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MANDIBULAR ROTATION AND TRANSLATION DURING SPEECH

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MANDIBULAR ROTATION AND TRANSLATION DURING SPEECH

by

JAN EDWARDS

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.

1985

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.

8/5/85
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Abstract

MANDIBULAR ROTATION AND TRANSLATION DURING SPEECH

by

Jan Edwards

Adviser: Professor Katherine S. Harris

A two-dimensional rigid-body model of jaw movement was used to describe jaw opening and closing gestures for vowels and for bilabial and alveolar consonants. Jaw movements associated with VC and CV demisyllables were decomposed into three components: rotation about the terminal hinge axis, and the horizontal and vertical translation of that axis. The three-component model was chosen on anatomical and physiological grounds. Data were collected for three subjects, each of whom was recorded on two separate occasions. Multiple regression analysis was used to examine the relationships among the components of jaw movement across changes in the segmental, suprasegmental, and coarticulatory context. The results of the multiple regression analyses revealed consistent inter-subject differences: for two subjects, but not for the third, an interdependence between jaw rotation and the first principal component of jaw translation was observed. It was hypothesized that this inter-subject difference could be predicted on the basis of Occlusal Class differences. For these two subjects, the first degree of freedom of jaw movement corresponded to a combination of rotation and the first principal component of translation. For the third subject, the first degree of freedom of jaw movement corresponded to rotation alone. For all three subjects, the first degree of freedom accounted for a consistently high percentage of maximum jaw displacement measured at the front teeth. The contribution of the first principal component of jaw movement to mid-tongue displacement at maximum displacement was calculated using three models: the three-component model, a pure rotation model, and a pure translation model. It was found that the predictions of the pure rotation model were consistently more accurate than those of the pure translation model across the three subjects. however, using the pure rotation model, as compared to the three-component model, to calculate the jaw component of mid-tongue displacement introduced small errors both in magnitude and in direction for those two of the three subjects for whom translation and rotation were inter-related. The fact that the three-component model was sensitive to phonetic context effects and that it was robust enough to preserve inter-subject differences across two separate recording sessions suggests that this model provides a useful description of jaw movement during speech.

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In all of the scatter plots, the units for TX and TY are mm x 10; the units for θ are degrees x 100.

†
In all of the raw data plots for CG and JE, every fifth data point is plotted.

CHAPTER 1

INTRODUCTION

Articulatory control is a major focus of modern speech research. However, understanding the control process is made difficult by the complex physical relations among the articulators. In the upper vocal tract, a major source of this complexity is due to the fact that both the tongue and the lower lip rest on the jaw. Thus, tongue and lip positions at any moment in time can be decomposed into two components: a jaw-related component and a component that is generated by the activity of the lingual or labial muscles. Therefore, an accurate description of jaw movement is required in order to realistically model tongue and lower lip movements during speech. However, the descriptions of jaw movement in current vocal tract models are inadequate to this purpose.

Jaw movement during speech has generally been described in terms of a single point on the jaw. As illustrated in Fig. 1.1, the movement of this point is represented either as pure vertical translation (Kakita and Fujimura, 1977) or as pure rotation (Coker, 1976; Mermelstein, 1973a). In the pure translation model, the jaw simply translates in some direction, which is usually defined as the principal component of jaw position variation. In the pure rotation model, the

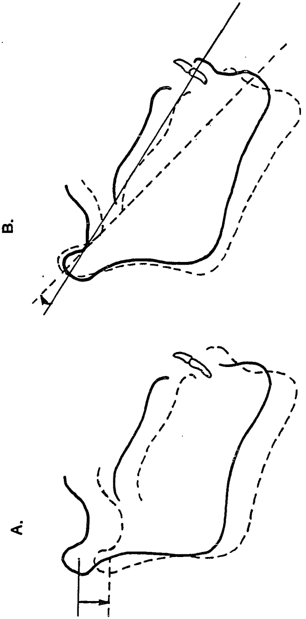


Figure 1.1 Point models of jaw movement during speech. A. a pure translation model; B. a pure rotation model.

jaw rotates about a transverse axis that presumably passes through the mandibular condyles.

However, the jaw is a rigid body, capable of both rotation about an axis and translation of that axis. Therefore, a description of jaw position in terms of a single point on the jaw does not provide enough information to predict the position of every other point on the jaw. Furthermore, a rich literature on the physiology of mastication shows clearly that the simple translation and rotation models are anatomically inaccurate, at least for non-speech opening and closing gestures with displacements of comparable magnitude to those observed in speech-related movements (Hjortso, 1955; Posselt, 1968; Sarnat, 1964; Gibbs, et. al., 1971). It has been known for some time that jaw opening is produced by a combination of clockwise rotation about a transverse axis and the simultaneous forward and downward translation of that axis. Conversely, jaw closing is produced by counterclockwise rotation about the same axis and the upward and rearward translation of that axis (Posselt, 1968; Sarnat, 1964).

The movement of the mandible, like the movement of any rigid body, can be described in terms of the rotation about any abitrarily chosen axis and the translation of that axis or, equivalently, as pure rotation about an instantaneous center of rotation. Thus, there are many rigid-body descriptions of jaw movement that will be mathematically equivalent. What criteria can be used to distinguish among these models? For the purposes of speech production, it can be argued that an anatomically and physiologically accurate model is preferable in that it is arguably more likely to provide insights about jaw movement control, in addition to describing jaw position. Let us therefore consider the anatomy and physiology of the mandible in more detail.

1.1 Anatomy and Physiology of the Mandible and the Temporomandibular Joint

1.1.1 Anatomy of the Mandible

The anatomy of the mandible is illustrated in Fig. 1.2. The mandible has a horseshoe-shaped body (in the horizontal plane) which extends up and back on both sides into the mandibular ramus. The posterior border of the ramus and the inferior border of the mandibular body meet at the mandibular angle. A crest, the mylohyoid line, extends diagonally down and forward on the inner surface of the body; the mylohyoid muscle originates from this crest. The mandibular foramen is situated in the center of the inner surface of the ramus. The mylohyoid groove, which houses the mylohoyoid nerve, begins at the posteroinferior circumference of the mandibular foramen and runs down and forward.

The ramus ends in two processes: the anterior coronoid process and the posterior condylar process, which articulates with the temporal

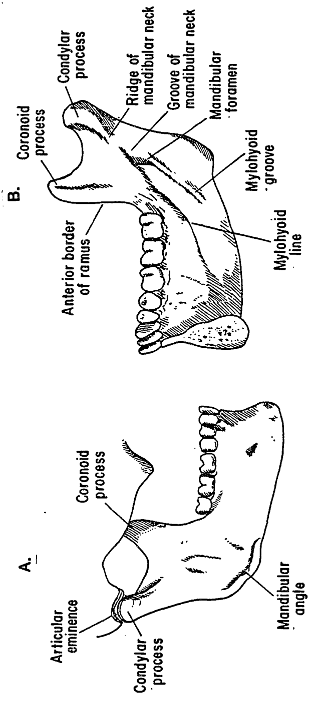


Figure 1.2 The anatomy of the mandible. A. the outer surface, right side; B. the medial surface, right side.

bone. The mandibular condyle is situated on the condylar process. The mandibular condyle, an irregularly-shaped cylindrical structure, is connected to the ramus by the mandibular neck. Above the neck, the condyle is bent anteriorly: the articulating surface faces up and forward (Sicher and DuBrul, 1975).

1.1.2 Anatomy of the Temporomandibular Joint

The temporomandibular joint attaches the mandible to the temporal bone of the skull. The anatomy of the temporomandibular joint is illustrated in Fig. 1.3. An articular disc, interposed between the head of the mandibular condyle and the articular eminence of the temporal bone effectively divides the temporomandibular joint into separate upper and lower compartments. The articular disc is fused to the articular capsule anteriorally, whereas posteriorally a thick layer of loose connective tissue (retrodiscal pad) results in a moveable connection of the disc and the articular capsule. In lateral and medial directions, the disc has no direct connection to the capsule, but is directly connected to the mandibular neck.

The condyle is attached to the temporal bone via the temporomandibular ligament and two accessory ligaments, the sphenomandibular and the stylomandibular ligaments. The temporomandibular ligament originates at the zygomatic processes of the temporal bone and extends inferiorally and posteriorally to attach to the lateral and posterior surfaces of the mandibular neck. This ligament limits lateral movement of the condyles and also limits the

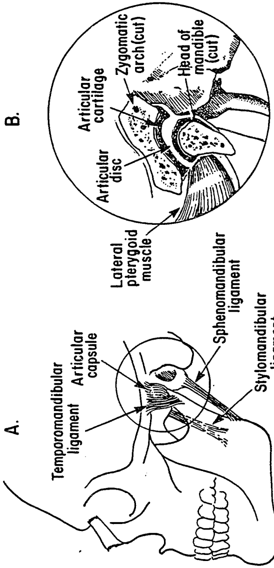


Figure 1.3 The anatomy of the temporomandibular joint. A. a left lateral view; B. the medial surface of a sagittal section.

amount of purely rotational mandibular movement. The sphenomandibular ligament originates at the angular spine of the sphenoid body and inserts into the lower border of the mandibular foramen and the mandibular neck. The stylomandibular ligament originates from the styloid process and the stylohyoid ligament. Some fibers of the stylomandibular ligament insert into the mandible at the region of the mandibular angle, but the majority insert into the medial surface of the medial pterygoid muscle. The two accessory ligaments become taut only during extreme protrusion of the mandible.

1.1.3 Positions and Movements of the Mandible

The anatomy of the temporomandibular joint produces three positions of the mandible that are repeatable in principle: rest (or postural) position; intercuspation (or centric occlusion); and terminal hinge position (or centric relation) (Nekavari, 1956; Posselt, 1968; Sarnat, 1964). Rest position is defined as "the position the mandible adopts when all the tissues attaching it to the cranium permit the forces of gravity to have maximal effect without parting the lips." (Thomson, 1981, p.4). In rest position, the lips are closed and the gap between the teeth normally ranges from about 2 to 4 mm across individuals (Posselt, 1968). Non-contact movements of the jaw begin and end at rest position. In speech, the jaw is lowered from and returns to rest position. In deglutition, the jaw is raised from and returns to rest position. Intercuspation is defined as the position that the mandible adopts when "the culps and sulci of the mandibular and maxillary teeth mesh tightly and where the mandible is in its most cranial position." (Posselt, 1968, p.37). The jaw moves to intercuspation during deglutition and mastication, but not during speech. Terminal hinge position is defined as the position that the mandible adopts when the mandibular condyles are in their most posterior and superior position in the articular capsule and the mandible is "midmost, uppermost, and rearmost" (Thomson, 1981, p.5). Although most individuals can be trained to achieve a consisent terminal hinge position, the jaw does not normally adopt this position during mastication, deglutition, or speech.

The anatomy of the temporomandibular joint allows two basic movements of the mandible: rotation and translation. In the lower compartment of the temporomandibular joint, the mandibular condyle rotates against the inferior surface of the articular disc; in the upper compartment, the articular disc glides downward, forward, and sideward (Hjortso, 1955). Thus, the jaw is capable of rotating about a transverse or a vertical axis located through the condyles and of translating that axis in anterior-posterior, inferior-superior, and lateral-medial directions (Gibbs, _et. al._, 1971). All functional movements of the mandible are produced by different combinations of these basic movements.

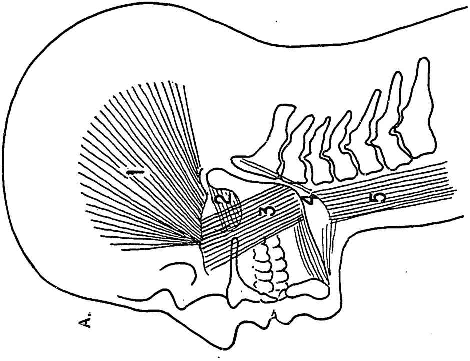
Three distinct functional movements of the mandible have been described (Posselt, 1968; Sarnat, 1964; Gibbs, _et. al._, 1971). These three movements are: opening and closing; symmetrical protrusion and retrusion; and assymetrical lateral movement. Jaw opening and closing involves rotation about a transverse axis located approximately through the condyles and the anterior-inferior translation of this axis to open the jaw and posterior-superior translation of this axis to close the jaw. Roentgenographic studies of jaw movement (Sarnat, 1964) have revealed that jaw opening is composed of two stages: first, it is primarily rotatory from intercuspation of the teeth to rest position; second, it involves a smooth combination of translation and rotation until maximal opening is reached. Jaw closing is composed of three stages: first, it involves primarily posterior translation from maximal opening to two-thirds of maximal opening; second, it involves a smooth combination of translation and rotation until rest position is reached; and, third, it is primarily rotatory from rest position to intercuspation. Anterior-posterior positions of the jaw have been found to be highly correlated with inferior-superior positions during non-speech opening and closing gestures from rest position to 2/3 of maximal opening (Gibbs, et. al., 1971).

Symmetrical protrusion of the jaw from rest position involves primarily anterior translation of the articular disc. Conversely, a reversal of this forward movement involves primarily posterior translation of the articular disc.

Assymetric lateral movements of the mandible are produced by the forward, downward, and medial translation of one condyle and the simultaneous rotation of the other condyle about a nearly vertical axis and a so-called "evasive movement," a small forward and lateral translation of this axis. This evasive movement, also known as the Bennett movement, is observed during mastication.

1.1.4 Muscles of the Mandible

The mandibular muscles, illustrated in Fig. 1.4, are traditionally divided into three groups, on the basis of their contributions to the functional movements of the lower jaw (Moller, 1974). These three groups are: (1) elevators; (2) depressors; and (3) protractors. However, several of the elevator and depressor muscles also have functionally independent retrusive or protrusive components (Moller, 1974; Gay and Piesuch, 1984). The masseter, temporalis, and medial pterygoid muscles are traditionally classified as jaw elevators. The masserter has two portions: the superficial part of the masseter originates from the anterior portion of the zygomatic arch and runs down and back to insert into the superficial surface of the angle of the mandible; the deep part of the masseter originates along the entire length of the zygomatic arch and extends inferiorly to insert into the lateral surface of the mandible and part of the coronoid process. Both parts of the masseter act to elevate and clench the jaw. The superficial masseter also functions independently as a jaw protractor and the deep masseter functions independently as a jaw retractor. The temporalis muscle is a broad fan-shaped muscle that originates along the lateral surface of the cranium and inserts into the medial surface



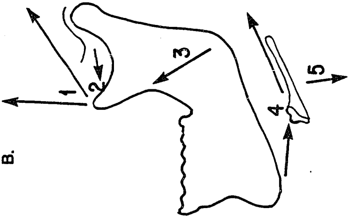


Figure 1.4 The muscles of the mandible: A. a saggital view of the mandibular muscles: 1. the temporalis muscle; 2. the external pterygoid; 3. the masseter and internal pterygoid muscles; 4. the digastric muscle; 5. the infrahyoid muscles. B. a schematic drawing of their directional pulls.

and the anterior border of the coronoid process and the anterior border of the mandibular ramus. It also has two portions: an anterior portion in which the fibers are nearly vertical and a posterior portion in which the fibers run down and forward. Both portions of the temporalis act to raise the jaw. The posterior temporalis also functions independently as a jaw retractor. The medial pterygoid, which runs parallel to the masseter, originates along the medial surface of the lateral pterygoid plate and runs downward, backward, and outward to insert into the medial surface of the mandibular angle. The medial pterygoid acts to elevate and to protract the jaw. Electromyographic activity has consistently been observed for all three elevators during mastication (Moller, 1974; Gay and Piesuch, 1984). However, the results for speech are more variable. Activity of the masseter and temporalis has been observed by some researchers (Folkins and Zimmerman, 1981; Folkins, 1981; Gay and Piesuch, 1984), but not by others (Sussman, et. al., 1973; Folkins and Abbs, 1975; Tuller, et. al., 1981). Activity of the medial pterygoid for jaw raising during speech has been more consistently observed across subjects and across experiments (Folkins and Abbs, 1975; Tuller, et. al., 1981; Folkins, 1981; Gay and Piesuch, 1984), but it has not been observed by all researchers (Sussman, et. al., 1973).

The anterior belly of the digastric, the mylohyoid, and the geniohyoid muscles are traditionally classified as depressors. The digastric muscle consists of two parts connected by a tendon: the posterior belly originates at the mastoid process; the intermediate tendon is connected to the hyoid bone; and the anterior belly inserts into the lower border of the mandible approximately at midline. The anterior belly of the digastric acts to depress and to retract the jaw. The infrahyoid muscles, the geniohyoid and the mylohyoid, also act to depress and retract the jaw, if the hyoid bond is fixed. The mylohyoid originates from the inner surface of the mandible along the mylohyoid groove and runs medially and posteriorly to insert to the upper border of the hyoid bone. The geniohyoid muscle originates from the inner surface of the mandible, approximately at midline, and runs posteriorly and inferiorly to insert into the upper half of the hyoid. Electromyographic activity of both the anterior belly of the digastric, the mylohyoid, and the geniohyoid has been observed during mastication (Moller, 1974), deglutition, and speech (Sussman, et. al., 1973; Folkins, 1981; Tuller, et. al., 1981; Gay and Piesuch, 1984).

The lateral pterygoid muscle is the primary mandibular protractor: It has two heads that have been observed to function independently (MacNamara, 1973; Tuller, et. al., 1981; Gay and Piesuch, 1984). The inferior head originates from the outer surfaces of the lateral pterygoid plate; the superior head originates from the infratemporal surface of the the greater sphenoid wing. The fibers of the two heads fuse in front of the temporomandibular joint and attach to the articular capsule, the anterior border of the articular disc, and the mandibular neck. It should be noted that this is the only muscle which attaches to the articular capsule and disc. Activity of the superior head of the lateral pterygoid has been observed during jaw raising, but not during jaw lowering or jaw protrusion; activity of the inferior head of the lateral pterygoid has been observed during jaw lowering and protrusion, but not during jaw raising. Activity of both heads of the lateral pterygoid is observed during mastication and deglutition (Moller, 1974; Gay and Piesuch, 1984). Activity of the inferior head of the lateral pterygoid has also been observed during jaw lowering gestures for speech (Tuller, et. al., 1981; Gay and Piesuch, 1984). Activity of the superior head of the lateral pterygoid has been observed during jaw raising gestures for speech (Tuller, et. al., 1981; Gay and Piesuch, 1984).

1.1.5 Constraints on Mandibular Movement

The two basic movements of the mandible, the rotation of the condyle and the translation of the articular disc, are functionally independent, within limits dictated by physical constraints. As discussed above, the inferior head of the lateral pterygoid and the superficial masseter function to protrude the jaw; the deep masseter and the posterior temporalis function to retrude the jaw, independently of raising and lowering gestures. However, physical constraints place limits on these basic rotatory and translatory movements and on their functional independence. First, the slope of the articular eminence limits the path of the articular disc during anterior-inferior and posterior-superior translation. Second, the temporal bone limits posterior-superior translation of the disc. Third, the sphenomandibular and stylomandibular ligaments become taut at extreme mandibular protrusion, limiting forward translation of the articular disc. Fourth, the temporomandibular ligament and the lateral connections of the articular disc to the condyle limit lateral-medial translation of the disc. Finally, the temporomandibular ligament limits the amount of condylar rotation that can occur without translation of the disc and also restricts the general nature of the relationship between rotation and translation during opening and closing gestures. During opening gestures, the temporomandibular ligament becomes taut as the condyle rotates forward. Anterior-inferior translation of the disc decreases this tautness and thus allows additional rotation.

Barager and Osborn (1984) examined the relationship between condylar rotation and translation of the articular disc for different degrees of jaw opening. Their model included three physical constraints, based on measurements of a single skull. These three constraints were: (1) the length and slope of the articular eminence; (2) the length of the temporomandibular ligament; and (3) the length of the sphenomandibular ligament. Their results are illustrated in Fig. 1.5. The shaded areas indicate the range of possible positions for the center of the condyle at different degrees of jaw opening. The center of the condyle is presumably quite close to the axis of condylar rotation and thus its position will be relatively unaffected by

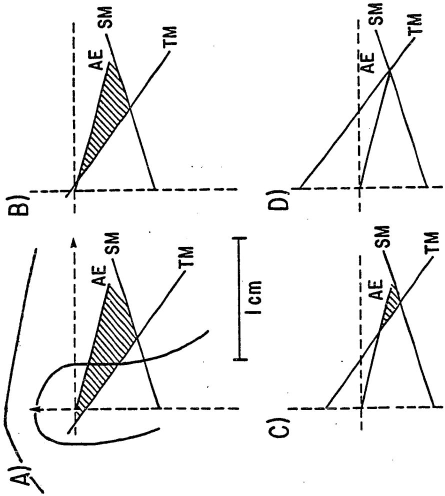


Figure 1.5 The constraints on the center of the condyle are plotted for four different degrees of jaw opening. AE is the articular eminence constraint; TM and SM are the temporomandibular and sphenomandibular constraints. The actual articular eminence lies about 1 cm above the AE constraint line because the bone of the condyle and the soft tissues of the joint lie between it and the center of the condyle. Arrows on the x and y axes indicate anterior and superior directions, respectively. Jaw opening increases progressively from A. (intercuspation) to D. (wide opening). For each amount of jaw opening shown, the center of the condyle can only lie in the shaded triangular region. [Barager & Osborn, 1984, p. 762]

rotational movements. However, because the disc is attached to the condyle, the condyle will move down and forward along with the articular disc during anterior-inferior translation for jaw opening. It can be observed that the range of possible condylar positions increases as the degree of jaw opening decreases, permitting considerable latitude with respect to the relationship between condylar rotation and disc translation at small degrees of jaw opening. Thus, for the relatively small jaw displacements observed during speech (cf. Fig. 1.5b), the relationship between rotation and translation is not highly restricted by physical constraints. However, at the more extreme jaw displacements observed during mastication (cf. Figs. 1.5c and 1.5d), the relationship between translation and rotation is highly limited by physical constraints.

The predictions of the Barager and Osborn model are corroborated by actual comparisons of mandibular movement during mastication and speech. Gibbs and Messerman (1972) found the range of inferior-superior positions of the mandible relative to the range of anterior-posterior positions to be more limited during opening gestures for mastication, as compared to speech. They found that the ratio of the range of movement in an inferior-superior direction, as compared to the range of movement in an anterior-posterior direction to be 7:1 during mastication, as compared to 3:1 during speech.

1.2 Jaw Movement During Mastication

In many respects, mastication is a more complex process than speech. It utilizes all three of the functional jaw movements enumerated above (Sarnat, 1964). The initial phase of mastication, the cutting phase, begins with an opening movement which is followed by a closing movement, accompanied by a protrusive movement, which is then followed by a retrusive movement. The second phase of mastication, the grinding phase, involves a combination of jaw opening and a lateral rotatory movement on the working side followed by jaw closing and a medial rotatory movement on the working side which brings the mandible back to a symmetrical occlusal position. Studies of jaw movement during the grinding phase of mastication have revealed that two degrees of freedom are constrained by what is called a "working functional movement" (Gibbs, et. al., 1971): The medial movement of the condyle on the working side is coordinated with both the up and rearward lateral movement of the non-working condyle and with the up and medial movement of the central incisor.

> Starting from the closed position, a typical motion of the mandible can be summarized as follows: Both condyles begin the opening immediately downward and forward. Early in the closing stroke, the entire mandible moves laterally. The working side (lateral) condyle moves upward and rearward and reaches its terminal position at the most vertical rearward position of its path before the teeth approach each other far enough to intercuspate. This working side condyle appears to be nearly stationary in the saggital view for the remaining part of the closing stroke, which is termed the Working Functional Movement (WFM). During the WFM, the working side condyle moves medially to its closed position, while the

non-working side condyle goes upward and laterally to its closed position. [Gibbs, *et. al*., 1971].

1.3 Jaw Movement During Speech

A comparison of the speech and dental literature suggests that, in many respects, jaw movement during speech appears to be more constrained than during mastication. It has consistently been observed that there is essentially no lateral movement of the jaw during speech (Gibbs and Messerman, 1972; Gentil and Gay, 1982). For example, Gentil and Gay (1982) observed less than .1 mm of jaw movement in the frontal plane during speech. These observations exclude condylar rotation about a vertical axis and lateral-medial translation of the articular disc during speech. Furthermore, the range of jaw opening and closing movements during speech is considerably less than during mastication. Gibbs and Messerman (1972) found that the maximal vertical opening of the jaw, measured at the central incisor, was two to four times greater for mastication than for speech. Speech-related jaw opening and closing movements typically begin at and return to rest position, whereas chewing-related jaw movements typically begin at and return to intercuspation. Thus, speech-related movements should uniformly lie within the range of vertical jaw position that involve a smooth combination of rotatory movements about a transverse axis and anterior-posterior, inferior-superior translation of this axis (Sarnat, 1964). This movement pattern was observed in the one study of speech-related jaw movements in which condylar motion was calculated using three other points on the jaw (Gibbs and Messerman, 1972). In this study, the mandibular condyle was observed to move down and forward during opening gestures and to move up and rearward during closing gestures.

1.4 A Model of Jaw Movement during Speech

The results of these previous studies of jaw movement during speech suggest that an anatomically and physiologically accurate model should decribe jaw movement as a combination of rotation about a transverse axis and the vertical and horizontal translation of this axis in a plane. Fig. 1.6 illustrates this proposed model. This study was designed to develop the methodology for such a model and to examine its utility by considering two issues of concern to current research in speech production

1.4.1 Degrees of Freedom of Jaw Movement

The first issue concerns the functional relationships among the three jaw movement components that are observed during simple opening and closing gestures for vowels and bilabial and alveolar consonants.[1] In principle, such movements could utilize up to three degrees of freedom, if horizontal jaw translation, vertical jaw translation, and jaw rotation all function independently of each other. As disscused above, however existing articulatory models use a single degree of freedom to describe jaw movement, even though at least two degrees of

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[1] It should be noted that a description of the symmetrical protrusion of the jaw for the labiodental fricatives /f/ and /v/ and the interdental fricatives /θ/ and /ð/ is beyond the scope of this study.

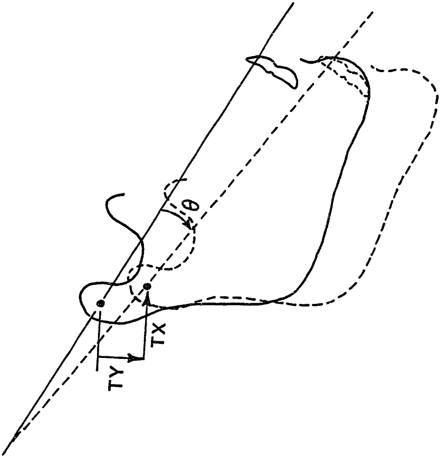

Figure 1.6 A two-dimensional rigid-body model of jaw movement during speech. Jaw movement is described as a combination of three components: , rotation; TX, horizontal translation of the axis of rotation; and TY, vertical translation of the axis of rotation.

freedom have been observed in previous studies of speech-related opening and closing gestures of the jaw. For example, Gibbs and Messerman (1972) examined the jaw movements of six American English speakers, using a phonetically-varied stimuli set (including both the single words "wan", "tus", "read", "nor" and paragraphs read aloud). They found the ratio of the range of movement along the first principal axis relative to the range of movement along the second principal axis to be 3:1. Kiritani _et. al._ (1983) used Japanese speakers and a more limited speech materials (VCV syllables with the vowels /i/, /a/, /ɛ/, /u/ and the consonants /s/, /p/, /t/, /k/) and found this ratio to be 4.5:1.

A description of jaw movement during speech as a combination of rotation and horizontal and vertical translation can be used to address three questions related to the degree of freedom issue. First, is there a functional relationship between any two of the three components of jaw movement (horizontal translation of the center of rotation, vertical translation of the center of rotation, and jaw rotation) which reduces a three degrees of freedom system to a simpler two degrees of freedom system? Second, regardless of whether any functional constraints are observed, how are the two (or three) degrees of freedom of jaw movement related to these three anatomical components? Third, what phonetic correlates, if any, correspond to the second (and possibly third) degrees of freedom of speech-related jaw movements?

1.4.2 Decomposition of Tongue Position

A description of jaw movement as a combination of rotation and translation can also be used to address a second issue of concern: what are the effects of jaw movement on attached structures (the lower lip and the tongue, in particular). As discussed above, a two-dimensional rigid-body model of jaw movement is needed in order to describe the position of every point on the mandible at any moment in time. At present, researchers must choose between pure rotation and pure translation models that describe jaw position in terms of the movement of a single point. Because both the pure translation and the pure rotation models are incomplete, neither model can accurately calculate the jaw-related component of lower lip or tongue displacement. As illustrated in Fig. 1.7, a pure translation model predicts equal displacement of any point on the jaw, whether it is located, say, on the lip or in the vicinity of the tongue body. Figure 1.7 also illustrates that a pure rotation model predicts that the approximately linear displacement of a point on the jaw depends on the distance of that point from the axis of rotation. Thus, it predicts a greater displacement due to jaw movement for a point located on the lower lip, than for a point located on the tongue body.

Let us consider the effect of using one of these simplified models to predict the jaw component of lower lip or tongue body positions. In a pellet-based data collection system, such as the X-ray microbeam system (Kiritani, et. al., 1975), there will usually be a pellet attached to the lower lip, a pellet attached to the central incisor, and several pellets attached to the superior surface of the tongue. Decomposition based on a purely translational model will overestimate the jaw component of tongue pellet positions and underestimate the jaw

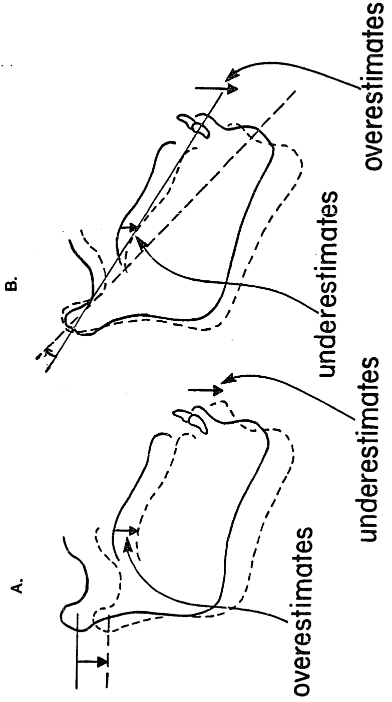

Figure 1.7 Point models of jaw movement during speech cannot describe the position of every point on the jaw. A. the pure translation model overestimates the jaw component of tongue body displacement and underestimates the jaw component of lower lip displacement. B. the pure rotation model underestimates the jaw component of tongue body displacement and overestimates the jaw component of lower lip displacement.

component of lower lip positions. Conversely, decomposition based on a purely rotational model will underestimate the jaw component of tongue pellet positions and overestimate the jaw component of lower lip positions. Thus, it is clear that a rigid-body two-dimensional model is needed in order to accurately decompose lower lip and tongue displacements into their intrinsic and their jaw-related components. Futhermore, such a model can be used to determine the magnitude of error that is introduced by using the simplified models and to develop a method of correcting such error, if it is predictable.

1.5 Purpose of this Study

The purpose of this study, then, was to examine jaw movement using the model proposed above and illustrated in Figure 6. Speech-related jaw movements were decomposed into three components: rotation about a transverse axis located approximately through the condyles and the horizontal and vertical translation of this axis in the mid-saggital plane. Multiple regression analysis was used to examine the relationships between these components as a function of phonetic variation. Because jaw movement has been observed to be influenced by the segmental, the suprasegmental, and the coarticulatory contexts (Fujimura and Miller, 1979; Gay, 1974; Kiritani and Hirose, 1979; Lindblom and Sundberg, 1971; Macchi, 1985; Mermelstein, 1973b; Stone, 1981; Sussman, *et. al.*, 1973), all of these variables were varied in all combinations in designing the speech materials. The results of the multiple regression analyses were used to address three questions: (1) does jaw movement during speech-related opening and closing gestures utilize two or three degrees of freedom; (2) how are these two (or three) degrees of freedom related to the three jaw movement components; and (3) what are the phonetic correlates of the second (and possibly third) degrees of freedom? The contribution of the first degree of freedom of jaw movement to tongue displacement at maximal opening was calculated using all three models--the two simplified models and the new empirically determined model. The predictions of the three models were compared in order to determine which of the two simplified models was more accurate, what magnitude of error was introduced, and whether the error was predictable.

This analysis was done on an individual subject basis for three speakers, all of whom were recorded on two separate occasions. The methods used to record, process, and analyze the data are discussed in Chapter 2. The results of the first recording session for each subject are presented in Chapters 3. The issue of intra-speaker variability is addressed in Chapter 4, where the results of the second recording session for the three subjects are presented. A discussion of the results and the conclusions are presented in Chapter 5.

CHAPTER 2

METHODS

2.1 Subjects

The subjects were three normally dentate adult female native speakers of Standard American English (CG, JE, LF). All subjects were screened by a dentist to ensure that they did not exhibit any symptoms of temporomandibular joint disorder and also that they did not exhibit a midline shift during retrusive movements of the jaw. The same dentist, using Angle's classification (1907) determined that two subjects (CG and JE) have Class II occlusions and one subject (LF) has a Class I occlusion. In a Class I occlusion, the mesiobuccal cusp of the upper first molar rests in the buccal groove of the lower first molar. In a Class II occlusion, the mesiobuccal cusp of the upper first molar is anterior to the buccal groove of the lower first molar (Graber, 1972). Two of the subjects were speech pathologists who are engaged in speech production research (JE and CG) at Haskins Laboratories: one of these subjects (JE) was the experimenter; the other (CG) was aware of the general purpose of the experiment. The third subject (LF) was a linguist and was naive to the purpose of the experiment. On the basis of the results of Tuller (1980) and Abbs (in press), it was assumed that although phonetic training may serve to reduce intra-speaker variability, experimental sophistication would have no other effect on the experimental results.

2.2 Speech Materials

The speech materials were 54 V1CV2 utterance types, all of which were surrounded by /p/ for CG and JE and embedded in the carrier phrase "a _______ again". For LF, the V1CV2 utterance types were surrounded by /t/ instead of /p/ because it was observed that the jaw appliance (described in the next section) appeared to interfere with bilabial closure. The same carrier phrase, "a _______ again" was used for all three subjects. All nine combinations of /i/ (e.g. "Pete"), /a/ (e.g. "pot"), /ae/ (e.g. "pat") were used for the V1-V2 context; the intervocalic consonant was a syllable-initial /p/, /t/, or /s/; lexical stress was placed on either V1 or V2. The intervocalic consonant /s/ was not included in the first data recording session for JE, because she had a mild inter-dental lisp at that time. For CG and JE, the utterances were blocked in groups of 6. Within each group, the first vowel (V1) and the intervocalic consonant (C) remained constant. The second vowel (V2) was varied in the order: /i/, /a/, /ae/, /i/, /a/, /ae/. Within each block of six, primary stress alternated between V1 and V2. Whether V1 or V2 received primary stress on the first utterance within each block was chosen randomly. The order of presentation of the 9 blocks of 6 utterance types was also randomized. Each of the nine block was presented to the subject on a 9 by 12 index card. An example of a block is given in Table 2.1.

The subject paused after each utterance type so that she and another observer could monitor the position of the reference LED's on an oscilloscope. The utterance types were also presented in blocks of 6 for LF, but the order of presentation of all four phonetic parameters

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Table 2.1

Example of block presentation of 6 utterance types for CG and JE

a pa'tip again
a 'patap again
a pa'taep again
a 'patip again
a pa'tap again
a 'pataep again

(V1 identity, V2 identity, intervocalic consonant identity, stress pattern) was randomized. Five to seven tokens of each utterance type were produced sequentially. The first five correctly produced tokens were used for analysis. It was observed that the subjects generally produced five or six tokens as a single breath group. Tokens were discarded if either the experimenter or a second listener judged that the speaker did not produce the target utterance type correctly. Subjects were instructed not to reduce the vowel which did not receive primary stress. However, it was observed that all three subjects sometimes reduced the unstressed vowel; these utterances were accepted as correct without comment.

2.3 Appliances

Each subject was individually fitted by a prosthodontist with two appliances. These appliances are illustrated schematically in Fig. 2.1. The reference appliance consisted of a steel wire which was positioned to exit the the mouth in the mid-sagittal plane directly between the labial margins of the upper and lower lips. It was bonded directly to an upper front tooth for two subjects (CG and LF) and attached by means of an orthodontic band for the third subject (JE). Two light-emitting diodes (LED's) were attached to this appliance in order to monitor head movement during the course of the experiment. The jaw appliance consisted of three parts: (1) a cast steel plate, molded to fasten onto the labial surfaces of the lateral incisor and the first and second premolars; (2) a cast steel rod which exited the mouth near the corner of the labial margins and another steel rod which

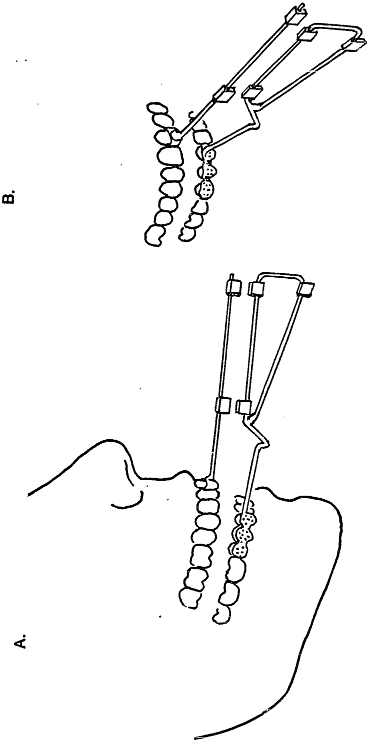

Figure 2.1 Schematic drawings of the reference and jaw appliances. A. a sagittal view; B. a frontal view.

extended back to the mid-saggital plane from the corner of the mouth; and (3) a triangle on which three LED's were positioned. The jaw appliance was bonded directly to three lower teeth for all three subjects. The devices were attached by a dentist at least one hour before data was recorded.

The appliances were bonded to the labial surfaces of the teeth with the same type of bonding material that is used to attach orthodontic devices. This material has not been observed to damage the enamel on the teeth. Thus, the only subject safety consideration is that a subject who is wearing the appliance must be very careful if he or she is walking or is a passenger in an automobile. If the subject should fall forward, there is a possibility that one of the two appliances could be pushed up and back through the hard palate.

The appliances were designed with three considerations in mind: (1) no interference with intercuspation or terminal hinge position; (2) minimal interference with normal speech production; and (3) maximal stability of the appliance. All goals apparently were achieved. First, the subjects reported no interference with intercuspation or terminal hinge positon. Second, the subjects reported and other observers noted only minimal interference with normal speech production. However, as mentioned above, the jaw appliance interfered with bilabial closure for LF. Because LF has a Class I occlusion, the distance between her upper and lower teeth in the anterior-posterior direction at intercuspation is smaller than for CG and JE. In order to avoid interference with centric occlusion, the jaw appliance for LF had to be placed somewhat lower on the labial surfaces of the lateral incisor and the first and second premolars. This positioning of the appliance resulted in noticeable interference with the production of bilabials and resulted in a change of the phonetic inventory (see below). Third, there was no observable slippage of the appliances, which were custom-made to fit onto the labial surfaces of three teeth. The triangle construction in cast steel resulted in a light, but stable, appliance, with no visually perceptible vibration or yielding during speech.

2.4 Data Acquisition

Jaw and head movements were recorded by means of an opto-electronic tracking system (Kay et. al., 1985). A Selspot camera monitored the movement of infra-red light-emitting diodes; decoding electronics associated with the camera derived position data in x and y dimensions and represented them as analog voltages. These electrical signals were recorded on a multi-channel instrumentation tape recorder along with the speech acoustic signal. Calibration was achieved by moving one LED through a known distance (2 cm) in the field of view. A calibration of the Selspot optical system revealed that the output is linear plus or minus .05 cm for a 20 cm by 20 cm camera field, given a camera distance of 53 cm. Position variability due to measurement noise was calculated to be .0009 cm.

2.5 Data Processing

Both the acoustic and the movement data were digitized on a PDP 11/45 computer; the acoustic signal was sampled at a 10,000 sample per second rate and the movement signals were sampled at a 200 sample per second rate. Both were quantized with 12-bit precision. The simultaneously-recorded acoustic and kinematic waveforms were time-locked via a timing code generator/reader that is also interfaced to the computer. Following analog-to-digital conversion, all of the data were transferred to a VAX 11/780 for further processing and analysis. The temporal aligment of the acoustic and kinematic waveforms is accurate within 1 sample (plus or minus 5 ms).

2.5.1 Token Segmentation

The Haskins Laboratories Physiological Signal Processing software (Gulisano, 1982) was used to identify and extract the first five tokens of each utterance type, using the acoustic waveforms. The consonant release of the intervocalic /p/and /t/ and the voice onset after /s/, as observed in the acoustic signal, were used as the temporal center of each V1CV2 utterance. Subsequently, each utterance was divided into four gestures associated with: pV1, V1C, CV2, V2p for CG and JE; tV1, V1C, CV2, V2t for LF. These gestures will be referred to as "demisyllables" throughout the text. Figure 2.2 illustrates this division for one token of /'patap/ for CG. Velocity is shown on the top and the corresponding vertical jaw displacement is shown on the bottom. Points of zero-velocity were used to determine demisyllable boundaries so that opening and closing gestures could be analyzed separately. Velocity was derived from the jaw displacement data by the application of a central difference algorithm and then smoothed, using a 25 msec. smoothing window (Kay, et. al. 1985).

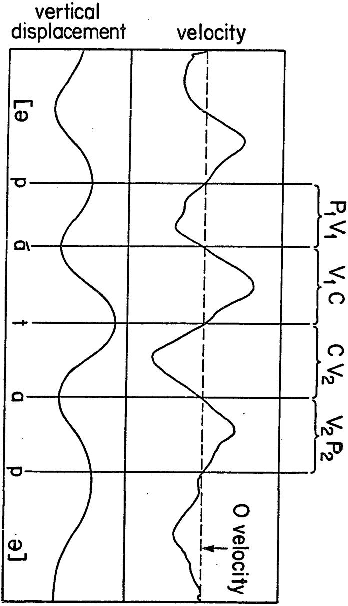

Figure 2.2 Demarcation of the utterance tokens into opening and closing gestures. Vertical jaw displacement is shown on the bottom; velocity is shown on the top.

2.5.2 Calibration

Two steps were involved in data calibration: (1) the scale factors relating digitized values to physical units were calculated; and (2) because DC offset voltages were added before amplifying during data recording (in order to optimize the dynamic range), these offsets had to be corrected in order to locate all LED's in a common coordinate system. Therefore, prior to each experiment, two calibration procedures were recorded. First, one LED, attached to a vernier caliper, was moved a distance of 2 cm. Second, the positions of all five LED's were recorded at zero offset volts and at 10 offset volts. The latter procedure was used so that offset volts/ cm could be calculated. Calibration constants were then calculated channel by channel: M, the slope of the function relating digitized values to physical units, was calculated by relating the 2 cm movement to its equivalent in digital values; B, the Y intercept of the same function, was calculated from the offset voltage converted to centimeters.

2.5.3 Correction for Head Movement

The data obtained from the two LED's attached to the reference appliance were used to correct for the translation and rotation of the head in the mid-saggital plane by a computer program. The formulas used for this procedure are given in Appendix A1. (1) for each data frame, the angle of rotation of the head from a fixed reference vector was calculated by evaluating the direction of the line connecting the two reference LED's; (2) the translation of the head was calculated as the remaining distance between the LED J1 (cf. Fig. 2.5) and its reference position after it had been corrected for head rotation. Corrections for head rotation and translation were then made on all points in the data frame. All further analyses were performed on the calibrated and corrected jaw displacement data.

It should be noted that this method does not allow for correction of head movement out of the assumed object plane, which would result in the distortion of the distance between two fixed points. Therefore, during data collection, the subject was required to monitor the positions of the two reference LED's on an oscilloscope in order to minimize out-of-plane head movement. The amount of out-of-plane movement was examined by calculating the distance between the two reference LED's at three times (beginning, middle, end) during each experiment. Out-of-plane movement resulted in distance distortions of .006% (.03 cm), .008% (.02 cm), and .03% (.17 cm) for CG, JE, and LF, respectively, in the first experiment and of .007% (.02 cm), .006% (.03 cm), and .02% (.08 cm) in the second.

2.5.4 Location of Terminal Hinge Axis

It is necessary to specify the axis of jaw rotation in order to decompose jaw movement into a combination of rotation and translation, as discussed in Chapter 1 and illustrated in Fig. 1.6. However, because speech-related movements include both rotation and translation, the axis of rotation cannot be derived uniquely from the data. Therefore, a series of non-speech, purely rotational gestures was also recorded for each subject. As discussed in Chapter 1, the terminal hinge position of the jaw is defined as that position in which the mandibular condyles are in their most posterior and superior position in the articular capsule. Most individuals can be taught to open and close their jaw a small amount while maintaining terminal hinge position. (Sarnat, 1964). This purely rotational gesture is used by dentists to locate the axis of jaw rotation (terminal hinge axis).

Prosthodontists and orthodontists utilize a mechanical device such as a facebow or an adjustable articulator for axis location (Posselt, 1968). The device is attached to the jaw at two points: the lower front teeth and the mandibular condyles. The patient produces a purely rotational gesture and a stylus traces mandibular movement at the point of the condylar attachment. The dentist adjusts the location of the condylar attachment until it is directly on the axis of rotation so that the stylus tracing produces a point rather than a line. This condylar position is taken to be the terminal hinge axis.

A similar procedure was used in this experiment for axis location. Each subject was trained to perform a purely rotational maneuver using the following instructions:

1. raise jaw to intercuspation;
2. retrude jaw to terminal hinge position;
3. lower and raise jaw a small amount
   (several mm) several times in succession
   while maintaining condylar position.

Palpation of the condyle by the experimenter and by the subject was used during training. The subject practiced these movements for several weeks prior to each data recording session. During each experiment, five of these movements were recorded preceding and following the recording of the speech data. In four out of six experiments, the condyle was palpated by the experimenter in order to monitor whether the subject was maintaining condylar position. Scatter plots of the x and y positions of the three points on the jaw during these movements were examined by eye and those movements in which there appeared to be any radial movement were discarded. Figure 2.3 shows two scatter plots for CG of the x and y positions of one of the three recorded points on the jaw during a sequence of rotational gestures. Note that some radial movement can be observed in Fig. 2.3a. Figure 2.3b shows the same sequences of rotational gestures with the data points containing radial movements excluded. All three subjects were able to produce some purely rotational jaw movements. It should be noted, however, that the three subjects varied in their ability to produce such gestures consistently. Subject JE was the most consistent: approximately 95% of the data points of her "purely rotational gestures" exhibited no detectable radial movement. Subject CG was somewhat less consistent: approximately 80% of the data points of her purely rotational gesture exhibited no radial movement. Subject LF was the least consistent: approximately 60% of the data points of her purely rotational gestures exhibited no radial movement.

A computational, rather than a mechanical model, was used to find the location of the terminal hinge axis. An iterative optimization procedure (Chambers and Wilks, 1981) was used to fit curves to the selected data points of the purely rotational gestures. This optimization procedure uses an adaptation of a Quasi-Newton algorithm designed to minimize a function of p variables, given the function, p

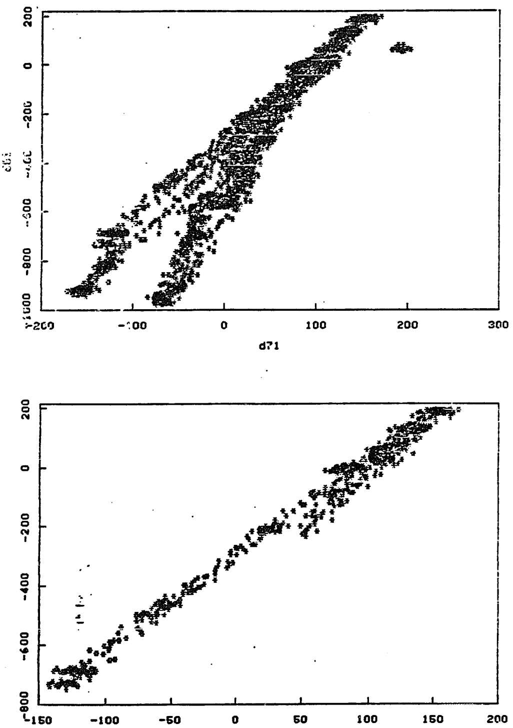

Figure 2.3 Vertical positions of LED J1 (cf. Fig. 2.5) are plotted against horizontal positions during a series of "purely rotational" gestures. A. some radial movement can be observed. B. the same series with the radial movements deleted. The units on both axes are mm x 10.

partial derivatives, and p starting values (Dennis and Mei, 1979). Because three points on the jaw had been recorded, the function was written in order to minimize the variation of one center (x_0, y_0) and 3 radii. The error function and the five partial derivatives are given in Appendix A2. Starting values were chosen by eye for each data set.

Figure 2.4 illustrates the results of this curve-fitting for the first data recording session for subject CG. It can be observed that although the arcs represent very small portions of the circles (the angle which the arc subtended never exceeded 3 degrees), the fitting of the data points to the arcs is quite good. The mean squared error of the error function was consistently low within each experiment (.000077 cm, .00012 cm, and .000035 cm for CG, JE, and LF, respectively, in the first experiment and .000073 cm, .00014 cm, and .0000274 cm in the second) and similar terminal hinge axis coordinates were observed within subjects across the two data recording sessions (plus or minus .05 cm, .08 cm, and .05 cm for CG, JE, and LF, respectively).

2.5.5 Decomposition of Jaw Movement

Jaw movement during speech-related gestures was decomposed into rotation and horizontal and vertical translation, using the geometry illustrated in Fig. 2.5. The terminal hinge position of the jaw was defined as the reference position. The angle ϕ was defined as the angle that the line OJ1 made with the horizontal. The distance D was defined as the Euclidean distance between the point O (x_0, y_0) and the point J1 (x_{j_1}, y_{j_1}). The sine and cosine of ϕ and the distance D were calculated using the previously determined coordinates of the axis of

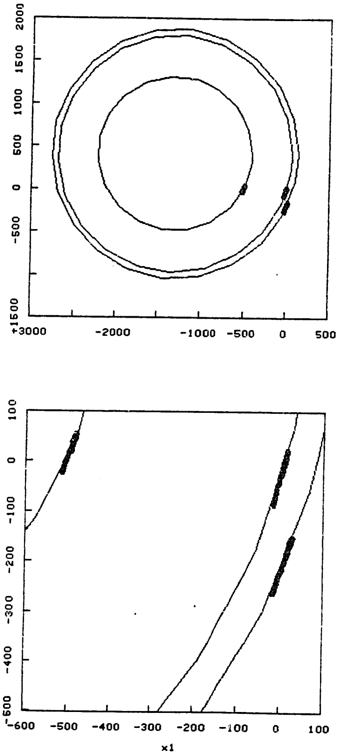

Figure 2.4 The results of the curve-fitting for CG in the first experiment. A. whole circles; B. enlarged arc sections. The units on both axes are mm x 10.

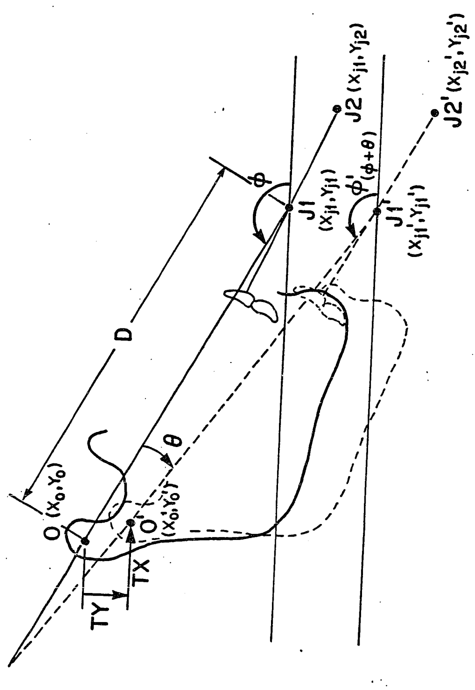

Figure 2.5 The geometry used for decomposition of jaw movement. Solid lines show the reference position of the jaw; dashed lines show the position of the jaw at some data frame.

rotation (O) and the reference coordinates of one jaw LED (J1). Jaw rotation was defined as the angle of rotation θ (in degrees) formed by the two line segments J1-J2 and J1'-J2'. The sine and cosine of θ were calculated, using the reference and the new coordinates of two jaw LEDs (J1 and J2). Then, the sine and cosine of the new angle $\phi'(\phi + \theta)$ that the line OJ1 made with the horizontal was calculated. The new location of the axis of rotation (O') was calculated, using the angle ϕ', the distance D (assumed to be constant), and the coordinates of point J1'. Finally, the x and y components of jaw translation (TX and TY), defined as the horizontal and vertical vectors from O to O' were calculated. All of the formulas used in this procedure are given in Appendix A3. Thus, the output of this procedure was a frame-to-frame description of jaw movement as a combination of three components: θ, the rotation in degrees about a fixed hinge axis relative to the reference position; TX, the horizontal translation of the terminal hinge axis; and TY, the vertical translation of the terminal hinge axis.

2.6 Data Analysis

2.6.1 Removal of Outliers

For each of the four demisyllables, three scatter plots (TX x TY, θ x TX, x TY) were made containing the five tokens of each utterance type. These trajectories were examined by eye and outlying data points and tokens were removed. Again, the three subjects differed in their ability to reproduce gestures consistently: JE was the most consistent subject and LF was the least consistent subject. Accordingly, approximately 5% for JE, 15% for CG, and 35% for LF of the data points were not used in the subsequent statistical analyses. Appendix A4 gives the number of tokens used by utterance type for the V1t and the tV2 demisyllables for all three subjects. The results are qualitatively similar across different intervocalic consonants and across different demisyllable types. For all three subjects, the first and the last tokens of an utterance type were more frequently anomalous than the middle three tokens. Presumably, this is a sequence effect and is analogous (and, perhaps, inherently related) to the well-documented increased vowel durations of utterance-initial and utterance-final vowels (Lehiste, 1971; Lindblom and Rapp, 1973). Although the fifth token was not generally the last in the sequence of repetitions, all three subjects were generally observed to produce only 5 to 6 tokens as a single breath group.

Figure 2.6 illustrates the three scatter plots for the CV2 demisyllables for the data points of five tokens of the utterance type [pa'taep] for subject CG. The letters A, B, C, D, E represent the five different tokens. If the letters of the same identity were connected, the trajectory of each utterance would be shown. It can be observed that token-to-token variability is relatively low for this utterance; no tokens or data points were eliminated.

Note the relationships among the three components during jaw opening. The top-most plot illustrates how the axis of rotation moves down and forward during opening gestures. The middle plot illustrates how the angle of rotation becomes increasingly negative as the x component of translation increases during opening gestures. The bottom plot illustrates how both the angle of rotation and the y component of

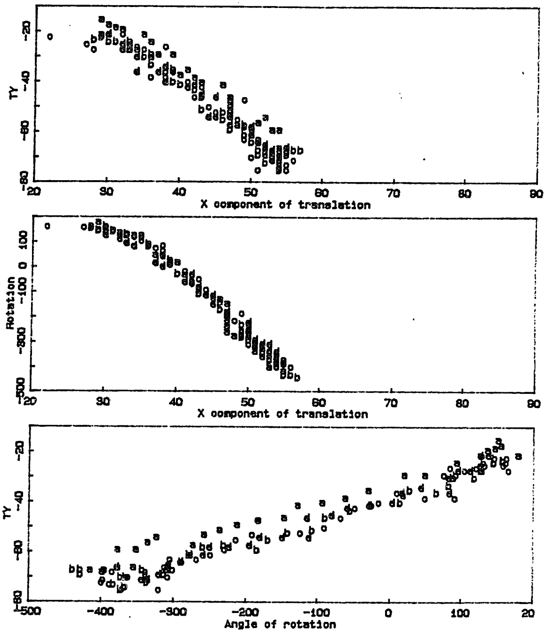

Figure 2.6 Components of jaw opening movement. Five opening gestures for the utterance /a'tae/ are shown for CG. Values of vertical translation are plotted against values of horizontal translation in the top plot. Values of the angle of jaw rotation are plotted against values of horizontal translation in the middle plot. Value of vertical translation are plotted against the angle of jaw rotation in the bottom plot. The letters A, B, C, D, E denote five different repetitions of the same utterance type.

translation become increasingly negative during opening gestures.

The opposite pattern is observed during jaw closing. The axis of rotation moves up and back; the angle of rotation increases as the x component of translation decreases; and both the angle of rotation and the y component of translation increase during closing gestures.

2.6.2 Coordinate Transformation

Multiple regresssion analysis was used to examine the relationships among jaw rotation and horizontal and vertical jaw translation as a function of changes in the segmental and the suprasegmental context. First, however, a coordinate transformation was performed. For each data subset on which a multiple regression analysis was performed (see Section 2.6.4.2 for a description of these subsets), the data points were rotated so that the first principal component of jaw translation was parallel to the x axis. The eigen-vectors of each data subset were determined from the covariance matrix (Green and Carrol, 1976). Figure 2.7 shows an example of these coordinate transformations. The same three trajectories are plotted for the transformed data points from Fig. 2.6. It can be observed that the x axis and the first principal component of jaw translation are parallel.

This coordinate transformation was performed for two reasons: first, so that the error terms in the regression analysis would be calculated using perpendicular rather than vertical distances to the best-fitting lines; and second, to permit meaningful discussion of inter-speaker differences.

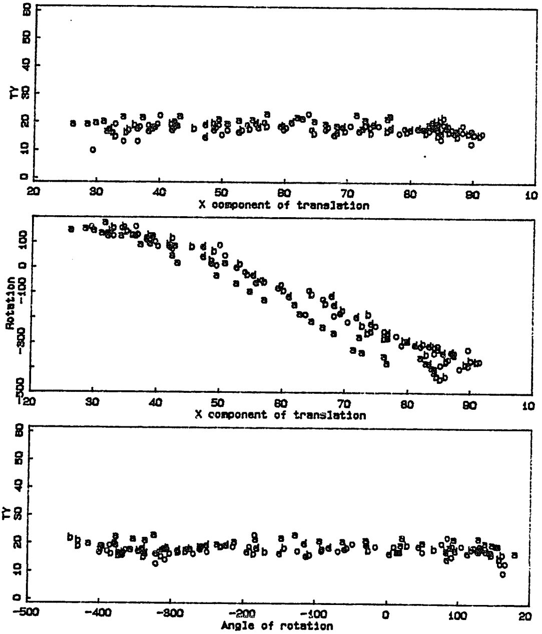

Figure 2.7 Rotated components of jaw opening movement. The same data as in Fig. 2.6 are replotted in a different coordinate system. The axes have been rotated so that the first principal component of jaw translation and the x axis are parallel. Values of second principal component of translation are plotted against values of the first principal component of translation in the top plot. Values of the angle of jaw rotation are plotted against values of first principal component of translation in the middle plot. Value of the second principal component of translation are plotted against the angle of jaw rotation in the bottom plot.

The data points of each experiment were described within arbitrary coordinate systems that were not defined with respect to any fixed anatomical landmarks (such as, for example, the Frankfurt line). The coordinate transformation facilitated discussion of inter-speaker differences because it resulted in coordinate systems that were defined with respect to the same functional criterion for all subjects. All subsequent discussion refers to the three components of jaw movement (TX, TY, θ) within the transformed coordinate systems. Thus, TX will be referred to both as the first principal component of jaw translation and as X translation; TY will be referred to both as the second principal component of jaw translation and as Y translation.

2.6.3 Anatomical Geometry

Prior to the coordinate transformation, two angles were calculated for each subject: (1) the angle α that the first principal component of translation makes with the horizontal (for the V1t demisyllables); and (2) the angle β that the tangent to the radius formed by connecting the point O (cf. Fig. 2.5) with a point on a lower front tooth makes with the horizontal. (Cf. Section 2.6.5.1 for a description of how the coordinate values of a point on the lower front tooth were calculated.) These angles are given in Table 2.2. These geometrical relationships are also illustrated in Figs. 2.8, 2.9, 2.10 for CG, JE, and LF, respectively. In these three figures, a common distance (8 cm) between the front teeth and the center of rotation is shown. In fact, however, this distance varied among the three subjects: 7.55 cm for

Table 2.2

Anatomical geometry for the three subjects for the V1t demisyllables

	CG	JE	LF
α	61°	34°	49°
β	61°	40°	75°

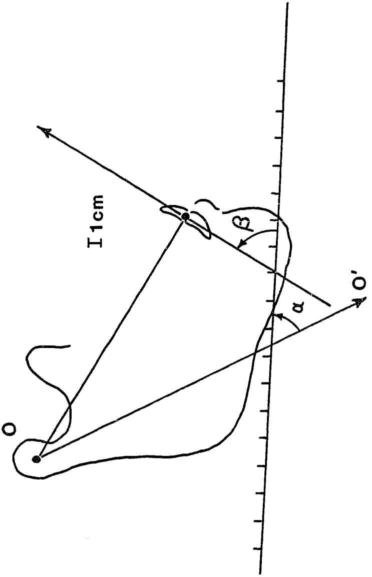

Figure 2.8 Anatomical geometry for CG.

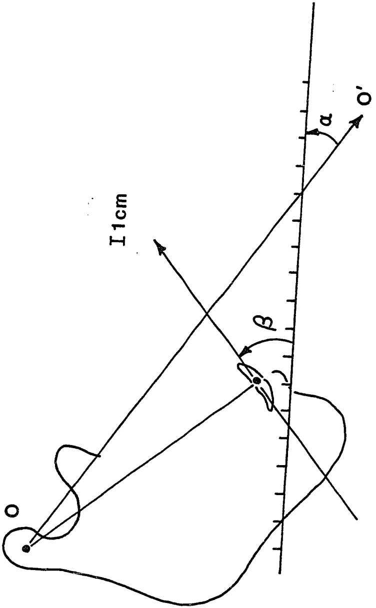

Figure 2.9 Anatomical geometry for JE.

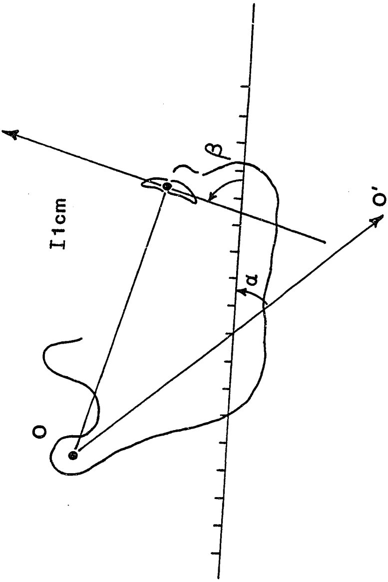

Figure 2.10 Anatomical geometry for LF.

CG; 12.75 cm for JE; 9.40 cm for LF.

As mentioned above, the data before the coordinate transformations for each subject are defined within arbitrary coordinate systems without any fixed anatomical landmarks as reference. For this reason, it is difficult to interpret the observed geometrical differences across subjects and no such interpretation will be attempted.

2.6.4 Multiple Regression Analysis

Multiple regression analysis was used to analyze the relationships among the three components of jaw movement during speech. Two questions were of particular interest: (1) did any of the three components of jaw movement translation exhibit a functional dependence on any other component; and (2) if such a dependence was observed, was it independent of phonetic context. Two functional relationships were considered as possibilities: (1) the first two principal components of jaw movement might be functionally interdependent; and (2) translation and rotation might be functionally interdependent. Therefore, two multiple regression analyses were performed on the trajectories of the four demisyllable types for each subject. First, the second principal component of jaw translation was analyzed as a function of the first principal component (hereafter, translation analysis or translation model). Second, the angle of rotation was analyzed as a function of the first principal component of translation (hereafter, rotation analysis or rotation model). The first principal component of jaw translation was taken as the independent variable in both analyses so that the results of the two analyses could be more easily compared. A disadvantage of this decision is that it leaves one pertinent question at least partially unresolved: i.e., can jaw rotation predict the first principal component of jaw translation. This issue will be returned to in Chapter 5.

2.6.4.1 Polynomial Order of the Regression Model.

A cubic model was used for the translation analysis and a quadratic model was used for the rotation analysis for all four demisyllables and for all three subjects based on empirical findings. The regression equations for the translation and rotation analyses are given in (2.1) and (2.2) below, respectively.

(2.1) $\hat{Y} = a_1X_1 + a_2X_1^2 + a_3X_1^3 + a_4.$

(2.2) $\hat{\theta} = b_1X_1 + b_2X_1^2 + b_3.$

The degree (i.e. the polynomial order of the equation) for each model was chosen by determining the highest degree for each model that appeared to fit the general shape of the data rather than specific data points for any demisyllable type for any subject. The same degree was used for all four demisyllables across all three subjects so that results could be compared across demisyllables and across subjects. For example, because a cubic model provided the best fit for the translation model for all four demisyllable types for subject JE, a cubic model was also used for the translation model for all four demisyllables for all three subjects, although a quadratic model might have been adequate for CG and LF. The use of a higher order model than necessary will simply result in insignificant contributions to the squared multiple correlation of the higher order terms.

2.6.4.2 Combination of Phonetic Parameters

Within each demisyllable, each of the 54 utterance types can be completely described by specifying values of four phonetic parameters: (1) the stress pattern of the test syllable (either primary ("stressed)" or secondary ("unstressed")); (2) the identity of the vowel in the test syllable (/i/, /a/, or /ae/); (3) the identity of the vowel in the non-test syllable (also /i/, /a/, or /ae/); and (4) the identity of the intervocalic consonant in the test utterance (/p/, /t/, or /s/). Any of these phonetic parameters can be included as a covariate in the regression model. The simplest type of covariate is a binary variable which takes on the value "1" if a statement is true and is set to zero otherwise. The presence of a covariate adds an additional term to the regression equation in that the value of the y intercept of the best-fitting line (or curve) will vary as a function of the value of the covariate. Thus, the addition of a covariate will result in an increase of a squared multiple correlation only if the effect of the characteristic it represents has a substantial linear component.

A priori, it is not obvious which of these four phonetic parameters or which combinations of these parameters produced linear effects or effects with substantial linear components. Therefore, in order to determine which combinations of phonetic characteristics produced linear effects, the utterance types were analyzed across different combinations of these characteristics. All of the phonetic parameters were coded as binary-valued covariates. In those cases for which a phonetic parameter could take on three values (e.g. the identities of the test and non-test vowels and the identity of the intervocalic consonant), two binary covariates were used. For both the translation and rotation regression models, six different combinations for each subject were examined for all four demisyllable types.

First, the utterance types were combined across the two different stress patterns and across the three different vowels in the non-test syllable. This yielded nine data subsets within each demisyllable (3 vowels in test syllable x 3 intervocalic consonants in test utterance). The regression equations for the translation and rotation models for these analyses are given in (2.3) and (2.4) below, respectively.

$$(2.3)\quad \hat{Y} = a_1X_1 + a_2X_1^2 + a_3X_1^3 + a_4X_2 + a_5X_3 + a_6x_4 + a_7.$$

$$(2.4)\quad \hat{\theta} = b_1X_1 + b_2X_1^2 + b_3X_2 + b_4X_3 + b_5x_4 + b_6.$$

The covariates, X_2 and X_3 specify the identity of the non-test vowel; the covariate, X_4, specifies the stress pattern of the test syllable.

Second, the utterance types were combined across the two stress patterns and the three vowels in the test syllable. This also yielded nine data subsets within each demisyllable (3 vowels in non-test syllable x 3 consonants in test utterance). The regression equations for the translation and rotation models for these analyses are given in

(2.5) and (2.6) below, respectively.

$$(2.5)\ \hat{Y} = a_1X_1 + a_2X_1^2 + a_3X_1^3 + a_4X_2 + a_5X_3 + a_6X_4 + a_7.$$

$$(2.6)\ \hat{\theta} = b_1X_1 + b_2X_1^2 + b_3X_2 + b_4X_3 + b_5X_4 + b_6.$$

The covariates, X_2 and X_3 specify the test vowel identity; the covariate, X_4, specifies the stress pattern.

Third, the utterance types were combined across the different vowels in the test and the non-test syllables. This yielded six data subsets within each demisyllable (2 stess patterns x 3 consonants in test utterance). The regression equations for the translation and rotation models for these analyses are given in (2.7) and (2.8) below, respectively.

$$(2.7)\ \hat{Y} = a_1X_1 + a_2X_1^2 + a_3X_1^3 + a_4X_2 + a_5X_3 + a_6X_4 + a_7X_5 + a_8.$$

$$(2.8)\ \hat{\theta} = b_1X_1 + b_2X_1^2 + b_3X_2 + b_4X_3 + b_5X_4 + b_6X_5 + b_7.$$

X_2 and X_3 specify test vowel identity; X_4 and X_5 specify non-test vowel identity.

Fourth, the utterance types were combined across stress patterns, and the different vowels in both the test and non-test syllables. This yielded 3 data subsets within each demisyllable (3 consonants in test utterance). The regression equations for the translation and rotation models for these analyses are given in (2.9) and (2.10) below, respectively.

$$(2.9)\ \hat{Y} = a_1X_1 + a_2X_1^2 + a_3X_1^3 + a_4X_2 + a_5X_3 + a_6X_4 + a_7X_5 + a_8X_6 + a_9.$$

$$(2.10)\ \hat{\theta} = b_1X_1 + b_2X_1^2 + b_3X_2 + b_4X_3 + b_5X_4 + b_6X_5 + b_7X_6 + b_8.$$

X_2 and X_3 specify test vowel identity; X_4 and X_5 specify non-test vowel identity; X_6 specifies the stress pattern.

Fifth, the utterance types were combined across stress patterns, across different vowels in the non-test syllables, and across the three intervocalic consonants in the test utterance. This yielded three data subsets within each demisyllable (3 vowels in test syllable). The regression equations for the translation and rotation models for these analyses are given in (2.11) and (2.12) below, respectively.

$$(2.11)\ \hat{Y} = a_1X_1 + a_2X_1^2 + a_3X_1^3 + a_4X_2 + a_5X_3 + a_6X_4 + a_7X_5 + a_8X_6 + a_9.$$

$$(2.12)\ \hat{\theta} = b_1X_1 + b_2X_1^2 + b_3X_2 + b_4X_3 + b_5X_4 + b_6X_5 + b_7X_6 + b_8.$$

X_2 and X_3 specify non-test vowel identity; X_4 specifies the stress pattern; X_5 and X_6 specify the identity of the intervocalic consonant.

Sixth, the utterance types were combined across all four phonetic parameters, yielding one data set within each demisyllable. The regression equations for the translation and rotation models for these analyses are given in (2.13) and (2.14) below, respectively.

$$(2.13)\ \hat{Y} = a_1X_1 + a_2X_1^2 + a_3X_1^3 + a_4X_2 + a_5X_3 + a_6X_4 + a_7X_5 + a_8X_6 + a_9X_7 + a_{10}X_8 + a_{11}.$$

$$(2.14)\ \hat{\theta} = b_1X_1 + b_2X_1^2 + b_3X_2 + b_4X_3 + b_5X_4 + b_6X_5 + b_7X_6 + b_8X_7 + b_9X_8 + b_{10}.$$

X_2 and X_3 specify test vowel identity; X_4 and X_5 specify non-test vowel identity; X_6 specifies the stress pattern; X_7 and X_8 specify consonant identity.

For each subject, the optimal combination of phonetic parameters among the six alternative given above was defined as the maximum combination of phonetic parameters that produced: squared multiple correlations that were high, relative to the total range of squared multiple correlations for that subject; and (2) squared multiple correlations that were qualitatively similar across the four demisyllable types.

Because the contribution of a covariate to a squared multiple correlation indicates the influence of the phonetic characteristic it represents (i.e., the proportion of variance that it accounts for), multiple regression analysis can be used to assess the relative strengths of effects of the segmental context (identity of the vowel in the test syllable and the identity of the intervocalic consonant in the test utterance); of the suprasegmental context (stress pattern of the test utterance); and of the coarticulatory context (identity of the vowel in the non-test syllable). Although the relative influences of these different phonetic parameters were not the primary focus of this study, these results will be discussed in Chapter 3, as they help to elucidate the nature of the relationships among the three jaw movement components.

2.6.4.3 Effect of Blocking the Utterance Types for CG and JE

The effect of one additional covariate was also examined for subjects CG and JE. As described in Section 2.2, the order of presentation of utterance types was not fully randomized for these two subjects. It was assumed that the blocking of the utterance types would have no measurable effect on the relationships among the components of jaw movement. This assumption was tested by treating position within a block as an additional covariate with 6 values, each corresponding to a position between 1 and 6. This covariate was added to the rotation and translation analyses for subjects JE and CG for the V1C and CV2 demisyllables, combined across test vowel identity, stress pattern, and non-test vowel identity. As illustrated in Table 2.3, the predictive value of this covariate was found to be quite low: the proportion of variance it accounts for ranges from 0 to 3%. Several of the phonetic covariates consistently account for substantially higher proportions of the variance, as will be discussed in the next chapter. Thus, it will be assumed that the blocking the utterance types did not have a significant effect on the relationships among the three components of jaw movement.

2.6.5 Contributions of the Three Jaw Movement Components to Resultant Jaw Displacement At The Front Teeth

Table 2.3

Contribution of covariate representing order within block
to translation and rotation analyses for JE and CG
(percent equals proportion of variance accounted for)

Translation Analysis

	CG		JE	
	V1C	CV2	V1C	CV2
c=t	.03	.002	.013	.002
c=p	.03	.0001	.017	.003
c=s	.003	.007		

Rotation Analysis

	CG		JE	
	V1C	CV2	V1C	CV2
c=t	.005	.01	.009	.006
c=p	.012	.004	.007	.002
c=s	.003	.015		

2.6.5.1 Magnitudes of the Three Jaw Movement Components

In order to make quantitative comparisons among the three subjects, the amount of movement due to X and Y translation and of the movement due to jaw rotation at a selected point on the mandible were calculated for the maximal opening position for the low vowels /a/ and /ae/ for the V1t and tV2 demisyllables for each subject. The movement due to rotation was calculated using a straight line segment to approximate the arc which the angle subtended. The movement due to rotation will be referred to as "R."

Jaw opening at the front teeth was assumed to be the measurement of primary interest for speech production. Therefore, the radius was defined as the distance from the axis of rotation (O) (cf. Fig. 2.5) to a lower front tooth. The x and y coordinate values of a point on a lower front tooth were calculated by measuring the distance between LED J1 (cf. Fig. 2.5) and the tooth for each subject and then extending the line segment connecting LED's J1 and J2 (cf. Fig. 2.5) by this measured distance. All subsequent references to jaw displacement refer to the displacement of this point.

2.6.5.2 Projections of the Three Jaw Movement Components onto Resultant Jaw Displacement

These data were used to calculate resultant jaw displacement at maximal opening for the V1t demisyllables. The three jaw movement components were added vectorially, using the previously calculated angles and (cf. Section 2.6.3). In order to compare the relative contributions of the three jaw movement components, the projection of each component onto resultant jaw displacement was also calculated. These results are presented at the beginning of Chapters 3 and 4.

2.6.6 Jaw Component of Tongue Displacement

2.6.6.1 First Principal Component of Jaw Position Variation

These data were also used to estimate the contribution of the first principal component of jaw position variation to mid tongue displacement. The results of the translation and rotation analyses were used to determine which of the three jaw movement components (or combination thereof) corresponded to the first degree of freedom of jaw movement for each subject. This empirically-determined rigid-body model of jaw movement was then used to calculate the contribution of the first principal component of jaw movement to mid tongue position at maximal jaw opening.

2.6.6.2 Comparison of Three Models

The predictions of the empirically determined model were compared to the predictions of the simplified pure rotation and pure translation models. Given the pure translation model, the jaw component of mid tongue displacement was equal to the displacement of the lower front tooth along its first principal axis. Given the pure rotation model of jaw movement, the jaw component was calculated by multiplying total jaw displacement along its first principal axis by an appropriate proportional fraction for mid tongue displacement. Figure 2.11 shows

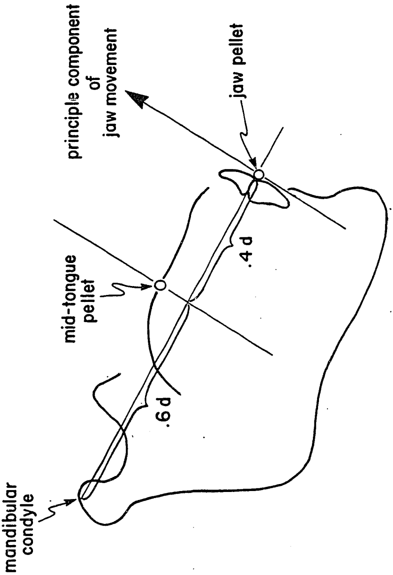

Figure 2.11 The jaw component of mid-tongue displacement, according to the pure rotation model. The displacement of the lower front tooth along its principal axis is multiplied by a proportional fraction. The proportional fraction is equal to the ratio of the distance of the jaw pellet to the axis of jaw rotation relative to the distance of the mid-tongue pellet to the axis of rotation.

how the proportional fraction was calculated. Given the relative positions of the mid tongue and jaw pellets in data acquired with the X-ray microbeam system, it was estimated that approximately 60 percent of jaw rotation will be reflected in mid tongue position. The predictions of the three models were compared by calculating the errors that the two simplified models introduce.

2.7 Replication

In order to assess intra-speaker variability, a second data recording session was run on all three subjects. The same procedure (including the order of presentation of the speech material) was followed during the two experiments for each subject. The only differences were that: (1) an additional intervocalic consonant (/s/) was included for subject JE; and (2) the triangle portion of the jaw appliance was detached and resoldered to the remaining portion for both JE and LF. This reattachement was done for JE to allow for additional labial protrusion and for LF because the two portions were detached after the first experiment when the appliance was removed. The period of time between the first and second data recording sessions was 1 week, 2 weeks, and 6 months for LF, CG, and JE, respectively. A subset of the data from the second recording session was selected for analysis: these data included only the V1C and the CV2 demisyllable types and only those utterances in which the intervocalic consonant was /t/.

CHAPTER 3

RESULTS

The results of the translation and rotation regression analyses are presented and discussed in this chapter. In sections 3.2 and 3.4, the second principal component of jaw translation is described as a function of the first principal component across changes in phonetic context. In sections 3.3 and 3.5, jaw rotation is described as a function of the first principal component of jaw translation across changes in phonetic context. For both analyses, regression curves will be plotted and discussed in those cases in which the regression model accounts for a substantial proportion of the variance. Raw data will be plotted and discussed in those cases in which the regression model does not account for a substantial proportion of the variance. For both of these analyses, the utterance types were combined across as many phonetic parameters as possible. That is, as discussed in Chapter 2, different combinations of phonetic parameters were examined in order to determine the maximal combination of parameters that yielded linear effects (or effects with substantial linear components). The results for subjects CG and JE are qualitatively similar and will be presented together in sections 3.2 and 3.3; the results for LF are dissimilar and will be discussed separately in sections 3.4 and 3.5. First, however, let us consider some more general similarities and differences among the three subjects.

3.1 Projections of the Three Jaw Movement Components onto Resultant Jaw Displacement

The results for the three subjects were grossly similar in that the displacement of the three components was in the predicted direction for both opening and closing gestures. For all three subjects, the center of rotation moved down and forward for jaw opening and moved up and back for jaw closing. Similarly, for all three subjects, the angle of jaw rotation became more negative (i. e. open) for jaw opening and less negative for jaw closing. Another similarity among the three subjects was that the magnitude of resultant jaw displacement at the front teeth was generally greater for high vowels, as compared to low vowels, and for stressed vowels, as compared to unstressed vowels. The three subjects differed, however, in that the magnitude of resultant jaw displacement was generally greatest for JE and least for LF.

3.1.1 Magnitude of the Three Jaw Movement Components

Table 3.1 give the magnitude of displacement for the three jaw movement components at the maximal opening position of the jaw for the low vowels /a/ and /ae/ for the V1C and the CV2 demisyllables for all three subjects. The data for /i/ are not included in these tables because all three subjects exhibited small and quite variable amounts of jaw displacement for this vowel. The data are presented only for those utterance types in which the intervocalic consonant is /t/, as this consonant was common to the utterances of all three subjects. These same data are presented graphically in Fig. 3.1 for the V1t demisyllables. Differences among the three subjects can be observed.

Table 3.1

Magnitudes of three jaw movement components in mm at maximal opening for V1t and tV2 demisyllables

							V1t				
test vowel	non-test vowel	stress	CG TX	CG TY	CG R	JE TX	JE TY	JE R	LF TX	LF TY	LF R
a	i	+	7.1	1.8	8.5	16.1	3.7	19.0	2.8	1.1	6.5
a	a	+	4.8	1.8	6.2	12.1	2.8	13.3	2.2	2.2	5.8
a	ae	+	5.7	1.7	7.3	12.0	4.1	13.6	2.6	1.9	6.0
a	i	-	5.1	2.1	5.9	5.0	2.3	7.8	3.4	1.2	6.8
a	a	-	4.9	1.6	5.8	5.5	2.4	8.1	2.0	.5	3.0
a	ae	-	4.9	2.0	5.9	3.7	1.7	6.3	2.0	1.1	3.7
ae	i	+	6.1	2.0	7.9	13.2	3.6	18.8	4.8	1.9	9.6
ae	a	+	4.9	1.7	6.1	15.4	3.4	18.4	2.7	2.2	8.0
ae	ae	+	6.9	2.3	8.1	14.7	5.5	17.8	2.7	1.2	7.7
ae	i	-	3.8	2.6	5.0	8.2	3.1	12.9	2.6	1.1	7.4
ae	a	-	4.9	1.9	6.8	6.1	2.3	8.8	2.6	.7	6.6
ae	ae	-	5.7	1.7	6.3	6.1	2.8	9.5	2.3	1.8	5.9
						tV2					
a	i	+	6.2	1.4	7.5	13.3	3.1	17.5	2.0	1.6	6.4
a	a	+	6.5	1.7	8.2	14.8	4.9	18.7	3.2	1.2	7.4
a	ae	+	6.7	1.5	8.1	14.5	4.6	17.2	3.7	1.2	6.5
a	i	-	3.8	1.4	5.5	7.4	3.5	11.7	2.2	1.5	5.0
a	a	-	4.0	1.5	6.0	4.7	2.0	6.7	1.7	1.4	5.6
a	ae	-	5.0	1.4	5.8	8.2	2.5	10.7	2.1	1.7	5.7
ae	i	+	5.6	1.4	5.2	15.5	4.0	20.7	2.6	2.0	8.8
ae	a	+	6.9	1.7	8.1	12.9	4.5	15.9	3.8	1.9	7.9
ae	ae	+	7.8	1.5	8.1	15.3	3.3	19.6	2.7	1.5	8.5
ae	i	-	4.7	1.5	5.5	11.8	4.2	14.9	1.9	1.8	7.3
ae	a	-	4.7	1.5	6.0	5.8	2.0	7.8	2.1	1.9	6.5
ae	ae	-	5.2	1.4	6.7	10.4	2.7	12.4	1.8	1.5	6.6

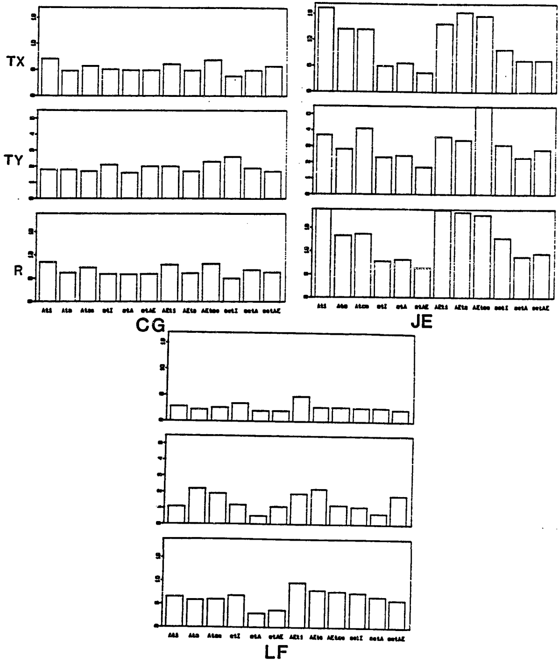

Figure 3.1 Histograms of the magnitude of displacement of the three jaw movement components for the V1t demisyllables. The data for CG are shown on the top left plot; the data for JE are shown on the top right plot; the data for LF are shown on the bottom plot. In each set of plots, the top row shows the data for TX; the middle row shows the data for TY; the bottom row shows the data for R. Upper-case letters indicate stressed demisyllables; lower-case letters indicate unstressed demisyllables. The units on the y axis are mm.

First, JE consistently exhibits the greatest magnitude of displacement for all three components. She has a maximum of 16.1 mm, 5.5 mm, and 20.7 mm for X translation, Y translation, and rotation, respectively. LF exhibits the smallest displacements of jaw translation. She has a maximum of 4.8 mm, 2.2 mm, and 9.6 mm for X translation, Y translation, and rotation, respectively. CG exhibits a greater amount of translation than LF and roughly comparable amounts of rotation. She has a maximum of 7.8 mm, 2.6 mm, and 8.5 mm of X translation, Y translation, and rotation, respectively. The greatest inter-subject differences are observed for X translation. JE exhibits about four times as much X translation as LF. CG exhibits almost twice as much X translation as LF.

3.1.2 Absolute Contributions of the Three Jaw Movement Components to Resultant Jaw Displacement

Similar quantitative differences among the three subjects are also observed when the direction of movement is taken into account, although the magnitude of the inter-subject differences decreases. Table 3.2 gives the projections of the three jaw movement components onto resultant jaw displacement for the V1t demisyllables. These data are also presented graphically in Fig. 3.2. Again, it can be observed that JE exhibits the greatest displacements for all three components. She has a maximum of 7.0 mm, 5.0 mm, and 15.2 mm for the projections of X translation, Y translation, and rotation, respectively. LF again exhibits the smallest amounts of translation. She has a maximum of 3.4 mm, 1.7 mm, and 9.3 mm for the projections of X translation, Y

Table 3.2

Projections in mm of the three jaw movement components onto resultant jaw displacement for V1t demisyllables

test	non-test		CG			JE			LF		
vowel	vowel	stress	TX	TY	R	TX	TY	R	TX	TY	R
a	i	+	5.6	1.2	8.0	7.0	3.3	14.1	2.0	.8	6.4
a	a	+	3.6	1.2	5.9	5.7	2.5	9.5	1.4	1.7	5.8
a	ae	+	4.3	1.1	6.9	5.2	3.7	10.2	1.7	1.4	6.0
a	i	-	3.9	1.4	5.6	1.9	2.1	6.6	2.5	.8	6.6
a	a	-	3.8	1.0	5.4	1.4	2.3	6.9	1.5	.3	2.9
a	ae	-	3.7	1.3	5.7	.9	1.6	5.4	1.4	.8	3.7
ae	i	+	4.6	1.4	7.5	4.6	3.2	15.2	3.4	1.3	6.6
ae	a	+	3.7	1.1	5.8	6.7	3.1	13.7	1.7	1.7	7.9
ae	ae	+	5.4	1.5	7.7	5.9	5.0	13.7	1.8	.9	7.6
ae	i	-	2.6	1.9	4.9	2.4	3.0	10.9	1.8	.8	7.3
ae	a	-	3.6	1.3	6.5	2.0	2.2	7.2	1.9	.5	6.5
ae	ae	-	4.5	1.1	5.9	1.7	2.6	8.1	1.5	1.4	5.9

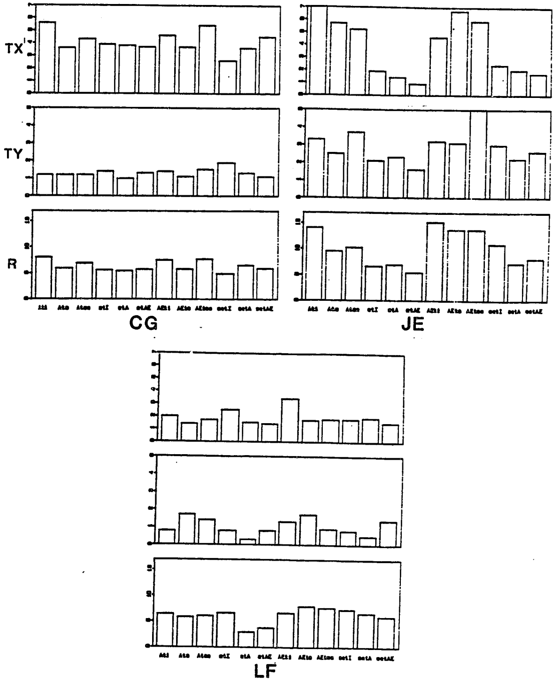

Figure 3.2 Histograms of the projections of the three jaw movement components onto resultant jaw displacement for the V1t demisyllables. The data for CG are shown on the top left plot; the data for JE are shown on the top right plot; the data for LF are shown on the bottom plot. In each set of plots, the top row shows the data for TX; the middle row shows the data for TY; the bottom row shows the data for R. Upper-case letters indicate stressed demisyllables; lower-case letters indicate unstressed demisyllables. The units on the y axis are mm.

translation, and rotation, respectively. CG again exhibits greater amounts of translation than LF and roughly comparable amounts of rotation. She has a maximum of 5.6 mm, 1.9 mm, and 8.0 mm for the projections of X translation, Y translation, and rotation, respectively. Thus, when the direction of movement is taken into account, the magnitude of the inter-subject differences decreases. Table 3.2 reveals that JE exhibits only twice as much X translation as LF and one and one-quarter as much X translation as CG.

3.1.3 Relative Contributions of the Three Jaw Movement Components to Resultant Jaw Displacement

The three subjects also differ with respect to the relative contributions of the three jaw movement components to resultant jaw displacement. These data are present in Table 3.3 and Fig. 3.3 for the V1t demisyllables. It can be observed that the relative contribution of rotation is greatest for LF (62 to 74%), less for JE (53 to 68%), and least for CG (52 to 57%). Conversely, the relative contribution of X translation is greatest for CG (31 to 39%) and roughly comparable for JE (11 to 32%) and LF (15 to 32%). Note that the relative contribution of Y translation is comparable for all three subjects: 8 to 20% for CG; 13 to 21% for JE; and 9 to 19% for LF.

3.1.4 Summary

The data in Tables 3.1, 3.2, and 3.3 reveal quantitative and gross qualitative differences among the three subjects. However, a finer-grained analysis of the relationships among the three jaw

Table 3.3

Relative (in %) contributions of three jaw movement components to resultant jaw displacement for V1t demisyllables

	non-			CG			JE			LF	
test vowel	test vowel	stress	TX	TY	R	TX	TY	R	TX	TY	R
a	i	+	38	08	54	29	14	58	22	09	70
a	a	+	34	11	55	32	14	54	16	19	65
a	ae	+	35	09	56	27	19	53	19	15	66
a	i	-	36	13	52	18	20	62	25	08	67
a	a	-	37	10	52	13	21	64	32	06	62
a	ae	-	35	12	54	11	20	68	24	14	63
ae	i	+	34	10	55	20	14	66	24	09	65
ae	a	+	35	10	54	29	13	58	15	15	69
ae	ae	+	38	10	53	24	20	56	17	09	73
ae	i	-	27	20	52	15	19	68	18	08	74
ae	a	-	31	11	57	18	19	63	22	06	74
ae	ae	-	39	10	52	14	21	65	17	16	68

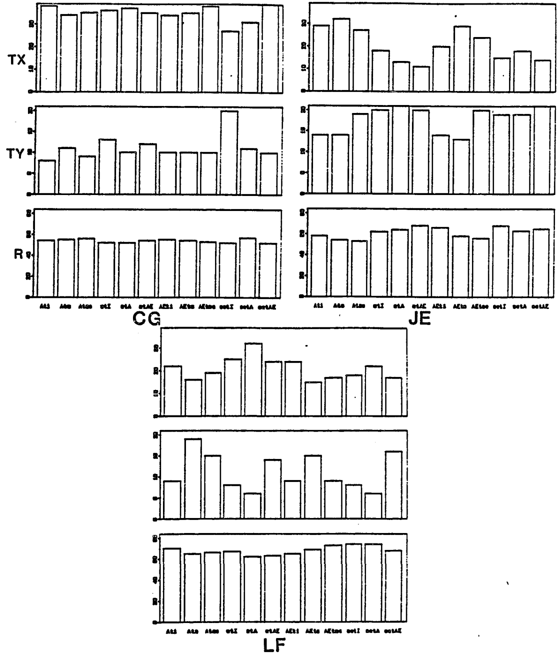

Figure 3.3 Histograms of the relative contributions of the three jaw movement components to resultant jaw displacment for the V1t demisyllables. The data for CG are shown on the top left plot; the data for JE are shown on the top right plot; the data for LF are shown on the bottom plot. In each set of plots, the top row shows the data for TX; the middle row shows the data for TY; the bottom row shows the data for R. Upper-case letters indicate stressed demisyllables; lower-case letters indicate unstressed demisyllables. The units on the y axis are percent.

movement components revealed similarities for CG and JE, as compared to LF. Let us first consider the results of the translation and rotation regression analyses for CG and JE.

3.2 Translation Analysis for CG and JE

3.2.1 Combination of Phonetic Parameters

As discussed in Chapter 2, the 54 utterance types differ along four phonetic parameters: stress pattern; identity of the vowel in the test syllable; identity of the vowel in the non-test syllable; and identity of the intervocalic consonant in the test utterance. Any combination of these phonetic parameters can be included as covariates in the regression model, but a covariate will make a significant contribution to a squared multiple correlation only if the effect of the phonetic characteristic it represents has a substantial linear component. Therefore, it was necessary to determine the maximal combination of phonetic characteristics that yielded linear effects. Table 3.4 gives the squared multiple correlations for the six utterance combinations described in Chapter 2 (Section 2.6.4.2) for all four demisyllable types. Note that the squared multiple correlations for the pV1 and the V2p demisyllables are similar to those for the V1C and the CV2 demisyllables, respectively. For this reason, the discussion will focus on the V1C and the CV2 demisyllables.

Several patterns can be observed in Table 3.4. First, the squared multiple correlations are generally greater for the demisyllables containing V2 than for those containing V1, when the utterance types

Table 3.4

Squared multiple correlations (TY on TX) for all of the utterance combinations of Chapter 2

Table 3.10

Squared multiple correlations (TY on TX) for all of the utterance combinations described in Chapter 2

Values of phonetic parameters if not combined				CG			
test vowel	non-test vowel	stress	consonant	pV1	V1C	CV2	V2p
i			t	.20	.11	.82	.85
a			t	.43	.29	.79	.82
ae			t	.16	.21	.75	.69
i			p	.61	.47	.47	.50
a			p	.38	.33	.87	.78
ae			p	.14	.11	.63	.41
i			s	.24	.16	.86	.85
a			s	.22	.35	.76	.46
ae			s	.30	.32	.79	.58
	i		t	.78	.48	.48	.46
	a		t	.63	.63	.24	.48
	ae		t	.54	.53	.29	.59
	i		p	.54	.68	.30	.53
	a		p	.83	.82	.30	.54
	ae		p	.40	.59	.24	.48
	i		s	.63	.71	.16	.60
	a		s	.75	.64	.49	.43
	ae		s	.85	.79	.42	.37
		+	t	.69	.65	.78	.79
		-	t	.66	.43	.84	.88
		+	p	.65	.71	.87	.80
		-	p	.58	.75	.61	.59
		+	s	.71	.70	.72	.79
		-	s	.73	.57	.77	.52
			t	.63	.51	.80	.80
			p	.58	.70	.72	.69
			s	.64	.58	.67	.59
			i	.46	.59	.27	.37
			a	.57	.43	.16	.27
			ae	.57	.61	.07	.10
				.19	.21	.10	.28

Table 3.4 (continued)

Values of phonetic parameters if not combined				JE			
test vowel	non-test vowel	stress	consonant	pV1	V1C	CV2	V2p
i			t	.34	.53	.65	.78
a			t	.46	.42	.55	.50
ae			t	.35	.42	.62	.64
i			p	.49	.32	.94	.88
a			p	.51	.48	.53	.70
ae			p	.41	.36	.76	.82
i			s				
a			s				
ae			s				
	i		t	.75	.78	.49	.48
	a		t	.69	.71	.44	.49
	ae		t	.38	.60	.49	.42
	i		p	.72	.83	.64	.66
	a		p	.70	.71	.37	.45
	ae		p	.66	.69	.42	.48
	i		s				
	a		s				
	ae		s				
		+	t	.51	.58	.55	.60
		-	t	.58	.58	.55	.55
		+	p	.69	.73	.67	.75
		-	p	.80	.87	.78	.83
		+	s				
		-	s				
			t	.42	.41	.41	.39
			p	.67	.72	.70	.76
			s				
			i	.28	.86	.33	.27
			a	.26	.55	.26	.23
			ae	.13	.33	.40	/35
				.30	.29	.29	.32

are combined across different stress patterns and different vowels in the non-test syllable (see the top-most block) and when the utterance types are combined across non-test vowels, stress, and intervocalic consonants (see the fifth block). Second, the squared multiple correlations are generally greater for the V1C demisyllables than for the CV2 ones, when the utterance types are combined across different stress patterns and different vowels in the test syllable (see the second block). Third, the squared multiple correlations generally decrease when the utterance types are combined across all four phonetic parameters (see the sixth block).

Given these patterns, the utterance types were combined across stress conditions and across vowels in the test and non-test syllables, but not across intervocalic consonants. This appears to be the optimal combination of phonetic parameters, using the definition given in Chapter 2, Section 2.6.4.2: first, the squared multiple correlations are high, relative to the overall range of squared multiple correlations for each subject; second, they are qualitatively similar both across demisyllable types. This result suggests that the vocalic parameters (i.e. vowel identity and stress) have effects with substantial linear components on jaw translation for these two subjects. On the other hand, the decrease in the squared multiple correlations when the utterance combinations are also combined across different intervocalic consonants suggests that the effect of consonant identity is non-linear.

The multiple regression equation that was used for the translation analysis was given in equation (2.9) and is repeated in (3.1) below.

$$(3.1)\quad \hat{Y} = a_1X_1 + a_2X_1^2 + a_3X_1^3 + a_4X_2 + a_5X_3 + a_6X_4 + a_7X_5 + a_8X_6 + a_9.$$

As discussed in Chapter 2, a cubic model was used. The covariates, X_2 and X_3 specify the identity of the test vowel; the covariates X_4 and X_5 specify the identity of the non-test vowel; the covariate, X_6 specifies the stress pattern. The results of the translation analyses revealed an assymetry between the effects of anticipatory and carryover coarticulation for both subjects.

3.2.2 Demisyllables Containing V1

Let us first consider the results for the two demisyllables containing V1. Table 3.5 gives the squared multiple correlations and the contributions of the phonetic covariates for the six multiple regression analyses of each subject. Figures 3.4 and 3.5 show the results of the regression analysis for the V1p demisyllables for subjects CG and JE, respectively. It should be noted that the units on both axes are mm x 10, but that the scale on the y axis relative to the x axis has been expanded for purposes of presentation. It can be observed that the identity of the vowel in the test syllable functions for both subjects to divide the V1p demisyllables into distinct groups. Notice that positions along the second principal axis correspond approximately to tongue front-back position for the vowels /ae/, /i/, /a/ for CG and /i/, /ae/, /a/ for JE. This will result in a more

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Table 3.5

Squared multiple correlations and contributions of covariates for TY regressed on TX for demisyllables containing V1

	demi-syllable	consonant	r2	test vowel	non-test vowel	stress
CG	PV1	t	.63	.12	.005	.05
	PV1	p	.58	.23	.004	.000
	PV1	s	.64	.40	.005	.009
	V1C	t	.51	.20	.01	.03
	V1C	p	.70	.36	.04	.04
	V1C	s	.58	.37	.002	.01
JE	PV1	t	.42	.04	.04	.02
	PV1	p	.67	.11	.001	.04
	PV1	s				
	V1C	t	.41	.05	.04	.01
	V1C	p	.72	.11	.003	.02
	V1C	s				

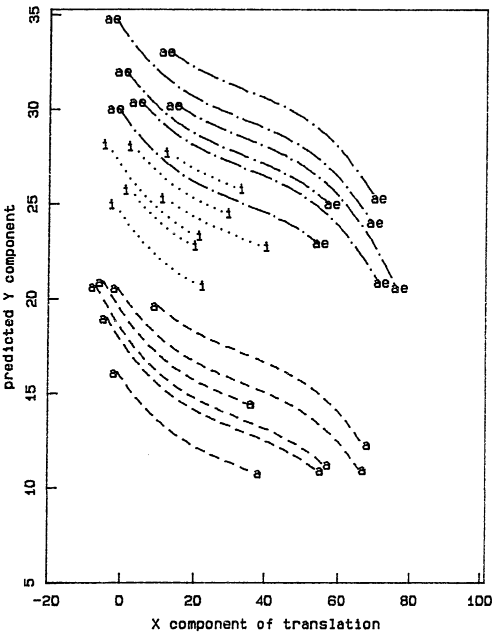

Figure 3.4 Predicted values of the Y component of jaw translation are plotted against values of the X component for the V1p demisyllables for CG. The dotted lines represent /ip/; the dashed lines represent /ap/; the dashed-and-dotted lines represent /aep/. The coordinate system has been rotated by 70 degrees clockwise.

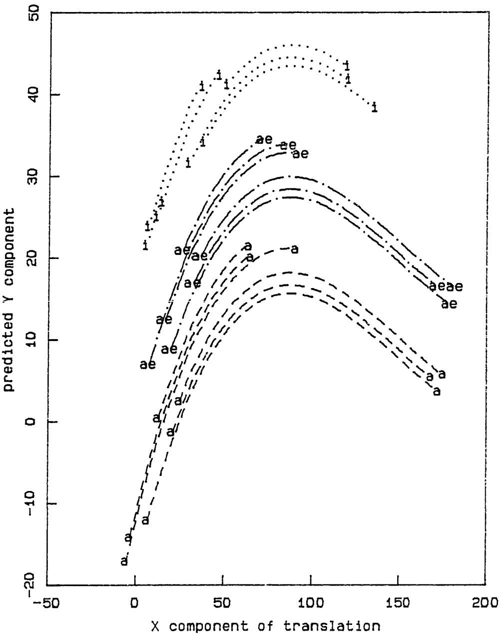

Figure 3.5 Predicted values of the Y component of jaw translation are plotted against values of the X component for the V1p demisyllables for je. The dotted lines represent /ip/; the dashed lines represent /ap/; the dashed-and-dotted lines represent /aep/. The coordinate system has been rotated by 36 degrees clockwise.

forward position of the mandible for front vowels, as compared to back vowels, in the unrotated coordinate systems for both CG and JE. It can also be observed that the cubic component of the function is much more pronounced for JE.

The stress pattern of the test syllable and the identity of the vowel in the non-test syllable both have similar effects on each of the three V1 to /p/ trajectories for both subjects. Therefore, let us consider only the /a/ to /p/ demisyllables, which are replotted in Figs. 3.6 and 3.7 for CG and JE, respectively. It can be observed that for both subjects the stress pattern functions to divide the /ap/ demisyllables into two groups and that stress differences primarily affect positions along the first principal component. Note also that the effect of the following vowel is similar for both stressed and unstressed demisyllables.

The squared multiple correlations are generally lower for both subjects when the intervocalic consonant is /t/, as compared to /p/. The reasons for this systematic decrease can be observed by comparing Figs. 3.8 and 3.9 which plot the V1p and the V1t demisyllables, respectively for CG. Figures 3.10 and 3.11 plot the corresponding demisyllables for JE. It should be noted here that for purposes of presentation, every fifth data point of each utterance token is plotted in all of the raw data plots for CG and JE in Chapters 3 and 4. For both CG and JE, it can be observed that there is much more overlap among the vowel groups when the intervocalic consonant is /t/, as compared to /p/. Furthermore, it can be observed that the orientations of the three vowels appear grossly similar for the V1p demisyllables

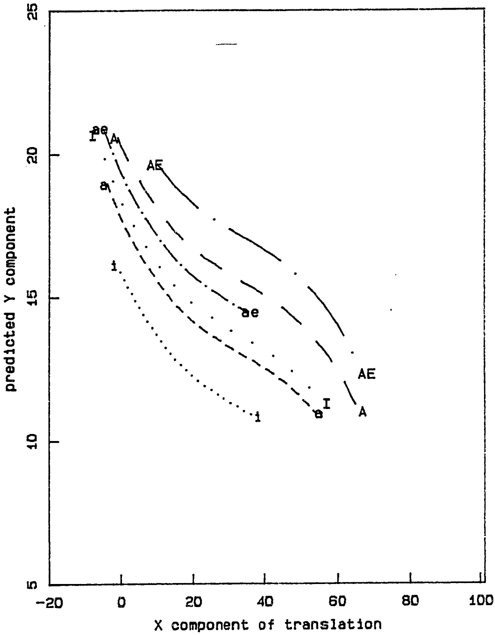

Figure 3.6 Predicted values of the Y component of jaw translation are plotted against values of the X component for the /ap/ demisyllables for CG. The dotted lines represent /ap/ demisyllables followed by /i/; the dashed lines represent /ap/ demisyllables followed by /a/; the dashed-and-dotted lines represent /ap/ demisyllables followed by /ae/. Upper-case letters represent stressed demisyllables; lower-case letters represent unstressed demisyllables.

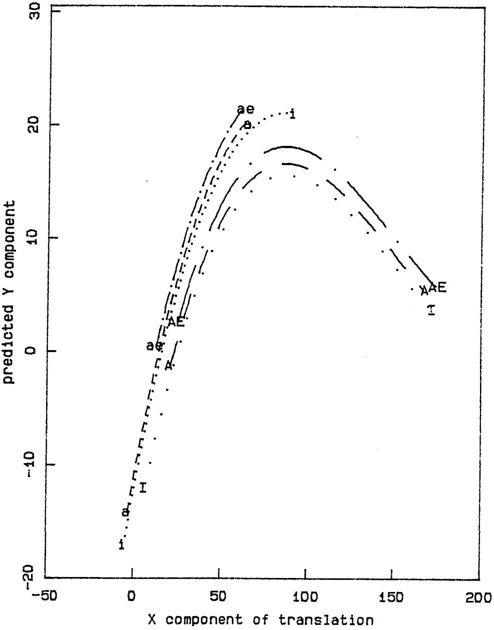

Figure 3.7 Predicted values of the Y component of jaw translation are plotted against values of the X component for the /ap/ demisyllables for JE. The dotted lines represent /ap/ demisyllables followed by /i/; the dashed lines represent /ap/ demisyllables followed by /a/; the dashed-and-dotted lines represent /ap/ demisyllables followed by /ae/. Upper-case letters represent stressed demisyllables; lower-case letters represent unstressed demisyllables.

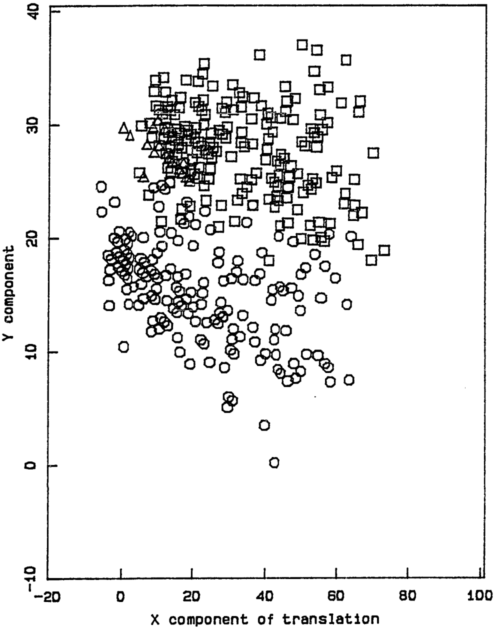

Figure 3.8 Values of the Y component of jaw translation are plotted against values of the X component for the V1p demisyllables for CG. Triangles represent /ip/; circles represent /ap/; squares represent /aep/. The coordinate system has been rotated by 70 degrees clockwise.

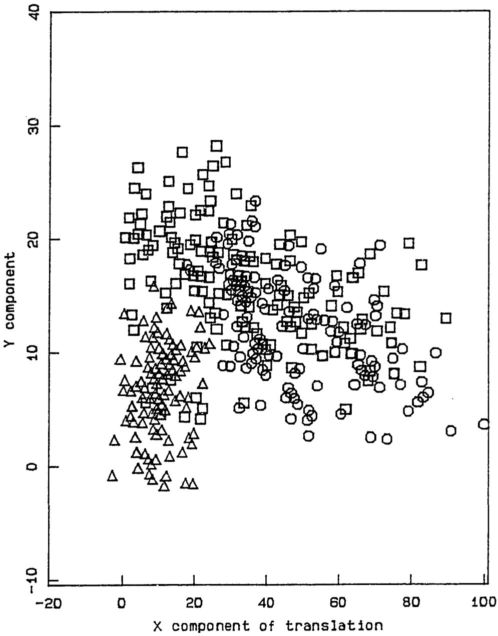

Figure 3.9 Values of the Y component of jaw translation are plotted against values of the X component for the V1t demisyllables for CG. Triangles represent /it/; circles represent /at/; squares represent /aet/. The coordinate system has been rotated by 61 degrees clockwise.

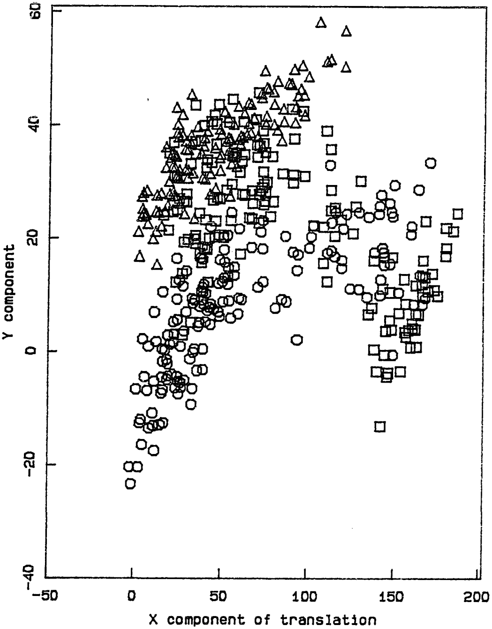

Figure 3.10 Values of the Y component of jaw translation are plotted against values of the X component for the V1p demisyllables for JE. Triangles represent /ip/; circles represent /ap/; squares represent /aep/. The coordinate system has been rotated by 36 degrees clockwise.

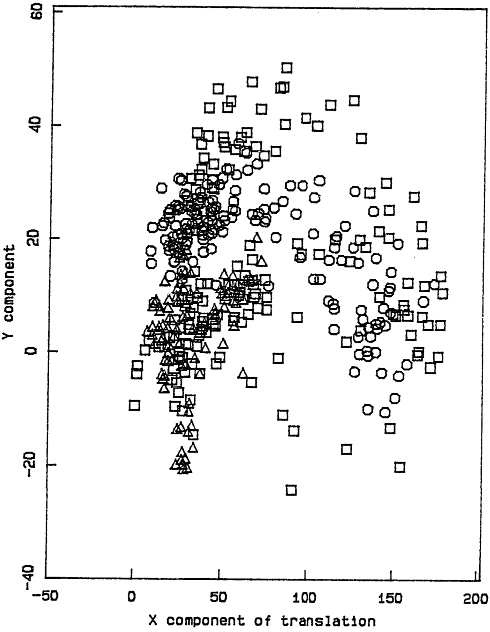

Figure 3.11 Values of the Y component of jaw translation are plotted against values of the X component for the V1t demisyllables for JE. Triangles represent /it/; circles represent /at/; squares represent /aet/. The coordinate system has been rotated by 34 degrees clockwise.

for both subjects. By contrast, the orientation of the /it/ trajectories appears to be dissimilar to the /at/ and /aet/ trajectories for both subjects. The phonetic covariates change the Y intercept of the regression equation, but they do not affect the slope of the function. Thus, the decrease in the squared multiple correlations for the V1t demisyllables, can be attributed to the increased overlap among the different vowel groups and to the different orientation of the /it/ , as compared to the /at/ and /aet/ demisyllables.

Figures 3.12 and 3.13 plot the predicted values of the Y component of translation against the x component of translaton for the V1t demisyllables for CG and JE, respectively. A comparison of Figs. 3.12 and 3.13 with Figs. 3.4 and 3.5 reveals why the utterance types could not be combined across different intervocalic consonants. It can be observed that for CG, the /it/ trajectories are below the /at/ trajectories, whereas the /ip/ trajectories are above the /ap/ trajectories. Similarly, it can be observed that for JE, the /it/ trajectories are below the /at/ and /aet/ trajectories, whereas the /ip/ trajectories are above to the /ap/ and /aep/ trajectories. Thus, for the V1t demisyllables, the relative position of the three vowels along the second principal axis does not correspond to tongue front-back position. For both CG and JE, Y positions for the /at/ and /aet/ trajectories overlap and /i/ is inferior to /a/ for both subjects.

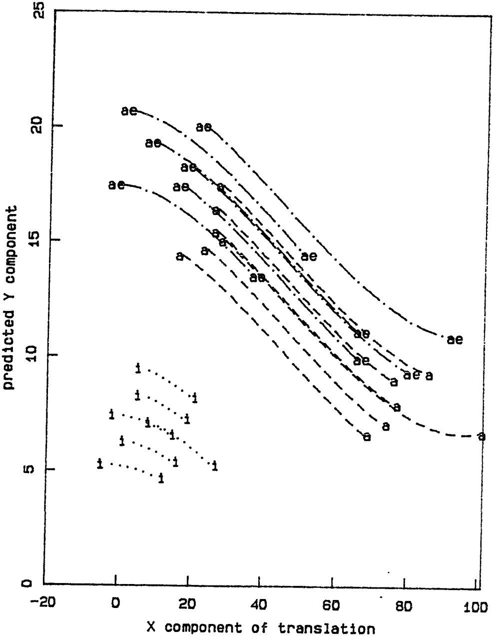

Figure 3.12 Predicted values of the Y component of jaw translation are plotted against values of the X component for the V1t demisyllables for CG. The dotted lines represent /it/; the dashed lines represent /at/; the dashed-and-dotted lines represent /aet/. The coordinate system has been rotated by 61 degrees clockwise.

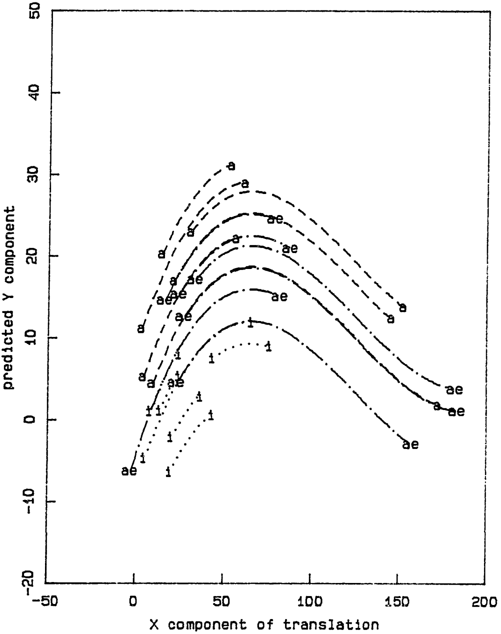

Figure 3.13 Predicted values of the Y component of jaw translation are plotted against values of the X component for the V1t demisyllables for JE. The dotted lines represent /it/; the dashed lines represent /at/; the dashed-and-dotted lines represent /æt/. The coordinate system has been rotated by 34 degrees clockwise.

As Table 3.5 illustrates, the relative effects of the other two phonetic covariates (identity of the non-test vowel and stress) were of similar magnitude for all three intervocalic consonants.

3.2.3 Demisyllables Containing V2

However, the relative effects of three phonetic parameters under consideration are somewhat different for the demisyllables containing V2 (CV2 and V2p). Table 3.6 gives the squared multiple correlations and the contribution of the phonetic covariates of these six multiple regression analyses for each subject. Figures 3.14 and 3.15 illustrate the results of the multiple regression analyses for the pV2 demisyllables for CG and JE, respectively. It can be observed that for both subjects, although the identity of the vowel in the test syllable is significant, it does not function to divide the trajectories into three distinct groups. However, the identity of the preceding (non-test) vowel does have such an effect, as shown in Figs. 3.16 and 3.17 for CG and JE, respectively. It is clear the the identity of the preceding vowel functions for both subjects to divide the pV2 demisyllables into three distinct groups with no overlap. By contrast, the effect of the vowel in the test syllable is to divide each of these three groups into three subgroups, as illustrated by Figs. 3.14 and 3.15. In the pV2 demisyllables, as in the V1p demisyllables, positions along the second principal axis correspond approximately to tongue front-back positions: /ae/, /i/, /a/ for CG and /i/, /ae/, /a/ for JE.

Table 3.6

Squared multiple correlations and contributions of covariates for TY regressed on TX for demisyllables containing V2

	demi-syllable	consonant	r2	test vowel	non-test vowel	stress
CG	CV2	t	.80	.006	.32	.03
	CV2	p	.72	.01	.41	.000
	CV2	s	.67	.006	.41	.000
	V2P	t	.80	.04	.26	.02
	V2P	p	.69	.06	.27	.001
	V2P	s	.56	.05	.27	.000
JE	CV2	t	.41	.008	.05	.004
	CV2	p	.70	.008	.11	.002
	CV2	s				
	V2P	t	.39	.01	.04	.000
	V2P	p	.76	.008	.10	.01
	V1C	s				

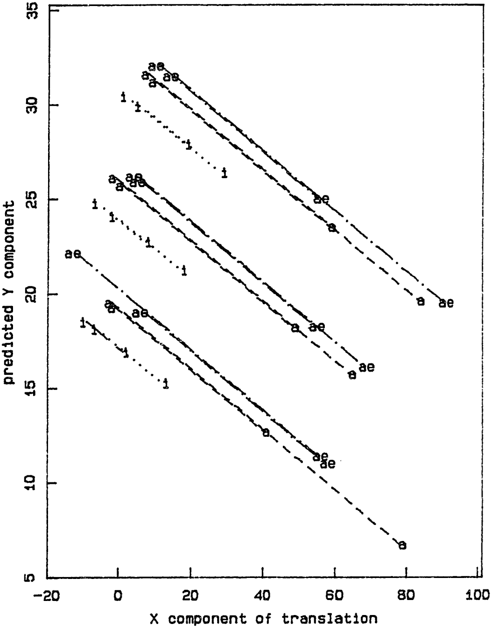

Figure 3.14 Predicted values of the Y component of translation are plotted against values of the X component for the pV2 demisyllables for CG. The dotted lines represent /pi/; the dashed lines represent /pa/; the dashed-and-dotted lines represent /pae/. The coordinate system has been rotated by 70 degrees clockwise.

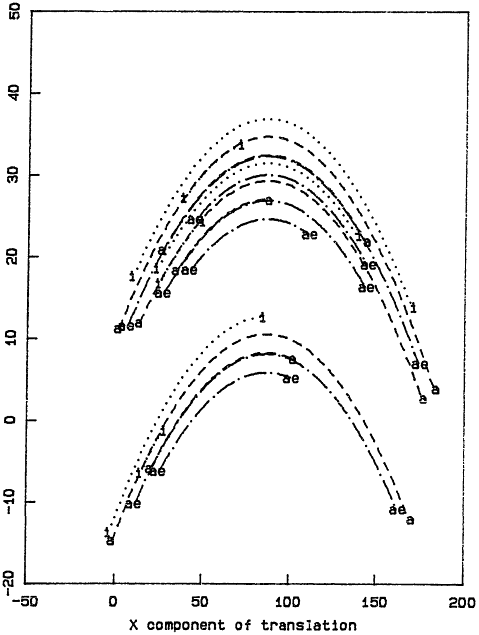

Figure 3.15 Predicted values of the Y component of translation are plotted against values of the X component for the pV2 demisyllables for JE. The dotted lines represent /pi/; the dashed lines represent /pa/; the dashed-and-dotted lines represent /pae/. The coordinate system has been rotated by 31 degrees clockwise.

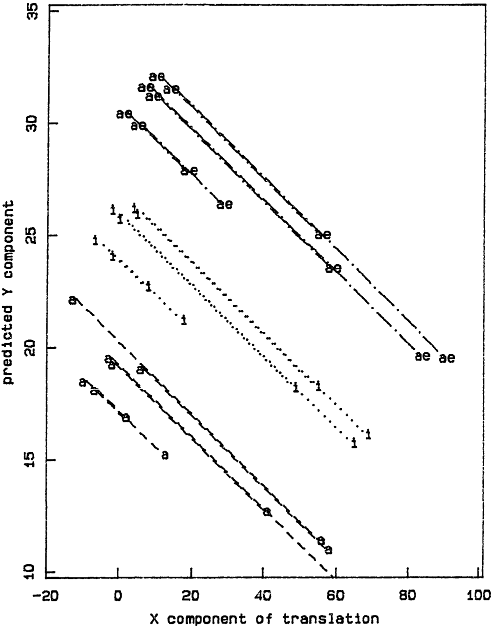

Figure 3.16 Predicted values of the Y component of translation are plotted against values of the X component for the pV2 demisyllables for CG. The dotted lines represent pV2 demisyllables preceded by /i/; the dashed lines represent pV2 demisyllables preceded by /a/; the dashed-and-dotted lines represent pV2 demisyllables preceded by /ae/.

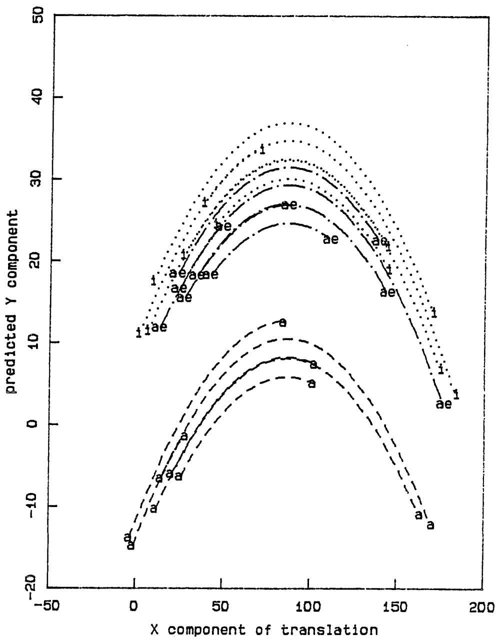

Figure 3.17 Predicted values of the Y component of translation are plotted against values of the X component for the pV2 demisyllables for JE. The dotted lines represent pV2 demisyllables preceded by /i/; the dashed lines represent pV2 demisyllables preceded by /a/; the dashed-and-dotted lines represent pV2 demisyllables preceded by /ae/.

The effect of the stress pattern of the test syllable on the two V2 demisyllables is similar for each of the three non-test vowels for both subjects. Therefore, let us consider the pV2 demisyllables preceded by /a/, which are plotted in Figs. 3.18 and 3.19 for CG and JE, respectively. For CG, it can be observed that the trajectories of stressed and unstressed demisyllables for each test vowel lie along the same path, but that the stressed demisyllables exhibit more extensive anterior-inferior movement than their unstressed counterparts. For JE, the differences between stressed and unstressed demisyllables are observed primarily along the first principal axis, with stressed demisyllables anterior to their unstressed counterparts.

Subjects JE and CG differ in that for JE, but not for CG, the squared multiple correlations for the demisyllables containing V2 are systematically lower when the intervocalic consonant is /t/, as compared to /p/. This decrease in the squared multiple correlation can again be attributed to a greater overlap among the different trajectory types when the intervocalic consonant is /t/. Figures 3.20 and 3.21 plot the pV2 and tV2 demisyllables, respectively for JE. The x component of jaw translation is plotted along the x axis and the y component of jaw translation is plotted along the y axis. The data points are coded by the identity of the preceding (non-test) vowel. It can be observed that there is more overlap between the three non-test vowel groups for the tV2 demisyllables in Fig. 3.21, than for the corresponding pV2 demisyllables in Fig. 3.20.

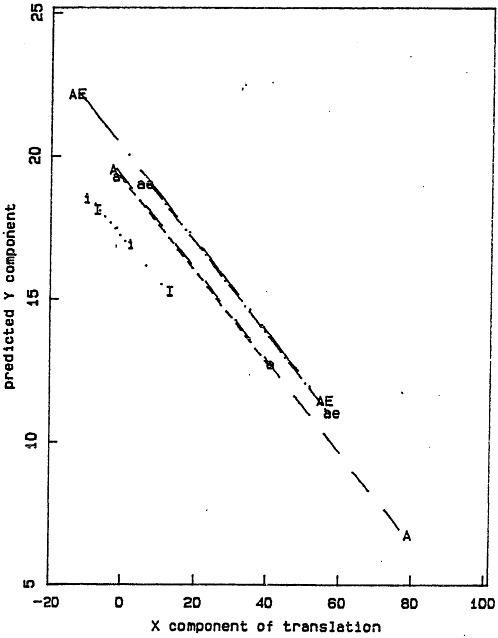

Figure 3.18 Predicted values of the Y component of translation are plotted against values of the X component for the pV2 demisyllables preceded by /a/ for CG. The dotted lines represent /pi/; the dashed lines represent /pa/; and the dashed-and-dotted lines represent /pae/. Upper-case letters represent stressed demisyllables; lower-case letters represent unstressed demisyllables.

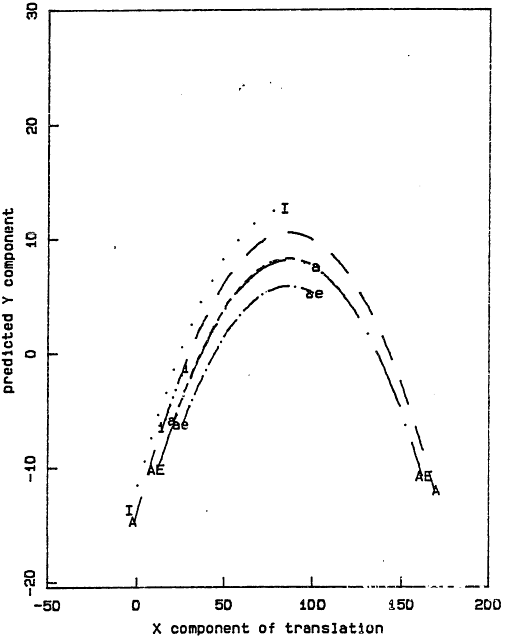

Figure 3.19 Predicted values of the Y component of translation are plotted against values of the X component for the pV2 demisyllables preceded by /a/ for JE. The dotted lines represent /pi/; the dashed lines represent /pa/; and the dashed-and-dotted lines represent /pae/. Upper-case letters represent stressed demisyllables; lower-case letters represent unstressed demisyllables.

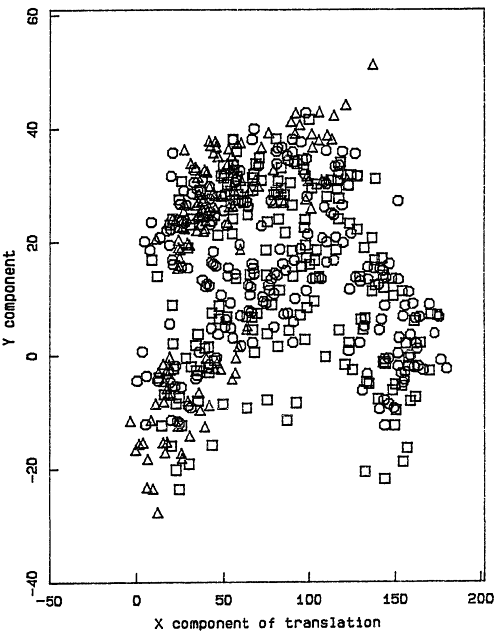

Figure 3.20 Values of the Y component of translation are plotted against values of the X component for the pV2 demisyllables for JE. Triangles represent pV2 demisyllables preceded by /i/; circles represent pV2 demisyllables preceded by /a/; squares represent pV2 demisyllables preceded by /ae/. The coordinate system has been rotated by 31 degrees clockwise.

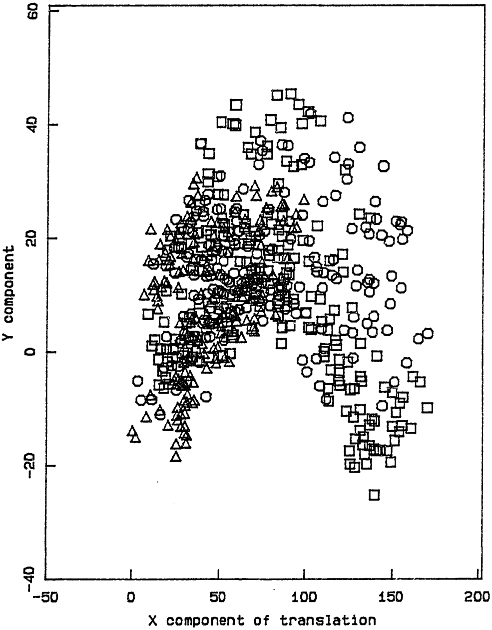

Figure 3.21 Values of the Y component of translation are plotted against values of the X component for the tV2 demisyllables for JE. Triangles represent tV2 demisyllables preceded by /i/; circles represent tV2 demisyllables preceded by /a/; squares represent tV2 demisyllables preceded by /ae/. The coordinate system has been rotated by 32 degrees clockwise.

Figures 3.22 and 3.23 plot the predicted values of the y component of translation against the values of the x component of translation for the tV2 demisyllables for CG and JE, respectively. As for the V1p and V1t demisyllables, a comparison of the pV2 and the tV2 demisyllables reveals why the utterance types could not be combined across different intervocalic consonants. It can be observed that for CG, the tV2 trajectories preceded by /i/ are inferior to those preceded by /a/, whereas the pV2 trajectories preceded by /i/ are superior to those preceded by /a/. Similarly, for JE, the tV2 trajectories preceded by /i/ are inferior to those preceded by /a/ and /ae/, whereas the pV2 trajectories preceded by /i/ are superior to those preceded by /a/ or /ae/. For the tV2 demisyllables, like the V1t demisyllables, the relative positions of the non-test vowel groups along the second principal axis doe not correspond to tongue front-back position for vowels. The trajectories overlap for the non-test vowels /a/ and /ae/ and both groups are superior to tV2 trajectories preceded by /i/.

As shown in Table 3.6, the relative effects of the three phonetic parameters under consideration are similar for the three utterance combinations within each of the two V2 demisyllables. From an examination of Tables 3.5 and 3.6, it can be observed that for both the two demisyllables containing V1 as well as the two demisyllables containing V2, the influence of the non-test vowel is greater on the immediately adjacent than on the subjacent demisyllable for both subjects. A sign tests revealed these differences to be significant for CG (p < .05). For JE, the sample size was too small to test the significance of this effect.

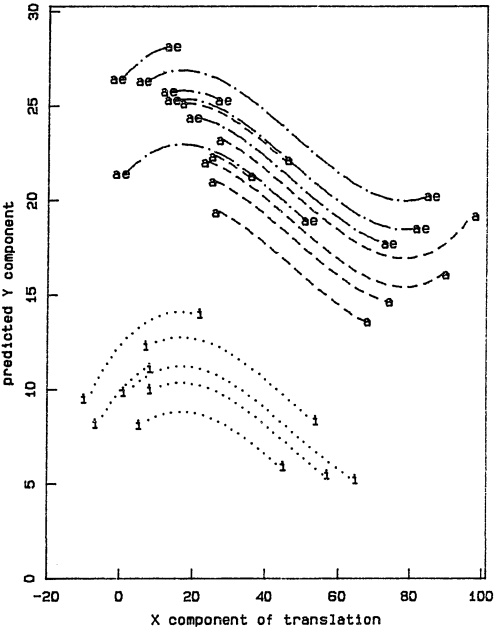

Figure 3.22 Predicted values of the Y component of translation are plotted against the X component for the tV2 demisyllables for CG. The dotted lines represent tV2 demisyllables preceded by /i/; the dashed lines represent tV2 demisyllables preceded by /a/; the dashed-and-dotted lines represent tV2 demisyllables preceded by /ae/. The coordinate system has been rotated by 64 degrees clockwise.

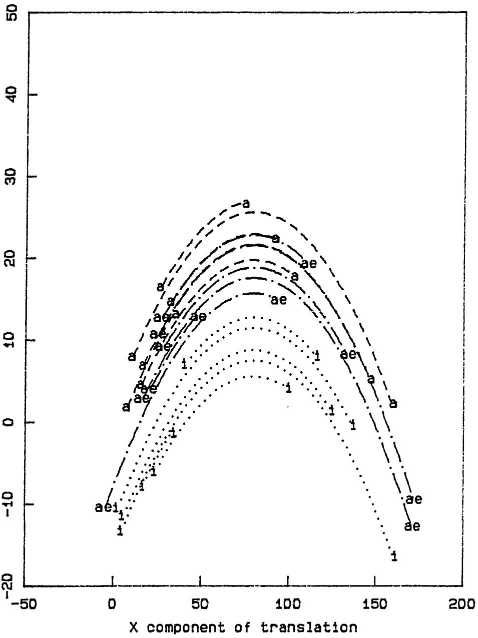

Figure 3.23 Predicted values of the Y component of translation are plotted against the X component for the tV2 demisyllables for JE. The dotted lines represent tV2 demisyllables preceded by /i/; the dashed lines represent tV2 demisyllables preceded by /a/; the dashed-and-dotted lines represent tV2 demisyllables preceded by /ae/. The coordinate system has been rotated by 32 degrees clockwise.

3.2.4 Summary

These results can be summarized as follows: for the two demisyllables containing V1, the influence of the vowel in the test syllable was substantially greater than that of the vowel in the non-test syllable. By contrast, for the two demisyllables containing V2, the influence of the identity of the vowel in the non-test syllable is substantially greater than that of the vowel in the test syllable. The effect of stress is similar for all four demisyllables. These results indicate an assymetry between anticipatory and carryover coarticulation. That is, the second principal component of jaw translation for these two subjects is more sensitive to carryover than to anticipatory coarticulatory influences. It should be noted that a similar assymetery between anticipatory and carryover coarticulation has been observed in VCV contexts by Sussman, et.al. (1973) for several of the mandibular muscles and by Bell-Berti and Harris (1976) for the genioglossus muscle and in three acoustic studies (Bell-Berti and Harris, 1976; Fowler, 1981; Ohde and Sharf, 1977).

More generally, these results indicate that the relationship between the first two principal components of translation is highly dependent on the phonetic context. The phonetic covariates consistently account for a substantial proportion of the variance and the relative importance of different phonetic parameters varies over time. Furthermore, the total amount of variance accounted for by the translation model varies significantly across different utterance types for both subjects, ranging from .51 to .80 for CG and from .39 to .76 for JE. These results indicate that the relationship between the first two principal components of jaw translation is not highly constrained during speech, but varies with the phonetic context and perhaps also with other as-yet-undetermined factors.

3.3 Rotation Analysis for CG and JE

3.3.1 Combination of Phonetic Parameters

The second series of multiple regression analyses were performed in order to describe jaw rotation as a function of the first principal component of jaw translation. For these analyses also, the squared multiple correlations for all of the utterance type combinations described in Chapter 2 (Section 2.6.4.2) were computed. Table 3.7 gives these results for all four demisyllables for both subjects. Again, note that the squared multiple correlations for the pV1 and the V2p demisyllables are similar to those for the V1C and the CV2 demisyllables, respectively. Therefore, the discussion will continue to focus on the V1C and the CV2 demisyllables.

A comparison of Tables 3.4 and 3.7 reveals several differences between the patterns of results for the translation and rotation analyses. First, the squared multiple correlations are substantially higher for the rotation analysis, as compared to the translation analysis. Second, the proportion of variance accounted for remains relatively constant across different combinations of phonetic parameters for the rotation analysis, in contrast to the translation analysis. The only exception to this second generalization is a small decrease of the squared multiple correlations for CG when the utterance

Table 3.7

Squared multiple correlations (θ on TX) for all of the utterance combinations described in Chapter 2

Values of phonetic parameters if not combined				CG			
test vowel	non-test vowel	stress	consonant	pV1	V1C	CV2	V2p
i			t	.27	.10	.68	.87
a			t	.61	.86	.88	.85
ae			t	.52	.69	.81	.78
i			p	.33	.59	.37	.35
a			p	.72	.86	.93	.91
ae			p	.75	.88	.83	.62
i			s	.38	.45	.16	.09
a			s	.83	.83	.81	.81
ae			s	.46	.39	.62	.81
	i		t	.76	.80	.88	.93
	a		t	.79	.85	.90	.91
	ae		t	.77	.81	.76	.77
	i		p	.89	.92	.94	.92
	a		p	.81	.86	.87	.83
	ae		p	.70	.82	.90	.84
	i		s	.80	.72	.47	.67
	a		s	.85	.81	.87	.82
	ae		s	.69	.68	.54	.51
		+	t	.75	.83	.90	.88
		–	t	.70	.74	.80	.82
		+	p	.86	.91	.91	.87
		–	p	.59	.77	.85	.81
		+	s	.74	.71	.84	.87
		–	s	.74	.61	.50	.64
			t	.67	.75	.82	.83
			p	.74	.84	.87	.80
			s	.62	.56	.58	.65
i				.33	.38	.65	.55
a				.66	.83	.69	.61
ae				.49	.72	.63	.51
				.50	.59	.62	.62

Table 3.7 (continued)

Values of phonetic parameters if not combined				JE			
				pV1	V1C	CV2	V2p
test vowel	non-test vowel	stress	conso-nant				
i			t	.55	.53	.89	.91
a			t	.99	.98	.97	.99
ae			t	.98	.97	.97	.98
i			p	.95	.94	.95	.97
a			p	.99	.99	.97	.99
ae			p	.98	.98	.98	.99
i			s				
a			s				
ae			s				
	i		t	.97	.97	.97	.98
	a		t	.97	.98	.98	.99
	ae		t	.97	.97	.96	.98
	i		p	.97	.98	.98	.99
	a		p	.99	.98	.98	.99
	ae		p	.99	.98	.98	.99
	i		s				
	a		s				
	ae		s				
		+	t	.97	.97	.97	.98
		-	t	.96	.94	.96	.98
		+	p	.99	.98	.98	.99
		-	p	.94	.96	.97	.98
		+	s				
		-	s				
			t	.96	.96	.96	.98
			p	.98	.97	.98	.98
			s				
i				.80	.90	.97	.89
a				.98	.98	.97	.97
ae				.97	.97	.96	.98
				.96	.95	.96	.97

types are combined across the identity of the intervocalic consonant in the test utterance. Third, within a particular combination of phonetic parameters, the proportion of variance accounted for remains relatively constant across different values of these parameters for the rotation analysis, in contrast to the translation analysis. The only exceptions to this third generalization are that the squared multiple correlations are generally lower for utterance combinations that contain only the vowel /i/ in either the test or non-test syllable or those that contain the intervocalic consonant /s/. Fourth, the proportion of the variance accounted for is similar for both demisyllables containing V1 and those containing V2 within each combination of phonetic parameters for the rotation analysis, in contrast to the translation analysis.

Thus, all of the phonetic parameters (with the possible exception of intervocalic consonant identity) appear to have additive or negligible effects on the relationship between jaw rotation and jaw translation for these two subjects. In order to facilitate comparisons between the translaton and rotation models, the same combination of phonetic parameters were used for the rotation analyses as had been used for the translation analyses. The regression equation used for the rotation analysis was given in equation (2.10) and is repeated in (3.2), below. below.

$$(3.2)\ \hat{\theta} = b_1X_1 + b_2X_1^2 + b_3X_2 + b_4X_3 + b_5X_4 + b_6X_5 + b_7X_6 + b_8.$$

The only difference between the two models is that a quadratic rather than a cubic model was used for the rotation analyses, as discussed in

Chapter 2.

The results for the rotation analyses differ from the results of the translation analyses in that the phonetic covariates provide substantially smaller contributions to the squared multiple correlations. This difference between the two analyses suggests that the function relating jaw rotation to jaw translation is relatively independent of phonetic context for these two subjects.

3.3.2 Demisyllables Containing V1

Let us first consider the demisyllables containing V1. Table 3.8 gives the squared multiple correlations and the contribution of each phonetic parameter for the six multiple regression analyses. It can be observed that the phonetic covariates account for a maximum of 17% (pV1, C=/p/) and 2% (pV1, C=/p/) of the variance for CG and JE respectively. By contrast, Table 3.5 shows that the phonetic covariates account for up to 41% (pV1, C=/s/) and 12% (pV1 and V1p, C=/p/) of the variance for CG and JE respectively for the corresponding translation analyses.

Figures 3.24 and 3.25 show the results of the regression analysis for the V1p demisyllables for subjects CG and JE, respectively. In both figures, the x component of translation, the predicting variable, is plotted along the x axis, and the predicted values of the angle of jaw rotation are plotted along the y axis. The units on the x axis are mm x 10 and the units on the y axis are degrees x 100. It can be observed that for both subjects the identity of the vowel in the test

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Table 3.8

Squared multiple correlations and contributions of covariates for θ regressed on TX for demisyllables containing V1

	demi-syllable	consonant	r2	test vowel	non-test vowel	stress
CG	pV1	t	.67	.10	.002	.004
	pV1	p	.74	.11	.05	.005
	pV1	s	.62	.03	.01	.01
	V1C	t	.75	.10	.007	.01
	V1C	p	.84	.08	.04	.000
	V1C	s	.56	.03	.000	.02
JE	pV1	t	.96	.01	.002	.004
	pV1	p	.98	.007	.007	.01
	pV1	s				
	V1C	t	.98	.01	.002	.003
	V1C	p	.98	.004	.01	.000
	V1C	s				

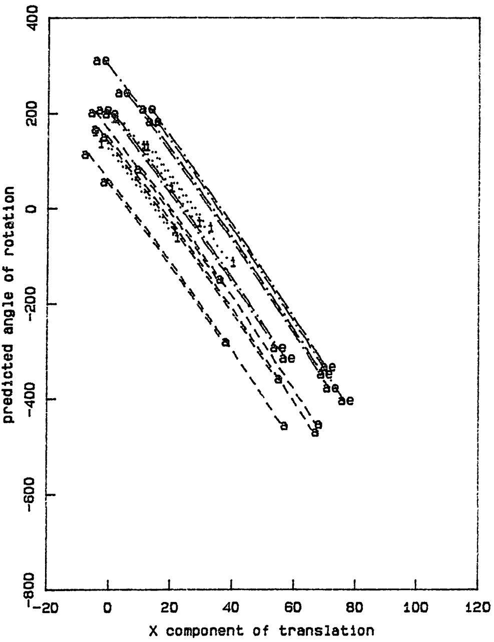

Figure 3.24 Predicted values of the angle of jaw rotation are plotted against values of the X component for the V1p demisyllables for CG. The dotted lines represent /ip/; the dashed lines represent /ap/; the dashed-and-dotted lines represent /aep/.

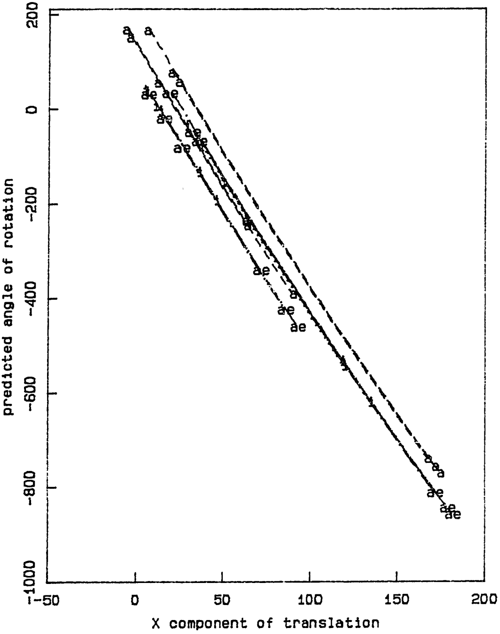

Figure 3.25 Predicted values of the angle of jaw rotation are plotted against values of the X component for the V1p demisyllables for je. The dotted lines represent /ip/; the dashed lines represent /ap/; the dashed-and-dotted lines represent /aep/.

syllable functions to divide the V1p demisyllables into six groups, two for each vowel. The subjects differ in that for CG the demisyllables containing the front vowels /ae/ and /i/, in contrast to those containing /a/, generally exhibit a greater amount of translation for a given angle of rotation. For JE, however, the demisyllables containing /a/, as compared to those containing /i/ or /ae/, generally exhibit a greater amount of translation for a given angle of rotation.

The effects of the following (non-test) vowel are similar for all three V1 to /p/ trajectories. Therefore, let us consider only the /ap/ demisyllables, which are plotted in Figs. 3.26 and 3.27 for CG and JE, respectively. A somewhat different pattern is observed for the two subjects. For CG, both the stressed and unstressed demisyllables followed by /i/ exhibit a lesser amount of translation for a given angle of rotation, as compared to the stressed and unstressed demisyllables followed by /a/ and /ae/. For JE, however, no effect of the following vowel is observed: all three stressed demisyllables exhibit a greater amount of translation for a given angle of rotation.

V1p demisyllables followed by /a/ are plotted in Figs. 3.28 and 3.29. Again, the two subjects exhibit somewhat different patterns. For CG, no effect of stress is observed. For JE, stressed /at/ and /aet/ demisyllables exhibit a greater amount of translation for a given angle of rotation than their unstressed counterparts.

Figures 3.30 and 3.31 plot the predicted values of the angle of rotation against the values of the x component of translation for the V1t demisyllables for CG and JE, respectively. As for the translation

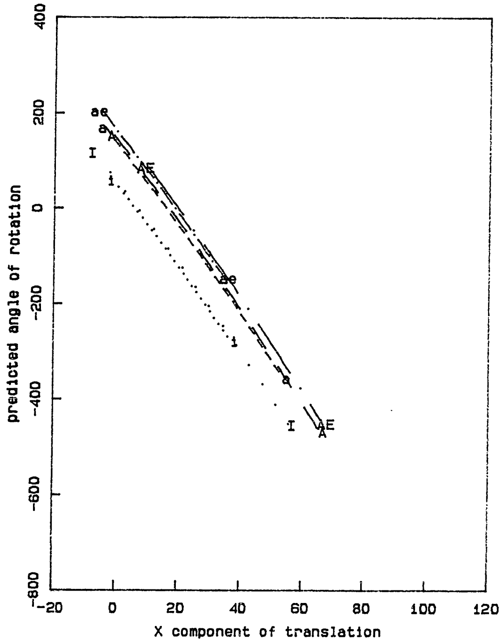

Figure 3.26 Predicted values of the angle of jaw rotation are plotted against values of the X component for the /ap/ demisyllables for CG. The dotted lines represent /ap/ demisyllables followed by /i/; the dashed lines represent /ap/ demisyllables followed by /a/; the dashed-and-dotted lines represent /ap/ demisyllables followed by /ae/. Upper-case letters represent stressed demisyllables; lower-case letters represent unstressed demisyllables.

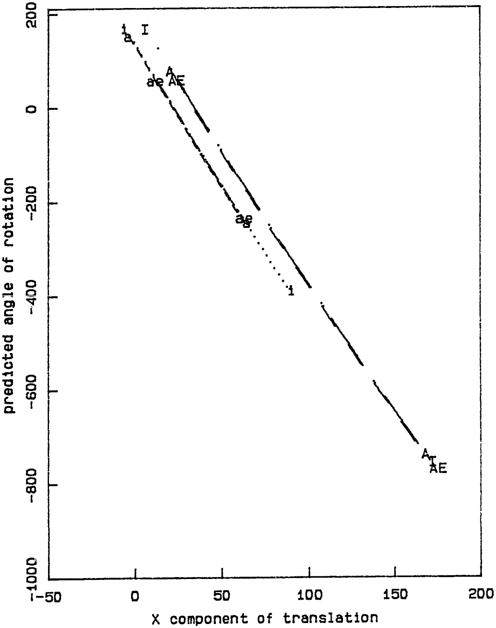

Figure 3.27 Predicted values of the angle of jaw rotation are plotted against values of the X component for the /ap/ demisyllables for JE. The dotted lines represent /ap/ demisyllables followed by /i/; the dashed lines represent /ap/ demisyllables followed by /a/; the dashed-and-dotted lines represent /ap/ demisyllables followed by /ae/. Upper-case letters represent stressed demisyllables; lower-case letters represent unstressed demisyllables.

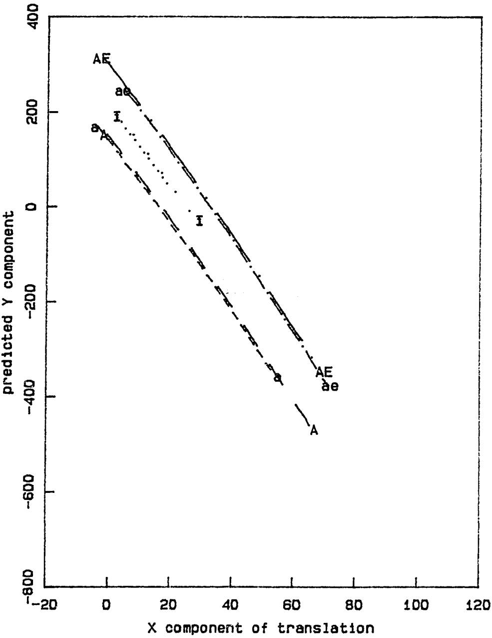

Figure 3.28 Predicted values of the angle of jaw rotation are plotted against values of the X component of translation for the V1p demisyllables followed by /a/ for CG. The dotted lines represent /ip/; the dashed lines represent /ap/; the dashed-and-dotted lines represent /aep/. Upper-case letters represent stressed demisyllables; lower-case letters represent unstressed demisyllables.

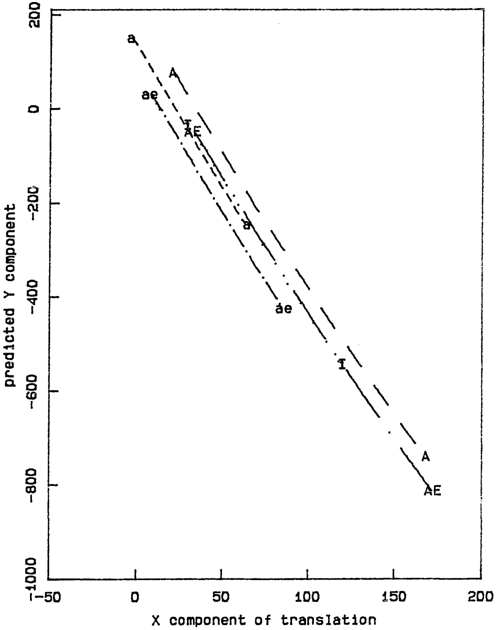

Figure 3.29 Predicted values of the angle of jaw rotation are plotted against values of the X component of translation for the V1p demisyllables followed by /a/ for JE. The dotted lines represent /ip/; the dashed lines represent /ap/; the dashed-and-dotted lines represent /aep/. Upper-case letters represent stressed demisyllables; lower-case letters represent unstressed demisyllables.

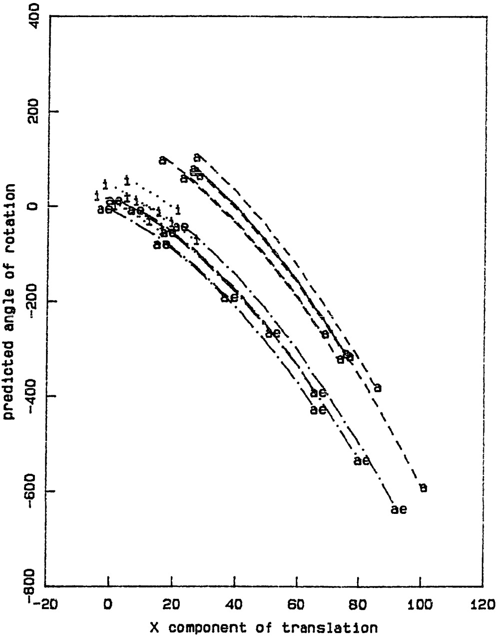

Figure 3.30 Predicted values of the angle of jaw rotation are plotted against values of the X component for the V1t demisyllables for CG. The dotted lines represent /it/; the dashed lines represent /at/; the dashed-and-dotted lines represent /aet/.

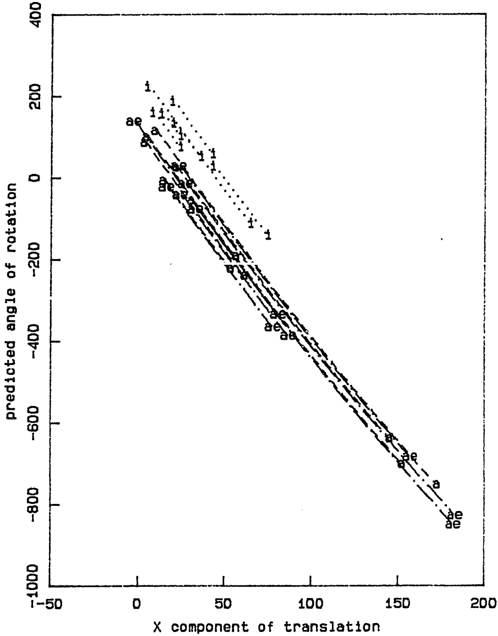

Figure 3.31 Predicted values of the angle of jaw rotation are plotted against values of the X component for the V1t demisyllables for JE. The dotted lines represent /it/; the dashed lines represent /at/; the dashed-and-dotted lines represent /aet/.

model, a comparison of Figs. 3.24 and 3.25 with Figs. 3.30 and 3.31 reveals consonant-dependent differences. It can be observed that for CG, the /at/ trajectories are anterior to the /aet/ trajectories, whereas the /ap/ trajectories are posterior to the /aep/ trajectories. For JE, the /it/ trajectories are anterior to the /at/ trajectories, whereas the /ip/ trajectories are posterior to the /ap/ trajectories.

As Table 3.8 illustrates, the relative effects of the three phonetic parameters under consideration are similar for all three intervocalic consonants.

3.3.3 Demisyllables Containing V2

Let us now consider the demisyllables containing V2. Table 3.9 gives the squared multiple correlations and the contributions of each phonetic parameter for the six multiple regression analyses for the CV2 and the V2p demisyllables. It can be observed that the results for the V1 and V2 demisyllables are similar in that the contribution of the phonetic covariates is again quite small. Table 3.9 shows that the phonetic covariates account for a maximum of 12% and 3% of the variance for CG and JE respectively. By contrast, Table 3.6 shows that the phonetic covariates account for up to 42% and 12% of the variance for CG and JE respectively for the translation analyses.

In Figs. 3.32 and 3.33, the pV2 demisyllables are plotted for CG and JE, respectively, coded by the identity of the vowel in the test syllable. Extensive overlap among the three vowel groups can be observed for both subjects. In Figs. 3.34 and 3.35, the pV2

Table 3.9

Squared multiple correlations and contributions of covariates for θ regressed on TX for demisyllables containing V2

	demi-syllable	consonant	r2	test vowel	non-test vowel	stress
CG	CV2	t	.82	.04	.07	.005
	CV2	p	.86	.01	.05	.003
	CV2	s	.58	.08	.005	.002
	V2P	t	.83	.01	.01	.003
	V2P	p	.80	.01	.02	.002
	V2P	s	.65	.08	.003	.002
JE	CV2	t	.96	.007	.01	.01
	CV2	p	.98	.006	.006	.002
	CV2	s				
	V2P	t	.98	.005	.005	.001
	V2P	p	.98	.000	.002	.000
	V2P	s				

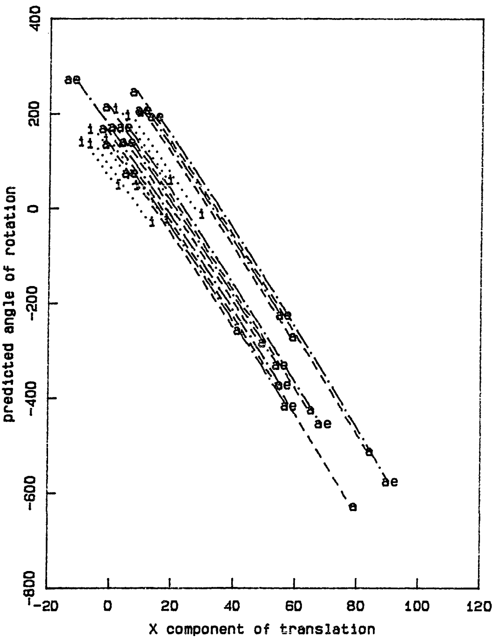

Figure 3.32 Predicted values of the angle of rotation are plotted against values of the X component for the pV2 demisyllables for CG. The dotted lines represent /pi/; the dashed lines represent /pa/; the dashed-and-dotted lines represent /pae/.

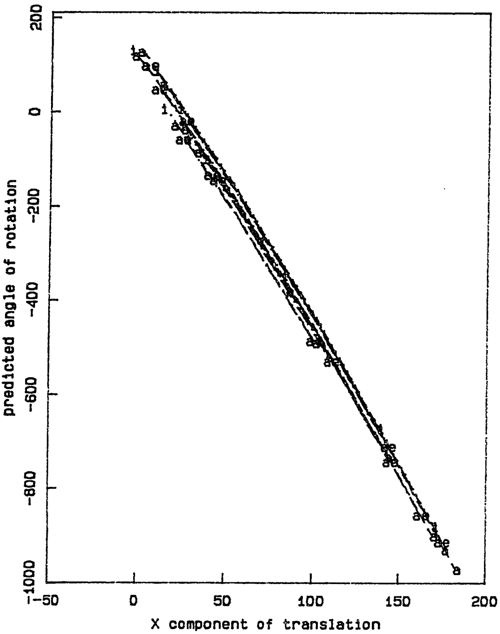

Figure 3.33 Predicted values of the angle of rotation are plotted against values of the X component for the pV2 demisyllables for JE. The dotted lines represent /pi/; the dashed lines represent /pa/; the dashed-and-dotted lines represent /pae/.

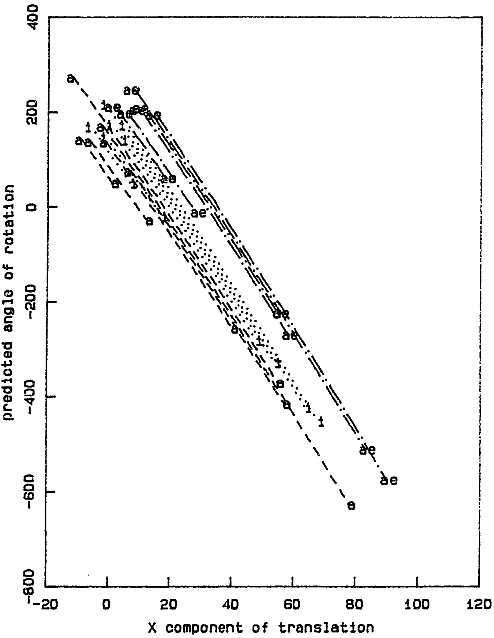

Figure 3.34 Predicted values of the angle of rotation are plotted against values of the X component for the pV2 demisyllables for CG. The dotted lines represent pV2 demisyllables preceded by /i/; the dashed lines represent pV2 demisyllables preceded by /a/; the dashed-and-dotted lines represent pV2 demisyllables preceded by /ae/.

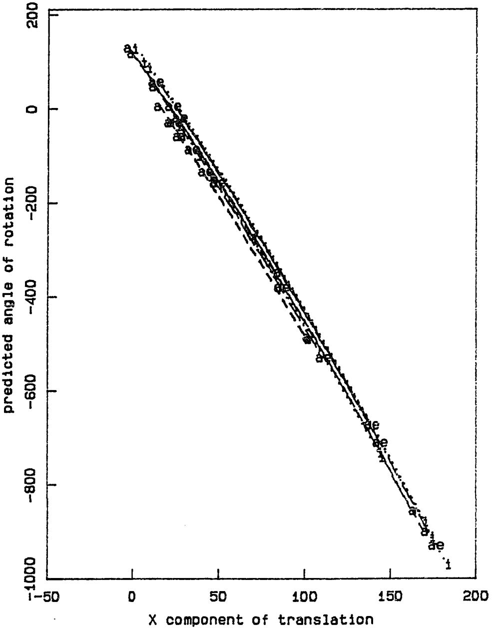

Figure 3.35 Predicted values of the angle of rotation are plotted against values of the X component for the pV2 demisyllables for JE. The dotted lines represent pV2 demisyllables preceded by /i/; the dashed lines represent pV2 demisyllables preceded by /a/; the dashed-and-dotted lines represent pV2 demisyllables preceded by /ae/.

demisyllables are plotted again, coded by the identity of the non-test vowel. It can be observed that for CG, the identity of the vowel in the non-test syllable functions to divide the pV2 trajectories into three groups. Note that the separation among the three groups is much less pronounced than for the corresponding translation analysis illustrated in Fig. 3.16. For JE, neither the identity of the test vowel or the identity of the non-test vowel effectively subdivides the trajectories.

In Figs. 3.36 and 3.37, tV2 demisyllables for CG and JE, respectively, are plotted, coded by the identity of the vowel in the test syllable. For both subjects, a wider range of angles of rotation for a given amount of translation is observed, than in the pV2 demisyllables. However, the tV2 demisyllables are similar to the pV2 demisyllables in that, again, the test vowel does not function to divide the trajectories into three groups for either subject. In Figs. 3.38 and 3.39, for CG and JE, respectively, the tV2 demisyllables are coded by the identity of the vowel in the non-test syllable. For both subjects, it can be observed that the effect of the non-test vowel is to divide the tV2 trajectories into three groups. Again, it can be noted that the separation among the three groups is much less pronounced than for the corresponding translation analyses, illustrated in Figs. 3.22 and 3.23.

A comparison of Tables 3.6 and 3.9 also reveal a tendency toward the assymetry between anticipatory and carryover coarticulation that was observed for the translation analysis for the intervocalic consonants /t/ and /p/. However, both the tables and the figures

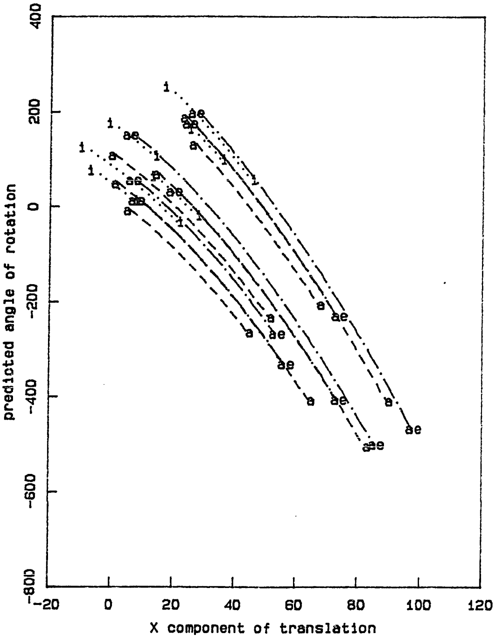

Figure 3.36 Predicted values of the angle of rotation are plotted against values of the X component for the tV2 demisyllables for CG. The dotted lines represent /ti/; the dashed lines represent /ta/; the dashed-and-dotted lines represent /tae/.

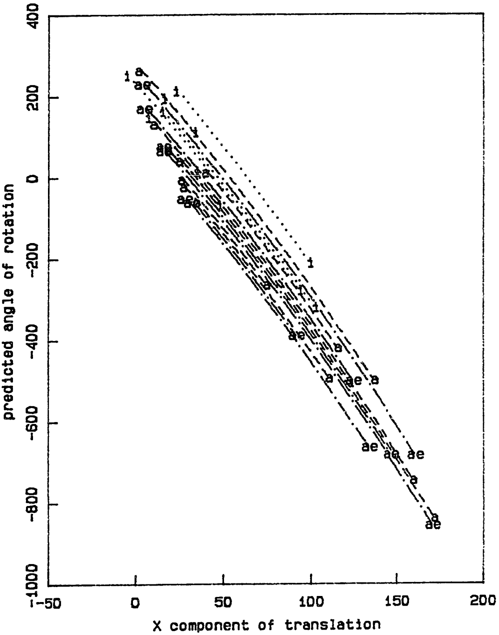

Figure 3.37 Predicted values of the angle of rotation are plotted against values of the X component for the tV2 demisyllables for JE. The dotted lines represent /ti/; the dashed lines represent /ta/; the dashed-and-dotted lines represent /tae/.

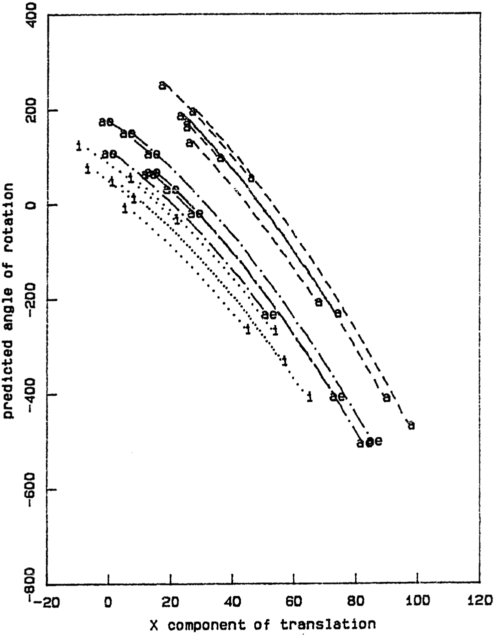

Figure 3.38 Predicted values of the angle of rotation are plotted against the X component for the tV2 demisyllables for CG. The dotted lines represent tV2 demisyllables preceded by /i/; the dashed lines represent tV2 demisyllables preceded by /a/; the dashed-and-dotted lines represent tV2 demisyllables preceded by /ae/.

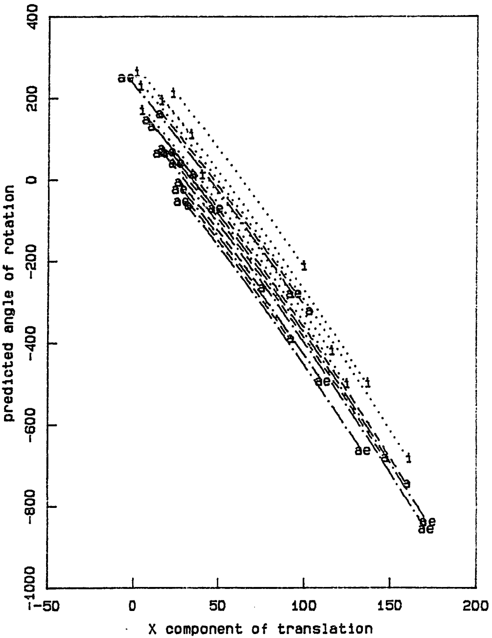

Figure 3.39 Predicted values of the angle of rotation are plotted against the X component for the tV2 demisyllables for JE. The dotted lines represent tV2 demisyllables preceded by /i/; the dashed lines represent tV2 demisyllables preceded by /a/; the dashed-and-dotted lines represent tV2 demisyllables preceded by /ae/.

indicate that the assymetry is much less pronounced for the rotation analysis, as compared to the translation analysis when the intervocalic consonant is /t/ or /p/; when the intervocalic consonant is /s/, the influence of the test vowel is always greater than that of the non-test vowel. Table 3.9 shows that for the demisyllables containing V2, the influences of the test and non-test vowels are almost equal for both CG and JE. Furthermore, the proportion of variance accounted for by the covariate representing the non-test vowel is at most 4% greater than that accounted for by the covariate representing the test vowel (as compared to a difference of up to 40% for the translation analysis). In contrast to the translation analyses, an examination of Tables 3.8 and 3.9 reveals that for both the two demisyllables containing V1 as well as the two demisyllables containing V2, the influence of the non-test vowel is not systematically lower for the subjacent, as compared to the immediately adjacent, demisyllable for either CG or JE. (For CG, $p > .10$, using a sign test; for JE, the sample size was too small to use a sign test.)

3.3.4 Summary

These results indicate that for CG and JE, jaw rotation exhibits a systematic and highly significant functional dependence on jaw translation. For both subjects, the effects of phonetic context are evident, but these effects are relatively small in magnitude, especially as compared to the parallel phonetic context effects on the relationship between the first two principal components of jaw translation. Furthermore, phonetic context effects were not found to vary significantly over time and the total proportion of variance accounted for by the rotation model remained constant across different utterance types. These results suggest that the relationship between the first principal component of jaw translation and jaw rotation is highly constrained during speech for these two subjects.

3.4 Translation Analysis for LF

3.4.1 Combination of Phonetic Parameters

For LF, as for JE and CG, it was necessary to determine the optimal combination of phonetic characteristics that produced linear effects or effects with a substantial linear component. Table 3.10 gives the squared multiple correlations for the six utterance combinations described in Chapter 2 (Section 2.6.4.2) for all four demisyllable types. Note that the results for the tV1 and tV2 demisyllables are qualitatively similar to those for the V1C and the CV2 demisyllables, respectively. For this reason, the discussion will continue to focus on the V1C and the CV2 demisyllables. Several patterns can be observed in this table. First, the squared multiple correlations within any combination of phonetic parameters are quite variable across different parameter values within a given utterance combination when /p/ is the intervocalic consonant in the test utterance. This variability may be due to the fact that the jaw appliance interfered with bilabial closure for LF. Although the V1CV2 utterance types were surrounded by /t/ instead of /p/ for LF, the V1pV2 utterance types had still been included as stimuli. These utterance types were excluded from further analysis, given the generally low

Table 3.10

Squared multiple correlations (TY on TX) for all of the utterance combinations described in Chapter 2

Values of phonetic parameters if not combined				LF			
test vowel	non-test vowel	stress	consonant	tV1	V1C	CV2	V2t
i			t	.83	.82	.53	.36
a			t	.29	.25	.57	.55
ae			t	.53	.47	.43	.60
i			p	.62	.64	.20	.22
a			p	.39	.22	.31	.55
ae			p	.26	.14	.23	.45
i			s	.22	.16	.41	.43
a			s	.24	.40	.47	.48
ae			s	.57	.40	.49	.51
	i		t	.68	.62	.61	.64
	a		t	.46	.52	.21	.19
	ae		t	.38	.43	.42	.28
	i		p	.69	.42	.26	.57
	a		p	.72	.77	.43	.55
	ae		p	.27	.28	.10	.26
	i		s	.30	.36	.16	.46
	a		s	.56	.58	.30	.49
	ae		s	.56	.45	.47	.45
		+	t	.47	.43	.12	.24
		-	t	.61	.59	.48	.57
		+	p	.54	.41	.15	.18
		-	p	.16	.19	.28	.37
		+	s	.40	.24	.33	.34
		-	s	.59	.48	.32	.49
			t	.39	.38	.38	.51
			p	.25	.26	.19	.21
			s	.35	.21	.20	.24
i				.31	.30	.38	.38
a				.28	.27	.27	.27
ae				.10	.18	.22	.21
				.17	.14	.15	.14

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(cf. p. 158)

squared multiple correlations and the observed variability of the results.

However, it can be observed that the squared multiple correlations are relatively low, in general, even if the V1pV2 utterance types are excluded. Let us consider each combination of phonetic parameters. First, when the utterance types are combined across stress patterns and across the identity of the vowel in the non-test syllable, less than 50% of the variance is accounted for in 9 out of 12 utterance combinations for the V1C and the CV2 demisyllables. Second, when the utterance types are combined across stress patterns and across the identity of the vowel in the test syllable, less than 50% of the variance is accounted for in 8 out of 12 utterance combinations for the V1C and the CV2 demisyllables. Third, when the utterance types are combined across the identities of the vowels in both the test and non-test syllables, less than 50% of the variance is accounted for in 7 out of 8 utterance combinations for the V1C and the CV2 demisyllables. Finally, less than 50% of the variance is accounted for in all of the higher order combinations.

There are several reasons why the squared multiple correlations are generally low. First, as discussed in section 3.1, the absolute amount of jaw translation is quite small for LF, as compared to CG and JE. This difference for LF can also be observed in Table 3.11 which gives the amounts of X and Y translation at maximal opening for stressed V1t demisyllables, averaged across non-test vowels. Note that at maximal jaw opening for a V1t demisyllable, X translation averages about 1.4 mm for a stressed /it/, 2.5 mm for a stressed /at/, and 3.4

Table 3.11

Magnitudes (in mm) of X and Y translation at maximal opening for stressed V1t demisyllables, averaged across non-test vowels

	CG		JE		LF	
test vowel	TX	TY	TX	TY	TX	TY
i	1.3	1.6	2.7	2.5	1.4	1.4
a	5.9	1.8	13.4	3.5	2.5	1.7
ae	5.9	2.0	13.4	4.2	3.4	1.7

---

mm for a stressed /aet/; and Y translation averages about 1.4 mm for a stressed /it/, 1.7 mm for both stressed /at/ and /aet/. By contrast, corresponding values for CG and JE, respectively, average 1.3 and 2.7 mm for /it/, 5.9 and 13.4 mm for both /at/ and /aet/; Y translation for CG and JE respectively averages 1.6 and 2.5 mm for /it/, 1.8 and 3.5 mm for /at/, and 2.0 and 4.2 mm for /aet/. Thus, one reason why the squared multiple correlations are generally lower for LF is because a constant amount of measurement noise will result in proportionally greater variability, given smaller absolute values of jaw translation.

3.4.2 Interactions Among Phonetic Parameters

There is, however, another reason why these squared multiple correlations are so low. Virtually no combination of phonetic parameters yields additive effects for LF. An examination of the raw data reveals that the effects of two of these parameters, stress and the vowel in the non-test syllable, interact with the value of a third parameter, the vowel in the test syllable. Furthermore, the patterns of the interactions are not consistent across all values of a given phonetic parameter within a demisyllable or for the same value of a given phonetic parameter across demisyllables.

Let us first consider the effect of the vowel in the non-test syllable. Figure 3.40 plots the stressed /at/ demisyllables. It can be observed that a following /i/ or /a/ results in a more anterior /at/ trajectory, whereas a following /ae/ results in a more posterior /at/ trajectory.

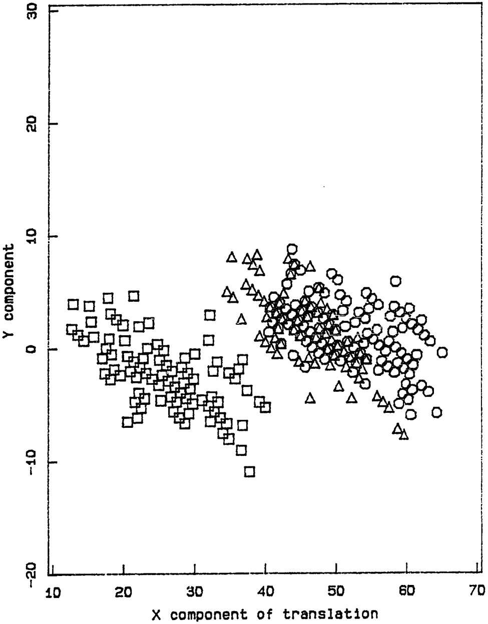

Figure 3.40 Values of the Y component of translation are plotted against values of the X component for stressed /at/ demisyllables for LF. Triangles represent /at/ demisyllables followed by /i/; circles represent /at/ demisyllables followed by /a/; squares represent /at/ demisyllables followed by /ae/. The coordinate system has been rotated by 36 degrees clockwise.

Figure 3.41 plots stressed /aet/ demisyllables. In this context, it can be observed that the three groups are less well-separated. A following /a/ results in a slightly more inferior and posterior /aet/ trajectory; whereas a following /i/ or /ae/ results in a slightly more anterior and superior /aet/ trajectory. The effects of the following vowel on the /it/ demisyllables are similar to those for the /aet/ demisyllables. A comparison of Figs. 3.40 and 3.41 indicates an interaction between the influences of the test and non-test vowels on stressed V1t demisyllables. For /at/ demisyllables, trajectories followed by /a/ are anterior to those followed by /i/ and /ae/, whereas for /aet/ and /it/ demisyllables, trajectories followed by /a/ are posterior to those followed by /i/ and /ae/.

An interaction among the test and non-test vowels is also observed for the demisyllables containing V2. The stressed /ta/ and /tae/ demisyllables are plotted in Figs. 3.42 and 3.43, respectively. In contrast to the V1t demisyllables, it can be observed that the influence of the non-test vowel is greater when the test vowel is /ae/, rather than /a/. Three distinct groups are observed for the /tae/ demisyllables: those preceded by /i/ are the most posterior; those preceded by /ae/ are the most anterior.

Some of these interactions can be given phonetic interpretations. For example, a plausible explanation for the pattern observed in Fig. 3.43 is that assimilatory coarticulation results in more anterior gestures for demisyllables following /ae/ and more posterior gestures for demisyllables following /a/. However, some cannot. For example, it is unclear why the non-test vowel has a greater influence on /at/

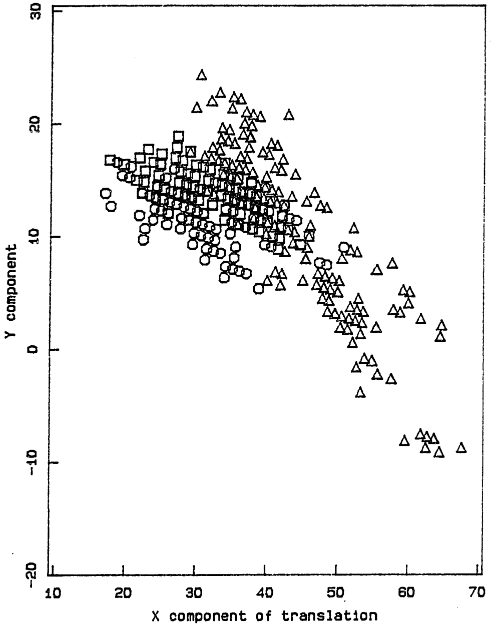

Figure 3.41 Values of the Y component of translation are plotted against values of the X component for stressed /aet/ demisyllables for LF. Triangles represent /aet/ demisyllables followed by /i/; circles represent /aet/ demisyllables followed by /a/; squares represent /aet/ demisyllables followed by /ae/. The coordinate system has been rotated by 25 degrees clockwise.

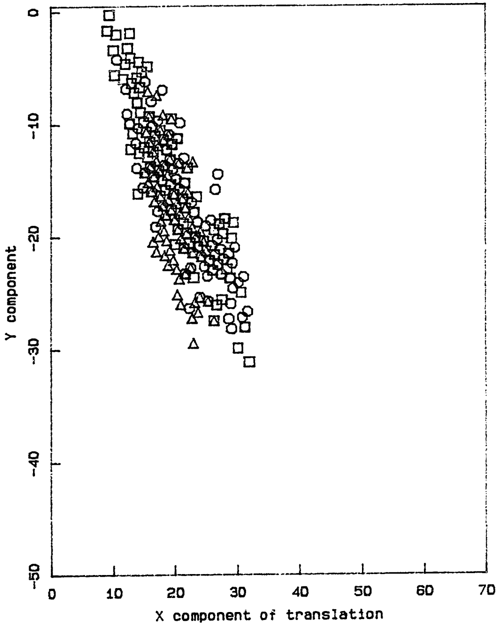

Figure 3.42 Values of the Y component of translation are plotted against values of the X component for stressed /ta/ demisyllables for LF. Triangles represent /ta/ demisyllables preceded by /i/; circles represent /ta/ demisyllables preceded by /a/; squares represent /ta/ demisyllables preceded by /ae/. The coordinate system has been rotated by 74 degrees clockwise.

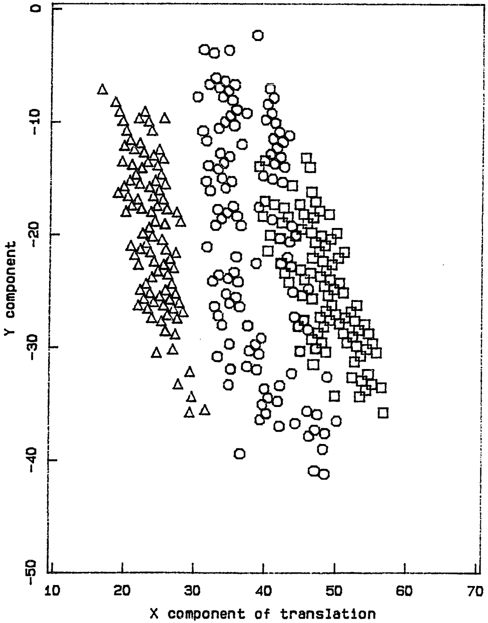

Figure 3.43 Values of the Y component of translation are plotted against values of the X component for stressed /tae/ demisyllables for LF. Triangles represent /tae/ demisyllables preceded by /i/; circles represent /tae/ demisyllables preceded by /a/; squares represent /tae/ demisyllables preceded by /ae/. The coordinate system has been rotated by 67 degrees clockwise.

and /tae/ demisyllables, as compared to /aet/ and /ta/ demisyllables or why /at/ demisyllables followed by /ae/ are more posterior than those followed by /a/.

The effect of stress also depends on the identity of the vowel in the non-test syllable. Figures 3.44 and 3.45 plot stressed and unstressed /at/ and /aet/ demisyllables, respectively, both followed by /a/ and /ae/. It can be observed that for both /at/ and /aet/ demisyllables, the stressed trajectory is anterior to the corresponding unstressed one if the following vowel is /a/. On the other hand, for both /at/ and /aet/ demisyllables, the stressed trajectory is posterior to the corresponding unstressed one if the following vowel is /ae/. This pattern is also readily explicable. Because primary stress was varied orthogonally between V1 and V2, it is always the case that when V1 is unstressed (i.e. has primary stress), V2 is stressed (i.e. has secondary stress) and vice versa. Thus, for LF, the effect of the non-test vowel is greater when the test vowel is unstressed and the non-test vowel is stressed. This observed assymetry between stressed and unstresssed demisyllables is consistent with reports in the literature of greater acoustic influence of stressed vowels on adjacent unstressed vowels, than the opposite (Fowler, 1981).

Observe that in Figs. 3.44 and 3.45, a stressed /ae/ in the following <u>non</u>-test syllable results in a more anterior /at/ or /aet/ trajectory; conversely, a stressed /a/ in the following <u>non</u>-test syllable results in a more posterior /at/ or /aet/ trajectory. These results may also be due to assimilatory coarticulatory influences.

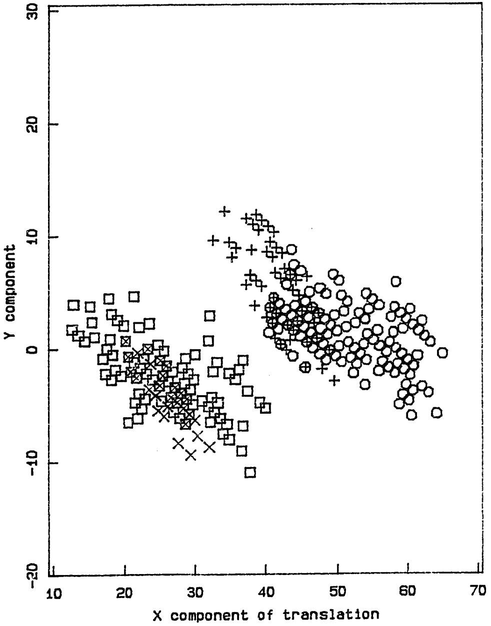

Figure 3.44 Values of the Y component of translation are plotted against values of the X component for /at/ demisyllables for LF. Circles represent stressed /at/ demisyllables followed by /a/; X's represent unstressed /at/ demisyllables followed by /a/; squares represent stressed /at/ demisyllables followed by /ae/; crosses represent unstressed /at/ demisyllables followed by /ae/. The coordinate system has been rotated by 39 degrees clockwise.

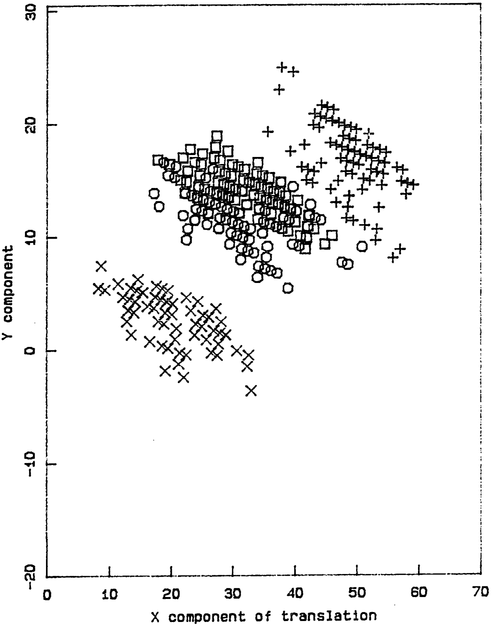

Figure 3.45 Values of the Y component of translation are plotted against values of the X component for /aet/ demisyllables for LF. Circles represent stressed /aet/ demisyllables followed by /a/; X's represent unstressed /aet/ demisyllables followed by /a/; squares represent stressed /aet/ demisyllables followed by /ae/; crosses represent unstressed /aet/ demisyllables followed by /ae/. The coordinate system has been rotated by 37 degrees clockwise.

Interactions among the effects of test vowel identity, non-test vowel identity and stress are observed for the tV2 demisyllables as well. The /ta/ and /tae/ demisyllables are plotted in Figs. 3.46 and 3.47, respectively. When the test vowel is /a/, it can be observed that stressed demisyllables are anterior to their unstressed counterparts for both non-test vowels. By contrast, when the test vowel is /ae/, stressed demisyllables are posterior to their unstressed counterparts for both non-test vowels. If the tV2 demisyllable is unstressed and preceded by /a/, it is the most posterior of the four /ta/ trajectories, but is the most anterior of the four /tae/ trajectories.

3.4.3 Summary

These interactions among the influences of stress and the identities of the vowels in the test and non-test syllables will result in low squared multiple correlations if the utterance types are combined across two or three of these phonetic parameters. Therefore, the utterance types were combined only across a single phonetic parameter, the identity of the vowel in the test syllable. The regression equation for the translation analysis for LF is given in (3.3) below.

$$(3.3)\ \hat{Y} = a_1X_1 + a_2X_1^2 + a_3X_1^3 + a_4X_2 + a_5X_3 + a_6.$$

Table 3.12 shows the squared multiple correlations and the effect of the test vowels for all four demisyllable types. It can be observed

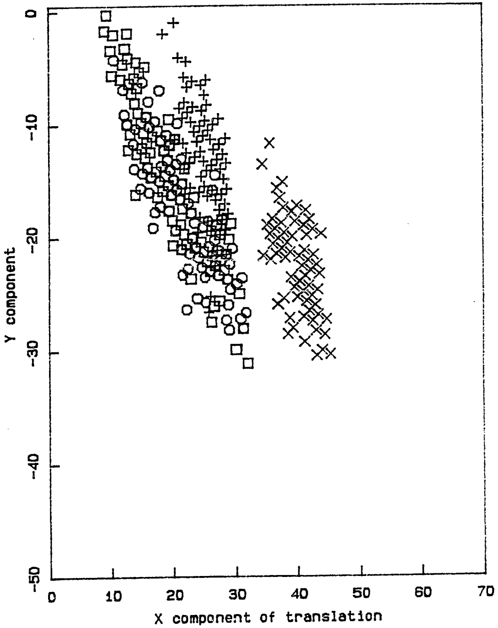

Figure 3.46 Values of the Y component of translation are plotted against values of the X component for /ta/ demisyllables for LF. Circles represent stressed /ta/ demisyllables preceded by /a/; X's represent unstressed /ta/ demisyllables preceded by /a/; squares represent stressed /ta/ demisyllables preceded by /ae/; crosses represent unstressed /ta/ demisyllables preceded by /ae/. The coordinate system has been rotated by 65 degrees clockwise.

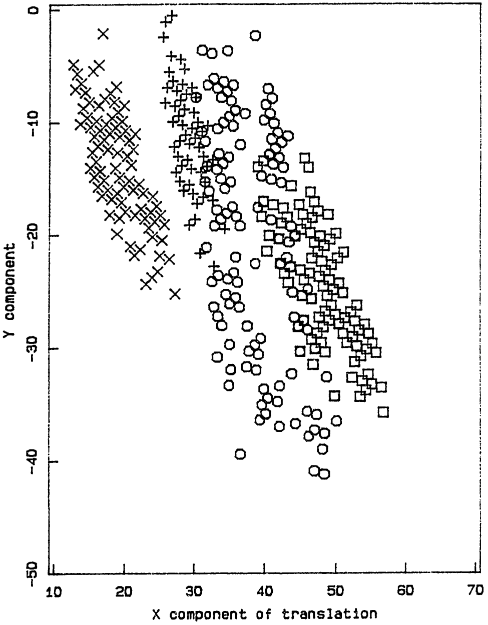

Figure 3.47 Values of the Y component of translation are plotted against values of the X component for /tae/ demisyllables for LF. Circles represent stressed /tae/ demisyllables preceded by /a/; X's represent unstressed /tae/ demisyllables preceded by /a/; squares represent stressed /tae/ demisyllables preceded by /ae/; crosses represent unstressed /tae/ demisyllables preceded by /ae/. The coordinate system has been rotated by 67 degrees clockwise.

Table 3.12

Squared multiple correlations (TY on TX) and contribution of test vowel covariate for all four demisyllables

			tV1		V1C	
non-test vowel	stress	consonant	r2	vowel	r2	vowel
i	+	t	.74	.22	.69	.27
i	-	t	.78	.16	.66	.18
a	+	t	.88	.18	.88	.21
a	-	t	.66	.05	.65	.06
ae	+	t	.76	.24	.80	.26
ae	-	t	.60	.21	.68	.03
i	+	s	.36	.07	.52	.30
i	-	s	.81	.09	.74	.08
a	+	s	.78	.28	.71	.25
a	-	s	.79	.34	.84	.30
ae	+	s	.84	.003	.82	.03
ae	-	s	.72	.24	.60	.31
			V2C		V2t	
i	+	t	.45	.02	.54	.03
i	-	t	.80	.08	.74	.02
a	+	t	.56	.19	.75	.26
a	-	t	.77	.26	.65	.25
ae	+	t	.64	.30	.31	.15
ae	-	t	.66	.21	.60	.17
i	+	s	.29	.10	.56	.20
i	-	s	.17	.05	.68	.31
a	+	s	.76	.22	.69	.19
a	-	s	.75	.12	.73	.13
ae	+	s	.74	.22	.45	.27
ae	-	s	.83	.25	.81	.17

that the squared multiple correlations are considerably higher than in Table 3.11: more than 50% of the variance is accounted for in 20 out of 24 utterance combinations for the V1C and the CV2 demisyllables.

However, it should also be noted that the nature of the phonetic interactions appears to escape commonly accepted segmental accounts. The relative effects of the three phonetic parameters under consideration vary both within and across demisyllables. Given the present level of analysis, no consistent pattern can be observed among these interactions, at least not within current linguistic models. Perhaps the current linguistic models are inadequate, or perhaps this lack of consistent phonetic influences indicates that LF is not exerting systematic phonetic control over jaw translation. In either case, these results suggest that the relationship between the first two components of jaw translation is not highly constrained during speech for LF.

3.5 Rotation Analysis for LF

3.5.1 Combination of Phonetic Parameters

Finally, let us consider the results of describing jaw rotation as a function of the first principal component of jaw translation for LF. Again, it was necessary to determine the optimal combination of phonetic parameters that produced effects with a substantial linear component. Table 3.13 gives the squared multiple correlations for the utterance combinations described in Chapter 2 (Section 2.6.4.2) for all four demisyllable types. Again, the squared multiple correlations for

Table 3.13

Squared multiple correlations (θ on TX) for all of the utterance combinations described in Chapter 2

Values of phonetic parameters if not combined				LF			
test vowel	non-test vowel	stress	consonant	tV1	V1C	CV2	V2t
i			t	.37	.80	.10	.36
a			t	.12	.26	.57	.46
ae			t	.34	.26	.17	.26
i			p	.27	.60	.02	.33
a			p	.28	.21	.21	.35
ae			p	.20	.07	.09	.20
i			s	.37	.47	.07	.35
a			s	.37	.35	.16	.31
ae			s	.26	.18	.17	.33
	i		t	.56	.57	.59	.60
	a		t	.49	.50	.35	.44
	ae		t	.38	.40	.29	.45
	i		p	.53	.38	.40	.60
	a		p	.35	.44	.29	.53
	ae		p	.19	.10	.16	.61
	i		s	.53	.23	.12	.63
	a		s	.50	.36	.24	.43
	ae		s	.57	.41	.20	.47
		+	t	.35	.30	.40	.46
		–	t	.11	.16	.49	.63
		+	p	.37	.14	.18	.52
		–	p	.23	.26	.31	.66
		+	s	.55	.31	.06	.29
		–	s	.15	.09	.12	.48
			t	.20	.23	.37	.45
			p	.28	.21	.19	.55
			s	.38	.22	.07	.39
i				.43	.45	.10	.12
a				.16	.18	.11	.09
ae				.11	.11	.10	.10
				.09	.08	.08	.06

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the tV1 and the V2t demisyllables are similar to those for V1C and the CV2 demisyllables, respectively. Again, the V1pV2 utterance type were included in this analysis, but were excluded from all further analyses for reasons discussed in section 3.4.1.

A comparison of Tables 3.8 and 3.13 reveals significant differences for LF from the other two subjects with respect to the relationship between jaw rotation and jaw translation. First the squared multiple correlations for LF are generally quite low: over 50% of the variance is accounted for in only 6 out of the 62 multiple regression analyses presented in Table 3.13. By contrast, over 50% of the variance is accounted for in 44 out of the 44 and 55 out of the 62 multiple regression analyses presented in Table 3.8 for JE and CG, respectively. SEcond, for LF, the squared multiple correlations of a particular utterance combination are generally lower for the rotation analysis than for the corresponding translation analysis. By contrast, for JE and CG, the squared multiple correlations are generally higher for the rotation analyses than for the corresponding translation analyses. Third, for LF, the squared multiple correlations vary across different utterance types. By contrast, for JE and CG, the squared multiple correlations were relatively constant across different utterance types.

Figure 3.48 illustrates the different relationship of jaw rotation and jaw translation for LF. Recall that for CG and JE a given amount of translation corresponded to a relatively constant angle of rotation across different test vowels. For LF, however, the relationship between a given angle of rotation and the amount of jaw translation is

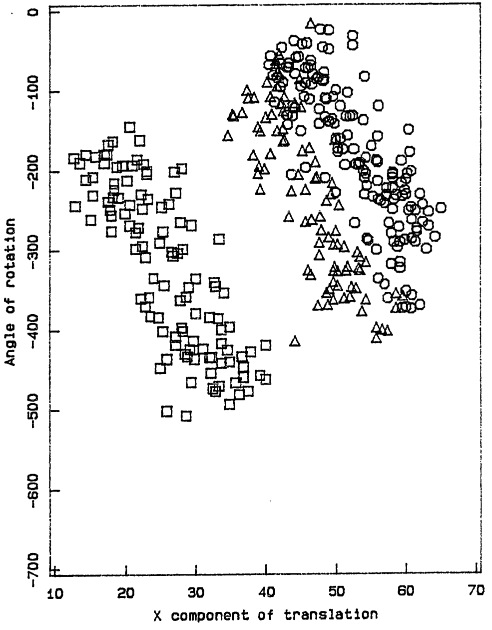

Figure 3.48 Values of the angle of rotation are plotted against values of the X component for stressed /at/ demisyllables for LF. Triangles represent /at/ demisyllables followed by /i/; circles represent /at/ demisyllables followed by /a/; squares represent /at/ demisyllables followed by /ae/.

highly dependent on the identity of the test vowel.

3.5.2 Interactions Among Phonetic Parameters

Thus, the relationship between rotation and translation is not independent of phonetic context for LF. This suggests that one reason for the low squared multiple correlations is that for the rotation analysis, as for the translation analysis, combining the utterance types across more than one phonetic parameter results in non-additive effects. Indeed, this is the case: as for the translation analyses, an examination of the relationship between jaw rotation and the first principal component of jaw translation across changes in phonetic context revealed complex and unstable interactions among the effects of the test vowel, the non-test vowel, and the stress pattern. Figure 3.49 plots the stressed /aet/ demisyllables. In Fig. 3.48, /at/ demisyllables followed by /i/ are posterior to those followed by /a/. By contrast, in Fig. 3.49, /aet/ demisyllables followed by /i/ are anterior to those followed by /a/.

An interactions between the effects of the test and non-test vowels is also observed for the demisyllables containing V2. Stressed /ta/ and /tae/ demisyllables are plotted in Figs. 3.50 and 3.51, respectively. It can be observed that the most posterior of the /ta/ trajectories is /ta/ preceded by /ae/, whereas the most anterior of the /tae/ trajectories is /tae/ preceded by /ae/. As in the translation analysis, the non-test vowel exerts a greater influence on the /at/ and /tae/ demisyllables, as compared to /aet/ and /ta/.

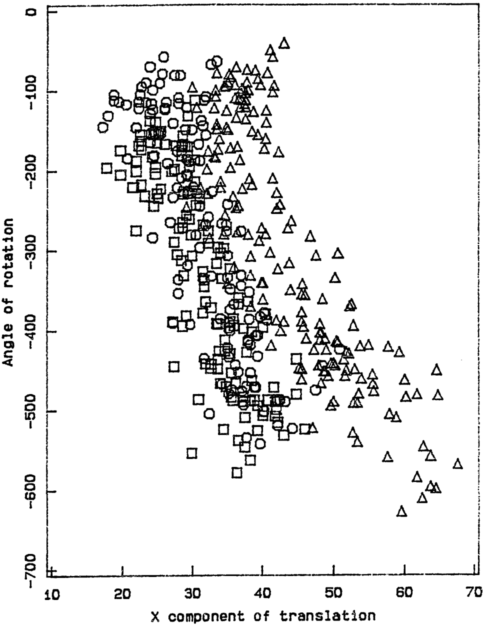

Figure 3.49 Values of the angle of rotation are plotted against values of the X component for stressed /æt/ demisyllables for LF. Triangles represent /aet/ demisyllables followed by /i/; circles represent /aet/ demisyllables followed by /a/; squares represent /aet/ demisyllables followed by /ae/.

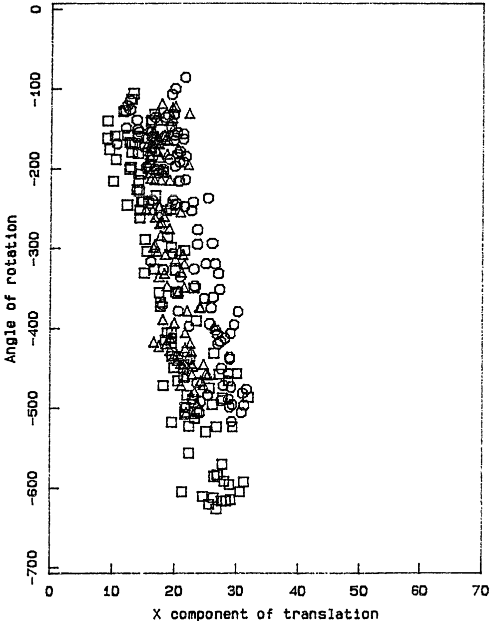

Figure 3.50 Values of the angle of rotation are plotted against values of the X component for stressed /ta/ demisyllables for LF. Triangles represent /ta/ demisyllables preceded by /i/; circles represent /ta/ demisyllables preceded by /a/; squares represent /ta/ demisyllables preceded by /ae/.

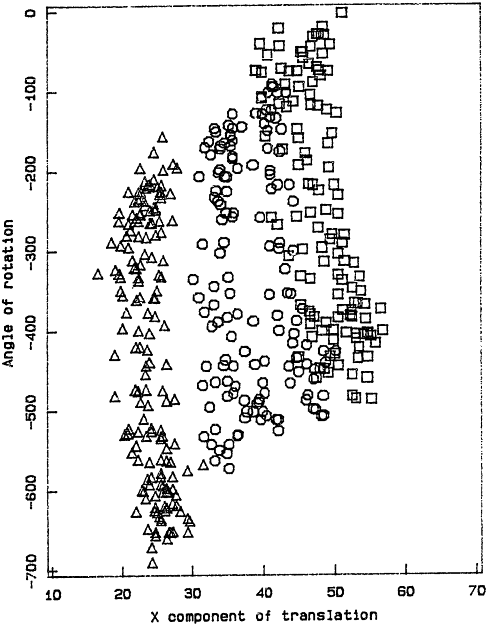

Figure 3.51 Values of the angle of rotation are plotted against values of the X component for stressed /tae/ demisyllables for LF. Triangles represent /tae/ demisyllables preceded by /i/; circles represent /tae/ demisyllables preceded by /a/; squares represent /tae/ demisyllables preceded by /ae/.

Interactions between stress and non-test vowel identity are also observed. The /at/ and /aet/ demisyllables, respectively, both followed by /a/ and /ae/ are plotted in Figs. 3.52 and 3.53. For both test vowels, it can be observed that stressed demisyllables followed by /a/ are anterior to their unstressed counterparts and that stressed demisyllables followed by /ae/ are posterior to their unstressed counterparts.

An interaction between the effects of the non-test vowel and stress is also observed for the demisyllables containing V2. Figures 3.54 and 3.55 plots the /ta/ and /tae/ demisyllables, respectively, both preceded by /a/ and /ae/. In Fig. 3.54, it can be observed that stressed /ta/ demisyllables are posterior to their unstressed counterparts for both non-test vowels. By contrast, in Fig. 3.55 it can be observed that stressed /tae/ demisyllables are anterior to their unstressed counterparts for both non-test vowels.

Thus the rotation analysis, like the translation analysis, reveals some interactions among the three phonetic parameters which can be given phonetic interpretations. Again, for example, the interaction between the effects of stress and the non-test vowel for the /at/ and /aet/ demisyllables can be explained as the relatively greater effect of assimilatory coarticulation of stressed vowels on unstressed vowels, rather than the reverse. However, it is again the case that the nature of the phonetic interactions vary across different demisyllables and across different values of a phonetic parameter within a demisyllable. That is, the relationship between jaw rotation and the first principal component of jaw translation, like the relationship between the first

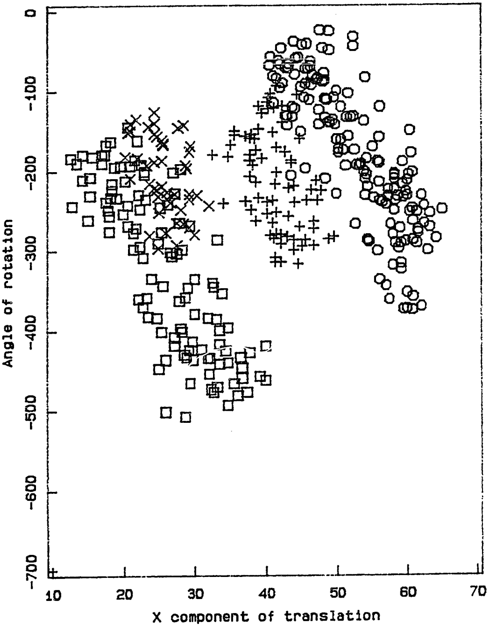

Figure 3.52 Values of the angle of rotation are plotted against values of the X component for /at/ demisyllables for LF. Circles represent stressed /at/ demisyllables followed by /a/; X's represent unstressed /at/ demisyllables followed by /a/; squares represent stressed /at/ demisyllables followed by /ae/; crosses represent unstressed /at/ demisyllables followed by /ae/.

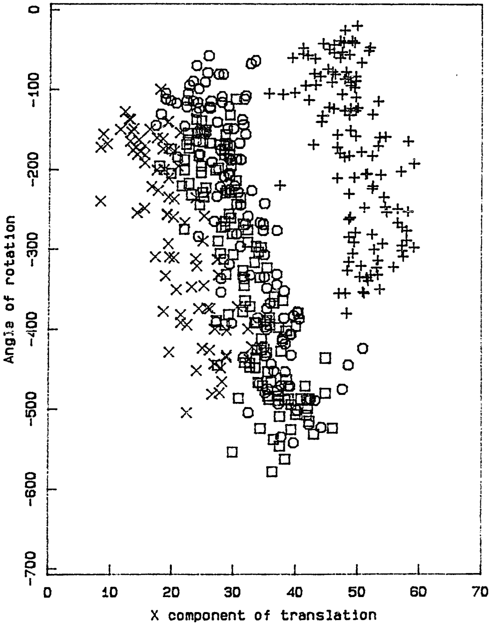

Figure 3.53 Values of the angle of rotation are plotted against values of the X component for /aet/ demisyllables. Circles represent stressed /aet/ demisyllables followed by /a/; X's represent unstressed /aet/ demisyllables followed by /a/; squares represent stressed /aet/ demisyllables followed by /ae/; crosses represent unstressed /aet/ demisyllables followed by /ae/.

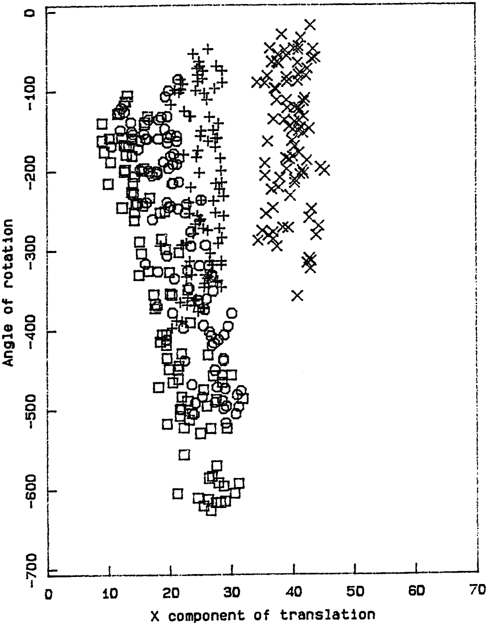

Figure 3.54 Values of the angle of rotation are plotted against values of the X component for /ta/ demisyllables. Circles represent stressed /ta/ demisyllables preceded by /a/; X's represent unstressed /ta/ demisyllables preceded by /a/; squares represent stressed /ta/ demisyllables preceded by /ae/; crosses represent unstressed /ta/ demisyllables preceded by /ae/.

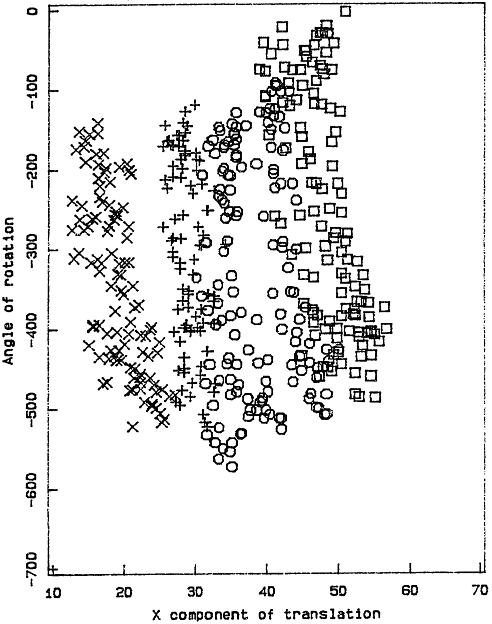

Figure 3.55 Values of the angle of rotation are plotted against values of the X component for /tae/ demisyllables. Circles represent stressed /tae/ demisyllables preceded by /a/; X's represent unstressed /tae/ demisyllables preceded by /a/; squares represent stressed /tae/ demisyllables preceded by /ae/; crosses represent unstressed /tae/ demisyllables preceded by /ae/.

two principal components of jaw translation, appears to be subject to a variety of phonetic influences, within which a pattern is not readily discernable, given current linguistic models.

3.5.3 Summary

The interactions among the effects of the test vowel, the non-test vowel, and stress will result in low squared multiple correlations if the utterance types are combined across two or three of these parameters. Therefore, for the rotation analysis also, the utterance types were combined only over the single phonetic parameter of the identity of the test vowel. The regression equation for the rotation analysis is given in (3.4), below.

$$(3.4)\quad \hat{\theta} = b_1X_1 + b_2X_1^2 + b_3X_2 + b_4X_3 + b_5.$$

Table 3.14 gives the squared multiple correlations and the effects of vowel identity for all four demisyllable types. The squared multiple correlations are generally somewhat higher than in Table 3.13, but they remain substantially lower than for the corresponding translation analyses. Over 50% of the variance is accounted for in 5 and 6 out of the 12 utterance combinations for the V1C and the CV2 demisyllables, respectively. By contrast, for the corresponding translation analyses, over 50% of the variance is accounted for in 11 and 9 out of the 12 utterance combinations for the V1C and the CV2 demisyllables, respectively.

Table 3.14

Squared multiple correlations (θ on TX) and contribution of test vowel covariate for all four demisyllables

			tV1		V1C	
non-test vowel	stress	consonant	r2	vowel	r2	vowel
i	+	t	.69	.28	.73	.21
i	-	t	.50	.07	.41	.02
a	+	t	.64	.40	.67	.56
a	-	t	.55	.26	.55	.35
ae	+	t	.72	.20	.65	.18
ae	-	t	.06	.000	.11	.05
i	+	s	.42	.03	.27	.05
i	-	s	.39	.02	.14	.02
a	+	s	.67	.14	.48	.10
a	-	s	.43	.19	.40	.23
ae	+	s	.70	.02	.54	.17
ae	-	s	.15	.003	.40	.16
			V2C		V2t	
i	+	t	.53	.03	.54	.05
i	-	t	.78	.24	.67	.11
a	+	t	.62	.26	.71	.32
a	-	t	.68	.31	.70	.11
ae	+	t	.72	.23	.60	.24
ae	-	t	.43	.11	.66	.11
i	+	s	.16	.01	.56	.21
i	-	s	.28	.10	.81	.33
a	+	s	.56	.20	.52	.21
a	-	s	.37	.01	.43	.10
ae	+	s	.29	.03	.38	.01
ae	-	s	.18	.06	.64	.02

Thus, the squared multiple correlations for the rotation analysis remain relatively low, even when non-additive phonetic effects are removed. This result suggests that for LF, in contrast to CG and JE, a significant proportion of jaw rotation is functionally independent of jaw translation.

3.6 Minimum and Maximum Values of Jaw Rotation as a Function of Vowel Identity For LF

The fact that jaw rotation appears to be functionally independent of jaw translation suggests that LF is differentiating jaw height for vowels on the basis of rotation alone. The following analysis was used to examine the effect of phonetic context on jaw rotation. For each utterance type, the minimum and maximum values of the angle of jaw rotation of three trajectory types were determined. These three trajectory types were: (1) the raw data; (2) the predicted values of jaw rotation from the analysis presented in Table 3.14; and (3) the residual values of jaw rotation from the analysis presented in Table 3.14. These values were regressed against three different sets of independent variables: (1) the two covariates that coded test vowel identity; (2) the two covariates that coded non-test vowel identity; and (3) the single covariate that coded stress. This analysis was performed on the V1C and the CV2 demisyllables only. The results are presented in Table 3.15.

Table 3.15

Squared multiple correlations for maximum and minimum values of jaw rotation for three trajectory types regressed against vocalic covariates

		VC	VC	CV	CV
		c=s	c=t	c=s	c=t
Regression of maximum and minimum values of jaw rotation against test vowel identity					
Raw data	Minimum	.73**	.76**	.80**	.81**
	Maximum	.29	.22	.10	.46*
Predicted	Minimum	.36*	.53**	.32	.58**
	Maximum	.30	.65	.13	.34*
Residual	Minimum	.75**	.64**	.55**	.51**
	Maximum	.61**	.48**	.29	.47**
Regression of same values against stress					
Raw data	Minimum	.17	.09	.13	.07
	Maximum	.08	.03	.19	.03
Predicted	Minimum	.43**	.07	.11	.16
	Maximum	.07	.00	.03	.21
Residual	Minimum	.12	.00	.15	.03
	Maximum	.19	.01	.23*	.31*
Regression of same values against non-test vowel identities					
Raw data	Minimum	.01	.00	.00	.01
	Maximum	.25	.46*	.32	.23
Predicted	Minimum	.02	.08	.22	.02
	Maximum	.21	.45*	.02	.18
Residual	Minimum	.02	.12	.03	.01
	Maximum	.04	.34*	.07	.01

Several patterns can be observed in this table. First, in general, the minimum and maximum values of the angle of jaw rotation do not predict the stress pattern of the test syllable or the identity of the vowel in the non-test syllable. However, these values are highly correlated with the identity of the vowel in the test syllable for all three trajectory types. It can be observed that the minimum value is generally a better predictor than the maximum value within a given trajectory type. Notice also that the raw data points and the residuals are generally more highly correlated with test vowel identity than the predicted values.

Figure 3.56 plots the minimum and maximum values of the angle of rotation for the raw data for the V1t demisyllables. Observe that for every utterance type, a more negative angle of rotation is seen for /ae/ than for /a/ and for /ae/ than for /i/ at maximal jaw opening.

These results suggest that LF relies primarily on jaw rotation, rather than jaw translation to differentiate jaw height for vowels. JE and CG, by contrast, rely on a combination of rotation and translation to distinguish among opening gestures for different vowels.

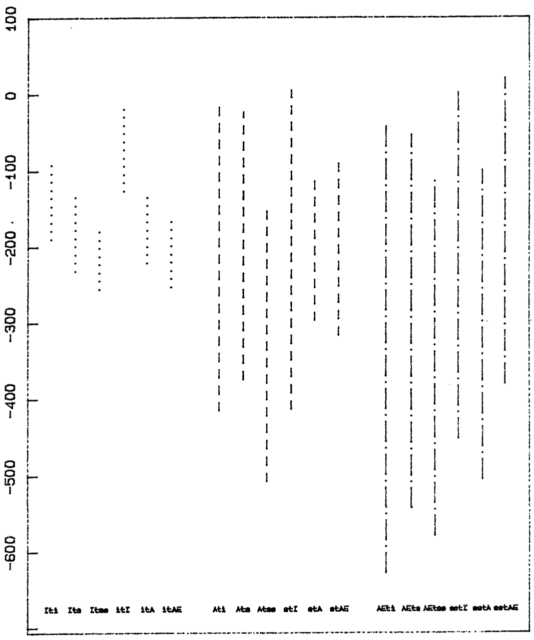

Figure 3.56 Minimum and maximum values for the angle of jaw rotation for each utterance type for the V1t demisyllables for LF. The dotted lines represent /it/; the dashed lines represent /at/; the dashed-and-dotted lines represent /aet/. Upper-case letters represent stressed demisyllables; lower-case letters represent unstressed demisyllables.

CHAPTER 4

INTRA-SPEAKER VARIABILITY

A second data-recording session was run on all three subjects so that the issue of within-speaker variability could be addressed. It is well known that speakers have been found to be quite variable with respect to the displacements of individual articulators for a particular speech segment, even if the phonetic context is held constant (Ostry & Munhall, 1985). In a paper presented at the 1983 conference on Invariance and variability in speech processes at M.I.T., Abbs (in press) observed:

> ..Since utterance numbers were not limited by ... [our] techniques, we obtained many repetitions of each utterance and usually studied four to six subjects. Analyses of ...[these] data indicated that the intra- and intersubject variability was not merely noise that blurred otherwise robust trends; rather, it appeared that hypothesized patterns might not exist, even for isolated productions... For every apparently consistent movement pattern in a particular subject, there were equal numbers of counter examples in the same and different subjects. Under circumstances where the subjects produced the same utterance repeatedly (10 to 20 times), the lip or jaw displacement variability for a particular gesture was often as large as 50 percent of the mean.

Given that intra-speaker differences are ubiquitous, three questions were of concern.

4.1 Intra-speaker Differences to be Addressed

4.1.1 Absolute Contributions of the Three Jaw Movement Components to Resultant Jaw Displacement

First, do the magnitudes of the three jaw movement components at maximal opening and their projections onto resultant jaw displacement remain invariant across two experimental sessions? A negative answer to this question was expected, given that jaw displacement for a given vowel in the same phonetic context has been observed to vary significantly within speakers across multiple repetitions. In addition, the acoustic output of a given vowel has been observed to vary across multiple repetitions. Furthermore, even if the acoustic output remains invariant, the same acoustic output can be produced by different vocal tract shapes and the same vocal tract shape can be produced by different combinations of tongue and jaw displacements.

4.1.2 Relative Contributions of the Three Jaw Movement Components to Resultant Jaw Displacement

Second, do the relative contributions of the three jaw movement components to resultant jaw displacement at remain invariant across two experimental sessions? A negative answer to this question was expected in light of the fact that intra-articulator adjustments can yield comparable jaw displacements for the three vowels under consideration. It should be noted that physical constraints limit the range of relative contributions of each component for a given jaw displacement. However, as discussed in Chapter 1 (Section 1.1.4), given the range of jaw displacements observed during speech-related gestures, the limits imposed by physical constraints permit considerable latitude with respect to the relationhips among the three components.

4.1.3 Qualitative Relationships Among the Three Jaw Movement Components

Third, are the same qualitative relationships among the three jaw movement components observed across the two experiments? Are inter-speaker differences preserved? Positive answers to these two related questions were expected. More specifically, it was predicted that for CG and JE, the relationship between jaw rotation and the first principal component of jaw translation would be highly constrained. By contrast, it was predicted for LF that no functional constraints would be observed and that LF would differentiate jaw height for vowels on the basis of rotation alone. It will be suggested in Chapter 5 that it may be possible to predict the presence or absence of functional constraints among the three components of jaw movement on the basis of occlusal class. If this hypothesis is correct, then this sort of structure-function relationship should remain invariant across two different recording sessions.

It should be noted at the outset of this chapter that an acoustic comparison of the two experimental sessions for each subject has not yet been performed. Thus, a limitation of the present discussion is that it remains unknown whether observed articulatory differences between the two experimental sessions are accompanied by significant acoustic differences.

4.2 Question 1: Absolute Contributions

4.2.1 Magnitude of the Three Jaw Movement Components

As predicted, the answer to question one was negative. Table 4.1 gives the magnitude of displacement for the three jaw movement components at maximal opening for the utterance types in which the test vowel was /a/ or /ae/ for all three subjects. These data are also illustrated graphically for the V1t demisyllables in Fig. 4.1. A comparison of these data with the parallel observations in Table 3.1 reveals different patterns of intra-speaker differences for each subject.

CG exhibits significantly smaller magnitudes of all three jaw movement components in the second experiment, as compared to the first: $t = 12.01$, $p < .0000$ for TX; $t = 5.12$, $p < .0000$ for TY; $t = 2.59$, $p < .05$ for R. JE exhibits significantly smaller magnitudes of the first and second principal components of translation and no significant differences for rotation in the second experiment as compared to the first: $t= 8.27$, $p < .0000$ for TX; $t = 6.37$, $p < .0000$ for TY; $t = 1.71$, $p > .10$ for R. LF exhibits no significant differences for the first principal component of translation, significantly smaller magnitudes of the second principal component of translation, and significantly greater magnitudes of rotation in the second experiment, as compared to the first: $t = -.63$, $p > .10$ for TX; $t = 3.78$, $p < .01$, $t = -8.89$, $p < .0000$ for R.

Table 4.1

Amount of three jaw movement components in mm at maximal opening in V1t and tV2 demisyllables

							V1t				
	non-										
test	test			CG			JE			LF	
vowel	vowel	stress	TX	TY	R	TX	TY	R	TX	TY	R
a	i	+	3.0	1.8	5.9	7.0	2.3	18.0	2.1	1.3	8.9
a	a	+	3.6	1.6	6.2	6.1	2.0	13.9	2.5	1.3	9.4
a	ae	+	4.1	1.3	6.4	5.3	2.0	13.4	2.6	1.3	9.3
a	i	-	2.8	1.4	5.2	4.2	1.8	10.2	1.9	1.1	7.1
a	a	-	2.6	1.6	5.2	4.0	2.1	9.4	1.8	.7	6.7
a	ae	-	2.7	1.1	5.0	3.5	2.1	9.6	1.8	1.2	4.9
ae	i	+	3.9	1.0	7.1	5.6	1.6	13.9	2.6	1.5	10.7
ae	a	+	4.2	1.2	6.9	4.7	1.4	11.7	2.9	1.5	12.0
ae	ae	+	4.1	1.6	6.4	5.1	1.8	13.5	3.2	.9	9.7
ae	i	-	3.4	1.1	6.4	5.8	2.2	15.1	2.2	1.2	9.1
ae	a	-	3.7	1.1	6.1	4.1	2.0	11.7	1.5	.8	9.2
ae	ae	-	4.3	1.5	8.0	3.5	1.9	9.7	1.5	.4	7.6
							tV2				
a	i	+	3.6	1.2	5.7	6.0	2.5	16.2	2.5	1.0	11.6
a	a	+	4.1	1.3	6.9	6.4	2.4	13.5	2.6	1.3	12.4
a	ae	+	4.3	1.2	6.5	6.5	1.7	12.6	2.4	1.2	11.8
a	i	-	1.8	1.5	4.0	3.5	1.7	12.5	1.9	1.5	6.6
a	a	-	3.0	.9	5.6	3.8	1.5	8.6	1.5	1.1	7.6
a	ae	-	3.5	1.0	5.9	2.5	1.8	7.6	1.8	1.2	9.1
ae	i	+	3.2	1.1	6.0	6.9	2.8	18.0	3.0	1.2	15.3
ae	a	+	4.3	1.0	6.3	6.6	2.1	15.9	3.3	1.4	14.0
ae	ae	+	5.6	1.4	9.2	5.2	1.9	12.6	2.3	1.1	11.7
ae	i	-	2.9	1.5	4.8	4.1	2.2	13.6	1.9	1.6	8.2
ae	a	-	2.5	1.0	4.8	4.2	2.3	10.8	2.6	1.7	9.6
ae	ae	-	4.0	1.5	6.4	2.8	1.8	9.5	2.0	1.3	8.9

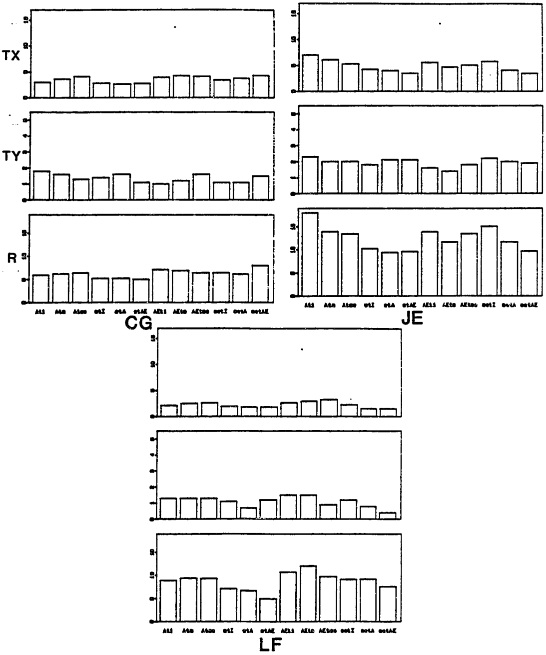

Figure 4.1 Histograms of the magnitude of displacement of the three jaw movement components for the V1t demisyllables. The data for CG are shown on the top left plot; the data for JE are shown on the top right plot; the data for LF are shown on the bottom plot. In each set of plots, the top row shows the data for TX; the middle row shows the data for TY; the bottom row shows the data for R. Upper-case letters indicate stressed demisyllables; lower-case letters indicate unstressed demisyllables. The units on the y axis are mm.

4.2.2 Projections of the Three Jaw Movement Components onto Resultant Jaw Displacement

Different patterns of intra-speaker differences were also observed when the direction of movement is taken into account. Table 4.2 gives the projections of the three jaw movement components onto resultant jaw displacement at the front teeth for the V1t demisyllables. These data are also presented graphically in Fig. 4.2. Again, a comparison of these data with their counterparts from the first experiment, given in Table 3.2, reveals differences among the three speakers.

CG exhibits significantly smaller projections of the first and second principal components onto resultant jaw displacement and no significant differences in rotation in the second experiment, as compared to the first: $t = 4.21$, $p < .01$ for TX; $t = 5.20$, $p < .001$ for TY; $t = .38$, $P > .10$ for R. JE exhibits significantly smaller projections of all three jaw movement components onto resultant jaw displacement in the second experiment, as compared to the first: $t = 4.97$, $p < .001$ for TX; $t = 3.63$, $p < .01$ for TY; $t = 2.34$, $p < .05$ for R. LF exhibits no significant differences for the first principal component of translation, significantly smaller projections of the second principal component of translation, and significantly greater projections of rotation onto resultant jaw displacement in the second experiment, as compared to the first: $t = .42$, $p > .10$ for TX; $t = 3.38$, $p < .01$ for TY; $t = -7.53$, $p < .0000$ for R.

Table 4.2

Projections in mm of the three jaw movement components onto resultant jaw displacement for V1t demisyllables

test vowel	non-test vowel	stress		CG			JE			LF	
			TX	TY	R	TX	TY	R	TX	TY	R
a	i	+	2.4	1.1	5.8	1.4	2.3	16.8	1.7	.8	8.9
a	a	+	3.0	.9	6.2	1.4	1.9	12.8	2.0	.8	9.4
a	ae	+	3.5	.7	6.3	1.0	2.0	12.5	2.1	.8	9.3
a	i	-	2.3	.8	5.2	.4	1.8	9.8	1.5	.7	7.1
a	a	-	2.1	1.0	5.2	.8	2.1	8.7	1.5	.4	6.7
a	ae	-	2.2	.6	4.9	.5	2.1	9.1	1.4	.5	5.2
ae	i	+	3.3	.5	7.0	1.1	1.6	12.9	2.1	.9	10.7
ae	a	+	3.6	.6	6.8	1.0	1.4	10.9	2.4	.9	12.0
ae	ae	+	3.4	.9	6.3	.9	1.8	12.7	2.7	.5	9.7
ae	i	-	2.9	.6	6.4	1.1	2.2	14.2	1.8	.7	9.1
ae	a	-	3.2	.6	6.1	.6	2.0	11.0	1.2	.5	9.2
ae	ae	-	3.6	.8	8.0	.5	2.0	9.2	1.2	.3	7.6

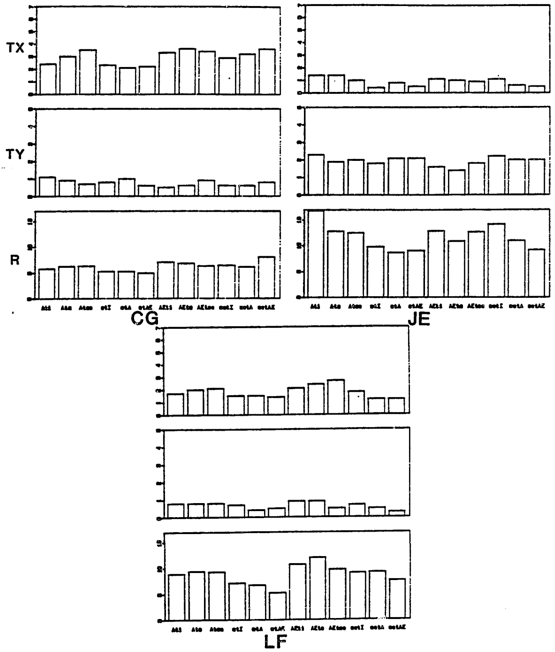

Figure 4.2 Histograms of the projections of the three jaw movement components onto resultant jaw displacement for the V1t demisyllables. The data for CG are shown on the top left plot; the data for JE are shown on the top right plot; the data for LF are shown on the bottom plot. In each set of plots, the top row shows the data for TX; the middle row shows the data for TY; the bottom row shows the data for R. Upper-case letters indicate stressed demisyllables; lower-case letters indicate unstressed demisyllables. The units on the y axis are mm.

Differences between the two experiments with respect to resultant jaw displacement at the front teeth were also examined. Different results were again observed for all three subjects. In the second experiment, as compared to the first, CG exhibited significantly smaller jaw displacements ($t = 3.28$, $p < .01$); JE exhibited no significant differences in jaw displacement ($t = 1.68$, $p > .10$); and LF exhibited significantly greater jaw displacements ($t = -4.38$, $p < .01$).

Thus, as predicted, significant differences between the two experiments were observed with respect to the magnitude of the three jaw movement components, their projections onto resultant jaw displacement, and resultant jaw displacment for all three subjects. It should also be noted that each speaker exhibited a different pattern of intra-speaker differences between the two experiments.

4.3 Question 2: Relative Contributions

The answer to question two was also negative, as predicted. Table 4.3 gives the relative contributions of the three jaw movement components to resultant jaw displacement for the V1t demisyllables. These data are also presented graphically in Fig. 4.3. These data were compared with the parallel observations from the first experiment, given in Table 3.3. Percentages were transformed into arcsine units in order to stabilize the order variance (Brownlee, 1965). All three subjects exhibited significantly smaller relative contributions of the first and second principal components of translation and significantly greater relative contributions of rotation to resultant jaw displacment in the second experiment, as compared to the first. For CG, $t = 25.77$,

Table 4.3

Relative contributions (in %) of the three jaw movement components to resultant jaw displacement for V1t demisyllables

test vowel	non-test vowel	stress		CG			JE			LF	
			TX	TY	R	TX	TY	R	TX	TY	R
a	i	+	25	12	62	11	07	82	15	07	79
a	a	+	30	09	62	12	09	80	16	07	77
a	ae	+	33	07	60	06	13	81	17	07	76
a	i	-	28	10	63	03	15	80	16	08	77
a	a	-	25	12	63	07	18	75	17	05	78
a	ae	-	28	08	62	04	18	78	20	07	73
ae	i	+	30	05	64	07	10	83	15	07	78
ae	a	+	33	05	62	08	11	83	16	06	79
ae	ae	+	32	08	59	06	12	83	21	04	76
ae	i	-	30	06	65	06	13	82	16	06	78
ae	a	-	33	06	63	04	15	80	11	05	84
ae	ae	-	29	06	65	04	17	79	13	03	84

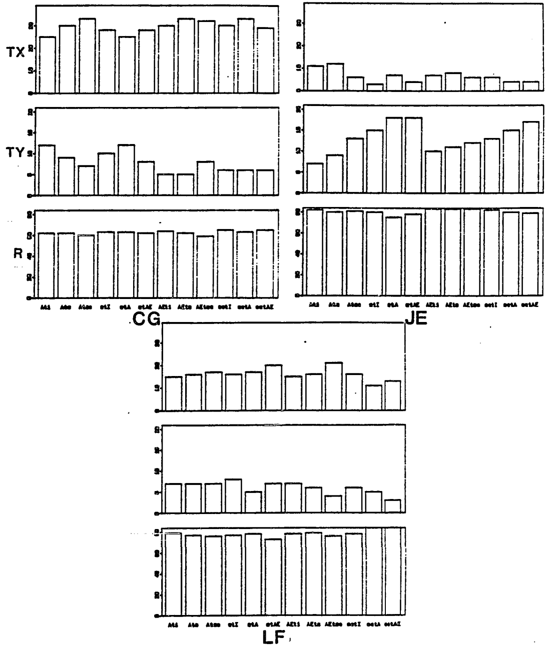

Figure 4.3 Histograms of the relative contributions of the three jaw movement components to resultant jaw displacment for the V1t demisyllables. The data for CG are shown on the top left plot; the data for JE are shown on the top right plot; the data for LF are shown on the bottom plot. In each set of plots, the top row shows the data for TX; the middle row shows the data for TY; the bottom row shows the data for R. Upper-case letters indicate stressed demisyllables; lower-case letters indicate unstressed demisyllables. The units on the y axis are percent.

$p < .0000$ for TX; $t = 15.4$, $p < .0000$ for TY; $t = -44.95$, $p < .0000$ for R. For JE, $t = 39.58$, $p < .0000$ for TX; $t = 9.23$, $p < .0000$ for TY; $t = -4.33$, $p < .01$ for R. For CG, $t = 30.88$, $p < .0000$ for TX; $t = 3.57$, $p < .01$ for TY; $t = -38.93$, $p < .0000$ for R.

4.4 Further Differences Between the Two Experiments

4.4.1 Differences in Token-to-token Variability

Another difference between the two experiments is that more token-to-token variability was observed in the second experiment, as compared to the first, for CG and JE. This increase in token-to-token variability was particularly pronounced with respect to the relationship between the first two principal components of jaw translation. Table 4.4 gives the correlation coefficients separately for each utterance type for the V1t and the tV2 demisyllables in which the test vowel was /a/ or /ae/ for the two experiments. These coefficients were calculated by correlating horizontal and vertical jaw translation on an utterance by utterance basis before outlying points or tokens had been deleted and before the coordinate systems were rotated. Sign tests revealed that the correlation coefficients are significantly lower in the second experiment, as compared to the first for CG ($p < .001$), JE ($p < .001$), but not for LF ($p > .10$). It is unclear what factors contributed to this increase in token-to-token variability. A substantial amount of this increase is probably a statistical artifact resulted from the smaller magnitudes of both TX and TY in the second experiment for CG and JE, assumed that a fixed amount of position variability exists as noise. It is also possible

Table 4.4

Correlations by utterance type for V1t and tV2 demisyllables
for experiments 1 and 2 (E1 and E2)

	non-		CG				JE			
test	test		V1t		tV2		V1t		tV2	
vowel	vowel	stress	E1	E2	E1	E2	E1	E2	E1	E2
a	i	+	-.93	-.15	-.84	-.27	-.96	-.65	-.94	-.83
a	a	+	-.79	-.39	-.93	-.68	-.97	-.73	-.95	-.41
a	ae	+	-.89	-.65	-.93	-.83	-.94	-.43	-.94	-.57
a	i	-	-.68	-.32	-.48	-.45	-.72	-.46	-.88	-.36
a	a	-	-.59	-.17	-.58	-.08	-.78	-.14	-.73	-.09
a	ae	-	-.64	.06	-.77	-.35	-.93	-.19	-.88	.20
ae	i	+	-.85	-.57	-.70	-.37	-.73	-.72	-.95	-.48
ae	a	+	-.83	-.82	-.89	-.58	-.96	-.71	-.93	-.51
ae	ae	+	-.86	-.65	-.95	-.72	-.96	-.65	-.96	-.53
ae	i	-	-.07	-.19	-.75	-.04	-.82	-.54	-.89	-.09
ae	a	-	-.74	-.65	-.63	-.33	-.86	-.33	-.91	.10
ae	ae	-	-.71	-.62	-.78	-.57	-.87	-.28	-.88	-.41

			LF			
			V1t		tV2	
			E1	E2	E1	E2
a	i	+	-.50	-.34	.15	-.24
a	a	+	-.71	-.31	-.45	-.50
a	ae	+	-.36	-.40	-.52	-.45
a	i	-	-.14	.10	-.35	-.52
a	a	-	-.20	-.03	-.31	-.15
a	ae	-	-.08	-.56	-.46	-.49
ae	i	+	-.86	-.34	-.68	-.11
ae	a	+	-.21	-.60	-.55	-.71
ae	ae	+	-.08	-.50	-.26	-.20
ae	i	-	-.52	.20	-.39	-.07
ae	a	-	-.04	-.02	-.33	-.36
ae	ae	-	-.38	-.30	-.21	-.22

that the smaller token-to-token variability (and the larger jaw displacements for CG) in the first experiment may be due, at least in part, to any of a number of non-statistical factors. For example, smaller token-to-token variability in the first experiment may be due to relatively greater stress differences between stressed and unstressed syllables or to slow and exaggerated articulation. It is also possible that the larger token-to-token variability in the second experiment is due to faster and more natural articulation.

4.4.2 Durational Differences

Durational differences between the two experiments were examined for a subset of the utterance types (/'ata/, /a'ta/, /'aetae/, /ae'tae/) in order to determine whether subjects used systematically different speaking rates in the two experiments. Three paired comparison t-tests were performed: (1) the durations of the V1 demisyllables in the two experiments were compared; (2) the durations of the V2 demisyllables in the two experiments were compared; and (3) the ratios of the duration of the vowel with primary stress relative to that of the vowel with secondary stress for each utterance token were compared. Significant durational differences for all three comparisons was observed only for JE, who exhibited longer demisyllable durations and greater differences between stressed and unstressed vowel durations in the first experiment, as compared to the second: $t = 3.59$, $p < .001$ for V1; $t = 2.60$, $p < .05$ for V2; $t = 6.31$, $p < .0000$ for the stressed to unstressed ratio. No significant durational differences were observed for CG: $t = -2.08$, $p > .05$ for V1; $t = 1.75$, $p > .05$ for V2;

t = .92, p > .10 for the stressed to unstressed ratio. For LF, significant durational differences were observed only for the V1 demisyllable, which was longer in the first experiment, as compared to the second: t = 3.79, p < .01 for V1; t = .87, p > .10 for V2; t = 1.0 p > .10 for the stressed to unstressed ratio.

Thus, CG and JE both exhibit increased token-to-token variability in the second experiment, as compared to the first, although significant durational differences are observed only for JE. This result suggests that for JE--but not for CG--increased token-to-token variability in the second experiment may be due, in part, to a faster speaking rate and to relatively lesser differences between stressed and unstressed vowels. It should also be noted that differences in movement durations are not congruent with differences in resultant jaw displacement across the two experiments. JE exhibits significantly longer movement durations in the first experiment, as compared to the second, but no significant differences in jaw displacement. By contrast, CG exhibits significantly greater jaw displacements in the first experiment, as compared to the second, but not significant differences in movement durations. LF exhibits significantly smaller jaw displacements in the first experiment, as compared to the second, longer movement durations for the V1 demisyllable.

4.4.3 Summary

Analysis of the acoustic differences between the two experiments and analysis of data within comparable ranges for both experiments may shed some light on what factors contribute to changes in token-to-token variability for CG and JE. Acoustic analysis is also needed in order to explain the patterns of intra-speaker differences across the two experiments that was observed for each subject. However, additional multiple runs on the same subjects, will, in all likelihood, be necessary to resolve the remaining questions.

A similarity between the two experiments is that in the second experiment, as in the first, these quantitative and gross qualitative measures reveal differences across all three speakers. For example, Table 4.2 reveals that in the second experiment, the magnitude of the projection of rotation onto resultant jaw displacement is greatest for JE and least for CG. Conversely, the magnitude of the projection of the first principal component of translation onto resultant jaw displacement is greatest for CG and least for JE. In addition, Table 4.3 reveals that the relative contribution of rotation to resultant jaw displacement is smallest for CG (62 to 65 percent) and roughly comparable for JE (75 to 83 percent) and LF (73 to 84 percent). The relative contribution of the first principal component of translation to resultant jaw displacement is greatest for CG (25 to 33 percent), less for LF (11 to 21 percent), and least for JE (3 to 9 percent). Thus, in the second experiment, as in the first, it was necessary to examine the relationships among the three jaw movement components by analyzing their trajectories in order to discover qualitative--and consistent--inter-speaker similarities.

4.5 <u>Question 3</u>: <u>Qualitative Relationships</u>

The answer to the third question was as predicted. The results of the multiple regression analyses of the second data-recording session, like the first, revealed similar relationships among the three jaw movement components across the two experiments for the three subjects. Thus, inter-speaker differences were preserved. In the second experiment, as in the first, results for CG and JE were qualitatively similar and the results for LF were dissimilar. As in Chapter 3, the results of the translation and rotation regression analyses for JE and CG will be discussed together; the results for LF will be presented separately. Let us first consider the results for JE and CG.

4.5.1 Translation Analysis for CG and JE

4.5.1.1 Combination of Phonetic Parameters

In section 4.1 above, it was posited that the similar relationships among the three components of jaw movement would be observed across the two recording sessions for each subject. To address this question, both the translation and the rotation regression analyses were performed on the V1t and the tV2 demisyllables for each subject. Let us first consider the translation analysis. Table 4.5 gives the squared multiple correlations computed for all of the utterance combinations described in Chapter 2. A comparison of these results with their counterparts in Table 3.4 reveal that the squared multiple correlations are systematically lower for the second experiment, as compared to the first, for both subjects across both V1C and CV2 demisyllable types.

Table 4.5

Squared multiple correlations (TY on TX) for all of the utterance combinations described in Chapter 2 for the V1t and tV2 demisyllables

Values of phonetic parameters if not combined			CG		JE	
test vowel	non-test vowel	stress	V1t	tV2	V1t	tV2
i			.29	.30	.33	.30
a			.22	.33	.20	.08
ae			.26	.34	.13	.07
	i		.45	.52	.03	.32
	a		.11	.21	.13	.18
	ae		.18	.33	.16	.18
		+	.15	.38	.12	.12
		–	.21	.22	.06	.25
			.14	.28	.10	.11

4.5.1.2 Demisyllables Containing V1

At first glance, one would argue that these substantially lower squared multiple correlations for CG and JE in the second experiment, as compared to the first, indicate that the relationship between the first two components of jaw translation is not qualitatively similar across the two data recording session. However, the decreases in the squared multiple correlations are due, at least in part, to the decreased range of the first two principal components of translation in the second experiment, as compared to the first. The V1t demisyllables are plotted in Figs. 4.4 and 4.5 for CG and JE, respectively. A comparison of Figs. 4.4 and 4.5 with their counterparts from the first experiment (Figs. 3.9 and 3.10) reveals that the data are concentrated within a much smaller range in the second experiment, as compared to the first. Within this smaller range, there is extensive overlap of the three vowel groups. Thus, several related factors (i.e. increased token-to-token variability and decreased range) will result in substantially reduced squared multiple correlations. Therefore, it is difficult to determine statistically whether the relationship between the first two principal components of jaw translation remains qualitatively similar across the two experiments. A gross qualitative similarity can be observed by comparing the relative positions of the three test vowel groups: for both subjects, the /it/ trajectories generally have the most posterior position in both experiments.

4.5.1.3 Demisyllables Containing V2

The tV2 demisyllables also exhibit a decreased range in the second

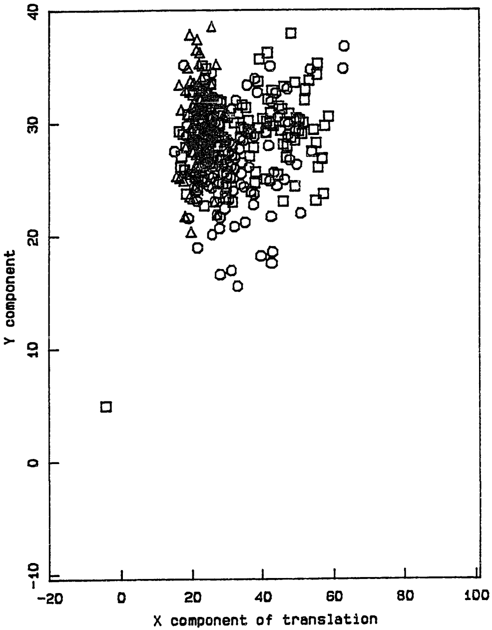

Figure 4.4 Values of the Y component of jaw translation are plotted against values of the X component for the V1t demisyllables for CG. Triangles represent /it/; circles represent /at/; squares represent /aet/. The coordinate system has been rotated by 78 degrees clockwise.

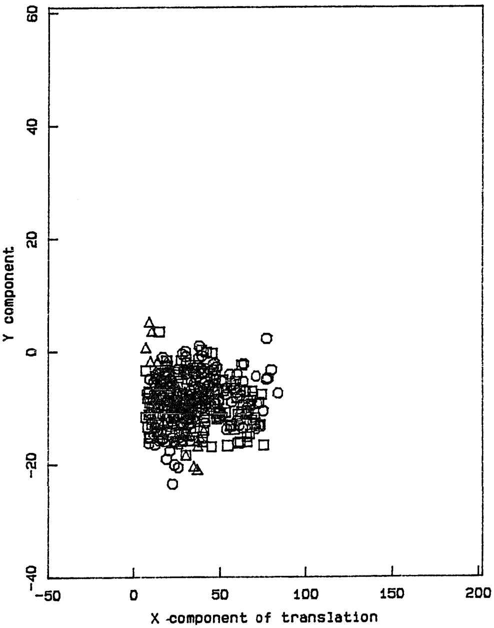

Figure 4.5 Values of the Y component of jaw translation are plotted against values of the X component for the V1t demisyllables for JE. Triangles represent /it/; circles represent /at/; squares represent /aet/. The coordinate system has been rotated by 14 degrees clockwise.

experiment, as compared to the first. Figures 4.6 and 4.7 plot the tV2 demisyllables for CG from the first and second experiments, respectively. The corresponding demisyllables for JE are plotted in Figs. 4.8 and 4.9. Again, it can be observed that the range of the data is substantially smaller in the second experiment, as compared to the first. Gross qualitative similarities are observed across the two experiments for both subjects. For CG, the /ti/ demisyllables are the most posterior and the /tae/ demisyllables are the most anterior in both experiments. Similarly, for JE, the /ti/ demisyllables are generally the most posterior in both experiments. A significant difference between the two experiments is that there is no evidence in the second experiment that the influence of the non-test vowel is greater than the influence of the test vowel for the tV2 demisyllables. It is unclear why this assymetry between anticipatory and carryover coarticulation was observed in the first experiment, but not in the second. This difference between the two experiments may be due to a relatively greater jaw contribution to tongue position in the first experiment, as compared to the second, or it may be due to relatively greater stress differences between V1 and V2, in the first experiment, as compared to the second.

4.5.1.4 Summary

Thus, for CG and JE, there appear to be both some differences and some similarities with respect to the relationship between the first two principal components of jaw translation across the two experiments. The lower squared multiple correlations in the second experiment, as

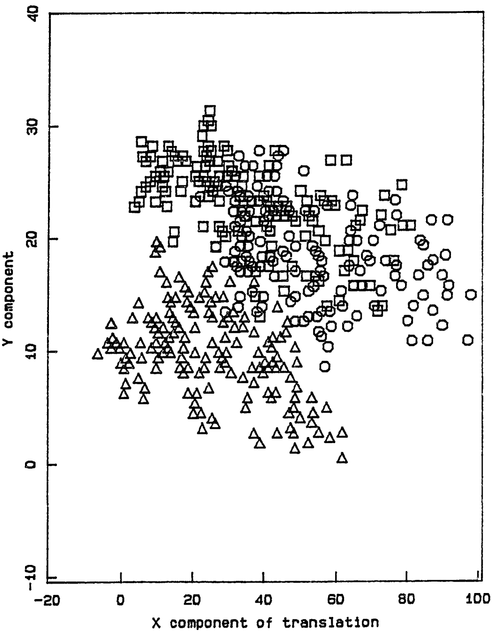

Figure 4.6 Values of the Y component of translation are plotted against values of the X component for the tV2 demisyllables from the first experiment for CG. Triangles represent /ti/; circles represent /ta/; square represent /tae/. The coordinate system has been rotated by 64 degrees clockwise.

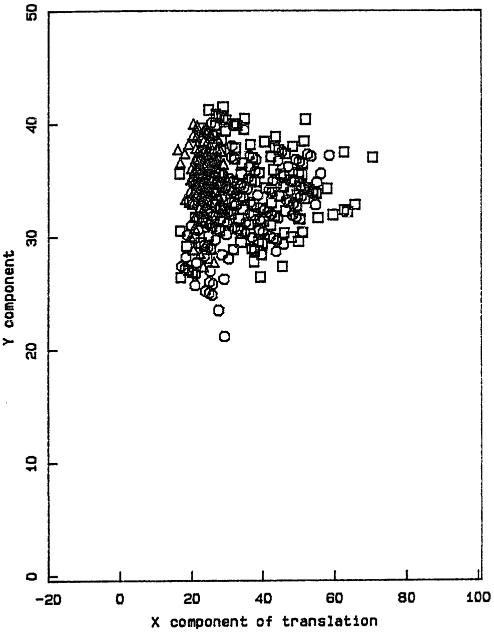

Figure 4.7 Values of the Y component of translation are plotted against values of the X component for the tV2 demisyllables from the second experiment for CG. Triangles represent /ti/; circles represent /ta/; square represent /tae/. The coordinate system has been rotated by 80 degrees clockwise.

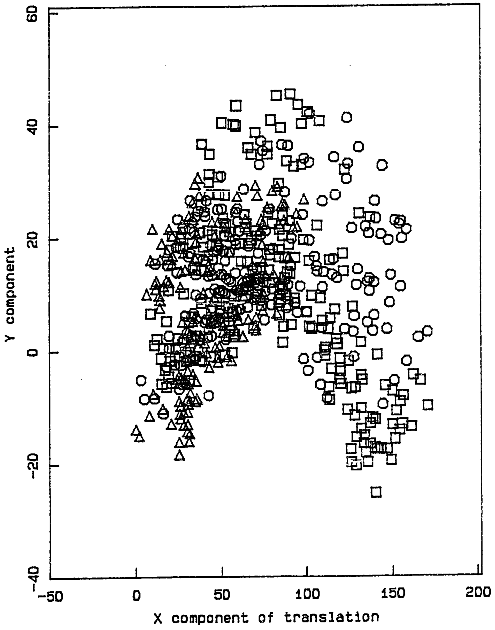

Figure 4.8 Values of the Y component of translation are plotted against values of the X component for the tV2 demisyllables from the first experiment for JE. Triangles represent /ti/; circles represent /ta/; square represent /tae/. The coordinate system has been rotated by 32 degrees clockwise.

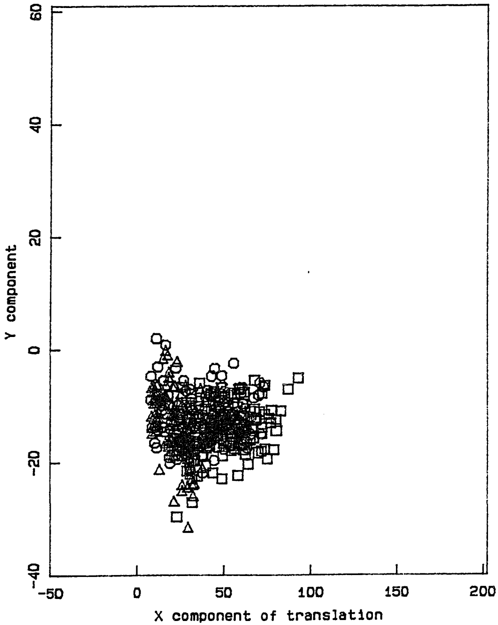

Figure 4.9 Values of the Y component of translation are plotted against values of the X component for the tV2 demisyllables from the second experiment for JE. Triangles represent /ti/; circles represent /ta/; square represent /tae/. The coordinate system has been rotated by 10 degrees clockwise.

compared to the first, can be attributed, at least in part, to the decreased range of the data. The relative positions of the three test vowel trajectories appears grossly similar for the tV1 and the tV2 demisyllables across the two experiment for both CG and JE. However, a difference between the two experiments is that a relatively greater influence of carryover, as compared to anticipatory, coarticulation was observed in the first experiment, but not in the second.

4.5.2 Rotation Analysis for CG and JE

4.5.2.1 Combination of Phonetic Parameters

The results of the rotation analysis also reveal similar relationships between jaw rotation and the first principal component of jaw translation across the two experiments for both CG and JE. Table 4.6 gives the squared multiple correlations for all of the utterance combinations described in Chapter 2. A comparison of these results with their counterparts from the first experiment, given in Table 3.8, reveals qualitatively similar squared multiple correlations across the two experimental sessions. The squared multiple correlations for the second experiment, as compared to the first experiment, tend to be slightly higher for CG and slightly lower for JE, but these differences are small and the overall patterns are comparable. As in the first experiment, the lower squared multiple correlations for both subjects are observed when the utterance types are not combined across different test vowels and the identity of the test vowel is /i/. With this exception, the squared multiple correlations range from .80 to .94 for CG (as compared to a range of .69 to .90 for the first experiment) and

Table 4.6

Squared multiple correlations (θ on TX) for all of the utterance combinations described in Chapter 2 for the V1t and tV2 demisyllables

Values of phonetic parameters if not combined			CG		JE	
test vowel	non-test vowel	stress	V1t	tV2	V1t	tV2
i			.23	.15	.77	.43
a			.80	.88	.97	.09
ae			.91	.90	.96	.96
	i		.85	.87	.91	.92
	a		.86	.90	.96	.96
	ae		.89	.94	.96	.93
		+	.87	.91	.95	.91
		-	.83	.87	.92	.91
			.85	.90	.92	.90

from .90 to .96 for JE (as compared to a range of .94 to .98 for the first experiment). Table 4.7 gives the contribution of the phonetic covariates for the V1C and CV2 demisyllables with the utterance types combined across test vowels, non-test vowels, and stress patterns. It can be observed that, as in the first experiment, the phonetic covariates account for very small proportions of the variance.

4.5.2.2 Demisyllables Containing V1

Figures 4.10 and 4.11 plot the predicted values of the angle of rotation against the values of the first principal component of jaw translation for the V1t demisyllables for CG and JE, respectively. In both figures, the data points are coded by the identity of the vowel in the test syllable. A comparison of these figures with their counterparts from the first experiment, Figs. 3.10 and 3.31, reveals that in both experiments jaw rotation exhibits a functional dependence on the first principal component of jaw translation. The only observable difference between the two experiments is that the distributions are tighter in the second experiment, indicating the reduced influence of phonetic context.

4.5.2.3 Demisyllables Containing V2

The tV2 demisyllables are plotted in Figs. 4.12 and 4.13 for CG and JE, coded by the identity of the test vowel. The same demisyllables are plotted again in Figs. 4.14 and 4.15, coded by the identity of the non-test vowel. A comparison of Figs. 4.12, 4.13, 4.14, 4.15 with their counterparts from the first experiment

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Table 4.7

Squared multiple correlation and contribution of covariates for θ regressed on TX for V1t and tV2 demisyllables

	demi-syllable	r2	test vowel	non-test vowel	stress
CG	V1t	.85	.002	.000	.002
	tV2	.90	.003	.004	.005
JE	V1t	.92	.02	.001	.002
	tV2	.90	.003	.003	.002

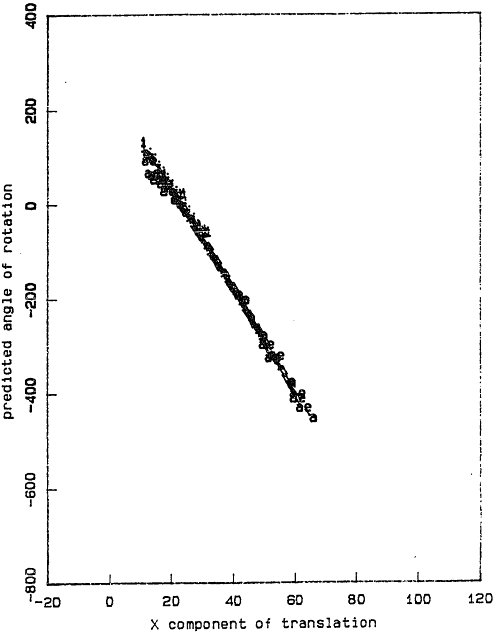

Figure 4.10 Predicted values of the angle of jaw rotation are plotted against values of the X component for the V1t demisyllables for CG. The dotted lines represent /it/; the dashed lines represent /at/; the dashed-and-dotted lines represent /aet/.

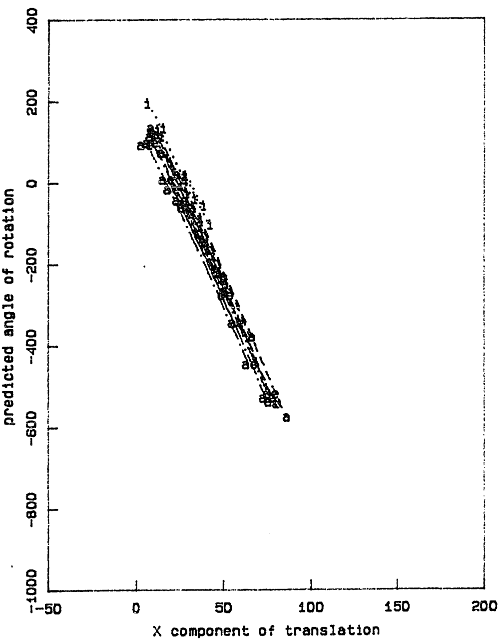

Figure 4.11 Predicted values of the angle of jaw rotation are plotted against values of the X component for the V1t demisyllables for je. The dotted lines represent /it/; the dashed lines represent /at/; the dashed-and-dotted lines represent /aet/.

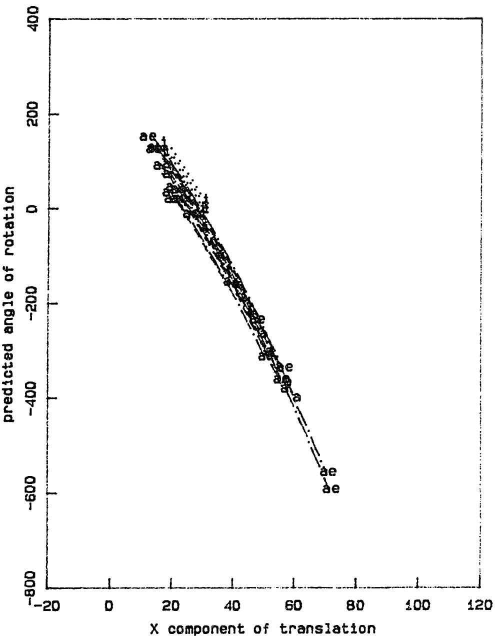

Figure 4.12 Predicted values of the angle of jaw rotation are plotted against values of the X component for the tV2 demisyllables for CG. The dotted lines represent /ti/; the dashed lines represent /ta/; the dashed-and-dotted lines represent /tae/.

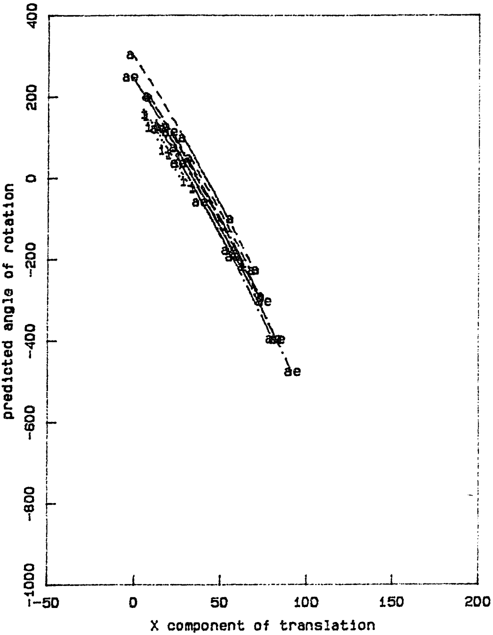

Figure 4.13 Predicted values of the angle of jaw rotation are plotted against values of the X component for the tV2 demisyllables for JE. The dotted lines represent /ti/; the dashed lines represent /ta/; the dashed-and-dotted lines represent /tae/.

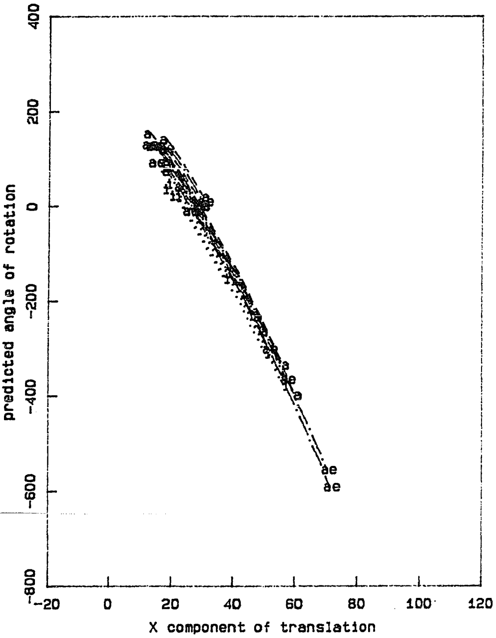

Figure 4.14 Predicted values of the angle of rotation are plotted against values of the X component for the tV2 demisyllables for CG. The dotted lines represent tV2 demisyllables preceded by /i/; the dashed lines represent tV2 demisyllables preceded by /a/; the dashed-and-dotted lines represent tV2 demisyllables preceded by /ae/.

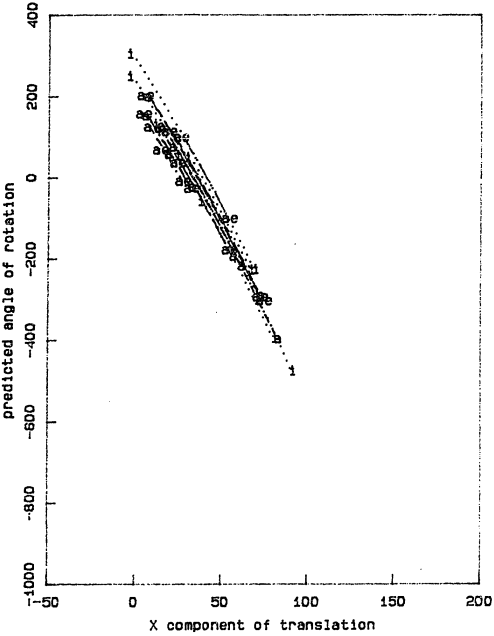

Figure 4.15 Predicted values of the angle of rotation are plotted against values of the X component for the tV2 demisyllables for JE. The dotted lines represent tV2 demisyllables preceded by /i/; the dashed lines represent tV2 demisyllables preceded by /a/; the dashed-and-dotted lines represent tV2 demisyllables preceded by /ae/.

(Figs. 3.36, 3.37, 3.38, 3.39) reveals that, again, in both experiments, the relationship between jaw rotation and the first principal component of jaw translation is highly constrained. The tV2 demisyllables, like the V1t demisyllables, exhibit tighter distributions in the second experiment, as compared to the first, indicating a reduced influence of the phonetic context. Nevertheless, it can still be observed that the relative positions of the three non-test vowels in Figs. 3.38 and 4.14 for CG and Figs. 3.39 and 4.15 for JE are qualitatively similar across the two experiments.

4.5.2.4 Summary

These results indicate that for CG and JE, the same functional relationships among the three jaw movement components were preserved across the two experiments: (1) the relationship between the first two principal components of jaw translation was not highly constrained and varied with the phonetic context; and (2) the relationship between jaw rotation and the first principal component of jaw translation was highly constrained and relatively independent of phonetic context.

4.5.3 Translation Analysis for LF

4.5.3.1 Combination of Phonetic Parameters

In section 4.1.3, it was posited that for LF, no functional constraints would be observed among the three components of jaw movement and that jaw rotation alone would exhibit systematic phonetic context effects. Both predictions were correct. First, it was found that the relationship of the second principal component of translation to the first exhibited complex interactions among the effects of the test vowel, the non-test vowel, and the stress pattern. Table 4.8 gives the squared multiple correlations for all of the utterance combinations described in Chapter 2 and also for utterances combined only across test vowels. A comparison of these results with their counterparts from the first experiment, given in Tables 3.11 and 3.12, reveals qualitative similarities. The squared multiple correlations range from .26 to .63 as compared to a range of .45 to .88 in the first experiment. Furthermore, interactions among phonetic context effects were observed in the second experiment.

4.5.3.2 Interactions Among Phonetic Parameters

Figures 4.16 and 4.17 plot the y component of jaw translation against the x component for the stressed /at/ and /aet/ demisyllables, respectively. A comparison of Figs. 4.16 and 4.17 with their counterparts from the first experiment (Figs. 3.40 and 3.41) reveals similar,although not identical patterns. In both experiments, for /at/ demisyllables, trajectories followed by /a/ are anterior to those followed by /i/ or /ae/. By contrast, for /aet/ demisyllables, in both experiments trajectories followed by /i/ are generally anterior to those followed by /a/ or /ae/. The two experiments differ in that the /at/ demisyllables followed by /ae/ overlap with the other /at/ demisyllables in the second experiment, but not in the first.

Table 4.8

Squared multiple correlations (TY on TX) for V1t and tV2 demisyllables

Values of phonetic parameters if not combined test vowel	 non-test vowel	 stress	V1t	tV2
i			.26	.40
a			.44	.08
ae			.62	.19
	i		.58	.16
	a		.17	.24
	ae		.57	.46
		+	.12	.24
		-	.22	.09
	i	+	.43	.42
	i	-	.63	.40
	a	+	.26	.24
	a	-	.53	.57
	ae	+	.63	.61
	ae	-	.39	.27
			.25	.12

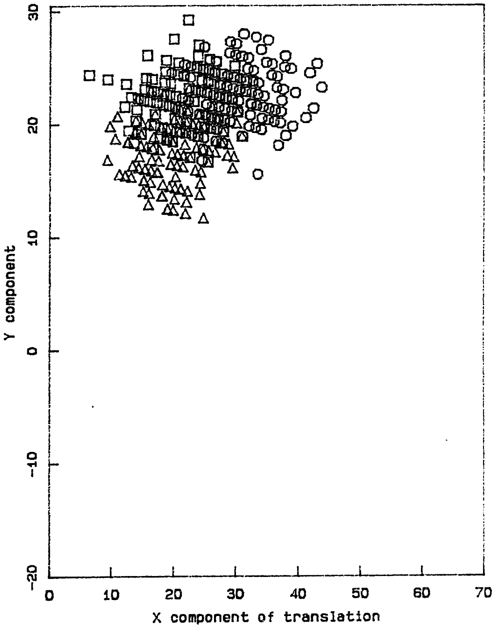

Figure 4.16 Values of the Y component of translation are plotted against values of the X component for stressed /at/ demisyllables for LF. Triangles represent /at/ demisyllables followed by /i/; circles represent /at/ demisyllables followed by /a/; squares represent /at/ demisyllables followed by /æ/. The coordinate system has been rotated by 76 degrees clockwise.

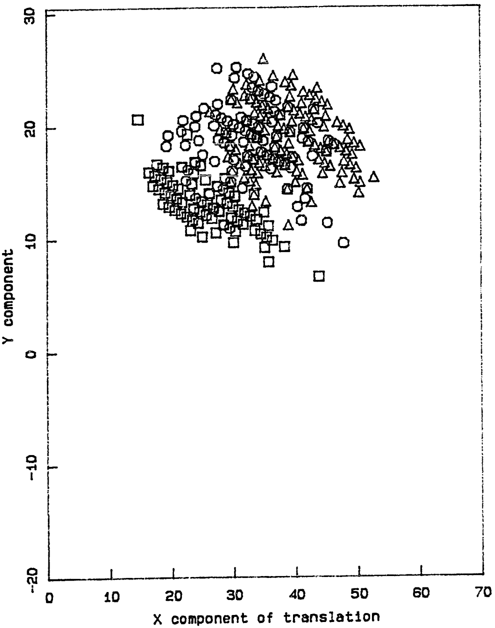

Figure 4.17 Values of the Y component of translation are plotted against values of the X component for stressed /aet/ demisyllables for LF. Triangles represent /aet/ demisyllables followed by /i/; circles represent /aet/ demisyllables followed by /a/; squares represent /aet/ demisyllables followed by /ae/. The coordinate system has been rotated by 88 degrees clockwise.

Similar results are observed for the demisyllables containing V2. Stressed /tae/ demisyllables are plotted in Fig. 4.18, which can be compared with Fig. 3.43, its counterpart from the first experiment. In both experiments, it can be observed that /tae/ demisyllables preceded by /i/ are the most posterior and that /tae/ demisyllables preceded by /a/ are the most inferior. Again, the two experiments differ in that the /tae/ demisyllables preceded by /i/ form a distinct group in the first experiment, but not in the second.

Interactions between stress and non-test vowel identity were observed in the second experiment, as in the first. The /at/ and /tae/ demisyllables, in which the non-test vowel is /a/ or /ae/ are plotted in Figs. 4.19 and 4.20, respectively. A comparison of Figs. 4.19 and 4.20, with their counterparts from the first experiment, Figs. 3.44 and 3.45, again reveals more separation among different non-test vowel groups in the first experiment, as compared to the second. It can be observed that the relative positions of the four /at/ trajectories are qualitatively similar across the two experiments, but that the relative positions of three of the four /tae/ trajectories (excluding those preceded by /i/) are dissimilar across the two experiments.

4.5.3.3 Summary

The results of the translation analyses indicate that for LF, similar interactions among the effects of the test vowel, the non-test vowel, and the stress pattern are observed in the two experiments. In the second experiment, as in the first, the patterns of these interactions are unstable in that they are not observed systematically

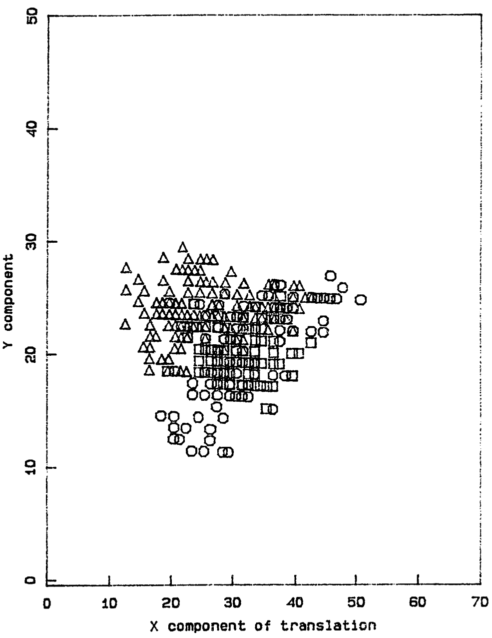

Figure 4.18 Values of the Y component of translation are plotted against values of the X component for stressed /tae/ demisyllables for LF. Triangles represent /tae/ demisyllables preceded by /i/; circles represent /tae/ demisyllables preceded by /a/; squares represent /tae/ demisyllables preceded by /ae/. The coordinate system has been rotated by 82 degrees clockwise.

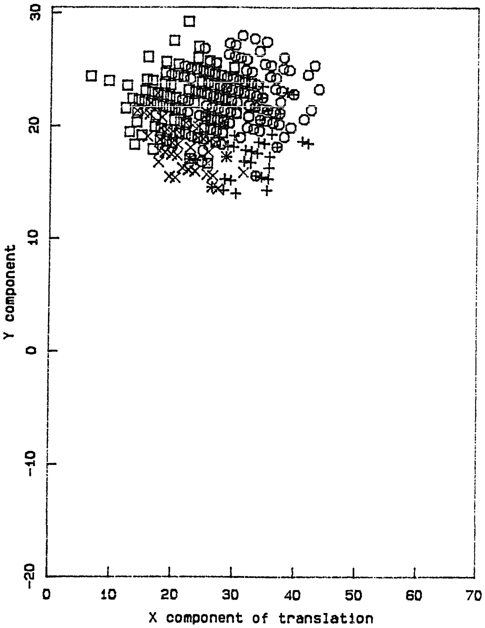

Figure 4.19 Values of the Y component of translation are plotted against values of the X component for /at/ demisyllables for LF. Circles represent stressed /at/ demisyllables followed by /a/; X's represent unstressed /at/ demisyllables followed by /a/; squares represent stressed /at/ demisyllables followed by /ae/; crosses represent unstressed /at/ demisyllables followed by /ae/. The coordinate system has been rotated by 72 degrees clockwise.

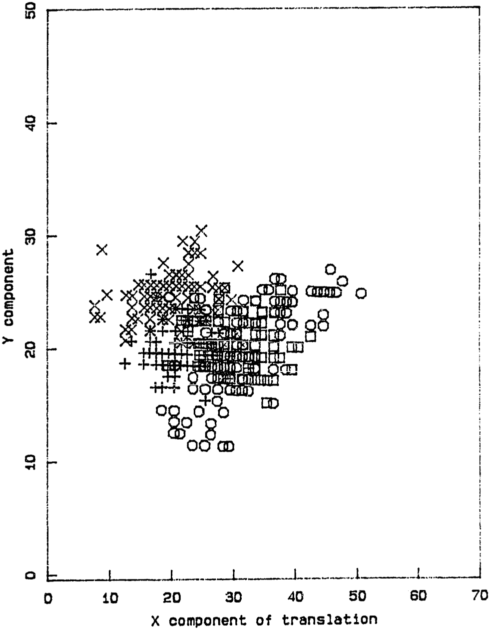

Figure 4.20 Values of the Y component of translation are plotted against values of the X component for /tae/ demisyllables for LF. Circles represent stressed /tae/ demisyllables preceded by /a/; X's represent unstressed /tae/ demisyllables preceded by /a/; squares represent stressed /tae/ demisyllables preceded by /ae/; crosses represent unstressed /tae/ demisyllables preceded by /ae/. The coordinate system has been rotated by 80 degrees clockwise.

across different demisyllable types or for all values of a phonetic parameter within a given demisyllable. The squared multiple correlations across the two experiments are qualitatively similar, although they tend to be lower in the second experiment, as compared to the first. This decrease of the squared multiple correlations in the second experiment is due, at least in part, to the increased token-to-token variability in this experiment. These qualitative similarities across the two experiments suggest that in the second experiment, as in the first, the second principal component of jaw translation is not functionally constrained by the first principal component and also that LF does not appear to exert systematic phonetic control over either of the first two principal components of jaw translation.

4.5.4 Rotation Analysis for LF

4.5.4.1 Combination of Phonetic Parameters

Furthermore, a similar relationship between jaw rotation and the first principal component of jaw translation was observed across the two experiments for LF. Table 4.9 gives the results of the rotation analysis for all of the utterance combinations described in Chapter 2 and also for utterances combined only across test vowels. A comparison of these results with their counterparts from the first experiment, given in Tables 3.13 and 3.14, reveal qualitative similarities. When the utterance types are combined only across test vowels, the squared multiple correlations range from .09 to .57, as compared to a range of .11 to .78 in the first experiment.

Table 4.9

Squared multiple correlations (θ on TX) for V1t and tV2 demisyllables

Values of phonetic parameters if not combined			V1t	tV2
test vowel	non-test vowel	stress		
i			.64	.49
a			.26	.23
ae			.37	.22
	i		.25	.32
	a		.41	.22
	ae		.43	.41
		+	.30	.34
		–	.11	.28
	i	+	.58	.49
	i	–	.09	.53
	a	+	.43	.53
	a	–	.43	.24
	ae	+	.16	.57
	ae	–	.27	.33
			.25	.23

4.5.4.2 Interactions Among Phonetic Parameters

Again, interactions among phonetic context effects were observed in the two experiments. Consider, for example, the /at/ and /aet/ demisyllables, followed by /a/ and /ae/, which are plotted in Figs. 4.21 and 4.22, respectively. A comparison of these figures with their counterparts from the first experiment, reveals that, again, the influence of the non-test vowel is greater in the first experiment, as compared to the second. Nevertheless, the second experiment also reveals that for both test vowels, unstressed trajectories followed by /a/ are posterior to their stressed counterparts, whereas unstressed trajectories followed by /ae/ are anterior to their stressed counterparts.

4.5.5 Minimum and Maximum Values of Jaw Rotation as a Function of Vowel Identity For LF

Finally, it was found that in the second experiment, as in the first, LF appears to be differentiating jaw height for the three different test vowels on the basis of jaw rotation alone. Table 4.10 presents the results of analyzing the maximum and minimum values of jaw rotation for the three trajectory types described in Chapter 3 (Section 3.6) as a function of the three phonetic parameters under consideration. A comparison of the squared multiple correlations of Table 4.10 with their counterparts from the first experiment, given in Table 3.15, reveals qualitative similarities. In both experiments, it can be observed that the identity of the test vowel, but not the identity of the non-test vowel or the stress pattern, is a reliable

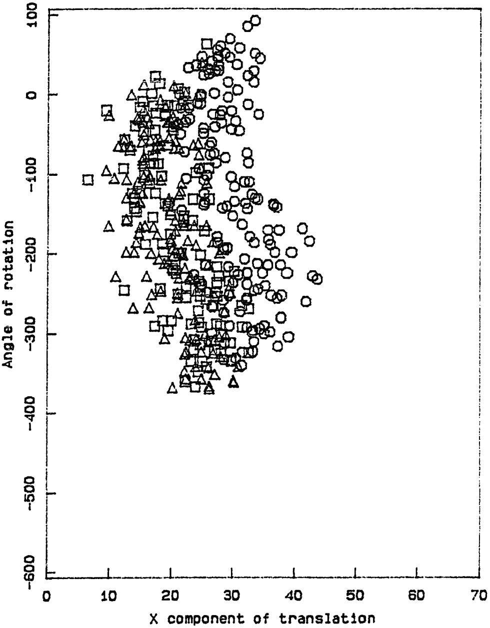

Figure 4.21 Values of the angle of rotation are plotted against values of the X component for stressed /at/ demisyllables for LF. Triangles represent /at/ demisyllables followed by /i/; circles represent /at/ demisyllables followed by /a/; squares represent /at/ demisyllables followed by /ae/.

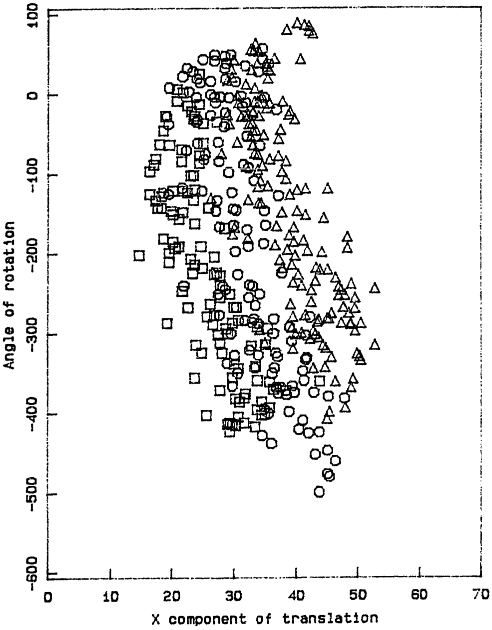

Figure 4.22 Values of the angle of rotation are plotted against values of the X component for stressed /aet/ demisyllables for LF. Triangles represent /aet/ demisyllables followed by /i/; circles represent /aet/ demisyllables followed by /a/; squares represent /aet/ demisyllables followed by /ae/.

Table 4.10

Squared multiple correlations for maximum and minimum of jaw rotation for three trajectory types regressed against vocalic covariates

		V1t	tV2
Maximum and minimum values of rotation against vowel identity			
Raw data	Minimum	.71***	.67***
	Maximum	.21	.19
Predicted	Minimum	.23	.45*
	Maximum	.25	.19
Residual	Minimum	.63***	.43*
	Maximum	.43*	.36*
Maximum and minimum values regressed against stress			
Raw data	Minimum	.16	.16
	Maximum	.07	.19
Predicted	Minimum	.51***	.19
	Maximum	.27	.12
Residual	Minimum	.09	.34*
	Maximum	.42**	.43**
Maximum and minimum values regressed against non-test vowel identities			
Raw data	Minimum	.02	.01
	Maximum	.14	.15
Predicted	Minimum	.05	.15
	Maximum	.13	.15
Residual	Minimum	.06	.01
	Maximum	.01	.02

predictor of minimum and maximum values of jaw rotation. In both experiments, higher squared multiple correlations were observed for minimum, as compared to maximum values of jaw rotation, and for raw data points and residuals, as compared to predicted values.

Thus, for LF, as for JE and CG, the relationship among the three components of jaw movement are qualitatively similar across the two experiments. In both experiments, LF differs from JE and CG in that she relies primarily on rotation to differentiate jaw height for the vowels /i/, /a/, /ae/.

CHAPTER 5

DISCUSSION AND CONCLUSIONS

5.1 Questions to be Addressed

In this study, a two-dimensional rigid-body model of jaw movement during opening and closing gestures (cf. Fig. 1.6) was used to describe jaw position during speech. Jaw movement was decomposed into three components: rotation about a transverse axis located approximately through the condyles and the horizontal and vertical translation of this axis. The relationships among these components were examined across changes in the segmental, suprasegmental, and coarticulatory context. Data were collected on two separate occasions for three subjects. It was argued in Chapter 1 that a two-dimensional rigid-body model of jaw movement is needed in order to describe the position of every point on the jaw. The model that was chosen was justified on anatomical and physiological grounds. In this chapter, the utility of such a description of jaw movement to speech production research is examined by addressing several issues of concern posed in Chapter 1. Let us again consider these questions.

5.1.1 Functional Degrees of Freedom of Jaw Movement During Speech

First, how many independent degrees of freedom of jaw movement are utilized during speech-related opening and closing gestures? Although jaw movement during speech has generally been modelled as a single degree of freedom system, the anatomy and physiology of the temporomandibular joint suggest that during opening and closing gestures the jaw can move with up to three independent degrees of freedom, corresponding to the three jaw movement components: horizontal translation, vertical translation, and rotation. Are these potentially independent components of jaw movement functionally constrained in any respect during speech? Furthermore, whether or not strong functional relationships are observed, it is of interest to determine how the degrees of freedom of jaw movement during speech are related to the three jaw movement components.

5.1.2 Phonetic Correlates of Functional Degrees of Freedom

Second, what are the phonetic correlates, if any, of the second and third degrees of freedom of jaw movement? Traditional phonetic descriptions of jaw movement during speech generally consider jaw opening gestures for vowels and jaw closing gestures for labial and alveolar consonants along a single high-low dimension. Are such descriptions empirically adequate?

5.1.3 Decomposition of Tongue Position

Third, how different are the predictions of a physiologically accurate model of jaw movement from the conventional pure rotation and pure translation models with respect to calculating the contribution of the first principal component of jaw displacement to tongue displacement? Models of jaw movement as pure rotation or pure translation are much simpler than a combined rotation-translation model, both with respect to data collection and analysis and also with respect to implementation. What magnitude of error do the simplified models introduce? Is this error predictable? Is either preferable to the other?

5.1.4 Predictability of Inter-speaker Differences

A fourth _post_ _hoc_ question concerns the consistent inter-speaker differences that were observed across the two experiments. Are these inter-speaker differences with respect to jaw movement during speech predictable and on what grounds? Gross inter-speaker differences with respect to jaw movement during speech have been widely observed and have been attributed to such various factors as language or dialect, social class, and personality type. It seems plausible that cranial-facial morphology may be relevant to these differences.

5.2 _Question_ _1_: _Functional_ _Degrees_ _of_ _Freedom_

Let us first consider the number of functional degrees of freedom that are observed during speech. Are the positions of the first two principal components of jaw translation and the angle of jaw rotation all mutually independent during speech-related opening and closing gestures?

5.2.1 Degrees of Freedom for CG and JE

For CG and JE, it is clear that a potentially three degrees-of-freedom system is functionally constrained to operate roughly as a two degrees-of-freedom system during speech. The results of the rotation analyses from both experiments revealed that jaw rotation can be interpreted as highly dependent on jaw translation for both subjects. For CG, the first principal component of translation accounted for 56 to 85 percent of the variance of the observed rotation in the first experiment and for 85 to 90 percent in the second experiment. For JE, the first principal component of translation accounted for 96 to 98 percent of the variance of the observed rotation in the first experiment and for 90 to 92 percent in the second experiment. Furthermore, this relationship was observed to be relatively independent of the tested phonetic context. The proportion of variance that was accounted for by the phonetic covariates ranged from 2 to 17 percent in the first experiment and from .4 to 1 percent in the second experiment for CG. For JE, phonetic covariates accounted for .2 to 2 percent of the variance in the first experiment and for .8 to 2 percent in the second. These results suggest that jaw rotation and jaw translation are functionally constrained to act mostly as a single degree of freedom during speech-related opening gestures for vowels and closing gestures for bilabial and alveolar consonants for these two subjects.

A disadvantage of the rotation analysis, as discussed briefly in Chapter 2, is that it does not reveal whether jaw rotation can be taken as the independent variable to predict the first principal component of jaw translation. Because the contribution of jaw rotation to jaw displacement (measured at the front teeth) exceeded the contribution of the first principal component of jaw translation for all three subjects across the two experiments, it can be argued that such a model would be preferable. An analysis of a subset of the data for CG and JE in which jaw rotation was taken as the independent variable and the first principal component of jaw translation was taken as the dependent variable (using a quadratic model) suggests that jaw rotation can be used to predict jaw translation, as well as the opposite. (The squared multiple correlations for the V1C and the CV2 demisyllables from the first experiment were .86(V1t), .87(V1p), .88(tV2), and .90(pV2), for CG and .95(V1t), .97(V1p), .95(tV2), and .98(pV2) for JE.)

Thus, for both CG and JE, it appears that jaw rotation and the first principal component of jaw translation are interdependent during simple opening and closing gestures. The first degree of freedom of jaw movement during speech corresponds to this combination of rotation and X translation for these two subjects. This first degree of freedom accounts for a relatively constant percentage of resultant jaw displacement across different utterance types and across the two experiments. For CG, the proportion of resultant jaw displacement at maximal opening produced by the first degree of freedom ranges from 80 to 92 percent in the first experiment (cf. Table 3.3) and from 88 to 95 percent in the second (cf. Table 4.3) for the V1t demisyllables. For JE, the proportion of resultant jaw displacement produced by the first degree of freedom ranges from 79 to 86 percent in the first experiment (cf. Table 3.3) and from 82 to 90 percent in the second experiment (cf. Table 4.3) for the V1t demisyllables. For both subjects, the relative contributions of rotation and translation vary across utterance types and across experiment, but the total proportion of jaw displacement produced by the first degree of freedom of jaw movement remains remarkably constant.

The second degree of freedom of jaw movement corresponds to the second principal component of jaw translation for both CG and JE. The squared multiple correlations of translation analyses were consistently lower than those of the corresponding rotation analyses in both experiments. For CG, the first principal component of jaw translation accounted for 51 to 80 percent of the variance of the second principal component of translation in the first experiment and for 14 to 28 percent in the second experiment. For JE, the first principal component of jaw translation accounted for 39 to 76 percent of the variance of the second principal component of translation in the first experiment and for 10 to 11 percent in the second experiment. For both subjects, it was observed that the decreased range of the data in the second experiment, as compared to the first, resulted in substantially lower squared multiple correlations overall.

The second degree of freedom of jaw movement also accounts for a relatively constant proportion of resultant jaw displacement across different utterance types and across the two experiments for both subjects. For CG, the proportion of resultant jaw displacement produced by the second degree of freedom ranges from 8 to 20 percent in the first experiment (cf. Table 3.3) and from 8 to 12 percent in the second (cf. Table 4.3) for the V1t demisyllables. For JE, the proportion of resultant jaw displacement at maximal opening produced by the second degree of freedom ranges from 13 to 21 percent in the first experiment (cf. Table 3.3) and from 10 to 18 percent in the second (cf. Table 4.3) for the V1t demisyllables.

5.2.2 Degrees of Freedom for LF

The results of the rotation and translation analyses indicate a different pattern of jaw movement control for LF, as compared to CG and JE. First, in both experiments, a substantial proportion of jaw rotation was observed to be independent of the first principal component of jaw translation for LF. Second, in both experiments, interactions were observed among three phonetic parameters: test vowel identity, non-test vowel identity, and stress for both the rotation and translation analyses. No consistent phonetic pattern could be determined in these interactions, either within or across experiments.

These results for LF suggest that there are no interdependent relationships among the available three degrees of freedom are functionally constrained during speech-related opening and closing gestures. Thus, for LF, the first degree of freedom of jaw movement for speech corresponds to jaw rotation alone. The proportion of resultant jaw displacement that is produced by the first degree of freedom ranged from 62 to 74 percent in the first experiment (cf. Table 3.3) and from 73 to 84 percent in the second (cf. Table 4.3) for the V1t demisyllables.

The second degree of freedom of jaw movement corresponds to the first principal component of jaw translation for LF. The proportion of resultant jaw displacement produced by the second degree of freedom ranges from 15 to 32 percent in the first experiment and from 13 to 21 percent in the second for the V1t demisyllables.

The third degree of freedom corresponds to the second principal component translation for LF. The proportion of resultant jaw displacement produced by the third degree of freedom ranged from 8 to 19 percent in the first experiment and from 3 to 8 percent in the second for the V1t demisyllables.

5.2.3 Summary

Thus, the two-dimensional description of jaw movement used in this study proves useful in that it can be used to determine the number of functional degrees of freedom of jaw movement during speech for a given speaker. It can also be used to relate these functional degrees of freedom to their anatomical components. For two speakers, CG and JE, two functional degrees of freedom of jaw movement during speech were observed: the first degree of freedom corresponds to a combination of rotation and the first principal component of translation; the second degree of freedom corresponds to the second principal component of translation. For a third speaker, LF, three functional degrees of freedom of jaw movement during speech were observed: the first degree of freedom corresponds to rotation; the second degree of freedom corresponds to the first principal component of translation; the third degree of freedom corresponds to the second principal component of translation. It should be noted that the first degree of freedom of jaw movement accounts for a consistently high percentage of resultant jaw displacement for all three subjects across the two experiments. A model of jaw movement in terms of movement along its principal axis would accurately describe 62 to 95 percent of resultant jaw displacement for these three subjects. For many purposes, such a model should provide an adequate description of resultant jaw displacement at the front teeth.

5.3 Question 2: Phonetic Correlates

5.3.1 First Degree of Freedom of Jaw Movement

The second question of interest is whether additional degrees of freedom of jaw movement are systematically related to any of the phonetic parameters under consideration during speech-related opening and closing gestures. For all three subjects, the first degree of freedom of jaw movement is systematically related to jaw height for vowels and labial and alveolar consonants. For CG and JE, the relationship between jaw height and the first degree of freedom of jaw movement can be observed in systematically more negative (i.e. open) angles of rotation and systematically more anterior positions of the X component of jaw translation for vowels, as compared to consonants; for low vowels, as compared to high vowels; and for stressed vowels, as compared to unstressed vowels. For LF, the relationship between jaw height and the first degree of freedom of jaw movement can be observed in systematically more negative angles of rotation for vowels, as compared to consonants; and for low vowels, as compared to high vowels.

5.3.2 Additional Degrees of Freedom of Jaw Movement

In the first experiment, it was observed that for CG and JE, positions along the second principal component of jaw translation (which is the second degree of freedom of jaw movement for these two subjects) corresponded approximately to tongue front-back positions for vowels when the inter-vocalic consonant was /p/, but not when it was /t/. It is difficult to explain this consonant-dependent difference on phonetic grounds. Therefore, it is simply noted that for some subjects, the second degree of freedom of jaw movement may be systematically related to anterior-posterior positions for vowels, at least in some phonetic contexts. As discussed in Chapter 4, it may also be the case that other, as-yet-undetermined factors (e.g. relative contributions of tongue and jaw, degree of articulatory precision, degree of stress) may influence whether such a relationship is observed.

For LF, no consistent phonetic correlates of the second and third degrees of freedom were observed, within the analysis framework. That is, although the second and third degrees of freedom of jaw movement were observed to be influenced by the phonetic context, these influences were found to be highly unsystematic, at least within the present descriptive framework.

Two additional factors should also be considered. First, tongue position may affect jaw position, as well as the converse. For example, the forward bunching of the tongue for high front vowels may push the jaw backwards. The contraction of the geniohyoid muscle in depressing the tongue for low vowels may result in a more posterior position of the mandible. Thus, it is possible that some of the inconsistent phonetic effects observed in this study should be attributed to the effects of tongue body movement on the mandible. Another possibility is that the second degree of freedom of jaw movement for CG and JE and the second and third degrees of freedom of jaw movement are due to random factors. Because the magnitudes of these additional degrees of freedom vary substantially across the three subjects (cf. Tables 3.1 and 4.1), this noise must be interpreted as a combination of measurement error in data collection and processing and physiological noise. The magnitude of measurement error is assumed to remain more-or-less constant across the three subjects, but it is possible that the magnitude of measurement noise varies with the magnitude of jaw displacement.

5.3.3 Summary

Thus, for all three subjects, the second (and third) degrees of freedom of jaw movement could not be systematically related to any of the phonetic parameters under consideration. Furthermore, the data analyzed in this study do not provide adequate information to distinguish between active and passive influences on these additional degrees of freedom or to distinguish between phonetically-controlled and random effects. The analysis of simultaneously recorded motion and muscle activity for the tongue and jaw will be needed in order to distinguish among these factors.

5.4 Question 4: Inter-speaker Differences

Before comparing the predictions of the three models with respect to predicting the jaw component of mid-tongue displacement, let us consider the fourth question: are inter-speaker differences predictable and on what grounds? In this study, CG and JE consistently differed from LF in several respects. First, CG and JE generally exhibited greater jaw displacements than LF. Second, jaw movement for speech for CG and JE reflected a difference kind of control than that for LF. For both CG and JE, but not for LF, two potentially independent degrees of freedom, jaw rotation and the first principal component of jaw translation, were functionally constrained to operate as a single degree of freedom during speech-related opening and closing gestures.

5.4.1 Occlusal Class Hypothesis

These differences in jaw behavior may be related to the structural difference between CG and JE, as compared to LF: CG and JE have Class II occlusions; LF has a Class I occlusion. It has been widely observed by dentists that speakers of different occlusal classes show systematic differences with respect to opening and closing movements of the jaw for speech (cf., e.g. Pound, 1977). These differences are used by prosthondists to determine the occlusal class of edentulous patients. It should be noted that descriptions of these occlusal-dependent differences for speech are generally perceptual and have not, to my knowledge, been studied quantitatively. Dentists have observed that individuals with Class II occlusions generally exhibit relatively large amounts of anterior-posterior movement for opening and closing gestures into and out of alveolar consonants; individuals with Class I occlusions generally exhibit relatively small amounts of anterior-posterior movement in the same phonetic contexts; and individuals with Class III occlusions generally exhibit virtually no anterior-posterior movement in the same phonetic contexts.

5.4.2 Consonantal Differences

The results of this study are consistent with the occlusal class differences reported in the dental literature. These differences can also be observed in Figs. 5.1, 5.2, and 5.3 for CG, JE, and LF, respectively, which plot the statistically predicted trajectories for the stressed /aC/ demisyllables from the first experiment. For CG, the /at/, /ap/ and /as/ demisyllables are plotted; for JE, the /at/ and /ap/ demisyllables are plotted, and for LF, the /at/ and /as/ demisyllables are plotted. The data values of the predicted trajectories have been rotated back to the original coordinate systems so that the regression curves corresponding to the different intervocalic consonants could be compared in a common coordinate system. For CG, it can be observed that anterior-posterior movement of the center of rotation is greatest when the intervocalic consonant is /s/ and is least when the intervocalic consonant is /p/. For JE, extensive anterior-posterior movement is observed for both /t/ and /p/. Note that for both CG and JE, the position of the center of rotation is more anterior in the /at/ demisyllables, as compared to the /ap/ demisyllables throughout the entire closing gestures. In addition, for

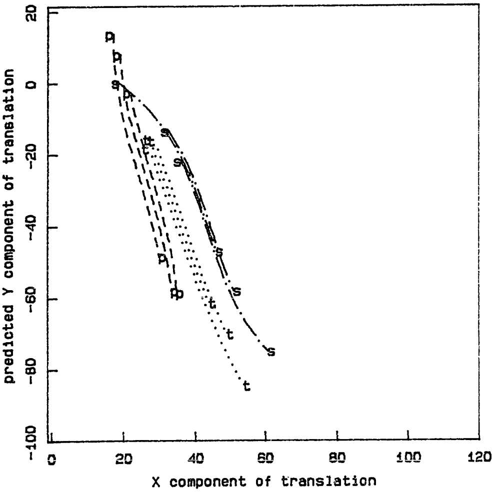

Figure 5.1 Predicted values of the Y component of jaw translation are plotted against values of the X component for the stressed /aC/ demisyllables from the first experiment for CG. The dotted lines represent /at/; the dashed lines represent /ap/; the dashed-and-dotted lines represent /as/. After the regression curves were calculated, the data values were rotated back to the original coordinate system.

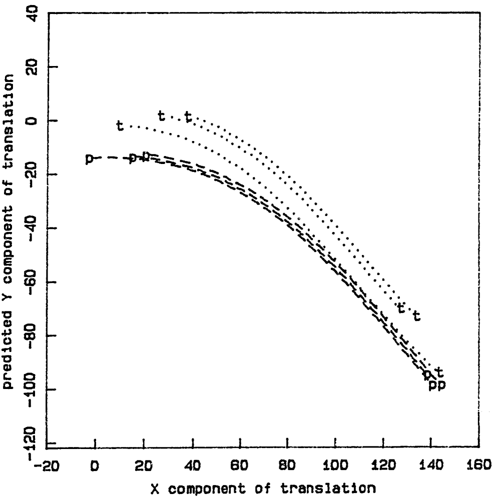

Figure 5.2 Predicted values of the Y component of jaw translation are plotted against values of the X component for the stressed /aC/ demisyllables from the first experiment for JE. The dotted lines represent /at/; the dashed lines represent /ap/. After the regression curves were calculated, the data values were rotated back to the original coordinate system.

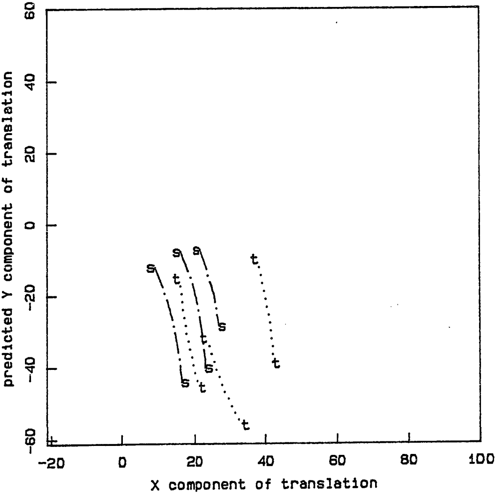

Figure 5.3 Predicted values of the Y component of jaw translation are plotted against values of the X component for the stressed /aC/ demisyllables from the first experiment for LF. The dotted lines represent /at/; the dashed-and-dotted lines represent /as/. After the regression curves were calculated, the data values were rotated back to the original coordinate system.

CG, the /as/ demisyllables are anterior to the /at/ demisyllables. For LF, relatively little anterior-posterior movement is observed for either /t/ or /s/. Furthermore, for LF, in contrast to CG and JE, the trajectories corresponding to the different consonant types do not form distinct groups and the /as/ trajectories are not systematically anterior to the /at/ trajectories. These differences among the three subjects suggest that anterior-posterior positions of the jaw for different consonants are more systematically controlled for CG and JE, as compared to LF.

5.4.3 Summary

It can be suggested, therefore, that the inter-speaker differences enumerated above are a function of occlusal class differences. That is, it is hypothesized that individuals with Class II occlusions exhibit control of opening gestures for vowels and closing gestures for labial and alveolar consonants in two dimensions; by contrast, individuals with Class I occlusions exhibit one-dimensional control. Of course, the jaw movements of a number of different subjects of all three occlusal classes must be analyzed in order to support or rule out this hypothesis. The method used in this study seems useful for such quantitative studies. Furthermore, the fact that inter-speaker differences were preserved across two experiments supports the occlusal class hypothesis. Of course, even if such a hypothesis is corroborated, it may be the case that inter-speaker differences with respect to jaw movement during speech should ultimately be related to more general aspects of cranial-facial morphology. If any such hypothesis is correct, it has important implications in that it suggests that some specifiable aspects of inter-speaker variation are predictable on the basis of measurable anatomical differences.

5.5 Question 3: Decomposition of Tongue Position

Finally, let us consider the differences among the three models of jaw movement--the empirically-determined model, the pure translation model, and the pure rotation model--with respect to predicting the contribution of the first principal component of jaw movement to tongue displacment. Table 5.1 presents the results of using each of the three models to calculate the contribution of the first degree of freedom of jaw movement to mid-tongue displacement at maximal jaw opening The results are averaged across low vowels with primary stress.

For CG and JE, the contribution of the first degree of freedom of the empirically-determined model was calculated by vectorial summation of X translation and 60 percent of jaw rotation. For LF, because the first degree of freedom of jaw movement corresponded to jaw rotation alone, the pure rotation model was also used as the empirically-determined model. The predictions of the pure rotation and the pure translation models were calculated as described in Chapter 2.

5.5.1 Results for LF

The results for LF are quite straightforward. Because the first degree of freedom of jaw movement corresponds to jaw rotation, no error was introduced by using the pure rotation model to calculate the

Table 5.1

Contributions of jaw displacement to tongue displacement

		Rotation + X Translation (mm)	Pure Rotation (mm)	Pure Translation (mm)	Rotation error (%)	Translation error (%)
CG						
Experiment 1	V1t	9.1	6.7	11.6	26	27
	tV2	9.9	7.5	12.5	24	26
Experiment 2	V1t	7.3	5.9	9.8	19	34
	tV2	7.8	6.2	10.4	21	33
JE						
Experiment 1	V1t	14.8	11.2	18.6	24	26
	tV2	15.2	11.7	19.5	23	28
Experiment 2	V1t	9.3	8.5	14.2	09	53
	tV2	9.6	8.8	14.6	08	52
LF						
Experiment 1	V1t		4.4	7.3	0	40
	tV2		4.7	7.9	0	40
Experiment 2	V1t		6.0	10.0	0	40
	V1t		7.7	12.8	0	40

contribution of the first principal component of jaw movement to tongue displacement. The errors introduced by using the pure translation model are, of course, always 40 percent of the predicted contribution, using the empirically-determined model.

5.5.2 Results for CG and JE

For CG and JE, the simplified models will result in two errors: an error in magnitude and an error in orientation. Because the jaw component of mid-tongue displacement contains a proportional fraction of jaw rotation, the principal component of jaw movement measured at the front teeth is not parallel to the principal component of jaw movement measured at mid-tongue. The errors in orientation ranged from four to seven degrees for CG across the two experiments and from nine to fifteen degrees for JE. The errors in magnitude ranged from from 8 to 53 percent of the predicted contribution, using the combined rotation and translation model. In the first experiment, the differences between the two simplified models were quite small, although the pure rotation model was slightly more accurate for both subjects. For CG, the errors introduced by the pure rotation model averaged 24 to 26 percent of the predicted contribution, using the combined rotation and translation model; the errors introduced by the pure translation model averaged 26 to 27 percent of the predicted contribution. For JE, the errors introduced by the pure rotation model averaged 23 to 24 percent; the errors introduced by the pure translation models averaged 26 to 28 percent.

In the second experiment, however, the predictions of the pure rotation model were systematically closer to the predictions of the combined rotation and translation model for both subjects. For CG, the errors introduced by the pure rotation models averaged 19 to 21 percent of the predicted contribution using the combined rotation and translation model; the errors introduced by the pure translation model averaged 33 to 34 percent. For JE, the errors introduced by the pure rotation model averaged 8 to 9 percent of the predicted contribution; the errors introduced by the pure translation model averaged 52 to 53 percent.

5.5.3 Summary

These results indicate that, of the two simplified models, the pure rotation model is generally more accurate across different subjects and across different experimental sessions. However, using the pure rotation model to estimate the contribution of the first principal component of jaw movement to tongue displacement will introduce errors both in magnitude and in orientation for some subjects. For CG and JE, the errors in magnitude ranged from errors ranging from 8 to 26 percent of the correct contribution; the errors in orientation ranged from four to fifteen degrees. It should be noted that these errors will, of course, increase for tongue positions that are further back in the mouth and will decrease for tongue positions that are further front.

Because the relative contributions of rotation and the first principal component of translation varied substantially across the two subjects, CG and JE, and across the two experiments, it is not possible to develop a simple method to correct the errors introduced by the pure rotation model for CG and JE. Thus, the occlusal class hypothesis suggests that subjects with Class I occlusions might be preferable for some experiments because the pure rotation model of jaw movement may more accurately predict the jaw component of tongue displacement for these speakers. Furthermore, if the occlusal class hypothesis is correct, researchers should be aware that using a pure rotation model to calculate the jaw component of tongue displacement will introduce small errors in both magnitude and direction for speakers with Class II occlusions.

5.6 Functional Relationships Among the Three Jaw Movement Components: Suggestions for Future Research

The relationship between jaw rotation and the first principal component of jaw translation for CG and JE is of particular interest, regardless of whether it can be predicted on the basis of occlusal class. These two subjects were observed to constrain a three degrees of freedom system to operate as a two degrees of freedom system during speech-related opening and closing gestures. Many researchers of motor control have posited that this kind of functional constraint underlies the organization of a variety of skilled motor behaviors. It would be of interest, therefore, to explore the nature of this functional constraint in more detail.

This study was limited to opening and closing gestures for vowels and bilabial and alveolar consonants. Are jaw rotation and the first principal component of jaw translation also functionally constrained during protrusive gestures for the labialdental fricatives /f/ and /v/ and the interdental fricatives /θ/ and /ð/? One would predict a negative answer to this question for two reasons. (1) on anatomical grounds, a negative answer would be predicted since jaw protrusion primarily involves forward translation of the articular disc and little or no rotation. (2) Given the results of the rotation analysis for CG, a negative answer would also be predicted. The first principal component of jaw translation consistently accounted for lower proportions of the variance of the observed rotation for CG when the intervocalic consonant was /s/, as compared to /p/ and /t/. Because /s/ is produced with a more protruded mandible than either /t/ or /p/, the lower squared multiple correlations for /s/ suggest that the functional interdependence of jaw rotation and the first principal component of jaw translation may only be observed during non-protrusive opening and closing gestures.

Thus, it can be argued that an extension of this work should begin to examine inter-speaker differences with respect to the control of jaw movement across consonants that involve differing amounts of jaw raising and protrusion (e.g. /k/, /p/, /t/, /s/, /f/, /θ/, /w/). It would be of interest to determine whether inter-speaker differences are preserved across a range of vocalic and consonantal parameters. Such a result would provide additional evidence for theories that posit that a general system of functional constraints--both inter-articulator and intra-articulator--underlies the motor control of speech.

5.7 Importance of the Model

Finally, it must be emphasized that any conclusions based on the results of this study must be regarded as preliminary, given the small number of subjects and the extremely limited phonetic corpus. Nevertheless, the study is important in that it has developed a methodology to describe jaw movement during speech as the movement of a rigid body, rather than as that of a single point. Furthermore, the model that was used appears to accurately reflect the anatomy and physiology of the mandible. Such a model appears to provide useful information on the control of jaw movement, at least for these three subjects. Furthermore, the model proved robust enough to preserve inter-speaker differences across two experiments. These results suggest that the methodology developed in this study in order to describe jaw movement in terms of its actual geometric components could now profitably be used in larger, more quantitative studies.

Appendix A1

Correction for head movement

Given reference positions of the two LED's, R1 and R2, on the reference appliance (cf. Fig. 2.1): (x_{r_1}, y_{r_1}), (x_{r_2}, y_{r_2}) and given the positions of the reference LED's at some data frame: (x_{r_1}', y_{r_1}'), (x_{r_2}', y_{r_2}')

I. Calculate the sine and cosine of the angle γ of head rotation.

$dx = x_{r_2} - x_{r_2}$ $\qquad$ $dx' = x_{r_2}' - x_{r_1}'$

$dy = y_{r_2} - y_{r_1}$ $\qquad$ $dy' = y_{r_2}' - y_{r_1}'$

$d = \sqrt{dx^2 + dy^2}$ $\qquad$ $d' = \sqrt{dx'^2 + dy'^2}$

$\sin \gamma = ((dy * dx') - (dx * dy'))/ d * d'$

$\cos \gamma = ((dx * dx') + (dy * dy'))/ d * d'$

II. Correct every point (x_i, y_i) in that data frame to (x_i', y_i')

$x_i' = \cos \gamma * (x_i - x_{r_1}') - \sin \gamma * (y_i - y_{r_1}') + x_{r_1}$

$y_i' = \sin \gamma * (x_i - x_{r_1}') + \cos \gamma * (y_i - y_{r_1}') + y_{r_1}$

Appendix A2

Error function and partial derivatives used to find the center of jaw rotation

Given three points, ranging fron 1 to N data frames:

(xa, ya), (xb, yb), (xc,yc) and

given five unknowns: xo, yo, ra, rb, rc (one center and three radii).

I. Error Function

$$\begin{aligned}\sum_{i=1}^{N} e^2 = \sum_{i=1}^{N} [\ & ((xa_i - xo)^2 + (ya_i - yo)^2 - ra^2)^2 + \\ & ((xb_i - xo)^2 + (yb_i - yo)^2 - rb^2)^2 + \\ & ((xc_i - xo)^2 + (yc_i - yo)^2 - rc^2)^2]\end{aligned}$$

II. Partial Derivatives

$$\begin{aligned}\sum_{i=1}^{N} \partial e^2/\partial xo = \sum_{i=1}^{N} -4 * [& ((xa_i - xo)^2 + (ya_i - yo)^2 - ra^2) * (xa_i - xo) + \\ & ((xb_i - xo)^2 + (yb_i - yo)^2 - rb^2) * (xb_i - xo) + \\ & ((xc_i - xo)^2 + (yc_i - yo)^2 - rc^2) * (xc_i - xo) +\end{aligned}$$

$$\begin{aligned}\sum_{i=1}^{N} \partial e^2/\partial yo = \sum_{i=1}^{N} -4 * [& ((xa_i - xo)^2 + (ya_i - yo)^2 - ra^2) * (ya_i - yo) + \\ & ((xb_i - xo)^2 + (yb_i - yo)^2 - rb^2) * (yb_i - yo) + \\ & ((xc_i - xo)^2 + (yc_i - yo)^2 - rc^2) * (yc_i - yo) +\end{aligned}$$

$$\sum_{i=1}^{N} \partial e^2/\partial ra = \sum_{i=1}^{N} -4 * [((xa_i - xo)^2 + (ya_i - yo)^2 - ra^2)]$$

$$\sum_{i=1}^{N} \partial e^2/\partial rb = \sum_{i=1}^{N} -4 * [((xb_i - xo)^2 + (yb_i - yo)^2 - rb^2)]$$

$$\sum_{i=1}^{N} \partial e^2/\partial rc = \sum_{i=1}^{N} -4 * [((xc_i - xo)^2 + (yc_i - yo)^2 - rc^2)]$$

Decomposition of jaw movement into three components (TX, TY, θ)

Given the center of jaw rotation (x_0, y_0) and the reference coordinates of the LED's J1 (x_{j_1}, y_{j_1}) and J2 (x_{j_2}, y_{j_2}), cf. Fig. 2.5, and given the positions of LED's J1 and J2 at some data frame: (x_{j_1}', y_{j_1}'), (x_{j_2}', y_{j_2}').

I. Calculate two constants, ϕ and D, using the reference coordinates.

$dx = x_0 - x_{j_1}$

$dy = y_0 - y_{j_1}$

$D = dx + dy$

$\sin \phi = dx/D$

$\cos \phi = dy/D$

II. Calculate the angle of jaw rotation, θ, for that data frame.

Also calculate the sine and cosine of θ.

$jx = x_{j_2} - x_{j_2}$ $\qquad$ $jx' = x_{j_2}' - x_{j_1}'$

$jy = y_{j_2} - y_{j_1}$ $\qquad$ $jy' = y_{j_2}' - y_{j_1}'$

$jd = \sqrt{jx^2 + jy^2}$ $\qquad$ $jd' = \sqrt{jx'^2 + jy'^2}$

$$\theta = \sin^{-1} [((jx * jx') + (jy * jy'))/jd * jd']$$

$\cos \theta = ((jx * jy') - (jy * jx'))/jd * jd'$

$\sin \theta = ((jx * jx') + (jy * jy'))/jd * jd'$

III. Calculate $\phi + \theta = \phi'$

$\cos \phi' = (\cos \phi * \cos \theta) - (\sin \phi * \sin \theta)$

$\sin \phi' = (\sin \phi * \cos \theta) + (\cos \phi * \sin \theta)$

IV. Calculate the translation of the center of rotation

$TX = jx' + D * \cos \phi' - x_0$

$TY = jy' + D * \sin \phi' - y_0$

Appendix A4

Number of tokens of each utterance type used for data analysis for V1t and tV2 demisyllables in experiments 1 and 2 (E1 and E2)

	non-		CG				JE			
test	test		V1t		tV2		V1t		tV2	
vowel	vowel	stress	E1	E2	E1	E2	E1	E2	E1	E2
i	i	+	5	4	5	4	4	4	4	4
i	a	+	5	5	4	4	5	5	4	4
i	ae	+	4	5	4	4	5	5	4	4
i	i	-	4	5	4	4	5	5	4	3
i	a	-	4	4	3	4	4	5	4	5
i	ae	-	4	5	4	5	4	5	5	4
a	i	+	5	5	3	5	5	5	5	4
a	a	+	5	5	5	4	5	5	5	3
a	ae	+	5	4	4	3	5	5	5	4
a	i	-	4	4	4	4	5	5	4	3
a	a	-	4	5	4	4	5	5	5	5
a	ae	-	3	5	3	4	5	5	4	5
ae	i	+	4	5	5	5	3	4	4	4
ae	a	+	5	5	5	5	5	5	4	3
ae	ae	+	5	5	4	5	5	5	4	5
ae	i	-	5	4	4	4	5	5	4	3
ae	a	-	4	5	4	5	5	5	4	4
ae	ae	-	4	5	5	5	5	5	5	5

			LF			
			V1t		tV2	
			E1	E2	E1	E2
i	i	+	5	4	4	5
i	a	+	4	4	4	5
i	ae	+	4	4	3	3
i	i	-	4	4	3	4
i	a	-	4	4	4	4
i	ae	-	3	5	4	4
a	i	+	3	3	5	4
a	a	+	4	4	5	4
a	ae	+	4	5	4	4
a	i	-	4	4	4	4
a	a	-	3	4	4	4
a	ae	-	4	5	3	4
ae	i	+	5	4	5	4
ae	a	+	4	5	4	4
ae	ae	+	4	4	4	4
ae	i	-	4	4	4	4
ae	a	-	4	4	4	4
ae	ae	-	3	4	3	3

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