum times are obtained from the control tokens. Zero is the acoustic onset of the first vowel.

The same data can be viewed differently: Figure 3.16 shows the difference in mean onset times between the jaw movement and the load, and between the velum movement and the load, as always, with respect to the vowel onset. These intervals were roughly similar across subjects. In other words, the load onsets corresponded to similar phases, or portions, of the jaw and velum movements across subjects. There were three exceptions: For subjects JP and FE the intervals between the mean onsets of the jaw movement and the load were about 150 msec longer than in the other subjects. Further, for BK the mean onsets of the jaw and velum movements were almost concurrent, so that in the mid loads the load onset occurred before the onset of the velar movement, unlike the rest of the subjects, in whom it occurred after the onset of the velar movement. Therefore, it appears that, given that the variability observed both within and across subjects in the onset of jaw and velum movements relative to the onset of the load is relatively small, it cannot account for the variability observed in the response patterns of the subjects.

Moreover, as an additional measure, the load onset times and the times of peak position of the jaw (movement offset) at /a/ and of the velum (movement offset) at /b/ in /mab/, were examined, and found to show again little variability. These intervals relative to vowel onset are shown in Figure 3.17. For all subjects, except AH, peak jaw position is attained about 50-100 msec after the vowel onset. For AH it is slightly later (150 msec). Similarly, for all subjects, except AH, peak velum position is attained about 200-300 msec after the vowel onset. For AH it is slightly later (400-450 msec). Again, there is slightly more variability in the velum measures than in the jaw measures. So, it appears that the load was applied at comparable times in the trajectories of the movements for the subjects in this study.

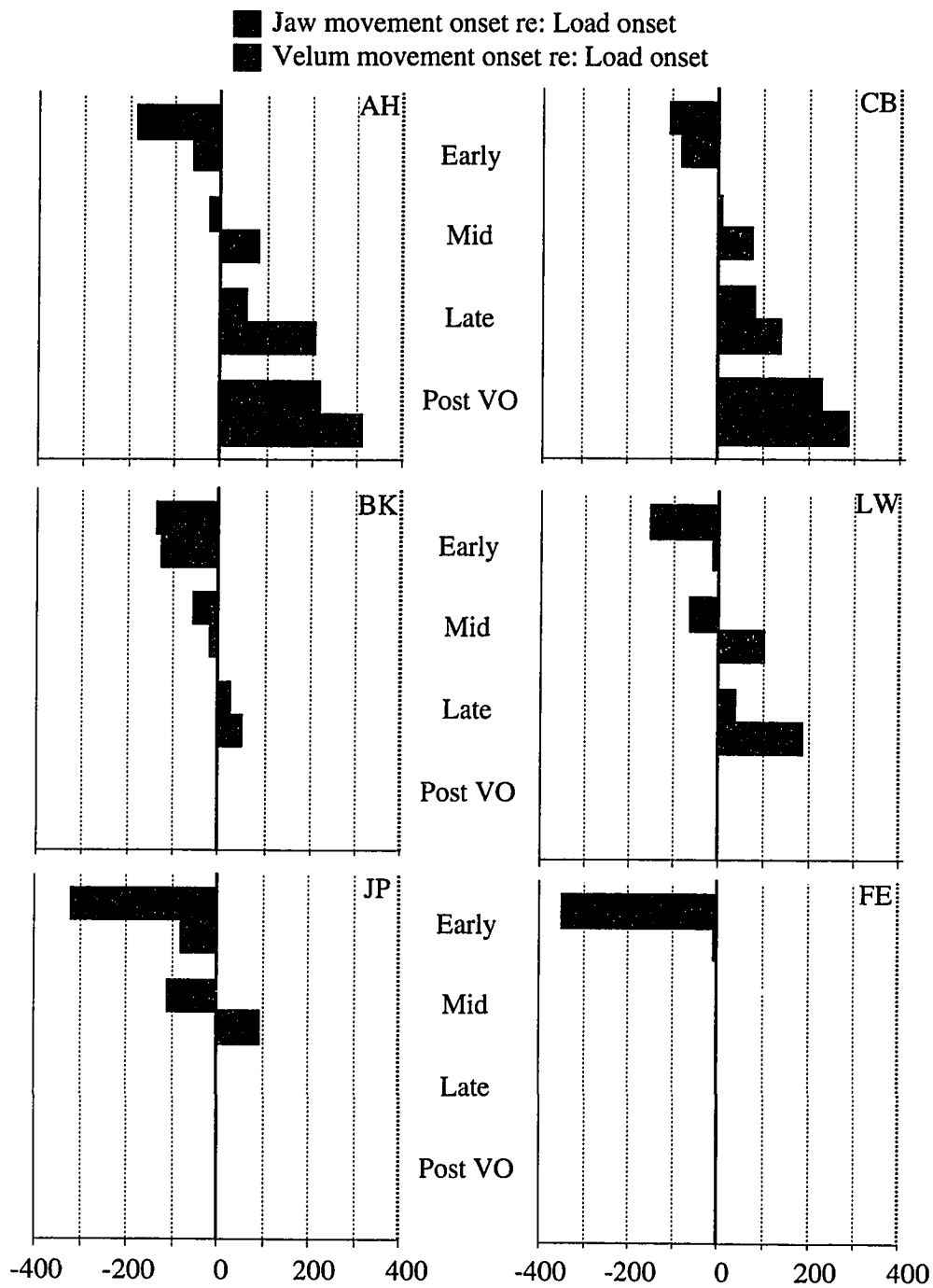


Figure 3.16 Mean durations of the interval between load onset and jaw and velum movement onsets per load group, in msec, for each subject. The jaw and velum times are obtained from the control tokens. Zero is the acoustic onset of the first vowel.

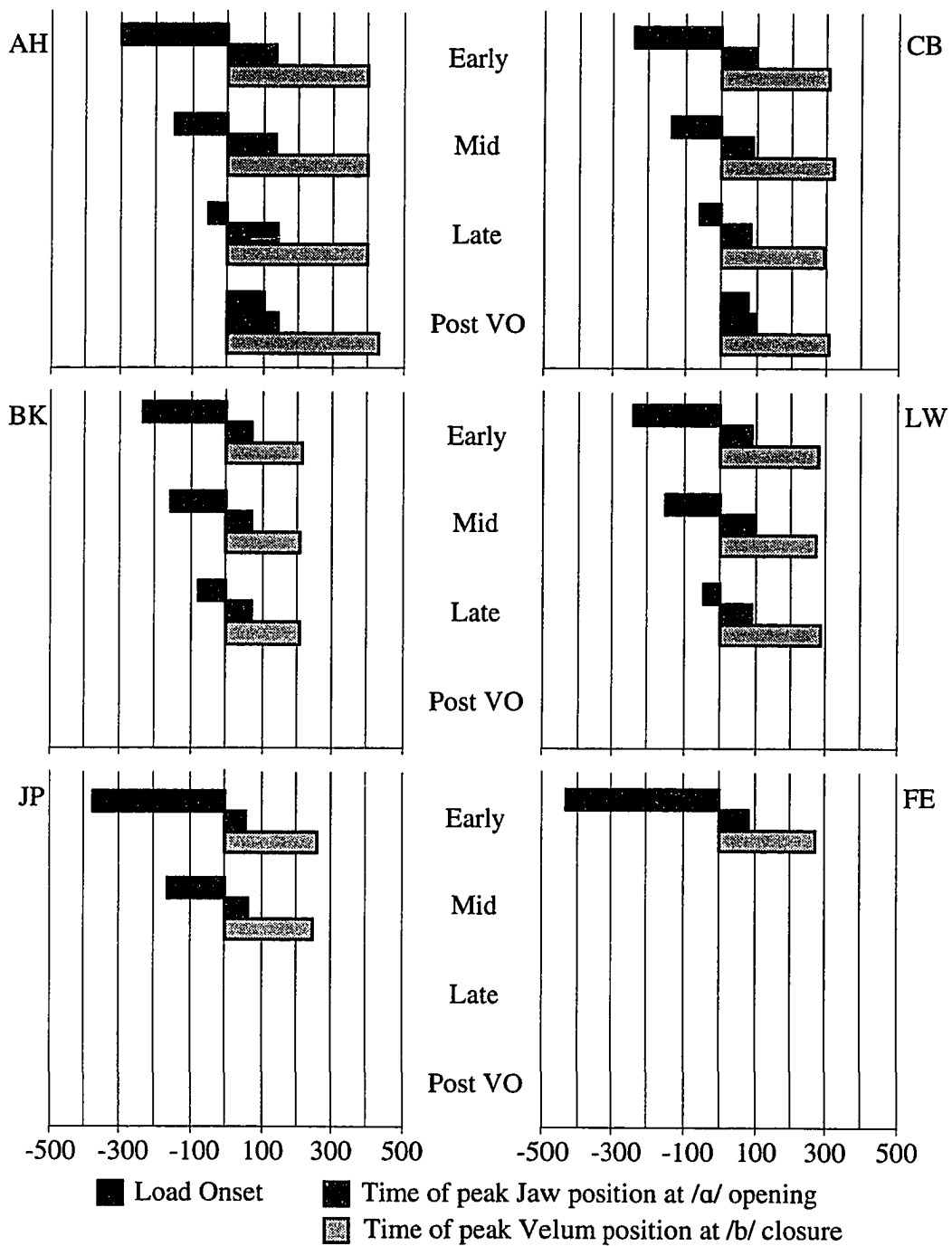


Figure 3.17 Mean times of load onset, peak jaw position at /a/ opening, and peak velum position for /b/ closure, per load group, in msec, for each subject. The jaw and velum times are obtained from the control tokens. Zero is the acoustic onset of the first vowel.

3.4 INTERARTICULATORY COORDINATION IN THE LOAD AND CONTROL CONDITIONS

In a previous study, (Kollia et al., submitted) the times of arrival at peak position and peak velocity relative to the vowel onset in /mab/ (of /mabnab/) were examined for the jaw, the upper lip and the velum. In that study, a correlational analysis revealed that the relative timing of the closing events for the velum and the jaw, and for the velum and the upper lip are related, but not as tightly as for the upper lip and the jaw. Further, for the /b/ closing movement in /mab/, the time of peak position –rather than the time of peak velocity– was found to be a better index of the cohesion between the velum and the jaw, and also between the velum and the upper lip. The order of the /b/ closure events was only slightly constrained; the upper and lower lips arrived at peak position at about the same time, first, and were followed by the jaw and the velum. The relative order within the two groups (upper lip–lower lip and jaw–velum) was not fixed.

3.4.1 Load effects on the interarticulator timing for /b/ closure.

The same measure of interarticulator cohesion was examined here. To determine whether interarticulator cohesion is maintained to the same degree in the face of perturbation, the times of arrival at peak position relative to the vowel onset in /mab/ were examined for the jaw, the upper lip and the velum in the load tokens. The times of arrival at peak position for closure were correlated across articulator pairs. These correlations were compared to the correlations obtained for the control tokens. Of the 16 possible comparisons (recall that upper lip data were obtained for 5 of the 6 subjects), only 4 showed a reduction in the correlation in the load condition. Of the remaining 12 comparisons, 9 showed increased correlations in the load condition, and 3

(seen in LW and BK) showed approximately equal correlation coefficients. For subject LW the good correlation observed in the control condition in the velum-jaw and velum-upper lip pairs dissolved in the load condition. On the contrary, for the same subject the jaw-upper lip correlation increased in the load condition. For BK even though a decrease in the value of the correlation coefficient in the load condition in the velum-jaw pair was seen, the correlation was significant ($p < .01$). These correlations are presented in Table 3.15. To illustrate, Figure 3.18 shows the times of arrival at peak position for /b/ closure for the upper lip (top) and the velum (bottom) plotted against the times for the jaw, for the load tokens for subject FE.

Table 3.15: Times of peak position for the first /b/ closing movement in /mabnab/: Correlations for Velum-Jaw and Upper Lip-Jaw. Correlations were significant at $p < .0001$ level, except where marked otherwise. The /b/ closing movement times are measured from the time of the acoustic onset of the 1st vowel (*: significant at $p < .01$, -: not significant).

SUBJECT	Upper Lip - Jaw		Velum - Jaw		Velum - Upper Lip	
	Controls	Loads	Controls	Loads	Controls	Loads
AH	.62	.70	.85	.81	.78	.80
BK	---	---	.78	.50 *	---	---
CB	.87	.92	.77	.83	.71	.80
FE	.74	.81	.59	.76	.69	.76
JP	.67	.60	.36	.49	.51	.56
LW	.89	.96	.65	.14 -	.73	.08 -
mean	.781	.848	.695	.639	.694	.653

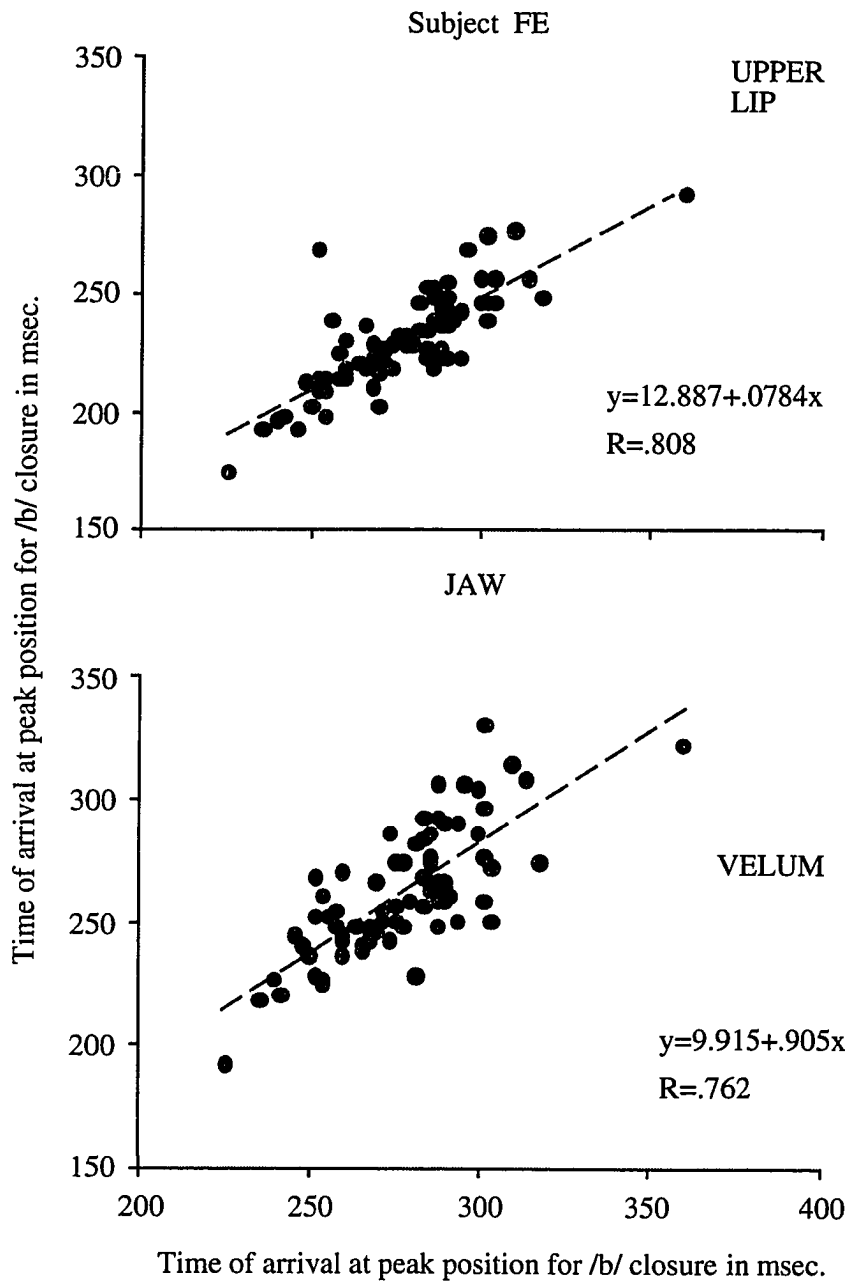


Figure 3.18 Times of arrival at peak position for /b/ closure for the upper lip and the velum, plotted against the corresponding times for the jaw, for subject FE. The data represent the load tokens only. The correlations and regression lines are indicated.

3.4.2 Load effects on the interpeak position interval for /b/ closure.

As an additional measure of interarticulator cohesion, the interval between closure events across articulator pairs was examined. In other words, the duration of the interval between the times of arrival at peak position for /b/ closure of, e.g., the jaw and the velum (see Figure 3.19 with some of the relevant intervals marked by a shaded bar) was compared across load and control tokens. All other possible pairings of articulators were also examined in this manner for every subject. The times of arrival at peak position for /b/ closure of the jaw, the velum and the lips were examined pairwise, for the two conditions.

In general, in the load condition the interpeak position intervals among jaw and upper lip, and jaw and lower lip became longer for all subjects. The intervals between the peaks of the jaw and the velum also became longer, with the exception of subject JP, who showed no significant change in the duration of that interval. It can be seen then, that, since the jaw closure was attained later for all subjects, the interval between its peak position and that of the other articulators was lengthened. In that sense the velum showed similar patterns of response as did the lips.

The upper lip–lower lip intervals were in general shortened (CB, FE, LW) or showed a tendency for shortening (AH), with the exception of JP whose interval was lengthened in the load condition compared to the control.

The lips–velum intervals showed more variability than the jaw–lips, or the jaw–velum intervals, but in most cases they remained the same in the load condition as in the control. There were two instances of lengthening of the lower lip–velum interval (BK, JP) and one of the upper lip–velum (AH). It appeared that the upper lip–velum and lower lip–velum intervals reflected the general trend observed in each subject.

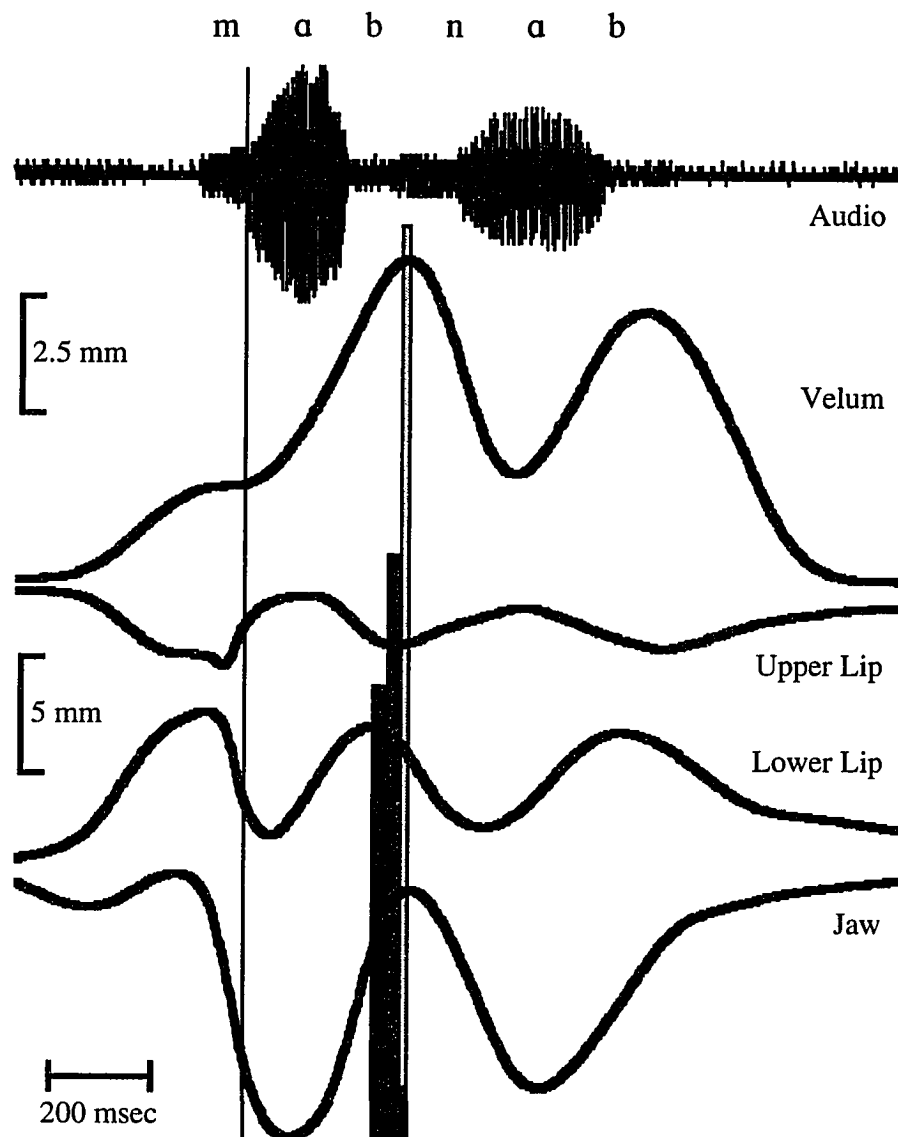


Figure 3.19 Shown are the interarticulator interpeak position intervals, with some of them being indicated by shaded overlapping bars. For example, the longest of the shaded bars indicates the jaw-velum interval, the next in size indicates the jaw-upper lip interval, and the shortest shaded bar indicates the jaw-lower lip interval. An acoustic waveform, with the vowel onset marked, is shown on the top for reference.

Looking at each subject separately, across articulator pairs, it appears that the subjects can be divided into two groups: those for whom all intervals that changed significantly were lengthened (AH, BK and JP), and those for whom only the intervals that involved the jaw (jaw–upper lip, jaw–lower lip, and jaw–velum) were lengthened, while the intervals that involved the lips (upper lip–lower lip, upper lip–velum, lower lip–velum) were shortened (CB, FE, and LW).

The interval duration changes in the load condition for each subject are presented in Table 3.16. The first three columns show the oral articulator pairs, while the following three columns show the pairings of the oral articulators with the velum. Each cell in the table shows, first, the kind of change in the interval in the load condition, then the F-value, and finally the significance level of the effect.

3.4.3 Load onset time effects on the interpeak position interval duration

The load onset time had a variable effect on the duration of the interpeak position interval. Recall that of the six subjects five had variable load onset times that were grouped into early, mid, late and post–Vowel Onset groups. Load group effects were seen mostly in the intervals that involved the jaw (jaw–lower lip, jaw–upper lip, jaw–velum), in three of the five subjects (AH, CB, JP), and in the intervals that involved the velum (velum–jaw, velum–lower lip, velum–upper lip) in the remaining two subjects (BK, LW). In both cases the load onset time effects were such that the intervals in question increased more with loads applied later rather than earlier.

As an example, the results for one of the subjects (AH) are described in detail below. The results for the remaining subjects can be viewed in Table 3.16.

3.4.4 Example: subject AH

As an example, the results from one of the subjects are described below. The findings for the other subjects can be described in a similar way. In sum, for AH the position interpeak interval durations that changed significantly were lengthened. The

Table 3.16: F-values, df 's, and p values for load vs. control analyses of variance for the interval duration between position peaks at /b/ closure (in /mab/) of the following articulator pairs for the six subjects.

Subj.	JAW- LOWER LIP		JAW- UPPER LIP		UPPER LIP- LOWER LIP		JAW- VELUM		LOWER LIP- VELUM		UPPER LIP- VELUM	
	Interval Duration	Interval Duration	Interval Duration	Interval Duration	Interval Duration	Interval Duration	Interval Duration	Interval Duration	Interval Duration	Interval Duration	Interval Duration	Interval Duration
AH	increased F[1,81]= 28.52 p=.0001	increased F[1,81]= 35.52 p=.0001	increased F[1,81]= 2.96 NS	increased F[1,81]= 31.03 p=.0001	increased F[1,81]= 2.07 NS	increased F[1,81]= 9.17 p=.003	increased F[1,66]= 12.14 p=.0001	increased F[1,66]= 38.67 p=.0001	increased F[1,74]= .24 NS	increased F[1,74]= 3.49 p=.06, NS	increased F[1,77]= 18.06 p=.0001	increased F[1,135]= 3.11 NS
BK	increased F[1,66]= 12.14 p=.0001	increased F[1,74]= 11.29 p=.0012	decreased F[1,74]= 6.93 p=.010	increased F[1,74]= 19.39 p=.0001	increased F[1,77]= .56 NS	decreased F[1,77]= 18.06 p=.0001	increased F[1,77]= 28.01 p=.0001	increased F[1,77]= 28.77 p=.0001	increased F[1,135]= 12.24 p=.0006	decreased F[1,47]= 7.69 p=.008	decreased F[1,47]= 20.95 p=.0001	decreased F[1,47]= 20.95 p=.0001
CB	increased F[1,74]= 45.96 p=.0001	increased F[1,74]= 11.29 p=.0012	decreased F[1,74]= 6.93 p=.010	increased F[1,74]= 19.39 p=.0001	increased F[1,77]= .56 NS	decreased F[1,77]= 18.06 p=.0001	increased F[1,77]= 28.01 p=.0001	increased F[1,77]= 28.77 p=.0001	increased F[1,135]= 12.24 p=.0006	decreased F[1,47]= 7.69 p=.008	decreased F[1,47]= 20.95 p=.0001	decreased F[1,47]= 20.95 p=.0001
FE	increased F[1,77]= 25.76 p=.0001	increased F[1,77]= 5.72 p=.019	decreased F[1,77]= 28.01 p=.0001	increased F[1,77]= 28.77 p=.0001	increased F[1,77]= .56 NS	decreased F[1,77]= 18.06 p=.0001	increased F[1,77]= 28.01 p=.0001	increased F[1,77]= 28.77 p=.0001	increased F[1,135]= 12.24 p=.0006	decreased F[1,47]= 7.69 p=.008	decreased F[1,47]= 20.95 p=.0001	decreased F[1,47]= 20.95 p=.0001
JP	increased F[1,135]= 23.88 p=.0001	increased F[1,135]= 13.04 p=.0004	decreased F[1,135]= 12.92 p=.0005	increased F[1,135]= 3.07 NS	increased F[1,135]= 12.24 p=.0006	decreased F[1,135]= 3.11 NS	increased F[1,135]= 12.92 p=.0005	increased F[1,135]= 3.07 NS	increased F[1,135]= 12.24 p=.0006	decreased F[1,47]= 7.69 p=.008	decreased F[1,47]= 20.95 p=.0001	decreased F[1,47]= 20.95 p=.0001
LW	increased F[1,47]= 23.92 p=.0001	increased F[1,47]= 21.40 p=.0001	decreased F[1,47]= 7.01 p=.011	increased F[1,47]= 38.92 p=.0001	decreased F[1,47]= 7.69 p=.008	decreased F[1,47]= 20.95 p=.0001	increased F[1,47]= 21.40 p=.0001	increased F[1,47]= 38.92 p=.0001	decreased F[1,47]= 7.69 p=.008	decreased F[1,47]= 20.95 p=.0001	decreased F[1,47]= 20.95 p=.0001	decreased F[1,47]= 20.95 p=.0001

interval durations increased in about the same way for the jaw–lower lip and jaw–upper lip pairs as they did for the jaw–velum and upper lip–velum pairs.

JAW–LOWER LIP (J–LL)

The interpeak position interval was significantly longer in the load groups (mean 140.0 msec) than in the controls (mean 89.9 msec). The increase in the interval duration was not significant in the mid group, but it was significant in the early, mid and post–VO groups. Further, the interval duration increased from the mid to the post–VO group in the load condition, while it did not vary in the control condition, creating a significant interaction ($F[3,81]= 3.16, p<.029$).

JAW–UPPER LIP (J–UL)

The interpeak position interval was significantly longer in all the load groups (mean 122.8 msec) than in the controls (mean 58.6 msec). The difference in the intervals increased gradually from the early to the post–VO group, but not so as to create a significant interaction.

UPPER LIP–LOWER LIP (UL–LL)

The interpeak position interval was slightly shorter in the load tokens (mean 17.2 msec) compared to the controls (mean 30.3 msec). There was a significant shortening in the interval between mid load tokens (mean 3.5 msec) and controls (mean 40.8 msec), and a slight decrease in the duration of the interval in the early and late load tokens compared to the controls, but they were not statistically significant. In the post–VO group the interval duration was slightly increased in the load condition. There was a gradual increase in the duration of the interval from mid to post–VO group in the load condition.

JAW–VELUM (V–J)

The interpeak position interval was significantly longer in the load groups (mean 39.2 msec) than in the controls (mean –.1 msec). The increase in the interval duration

was not significant in the mid group, but it was significant in the early, mid and post-VO groups. The difference in the intervals between load and control tokens increased from the early to the post-VO groups, causing a significant interaction ($F[3,81]= 4.02$, $p<.010$).

LOWER LIP-VELUM (V-LL)

The interpeak position interval was not significantly different in the load tokens (mean 100.8 msec) compared to the controls (mean 89.1 msec). There was an almost significant increase in the interval duration between early load and control tokens, and a similar trend in the late and post-VO loads. In the mid groups there was a slight reduction in the interval duration in the load tokens compared to the controls, but it was not statistically significant. The interval duration in the load tokens increased linearly from the mid to the post-VO group, but the differences among groups was not statistically significant.

UPPER LIP-VELUM (V-UL)

The interpeak position interval was significantly longer in the load groups (mean 83.7 msec) than in the controls (mean 58.8 msec). The increase was significant in the early, mid and late load groups, but non significant in the post-VO loads.

The results from the other five subjects can be described in a similar way. Table 3.16 provides details on the other subjects' interval duration changes in the load condition.

CHAPTER FOUR

DISCUSSION

The present study was designed and carried out to provide insight into certain issues in the general area of speech motor control. In particular, the question asked was whether the velum could be considered part of a coordinative structure that includes the lips and the jaw, for the production of an utterance that requires the synergy of all four articulators. This question pertains to the issue of the *size* of the functional unit in a coordinative structure: is the unit comprised of small local groups, or can it contain more remote elements? Further, if, with the use of a perturbation paradigm, a functional coupling between the velum, the lips and the jaw were established, the specific nature of that coupling could then be assessed. One way of assessing the nature of such a functional linkage between the jaw, the lips and the velum is to examine the relative responses of these articulators to perturbations applied to one of them. In addition, any differential effect of the time of application of the perturbation would provide greater detail regarding the patterning of multiarticulator coordination.

4.1 ABSENCE OF MECHANICAL LINKAGE OR REFLEX RESPONSE

Having established the absence of a context-independent reflex response of the velum to jaw perturbation, as well as the absence of a mechanical coupling between the velum and the jaw, the results of the present study were interpreted to reflect the articulatory organization of the velum and the jaw-lips complex when these articulators are functionally linked during speech production (cf. section 2.4.3).

Of primary interest in this study were the closing movements involved in producing the closure for the first /b/ in /mabnab/. The closing movements for the jaw, the lower lip, and the velum are upward movements, while for the upper lip it is a downward movement. The results for these closing actions are discussed below, following a brief consideration of the effects of the load on the opening movements (from /m/ to /a/).

4.2 LOAD EFFECTS ON THE OPENING MOVEMENT

With only a few exceptions, the load was applied before the acoustic onset of the first vowel of /mabnab/, and even in those cases where the load occurred post-vowel onset, it was still applied before the movement offset of the oral opening for /a/. Due to the load the opening movements of the jaw for /ma/ were in general of significantly greater displacement and velocity in the load condition. The same was true for the opening movements of the upper lip as well, for the majority of the subjects. As a result, an overall increase was seen in the composite displacement of the upper lip, the lower lip, and the jaw (as seen in the lip aperture measure). However, for three of the subjects the duration of the jaw and the overall oral (lip aperture) opening movements did not change in the load condition. It is worth noting, though, that the opening displacement of the lower lip was reduced in three of the subjects and was unaffected in another two. These changes indicate that the jaw and the lips often showed compensatory responses to the load as early as in the opening movement, perhaps in an attempt to maintain some of the timing aspects of the utterance and minimize the overall effect of the perturbation.

If we accept that the oral articulators' functioning is goal-directed, in other words that the articulators cooperate toward a specific target of oral opening, then a perturbation in the direction of the jaw movement (here, jaw lowering) may result in an overshoot of the target. Therefore, if the target is to be attained within its acceptable

range, a compensatory modification by the lips (or by the jaw as well) may be necessary to minimize the effect of the jaw loading.

For example, in the earlier-load tokens, jaw opening movements of smaller displacement than their controls were occasionally observed in three of the six subjects. As a result of the load, the jaw was lowered somewhat, just before the initiation of the opening movement. Therefore, the initial position of those movements was often lower than that of their controls', so that the jaw's necessary excursion to the "target oral opening" position was actually reduced. The reduction seen in the opening movement displacement indicated that this new excursion requirement was implemented in the motor plan, reflecting the sensory input of the altered peripheral conditions to the system. Therefore, the jaw and the lips exhibited compensatory adjustments to the load starting with the opening movement.

Moreover, differential load onset time effects on the opening movement displacements of the articulators were occasionally observed (e.g., AH) and were reflected in the closing movement displacements. This was mostly true for jaw displacements, and, at times, for the lips and the velum as well. The load onset time effects on the closing movements of the articulators are discussed later.

4.3 LOAD EFFECTS ON THE CLOSING MOVEMENT, IN GENERAL

As a consequence of the load, the spatial and temporal characteristics of the closing movements of the articulators were modified. Jaw, lower lip, upper lip, and –importantly– *velum* movements exhibited response patterns that were indicative of compensatory action. Such responses included modifications in the displacement, velocity, and duration of the movements. Further, the compensatory adjustments of the articulators were apparently directed at maintaining the interarticulatory cohesion normally present during unperturbed speech production. One of the interarticulatory

cohesion aspects between the jaw, the lips, and the velum is the high correlation found among the movement offset times across oral and velar articulators during the target task, as was also reported in Kollia et al. (submitted).

Moreover, the intra-articulator relationships between velocity, displacement, and duration remained generally stable in the load condition. More descriptively, if across load and control tokens the duration remained the same while the displacement increased in the load condition, a concomitant increase in velocity was frequently present. These results are consistent with results from previous studies that have shown compensatory responses of the lips to jaw loading (for example, Kelso et al., 1984; Shaiman, 1989; and others).

It is important to stress here the findings regarding the velum. It was hypothesized that, given that the action of the articulators during speech is goal directed, if the velum is functionally coordinated with the oral articulators (jaw and lips), then jaw perturbations that affect the kinematic parameters of the oral articulators, will also affect the velar articulator. In this way the oral-velar synergy necessary for /b/ production is maintained as the articulators compensate for the perturbation effects. Indeed, the velum showed compensatory activity for the perturbations applied to the jaw. This finding indicates that the organization of motor control for speech does not operate simply at the local constriction level. The speech motor organization apparently controls and coordinates motor actions at all the necessary constriction locations, both local and remote.

4.4 SUBJECTS' RESPONSES TO LOADING

Perhaps one of the interesting findings in this study is the variability of the subjects' responses to the perturbation. Subjects responded to the perturbation idiosyncratically. In controlling the kinematic parameters of their oral articulators, the six subjects

appeared to adopt one of two main strategies. One was a strategy of “constrained duration” and the other was one of “flexible duration”. These differences in apparent strategy adopted by the subjects did not seem to depend on the relative initial positions of the subjects’ jaw movements (the ones most affected by the perturbation) across load and control conditions, since these were the same for all subjects. The initial positions of the subjects’ lower lip movements were also the same across subjects, except for BK (cf. sections 3.1.3 and 3.1.4). Therefore, the load vs. control differences in initial conditions of the movements of the jaw and the lower lip did not appear to result in –or explain– the differential control of the kinematic parameters of the oral articulators across subjects.

The 2 subjects (LW and FE) whose response patterns obeyed a *constrained duration* strategy responded to the perturbation in a way that preserved the durational aspects of the movement. Whenever the closing movement displacements were bigger, the velocity was also greater, and vice versa: whenever the closing movement displacements were smaller, the velocity was also decreased.

The four subjects whose response patterns obeyed a *flexible duration* strategy seemed to respond to the perturbation by allowing the durational aspects of the movement to vary. Specifically, two of these subjects (AH and JP) constrained (did not modify) the overall velocities of their articulator movements in the load condition compared to the control. The other two subjects (BK and CB) adjusted *all* the kinematic parameters of their movements, including significant changes in the overall movement velocities of all four articulators in the load condition.

The question that arises from this last pattern is why the duration of these subjects’ movements varied despite changes in velocity. One conjecture is that even though the velocity increased significantly in the load condition, it did not increase enough for the greater displacement to be accomplished in the same amount of time. In that sense,

these two subjects fall in a category somewhere between the other two: the first category in which subjects' actions result in maintaining duration by adjusting velocity, and the second, in which subjects' actions result in variable duration but stable velocity.

This problem can be viewed from a kinematic perspective. If a perturbation brings about an increase in displacement, then for the displacement-velocity-duration scaling to be maintained in the load condition, either velocity, duration, or both must be altered. If, in the load condition, the closing displacement that must be covered is increased, then the duration of the closing movement can be maintained relatively stable if the movement velocity is sufficiently increased. A continuum of possible responses to the load emerges from the need to maintain this scaling. On one end of the continuum are responses that show modifications primarily of velocity and secondarily of duration, while on the other end of the continuum are modifications primarily of duration and secondarily of velocity. Responses that fall in the middle of the continuum imply equal proportions of change in both parameters. The six subjects in the study provided responses that were distributed along the continuum: two provided responses that tended mainly toward the primarily-velocity end of the continuum, two provided responses that tended toward the primarily-duration end, and the remaining two subjects' responses fell somewhere in the middle.

It is possible that in the case of the two subjects who maintained constant closing movement duration across conditions, the mode of response was *aimed* at retaining the duration constant. Similarly, it is possible that in the case of the two subjects who did not maintain constant closing movement duration across conditions, their response mode was not time-constrained, but rather was aimed at retaining the *velocity* constant. Finally, for those subjects who exhibited changes in both velocity and duration, modulation of both measures was the response type enabling them to achieve the specific task (/b/ production). It is possible that these different methods of response

might account –in part– for the great amount of variability seen in the subjects' responses. These different response patterns across subjects point to the complexity, the flexibility, and the goal-oriented nature of the motor control system for the generation of controlled actions.

4.5 GRADATION OF LOAD EFFECTS

The effect of the load on the characteristics of the closing movement varied as a function of two factors: first, the anatomical distance of the articulator in question from the site of the perturbation, and second, the load onset time.

4.5.1 Gradation of load effects as a function of distance from the site of the perturbation

Overall, the effect of the load decreased with increasing distance from the site of the perturbation. There are two ways of quantifying the load-related effects. One involves looking at the percentage of cases of significant change in the individual parameters, and the other involves looking at the percentage of cases where all three parameters (velocity, displacement and duration) showed a significant change concurrently.

Recall (section 3.3, Tables 3.7, 3.8, Figure 3.9) that the total number of possible load-related changes was 195 (4 articulators * 3 parameters * 6 subjects * load groups per subject); 113 (58%) were significant. Of those significant changes, 31% were seen in the jaw, 30% in the lower lip, 22% in the upper lip, and 17% in the velum. It is clear that the percentage of responses decreased with increasing distance from the jaw. That finding was also seen in the velum; the velum behaved in a manner similar to the other articulators'. Thus, the compensatory responses of the articulators to the load-related effects were distributed: some of the error correction was carried out by the jaw, some by the lower lip, and some by the upper lip. In continuation of the trend exhibited by the oral articulators, whose responses to the load were reduced with increasing distance

from the jaw, the velum also exhibited reduced response with increasing distance. The responses of the velum were fewer in frequency, and involved mostly changes in the velocity of the movement (41% of the velocities changed significantly), with fewer changes in the displacement and the duration (35% of each of these parameters changed significantly), indicating that the velum produced an adjusted response to the load rather than a generalized reaction to it.

Alternatively, one can look at the cases of “global” changes within an articulator (Table 3.7, Figure 3.9). “Global” changes are considered those that include significant concurrent changes in displacement, velocity, and duration, for a specific articulator in a specific load condition (e.g., jaw kinematic parameters in the late load condition in subject BK). In the 14 cases of the possible 65 (22%, $65=4$ articulators * 6 subjects * load groups per subject), in which all three kinematic parameters within an articulator changed significantly, 36% occurred in the jaw, 29% occurred in the lower lip, 21% occurred in the upper lip, and 14% occurred in the velum. It appears, again, that the effect of the load was heightened in the structures more proximal to the jaw, which was the site of the perturbation, and diminished somewhat in more removed structures such as the upper lip and the velum. Again, the percentage of “global” changes in the velum was the lowest of the group, indicating that the velum behaved in a way that was similar to, and continued a trend that was observed in the oral articulators. The interpretation is that, when functionally linked with the jaw and lips, the activity of the velum is directed by the same motor control principles as are the jaw and lips.

Another point that should be stressed here is the increased response of the jaw to its perturbation compared to the response of the other articulators. It appears that, looking at the response patterns in the above quantitative manner, the jaw provides the primary compensatory adjustment to the load-induced disturbances. Secondary compensation is provided by the lips, and analogous compensatory activity is also seen in the velum.

Similar results have been reported by Gracco & Abbs (1985) who found that given enough time for response to the perturbation, the perturbed articulator will provide the greatest degree of compensatory change.

The above discussion should not be taken to imply that topography alone is the principal determining parameter of compensatory activity. Given that the jaw and the lips are functionally implicated in the formation of the bilabial closure for /b/ –which is being perturbed– while the velum is not, it is reasonable to expect that the effect of the load will affect the implicated structures more than the non-implicated ones. The velum is functionally implicated in the /b/ production, but, obviously, not in the lip closure. However, /b/ production is dependent on both velopharyngeal and lip closure, and, as a result, the effects of the jaw perturbation can be seen in the activity of the velum as well. This issue is discussed further in section 4.8.

4.5.2 Gradation of load effects as a function of load onset time

Load-related changes frequently showed an increase –or decrease– from the earlier load onset times (early load groups) to the later ones. Occasionally such graded effects were seen in all three kinematic parameters of all four articulators. Alternatively, the effect of the load onset time (or, load group) varied depending on the parameter, the articulator, and the subject. When present, the effects of perturbations occurring post-Vowel Onset often resulted in a discontinuity from the preceding direction of change. In other words, changes due to perturbations occurring post-Vowel Onset often were in opposite direction to those induced by loads in the preceding load group.

In the 14 cases of the possible 65 (22%), in which all the parameters of the closing movement within a given articulator changed significantly, 21% occurred for the early loads, 29% for the mid loads, 36% for the late loads, and 14% for the post-VO loads. The effect of the load was, in this sense, heightened as load onsets were applied closer to the vowel onset. Again, the percentage of “global” changes showed a gradual

reduction in the velum compared to the other articulators, indicating an adjusted change to the load rather than a generalized reaction to it.

4.5.2.1 *Two different subject patterns*

Examination of the differential effects of load onset time, revealed that subjects' responses showed *predominantly* one of two observed trends, and *secondarily* the other of the two (that is, no subject had responses showing exclusively one of the two trends). The first trend was one of progressive enhancement of the load-related changes with later load application. The second, less frequent trend, was one of progressive diminishing of the load-related changes with later load application. Subjects AH, BK, and LW showed primarily the first trend, while CB and JP showed primarily the latter. Recall that subject FE has only early loads, and therefore shows no such pattern.

4.5.2.2 *Load onset time effects on duration, velocity, and displacement*

Load onset time had a differential effect on the various kinematic parameters. In this study, overall duration changes were dependent on load onset time. In particular, across subjects and articulators, a greater number of significant duration changes were seen in the later loads than in the earlier, with the number of significant changes at 50% for the post-Vowel Onset load group. In other words, of the durations in the late load condition, 73% changed significantly, as compared with 63% in the mid load group and 39% in the early load group. Similar results have been reported by Gracco (1984), who found that significant upper lip movement duration changes occurred more frequently with later lower lip loading than with earlier.

No such linear load-timing effects were seen in the velocity changes. Excluding the post-Vowel Onset loads that generally showed a discontinuity from the other load group emergent patterns, most of the significant velocity changes were found in the mid load group across articulators, while the late load group showed the fewest changes. Comparably, Gracco (1984) found that, pooled across all subjects, significant upper lip

movement velocity changes in response to lower lip loading occurred somewhat more frequently with loads occurring closer to the middle of the time continuum used in that study, than with earlier or later loads.

While the mid load group showed the highest number of significant velocity changes, the late load group showed the lowest number of significant velocity changes. The opposite pattern was found in the displacement changes, that is, the lowest number of significant changes was found in the mid load group, while the highest number of changes was seen in the late load group. Thus the relationship between velocity and displacement appears to be a reciprocal one, indicative of the attempt at regulation of the relations of the kinematic parameters of the articulators in the load condition. These differences in significant cases should be considered qualitatively, as indicators of the time dependency of perturbation effects along the course of the speech act.

4.6 INTERARTICULATOR COORDINATION FOR /b/ CLOSURE

In a previous study (Kollia et al., submitted), the closing events between the velum and the jaw, and the velum and the upper lip were found to be temporally related. However, the temporal cohesion of the velum with either the jaw or the upper lip was not as high as that between the jaw and the upper lip.

The same measure of interarticulator cohesion was examined in the load tokens: the correlations between the times of arrival at peak position for closure among articulator pairs for the load tokens were compared to the correlations obtained for the controls (section 3.4). The majority of the comparisons (75%, or 12 of 16) between load and control conditions showed either equal (3 of 12), or increased (9 of 12) correlation coefficients for the load tokens. Therefore, it appears that the perturbation resulted in a strengthening of the timing relations across articulators for the movement toward /b/

closure. Furthermore, no systematic effect of load onset time on these correlations was apparent.

In the Kollia et al. (submitted) study, temporal coupling between velar and lip movements, and velar and jaw movements was better indexed by the times of peak position for closure than by the times of peak velocity of the closing movement. It is perhaps worth mentioning here one explanation that might account for the reduced correlations in velar-oral peak *velocity* times compared to the correlations of peak *position* times. For local constriction-producing events, like oral closing, the timing of lip and jaw movement toward closure (indexed by the time of peak velocity) is more critical than the timing of the movement offset, i.e., of the actual contact (indexed by the time of peak position). In that case, the time of peak velocity is the measure more critically associated with the coordination of the multiple articulators. In contrast, for phonetic events that are less time-constrained, like velar raising and oral closing, the time of peak position is the variable more critically associated with their coordination (see also Kollia et al., submitted). In that sense, as interarticulator timing becomes more or less critical, the parameters that are indicative of coupling may also change: peak velocity relations may be more illustrative of critical or constrained timing relations, while peak position timing relations may reflect a less constrained coordinative coupling. Another possibility for the somewhat moderate relationship in peak position timing across articulators, is that for none of the languages spoken by the subjects is vowel nasalization phonologically contrastive.

An additional measure of interarticulator cohesion examined was the interval duration between closure events across articulator pairs. The times of arrival at peak position for /b/ closure of the jaw, the velum, and the lips were examined pairwise across load and control conditions. In general, in the load condition the interpeak position intervals among jaw and upper lip, jaw and lower lip, and jaw and velum were

lengthened. The reason for this lengthening was that the duration of the interval to peak position for /b/ closure was increased for the jaw, while the comparable intervals in the lips and the velum changed in a rather similar manner to each other. In that sense the velum exhibited comparable responses to jaw loading as did the lips, thereby maintaining the relative timing relations among articulators.

Stability of spatiotemporal relations is a reflection of intergestural cohesion, as Browman and Goldstein (1985, 1992) propound in their articulatory phonology model, with gestures being events that consist in the formation and release of constrictions in the vocal tract. The findings of the present study could therefore be described within the articulatory phonology framework. It appears then, that despite certain limitations in the current versions of the articulatory phonology and task-dynamic models, that are presently under development, the data from this study do not conflict with the predictions of these models. For example, the task dynamic model as detailed by Saltzman and Munhall (1989) posits that intergestural subgroups exhibit patterns of covariation, as was found here. By using gesture-specific dynamics, the effect of mechanical perturbations may be taken into account in modeling the formation of the movement patterns of the relevant articulators.

Even though the approach taken in this study is not one of a morphological analysis of the phenomenology of synergies such as the one adopted by Lee (1984), rather, one of functional or goal-directed aspects of coordination, the present findings may also be viewed from a morphological level, providing further insight into the nature of the functional synergies. From the theoretical framework of neuromotor synergies, the articulator synergies examined here mostly conform to the requirements of spatial, temporal, and scaling stability for a neuromotor synergy as posited by Lee (1984). Recall that Lee's requirements of synergy demand that the same set of muscles always be activated; synchronization, fixed temporal order, or fixed phase relationships must

hold over a range of movement parameters (cf. Kelso, Holt, Rubin, & Kugler, 1981), and, finally, that the properties of a synergy or the relations among its components must exhibit scaling after suprathreshold activation of these components.

While it is probably true that the same set of muscles are always activated, this would be due to the fact that the phonetic task remains the same in the load and control conditions. In other words, both oral and velopharyngeal closure tasks were required in both experimental circumstances, and were performed despite changes in the initial conditions of the articulators due to loading. Therefore, spatial stability—at least as specified by Lee—is possibly maintained. Further, temporal stability was also maintained, since phase relationships were generally found to hold over the range of movement parameters that were brought about as a result of the load. In the context of this study, phase relationships were indexed by interarticulator temporal cohesion as described earlier in the text. It should be noted, however, that in this study the articulator events showed no fixed temporal order in either load or control case, and synchronization, in a broad sense, was largely inherent to the task. Finally, scaling was seen in the relations among the kinematic components of each articulator in the synergy, and also in the relations among the articulators themselves, as noted earlier.

The findings in this study conform with the Fowler et al. (1980) conception of the goal being intrinsic to the system and of that goal being attainable from any given point. By perturbing the jaw movement during its opening phase, the initial conditions for the attainment of the goal (oral closure) were varied, yet the goal was successfully attained from these different starting positions. Accordingly, if the goal is intrinsic to the system, then a disturbance due to the load might provide an impetus for the marshaling of the necessary actions toward completion of the task. This is possibly one reason for the fact that interarticulator cohesion measures showed correlations for the load tokens that were usually increased compared to the controls, indicating a load-induced

strengthening of the timing relations across articulators. Moreover, given that no systematic effect of load onset time was found on the interarticulator timing relations, it seems that the effect of the load was global rather than temporally-contingent, at least not with the temporal resolution used in the present study.

Finally, inasmuch as interarticulator cohesion was shown to be maintained following jaw perturbation, Bell-Berti and Harris' (1981) position that articulatory timing relationships are *intrinsic* to the system also seems to be supported by the present findings. As noted earlier, the interarticulator interpeak intervals that involved the jaw were generally lengthened, while the ones that involved the lips and the velum changed in similar ways to each other. This finding suggests that the timing relationships are modulated on-line depending on the requirements of the task, in this case accommodating the varied initial conditions effected by the load.

4.7 DEFINING "COMPENSATION"

Compensation for a perturbation-induced change was initially expected to be of about equal amplitude as the change brought about by the perturbation. For example, Gay et al. (1981) found that subjects producing steady state vowels with their mandible fixed "compensated for the bite blocks by attempting to match the original, unconstrained state" (p. 806). In later studies (for example Folkins & Abbs 1975, Kelso et al. 1984 among others) compensation was considered to involve some concomitant, distributed change in the activity of associated articulators.

The dictionary definitions of the verb "to compensate" include "to provide with means of counteracting variation," "to supply an equivalent," and "to offset an error, defect, or undesired effect." The noun "compensation" is defined as "something that constitutes an equivalent," and "correction of an organic inferiority or loss by increased functioning of another organ or unimpaired parts of the same organ."

While for the purposes of this study no “organic inferiority or loss” occurred, a deviation from the normal activity of the articulators did occur. In that respect, we witnessed an “increased functioning of another organ or unimpaired parts of the same organ,” if we are willing to accept the analogy of a coordinative structure as an “organ.” If we accept the task-specific functional aggregation of the articulators into a coordinative structure, then each of the members of the coordinative structure can act individually to counterbalance the effect of a perturbation to another member. The “unimpaired parts of the organ,” here the lips and the velum, act to “supply an equivalent” product. The behaviors exhibited by the subjects in these experiments could be called compensations, in that they intended and succeeded “to offset an error, or undesired effect” produced by the loading of the jaw. In the present study, compensation is taken to occur when the speaker’s output results in an acceptable production of the intended utterance. Throughout the experiments the utterances produced by the subjects in the two conditions were indistinct from each other, at least according to informal assessment of these productions by two listeners.

The compensation observed in this investigation differs from that defined in the dictionary, in one interesting way: there was not only an “increased functioning of another organ or unimpaired parts of the same organ,” but there was also an increased functioning of the transiently perturbed articulator, namely the jaw. Compensatory responses of the perturbed articulator to its perturbation have been previously reported for the jaw (Shaiman, 1988, 1989) and for the lower lip (e.g., Gracco, 1984, Gracco and Abbs, 1985).

Further, the contribution of each individual articulator to the task (/b/ closure) seemed to be dependent on the relative contributions of the other articulators. In that sense, compensation did not necessarily imply an overall indiscriminate increase in movement amplitude. Compensatory adjustment was often manifested as a reduction in

action in the load condition. For example, in the load condition, the lower lip displacement was significantly decreased in three of the six subjects, presumably because the jaw and upper lip movements were sufficiently increased to make further displacement increases unnecessary. Indeed, in two of the cases where a significant increase in upper lip displacement was observed, it was actually accompanied by a significant decrease in lower lip displacement. Such distributed changes were also seen in the velocities of the movements. For example, for the subjects whose lower lip closing velocity was significantly different (greater or smaller) in the load tokens, the jaw closing velocity was significantly different in the opposite direction (smaller or greater). This pattern was seen in the velum as well. To illustrate, in the load condition CB's closing velocities were reduced for the jaw, but increased for the upper lip, the lower lip, and the velum. Conceivably the lips moved faster to counterbalance the slower jaw closing movement, and as the velum maintained its temporal relation to them for /b/ closure, it too showed modifications in its kinematic parameters. Clearly, then, what was required was a decrease in the lower lip displacement, and it was provided. Similar results have also been reported by Gracco (1984), who found reductions of upper lip movement velocity in the load condition in response to lower lip perturbation.

4.8 SIZE OF THE FUNCTIONAL UNIT IN A COORDINATIVE STRUCTURE

It is clear by now that the size of functional unit in a coordinative structure (as described by Turvey, 1977, and Fowler et al., 1980, among others) is as large as is necessary for the requirements of the task, which –in this case– includes the lips, the jaw and the velum. Therefore, the elements that comprise a coordinative structure are functionally linked and their activity goal directed and globally controlled.

The lips and the jaw occasionally showed compensatory responses in the opening movement, as well as the usually observed compensatory action in the closing

movement. This finding is not so surprising considering that there is a tendency for immediate error correction. Similarly, the velum showed graded, rather than all-or-none responses to the jaw perturbation –as did the lips and the jaw. The temporal adjustments that were seen in the velum can be considered functional in nature, since a specific temporal relationship exists between the velum and the lips for /b/ production. Indeed, of the significant changes observed in the velum across subjects and conditions, two thirds were in duration and in velocity.

What is not so clear is the purpose of the spatial (displacement) adjustments that represented 32% of the significant changes seen in the velum. Comparably, the spatial adjustments in the jaw, the lower lip, and the upper lip represented 37%, 35%, and 36% of the total significant adjustments seen in each of those articulators, respectively. Spatial adjustments were seen in three of the six subjects (AH, BK, CB) in the early, mid and late load onset conditions. These spatial adjustments were not functional in nature, in that as soon as the velum reaches a position at which the velopharyngeal port is closed, further upward displacement is not necessary, while at the same time it does not affect the quality of the valving. It might be the case that not every type of response to a perturbation is to be taken as compensatory in nature. There might, however, be another reason for the spatial adjustments seen in the velum, namely increased activation level in the articulators.

Even though no EMG data were obtained in this study, it is reasonable to postulate that the spatial adjustments found in the velum (as well as those seen in the jaw and lips) reflect an overall increase in the activation level of the system that occurs as a result of the loading. In fact, increased EMG activity has been reported in load trials in previous perturbation studies (e.g., Gracco, 1984; Abbs and Gracco, 1984; Shaiman, 1989). This argument would be consistent with the hypothesis of shared neural substrates among functionally associated structures.

Lindblom et al. (1979) suggested that, inferring from their bite block data, a vowel target is coded as a sensory goal, specified at a neurophysiological level. There is no direct way of testing this postulate given the data from this study, since no tongue kinematics were obtained due to technical limitations. It is possible that the tongue provided some compensatory responses to the jaw perturbation, thereby maintaining a position prespecified for /a/ production at a sensory level. If the control and load vocal tract area functions were found to be the same for the vowel /a/, then the Lindblom et al. suggestion would be supported. It is unclear, however, whether and how the low vowel /a/ is affected by differential jaw and lip positions, such as those that resulted from jaw loading. No systematic analysis of the acoustic consequences of the unexpected jaw loading was performed at this time, as such an analysis was beyond the scope of this study. Obviously, an acoustic analysis of the load vs. control tokens is a necessary follow-up to these findings.

In terms of remote compensation and its implications for the issue of the functional unit in a coordinative structure, the present study is most comparable with that of Munhall et al. (submitted), who probed the coordination between the lower lip and the larynx, in an experiment involving lower lip perturbation. Both studies examined the responses of articulators (the larynx and the velum) to perturbations occurring at more remote sites (the lower lip and the jaw, respectively). The velum showed clear evidence of compensatory responses to jaw loading in its temporal and spatial characteristics. While the timing adjustments were understandable in terms of interarticulator coordination –much like the laryngeal adjustments in the Munhall et al. study– the spatial adjustments were less well understood in terms of their possible functional purpose. As referred to above, given that once the velopharyngeal port is closed further elevation of the velum will not affect the port's valving, the spatial changes that resulted in a greater movement of longer duration might serve to maintain a temporal contiguity

with the longer movements of the oral articulators, similar to that in the control condition. As mentioned earlier, casual observation in the present study revealed no perceptual differences between load and control tokens. Further, the underlying assumption regarding production of the perturbed tokens was that compensation would result in productions of roughly perceptually equivalent tokens of comparable acceptability in the both conditions, as was indeed the case.

Even though Munhall and his colleagues reported “clear evidence of laryngeal compensation” (Munhall et al. manuscript p.17) during productions of the utterance /ipíp/, they questioned the functional nature of the observed laryngeal behavior. The question is a valid one, and it reflects on the problem discussed above. Their results showed increased /p/ VOT in the perturbed trials, which were frequently perceptually different to casual examination. However, these investigators do not specify whether the perturbed productions were acceptable, even if not perceptually equivalent, thereby reflecting compensation. The point being made here is that increased VOT might not necessarily reflect the lack of a functionally specific response. It is possible that, for the three subjects in the experiment, increasing the VOT in their /p/ productions, while at the same time reducing the closure duration, still resulted in acceptable /p/ productions, even if not in ones that were perceptually equivalent. In that sense, the observed laryngeal adjustments provided perhaps the most efficiently modulated response of the oral-laryngeal system in the load condition.

This problem of interpreting the functional role of remote articulators’ responses to perturbation, both in the case of the laryngeal timing results and in the case of the velar spatial results, points to the need for greater understanding of the range of acceptable behaviors of the articulators. Probably the speech production mechanism operates within the tolerance extent of the speech perception system. Compensation must be carefully defined before the responses of remote articulators can be assessed and

characterized as functional or compensatory. That is, compensation may consist of perceptual equivalence or of comparable acceptability in production. However, in neither of the above perturbation studies were spectral analyses performed on the acoustic signals from the perturbed tokens to establish their degree of similarity to their controls, nor were formal perceptual studies carried out to evaluate the acceptability or similarity of the perturbed tokens to their controls. Thus, acoustic analyses and perceptual follow-up experiments in this area are warranted. In addition, these studies might be improved by the inclusion of tokens with phonetic contrasts that would yield unacceptable productions in the absence of functional reorganizations following a perturbation, thus shedding more light into the issues at hand.

This problem brings to the foreground the issue of goal specification in speech production. For Fowler, as well as for Browman and Goldstein, the goal is articulatory and has acoustic consequences. For Lindblom, Lubker and Gay the goal is not only sensory, but it is also acoustic and listener-oriented. A distinction that perhaps should be made here is one of *level* of description. Introducing the communicative intent of the speaker ("listener-oriented programming", Lindblom et al. 1979, p.158) in parallel with other characteristics of the speech motor control mechanism ("context-sensitive, listener-oriented programming", p.158) confounds the issue by addressing it at one level, while it is a multi-level issue. The level of the hitherto analysis belongs to a *different* level of description. Clearly, the speaker's goal is (usually) communicative. However, a sensory or kinesthetic specification does not necessarily preclude an acoustic or an articulatory one. At the same time, it is well known that the acoustics of a few repetitions of the same utterance may show as much variation as the articulatory characteristics of its production. The way in which the listener perceives –or accounts for– all this variation is a different problem. A point of considerable debate is, then, whether speakers control the articulatory or the acoustic parameters of their productions.

Given that the articulatory adjustments in perturbation studies usually precede the acoustic output, and given that the acoustic output of perturbed utterances is usually non-distinct from non-perturbed utterances (e.g., the spectral analyses of Lindblom et al., 1979), the evidence points to articulatory rather than acoustic control in speech production. Described “vertically”, the speaker’s goal then, is to form constrictions in the vocal tract, that result in the desired acoustic output, and thus communicate the speaker’s intent.

Clearly then, the kinematic parameters of the articulators in a coordinative structure are adjusted –following a perturbation– in a manner that is goal specific and time sensitive. Temporal dependency makes sense in view of the differential consequences of the load that may be effected at various points in an articulator’s movement trajectory. Moreover, the compensatory adjustments of the speech system are found proportionally distributed across the articulators and their kinematic parameters, thereby reflecting the flexibility of the motor control system. Task-oriented functional coupling in speech motor control has been shown here as in earlier studies (Folkins and Zimmermann, 1982; Kelso et al., 1984; Shaiman, 1989; Munhall et al., submitted; and others).

The present results are compatible with the notion shared by a number of researchers (e.g., Gracco and Abbs, 1988, 1989; Gracco, submitted; Saltzman and Munhall, 1989; Mattingly, 1990) that the vocal tract may be controlled in a *global* manner, as a hierarchically structured mechanism whose elements show distributed modulations of their kinematic parameters depending on the task requirements, initial conditions, and the ongoing articulator states.

Such a view might also provide a preferable account for the findings of Lindblom et al (1979) than their proposed model of a predictive simulator. Recall that these investigators found that speakers whose jaw was fixed with a bite block were able to

produce steady state vowels with formant frequency patterns within the range of normally spoken vowels but modeled the control of the speech mechanism to a peripherally adaptive and centrally predictive error simulator. Yet, in their words, the task performed by the subjects “is possible... because normal speech motor programming is indeed ‘compensatory’. In other words, it operates in a context-sensitive mode to achieve listener-oriented goals and... the programming... must be capable of handling conditions never experienced before.” (p. 147). Admitting a speech system that is globally controlled, then, speech motor programming would be capable of handling novel conditions better by distributing the necessary modulations to all articulators involved in the specific task.

At this point, then, it seems clear that the speech motor control mechanism operates functionally, in other words, with the explicit goal of completing a required task, hierarchically, utilizing a vertical or pyramidal structure of organization of control, and globally, on as many constriction locations as are being employed for the achievement of a specific task.

APPENDIX: Example of the signal processing performed

1. DEMULTIPLEX THE SIGNAL FILES

When input was completed, the signal files were demultiplexed, i.e. extracted from their "appended" format and placed in individual channels.

PSP> DMX

DMX> MUX E1

DMX> F1-5,7-8=C1-5,7-8 (Files 1 through 5 become channels 1-5)

or F1-8 (files 1 through 8)

(write position files C1-8?) YES

2. CALIBRATE THE SIGNAL FILES

In one case the C1-8.PC1 files were each CALIBRATED separately, because the original 2 cm and 0 cm calibrations were input separately, so that the automatic calibration system available at input could not be utilized.

	<u>C1</u>	<u>C2</u>	<u>C4</u>	<u>C5</u>	<u>C6</u>	<u>C7</u>	
MAX	1591	1567	1621	1582	1590	1586	
MIN	-641	-618	-625	-652	-629	-625	then did: 1/[(MAX-MIN)/20]:
	.00896	.00915	.00890	.00895	.00901	.00905	

[(max value - min value) / 20 gives the number of points per mm. The inverse of that value gives the mms per point.]

Since there were no values available for C3, the value for C2 was used (.00915). Both C2 and C3 are velotrace signals.

3. SMOOTH THE SIGNAL FILES

PSP> SMT C#.PC1=42, where 42 is a 42 msec triangular window.

4. PLACE LABELS ON TOKENS

The experiment id is: (e.g.) JPV. To extract the individual tokens:

\$ PSP JPV

PSP> WES

WES> POR 2

WES> FIX S1 (*)

WES> WIN 1,10

WES> FIX C8.PCS=1

Names and numbers of the utterances:

/mabnab/ controls=1, loads=11, were then divided into:
 early controls=51, early loads=41 (>200 msec pre-load onset)
 mid controls=52, mid loads=42 (100-199 msec pre-load onset)
 late controls=53, late loads=43 (0-99 msec pre-load onset)

WES> IUT U1=6000,24000 (frames, 300 and 1200 msec left and right of the
 line-up point.)

utterance-speech relation=S1-2

utterance-channel relation=C1-10

utterance name:MABNAB

utt. lineup point:VOWEL ONSET

WES> IUT U2=6000,24000 (frames to the left and right of the lineup point)

WES> DPL octal code #

WES> Y (allows listening to the utterances)

On the display: place cursor at appx. voice onset, and zoom by typing **Z**. Place the cursor at the exact point of interest, and label this as utterance# by doing:

WES> ITK U# (inserts the utterance as U# and assigns a token #: e.g. U1T28)

5. SUBTRACT THE VARIOUS REFERENCES FROM THE SIGNALS

The reference channels were then subtracted from the appropriate channels as follows:

\$ PFM

```

files:          2
eq'n values:   A=1
                B=-1
                C=0
                D=0
                > C (clip; vs. S for scaling)
f1:            C10.PCS (jaw y channel)
f2:            C5.PCS (nose ref. y channel)
output file f3: C10.SUB
physical units: same

```

```

NOSE Y was subtracted from JAW Y (Jy'=Jy-Ny),
NOSE Y was subtracted from LOWER LIP Y (sLLy=LLy-Ny),
JAW Y' was subtracted from the subtracted LOWER LIP Y (LLy'=sLLy-Jy'),
NOSE Y was subtracted from UPPER LIP Y (ULy'=ULy-Ny),
VELOTRACE REF. X was subtracted from VELOTRACE X (Vx'=Vx-VRx).

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