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Tongue–jaw coordination in vowel production: Isolated words versus connected speech

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Abstract. This study investigates the positions of the tongue body and the jaw in the production of Italian vowels /i/ and /a/ in different phonetic, prosodic and utterance contexts, with the aim of assessing the role of and the coordination between the two articulators in the processes of coarticulation, reduction and compensation. The data indicate that, within the same phonetic context, a change in utterance type (from isolated words to words in connected speech) or in lexical stress position (from stressed to unstressed vowels) induces decreased displacement of the jaw and the tongue from their rest position along the high/low dimension for both vowels. Thus prosodic and utterance contexts induce vowel reduction through a decrease in displacement of both jaw and tongue. Variation in vowels as a function of the consonantal context (/t,d,z,ʃ,l/) was observed in jaw displacements only in the front/back dimension: vowels were more fronted when adjacent to fricatives. All the other coarticulatory effects concern tongue body movements and tend to increase, as does reduction, from isolated words to connected speech. In symmetric VCV sequences extensive compensatory tongue displacements in the back direction were observed during the production of reduced /a/ vowels: thus, if vowel reduction causes a decrease in the articulatory distance between /i/ and /a/ along the high/low dimension, this compensatory tongue movement appears to counteract such effect by increasing the articulatory distance along the front/back dimension. In asymmetric sequences, the V-to-V effects seem to overrule the compensatory movements, and, adding to the reduction effects, cause a further decrease in the articulatory distance between the two vowel types.

Zusammenfassung. Vorgestellt werden Untersuchungen zur Position des Zungenkörpers und Unterkiefers bei der Produktion der Vokale /i/ und /a/ des Italienischen in unterschiedlichen phonetischen und prosodischen Kontexten sowie in unterschiedlichen Typen von Äußerungen mit dem Ziel, die Rolle der beiden Artikulatoren und die Koordination zwischen ihnen in den Prozessen der Koartikulation, Reduktion und Kompensation zu definieren. Die Daten zeigen, daß eine Änderung des Äußerungstyps (Übergang von isolierten Wörtern zu zusammenhängender Rede) oder eine Änderung in des Position des lexikalischen Akzents (Übergang von betonten zu unbetonten Vokalen) eine weniger große Auslenkung des Unterkiefers und der Zunge aus ihrer Ruhelage entlang der Dimension hoch/tief für beide Vokale innerhalb desselben phonetischen Kontextes nach sich ziehen. Prosodischer Kontext und Äußerungstyp steuern folglich die Vokalreduktion über eine Einschränkung der Auslenkung des Unterkiefers und der Zunge. Variationen bei Vokalen in Abhängigkeit von konsonantischem Kontext (/t,d,z,ʃ,l/) wurden in der Unterkieferauslenkung (Vorn/hinten-Dimension) beobachtet: Vokale wurden weiter vorne artikuliert, wenn sie in der Nachbarschaft von Frikativlauten auftraten. Alle anderen koartikulatorischen Effekte betreffen Zungenkörperbewegungen. Sie sind, wie übrigens auch die Reduktion, in zusammenhängender Rede größer als in isolierten Wörtern. In symmetrischen VCV-Folgen wurden während der Produktion reduzierter /a/-Vokale bedeutende nach hinten gerichtete kompensatorische Zungenauslenkungen beobachtet: wenn also Vokal-reduktionen die Abnahme der artikulatorischen Distanz zwischen /i/ und /a/ entlang der Dimension hoch/tief verursacht, scheint diese kompensatorische Zungenbewegung einem solchen Effekt durch Zunahme der artikulatorischen Distanz entlang der Vorne/hinten-Dimension entgegenzuwirken. In asymmetrischen Lautfolgen scheinen die intervokalischen Effekte die kompensatorischen Bewegungen zu überlagern und in Ergänzung der Reduktionseffekte eine weitere Abnahme der artikulatorischen Distanz zwiscen den beiden Vokal-typen zu bewirken.

Résumé. Cette étude examine les positions du corps de la langue et de la mâchoire dans la production des voyelles italiennes /i/ et /a/ dans différents contextes phonétiques, prosodiques et phrastiques, dans le but d'évaluer le rôle des deux articulateurs, et leur coordination, dans les processus de coarticulation, de réduction et de compensation. Les données indiquent que, dans le même contexte phonétique, un changement dans le type de phrase (des mots isolés à des mots en parole continue) ou dans la position de l'accent lexical (de voyelles accentuées à voyelles inaccentuées) induit une réduction du déplacement de la mâchoire et de la langue par rapport à leur position de repos le long de l'axe haut/bas pour les deux voyelles. Les contextes prosodique et phrastique induisent donc une réduction vocalique par l'intermédiaire d'une réduction du déplacement à la fois de la mâchoire et de la langue. Une variation des voyelles en fonction du contexte consonatique (/t,d,z,ʃ,l/) a été observée pour les déplacements de la mâchoire seulement dans la dimension avant/arrière: les voyelles étaient plus avancées quand elles étaient adjacentes à des fricatives. Tous les autres effets de coarticulation concernent les mouvements du corps de la langue et tendent à augmenter, comme la réduction, des mots isolés à la parole continue. Dans des séquences symétriques VCV, des déplacements compensatoires extensifs de la langue vers l'arrière ont été observés pendant la production de voyelles /a/ réduites: donc, si la réduction vocalique cause une diminution dans la distance articulatoire entre /a/ et /i/ le long de l'axe haut/bas, ce mouvement compensatoire de la langue apparaît le long de l'axe avant/arrière. Dans des séquences assymétriques, les effets V-à-V semblent annuler les mouvements compensatoires, et, additionnés aux effets de réduction, causer une plus grande diminution dans la distance articulatoire entre les deux types de voyelles.

Keywords. Interarticulator coordination; vowel reduction; coarticulation; compensation.

1. Introduction

The relationship between the dynamics of the tongue body and the jaw in vowel production is an area still largely unexplored. The assessment of the role of and the coordination between these two articulators is important both for descriptive purposes and for a better understanding of the processes of coarticulation, reduction and compensation.

Within the hyper-hypospeech theory (Lindblom, 1990), the process of phonetic vowel reduction is viewed as a result of the interplay between timing (i.e. intervals between successive commands) and input articulatory force. On the one hand, a speeding up in the former (as in faster speech) with no change in the latter automatically induces target undershoot and a shift of formant values towards the consonantal context (Lindblom, 1963). On the other hand, the speaker can compensate for rapid timing by increasing the input force and can thus reduce coarticulatory effects, and enhance the acoustic contrasts among sound categories (Lindblom, 1983). In the experiment on labio-mandibular coordination (Lindblom, 1967), coarticulation results from the slow speed of jaw movements as compared to the lip movements: when a labial stop is flanked by low vowels, the early onset of jaw opening and the delay of jaw closing may result in very short lip closure durations. The experiment shows that speakers can compensate for the coarticulatory effects of jaw by increasing the strength of the lip closing movement in the context of low vowels. Thus, while reduction and coarticulation result from constraints on the speech production dynamics, compensation represents an output oriented mode of control and occurs when output oriented goals overrule system constraints.

According to the gestural theory of articulatory phonology (Browman and Goldstein, 1990, 1991) two main changes in the organization of articulatory gestures can account for variations observed in fast or in casual speech: an increase in temporal overlap between gestures, resulting in a decrease in movement displacement and in larger coarticulatory effects (Saltzmann and Munhall, 1989), and/or a decrease in the magnitude of the gestures, which can lead to various degrees of reduction, such as incomplete closures in stop consonants (Browman and Goldstein, 1991). Compensatory actions are intrinsic to the self-organized speech production system, and are the outcome of the coordination among its parts. Coordination ensures the achievement of articulatory goals by making the structures involved in a given production, temporarily and functionally interdependent so that a decrease in the contribution of one articulator is compensated for with an increase in the contribution of another (Fowler, 1985).

It can be seen that the two theories are compatible in their account of coarticulation and reduction but diverge substantially as far as the origin and the function of compensatory behaviour is concerned. Fowler's account implies automaticity in compensation, and such a view is supported by data showing negative correlations between jaw and tongue position in repeated production of the same vowel (Chuang et al., 1978). Lindblom's account leaves the speaker relatively free to choose between a listener oriented and a system oriented mode of production: compensation is selective and has acoustic/perceptual consequences.

Data on how compensation is instantiated in natural speech are scarce. Edwards (1985a), in a study on tongue–jaw coordination in the production of intervocalic /t/, observed compensatory jaw movements counteracting coarticulatory tongue body V-to-C effects. This experiment, together with Lindblom's study mentioned above, indicates that coarticulatory effects may be reduced or neutralized by compensatory movements: there are no studies, however, on interarticulator coordination in different utterance types or speech styles, in order to shed light on the relationship between compensation and reduction.

The focus of this pilot study is to explore the patterns of tongue and jaw coordination in the production of vowels and how they vary as a function of phonetic context, stress and utterance type (i.e. isolated words versus words produced in natural sentences). Within the sentences, consisting of four to five phrases, the keywords occupy pre-final phrase position, characterized, prosodically, by substantial durational compressions and by a weakening of lexical prominence with respect to words in other positions (Farnetani and Kori, 1990). If vowel reduction is a consequence of an increased temporal overlap, we should expect to observe a decrease in movement displacement and an increase in coarticulatory effects in these shorter and less prominent words as compared to isolated words. Items in isolation include nonsense and meaningful words: possible sources of differences between the nonsense sequences, typical lab speech, and the more natural meaningful words, is that the former may be samples of more careful pronunciation and thus exhibit larger movement displacements and smaller coarticulatory effects. As for unstressed vowels, previous acoustic studies on Italian indicate that open vowels are remarkably reduced with respect to their stressed counterpart, e.g. (Farnetani and Vayra, 1991).

2. Method

2.1. Equipment

Data were collected at the Speech Laboratory of Stockholm University by simultaneous use of the Movetrack magnetometer system (Branderud, 1985) and electropalatography. Tongue dorsum displacements were monitored by a receiver coil attached at the midline on the tongue dorsum, approximately 30 mm from the alveolar ridge (linear distance), in correspondence with the EPG area reflecting the constriction location for vowel /i/ (Farnetani, 1991). The receiver coil for tracking jaw displacements was attached at the midline on the lower incisors. The recording was carried out in three sessions. The alignment of the receiver coil axes with those of the transmitting coils was checked before and after each session (with the subject keeping a clenched teeth position for a few seconds). A detailed description of the calibration procedure for jaw and tongue measurements is in (Branderud, 1990). The Movetrack data acquisition and recording system has as its output independent signals for horizontal (x) and vertical (y) displacement of each coil. Thus, the present experiment considered four primary signals, tongue dorsum-x, tongue dorsum-y, jaw-x and jaw-y. Figure 1 is an example of the printout for three repetitions of the item /'data/ in isolation.

2.2. Speech material

The objects of study were the vowels /a/ and /i/ contained in symmetric and asymmetric bisyllabic sequences produced in three utterance types: (a) VCV pseudowords and words in isolation; (b) CVCV words in isolation; and (c) CVCV words in pre-final phrase position in complex natural sentences. All items have lexical stress on V1. For each V1–V2 combination the intervocalic consonants are /t/, /d/, /z/, /ʃ/ or /l/. The items are listed and transcribed phonemically in Table 1. As can be seen in the table, most VCVs are nonsense words.

A speaker of Standard Northern Italian read the speech material three times.

2.3. Analysis

Measurements for each vowel were made at the point of maximum displacement from the rest position (clenched teeth) for both jaw and tongue and for both horizontal and vertical displacement. It is well known that the measured position of the tongue results from a complex interplay of jaw

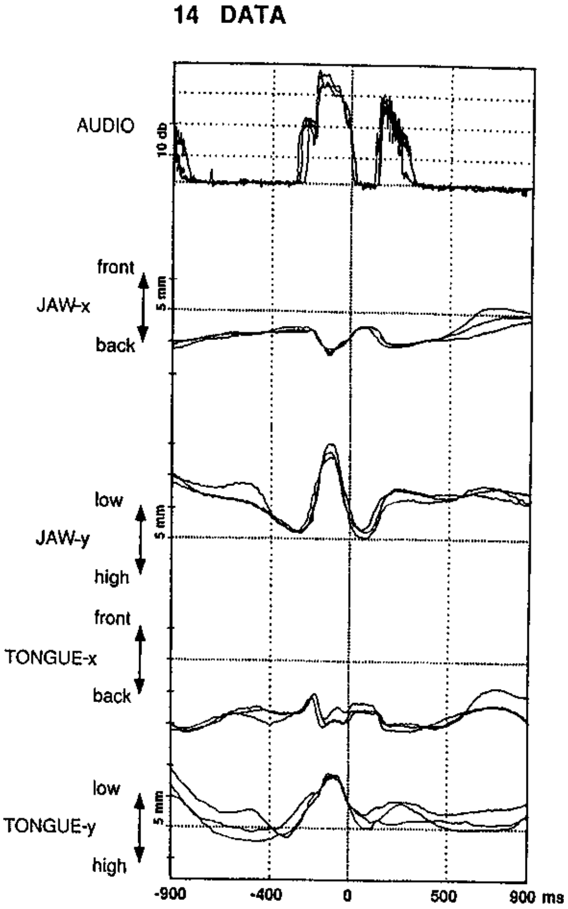


Fig. 1. Acoustic and articulatory printout for the three repetitions of item /data/ in isolation, lined up at the onset of the medial consonant. From top: audio signal, jaw-x, jaw-y, tongue-x, tongue-y.

Table 1
Speech materials in phonemic transcription. All items have penultimate stress. Items not glossed are pseudo-words. Glosses are approximate. An * in the "CVCV-connected" column indicates that the item listed in "CVCV-isolated" was also used in the connected sentences.

VCV-isolated	CVCV-isolated	CVCV-connected
ata	data "date"	amata "beloved"
iti	liti "quarrels"	*
ati	dati "data"	lati "sides"
ita	dita "fingers"	vita "life"
ada "PN"	rada "wasteland"	*
idi "Ides"	nidi "nests"	*
aza	raza "razed (sg.)"	*
izi	rizi "rice dish"	*
azi	razi "razed (pl.)"	*
iza	riza "laughter"	*
aʃa "axe"	laʃa "leave!"	*
iʃi	liʃi "smooth (pl.)"	*
aʃi	laʃi "you leave"	*
iʃa	liʃa "smooth (sg.)"	*
ala "wing"	mala "evil"	*
ili	fili "threads" (N)	*
ali "wings"		*
ila	fila "glides" (V)	*

movements and independent tongue movements. In order to study the tongue's independent contribution to its position, regression analysis was used. The independent variable (predictor) for tongue-y was jaw-y; the independent variables for tongue-x were jaw-x, jaw-y and tongue-y. The residual from each of these regressions represents that component of the original signal that is not accounted for by the predictor variable(s). It reflects the effects of independent movements of the articulator, as well as (potentially) the effects of other, unmeasured movements and of measurement error. The present method offers an alternative to current subtraction procedures, used for decomposing lower lip and tongue body positions into independent lip and jaw or tongue and jaw components. Edwards (1985a), in an X-ray microbeam study, decomposed tongue body height into independent jaw and tongue components by subtracting 60% of the jaw-y from the tongue-y. This figure was based on the assumption that the tongue pellet for that study was 60% of the way from the jaw's center of rotation to the jaw pellet. This solution presumes a relatively stable tongue-x. However, in the present study the tongue-x position varied over a range of 15–16 mm; consequently the residual from our regressions provides a better estimate of the tongue's independent contribution to its position than subtraction would. Regression analysis was also used to distinguish rotational and translational components in the jaw-x position. While rotation indeed contributes a substantial amount to jaw-x, the residual from the regression is assumed to represent translational (independent backward and forward) movement. This decomposition is simpler than Edwards' (1985b), which required the construction of a specialized dental appliance for each subject. ANOVAs were conducted both on the measured positions and on the residuals from the regressions. All results discussed below are significant at $p < 0.01$.

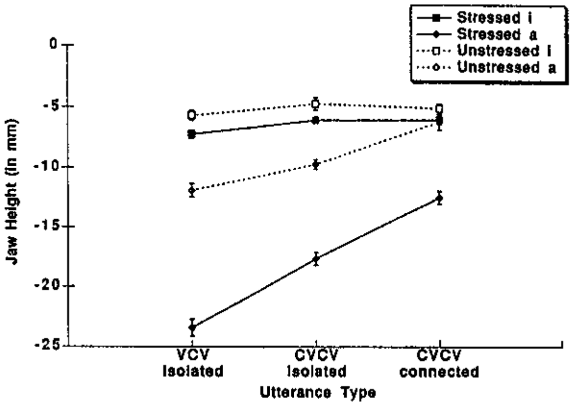


Fig. 2. Position of jaw along the high/low dimension (distance in mm from the rest position) for vowels /a/ and /i/ as a function of stress and utterance type in symmetric sequences.

3. Results

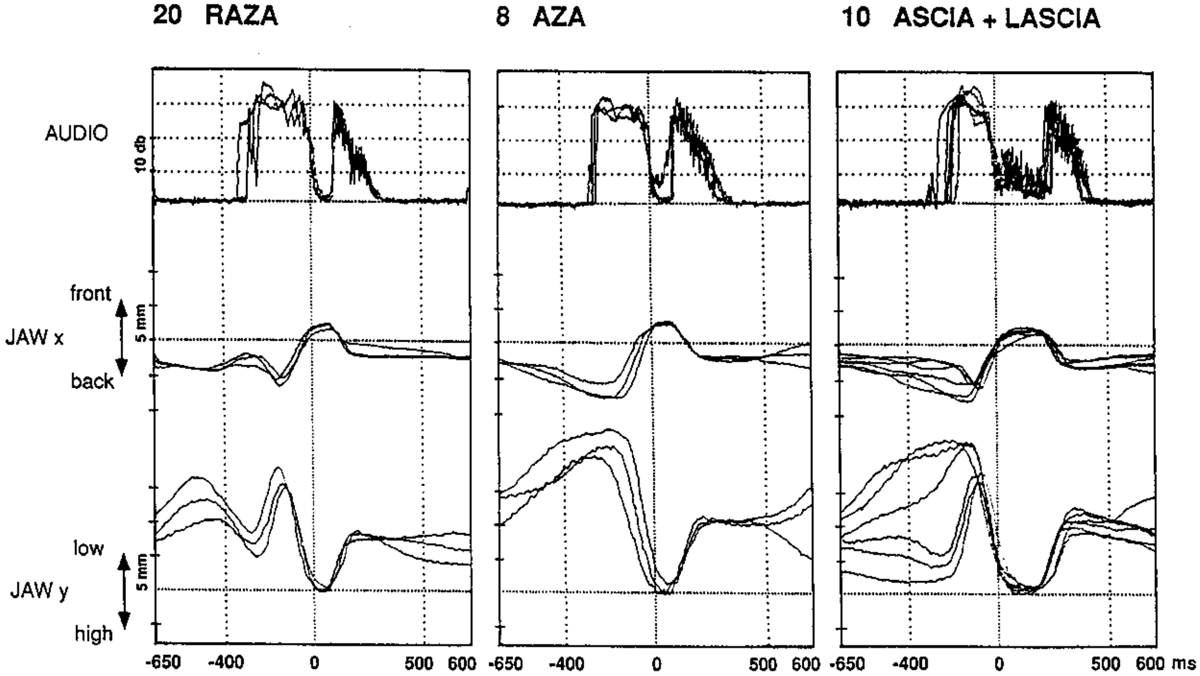
3.1. Reduction

Reduction is here defined as a decrease in the amplitude of displacement from the rest position, occurring independently of the phonetic context.

Jaw-y. Figure 2 shows the mean values of the two vowels in first and second position (stressed versus unstressed) in the three utterance types.

It can be seen that the jaw displacement for vowel /a/ decreases from nonsense to real words to connected speech and from stressed to unstressed vowels. The reductions of jaw displacement due to utterance type are as large as those related to stress: the two effects sum up so that unstressed /a/ in connected speech is as high as /i/. For /i/ only stress has an effect, and only in isolated items: the jaw during unstressed /i/ appears to be slightly less displaced from the rest position than during stressed /i/.

The jaw-*y* patterns are very clear: lack of stress, as expected, induces vowel reduction; also utterance type effects, though restricted to /a/, go in the expected direction. What is perhaps unexpected is the remarkable reduction of the stressed vowel in isolated CVCVs compared to VCVs. Is this because the latter are mostly nonsense words and perhaps samples of more careful pronunciation, or is it due to the presence or absence of an initial consonant?


20 RAZA

8 AZA

10 ASCIA + LASCIA

Fig. 3. Tracing of jaw movements along the front/back and the high/low dimension (jaw-*x* and -*y*, respectively) for /aza/, /raza/ and /aʃa/ + /laʃa/.

An analysis of the dynamic traces allowed us to distinguish between these two possibilities. As can be seen in Table 1, some of the VCV sequences are meaningful words in Italian and the comparison between these items and the corresponding CVCV items reveals that reduction of jaw displacement is a pure consequence of the presence of the consonant: i.e. a coarticulatory effect, as shown in Figure 3.

The figure compares a meaningful CVCV with a nonsense VCV, /raza/–/aza/, while on the right the traces of two meaningful words, /laʃa/ and /aʃa/, are superimposed. It can be seen that during V1 the jaw patterns are the same in the two VCV items and show a much larger jaw displacement than in the CVCV items: this indicates that the smaller jaw displacement in CVCVs is a consequence of the high jaw position required for the initial C, which interacts with the already ongoing movement towards /a/. The position for /a/ appears to be the result of a blending of two temporally overlapping movements with different goals. As for V2, the analysis indicates that also for unstressed /a/ the jaw is slightly but significantly higher in CVCVs than in VCVs (mean difference 2.17 mm, $p = 0.004$). This result is exemplified in the V2 traces in Figure 3, showing a difference in V2 between /aza/ and /raza/ but not between /aʃa/ and /laʃa/. Thus, part of the reduction of jaw displacement for vowel /a/ has to be attributed to the more elaborated articulation the speaker used in nonsense items.

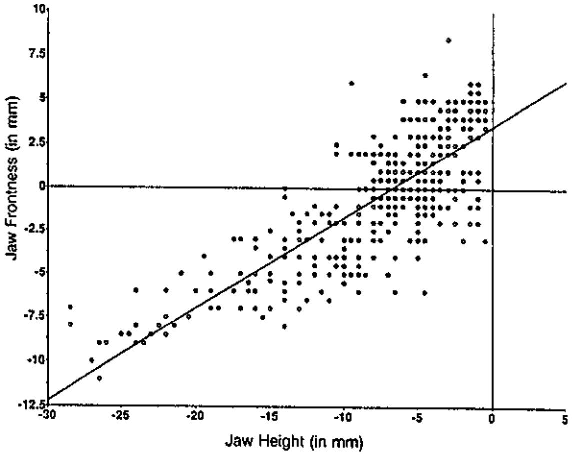


Fig. 4. Scatterplot of jaw-frontness against jaw-height.

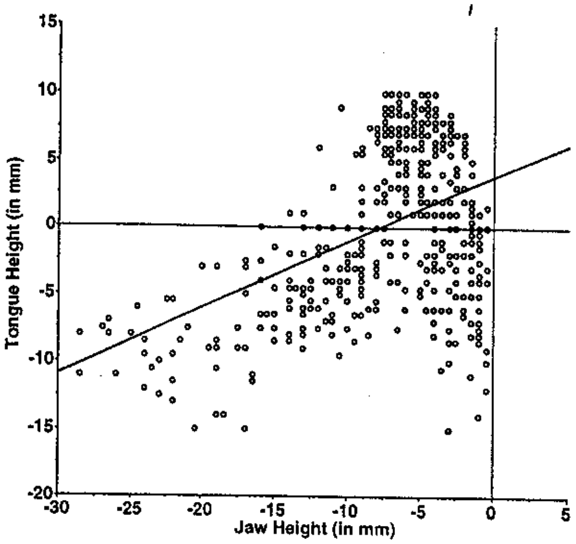


Fig. 5. Scatterplot of tongue-height against jaw-height.

Jaw-x. The regression analysis, carried out on the overall consonant and vowel data, indicates that jaw rotation accounts for 66.7% of the variance on the horizontal axis. The scatterplot in Figure 4 shows that independent jaw translation movements mainly occur when the jaw is high, and are related to consonant production (Faber and Farnetani, 1991). These forward–backward independent movements have coarticulatory effects on adjacent vowels, as will be shown below.

Tongue-y. The results of the regression analysis indicate that jaw-*y*, the only variable entering in the equation, accounts for only 19.7% of the variance (see Figure 5). The residuals patterns are very similar to the measured positions.

The tongue body vertical displacement is involved in the shaping of vowels, as expected, and is responsible for their reduction. Figure 6 shows the mean tongue body positions as a function of stress and utterance type. A comparison of the jaw positions (Figure 2) and the analysis of the residual patterns indicates that the tongue body actively rises for the production of /i/ (see in Figure 6 the difference with respect to the rest position – the baseline – when the jaw is high and the tongue is at rest), but rises less for unstressed than for stressed /i/, and rises less in connected speech than in isolated words. The comparison between Figures 6 and 2 clearly shows that the reduction of /i/ in

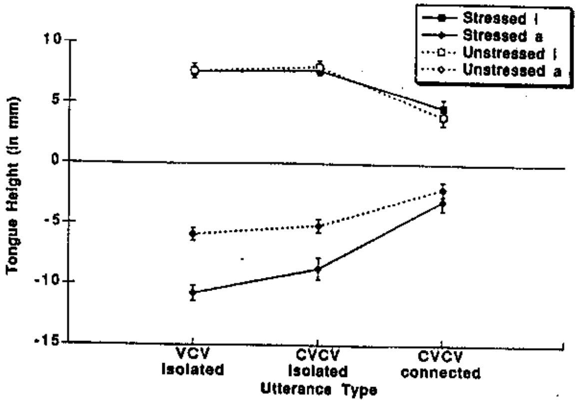


Fig. 6. Position of tongue body along the high/low dimension for vowels /a/ and /i/ as a function of stress and utterance type in symmetric sequences.

connected speech results exclusively from a decreased amplitude of the tongue articulator rising movement. As for /a/, the pattern of the residuals indicates that the tongue body is actively lowered from its rest position though much less than it is raised for /i/, and that the lowering is smaller in connected speech than in isolated words.

Tongue-x. The position of the tongue body along this dimension varies as a function of vowel and utterance type. The tongue is more fronted for /i/ than for /a/ (average difference = 10.664 mm), and in isolated words than in connected speech. The results of the regression are that jaw-*x*, tongue-*y* and jaw-*y* account in total for 44.8% of the variance in tongue-*x*. The analysis of the residuals for the symmetric utterances indicates that independent tongue movements along this dimension contribute to differentiate /a/ and /i/ mainly when they are unstressed or are produced in connected speech. This is achieved by a substantial back displacement for unstressed /a/, and for stressed /a/ in connected speech, precisely those vowels produced with reduced jaw displacement.

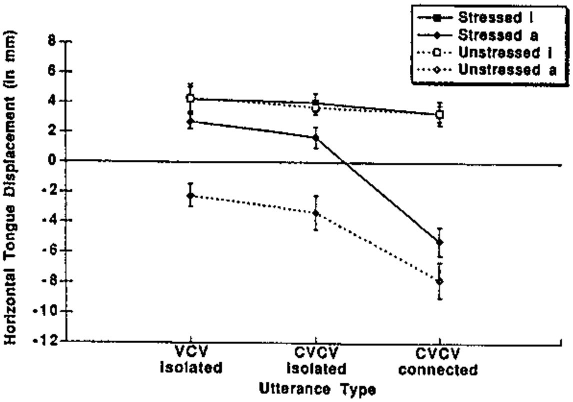


Fig. 7. Tongue articulator contribution to tongue body position for vowels /a/ and /i/ along the front/back dimension as a function of stress and utterance type in symmetric sequences.

Figure 7, relative to the regression residuals, shows the effect of such independent tongue body displacement. It is therefore reasonable to interpret this tongue movement as an active compensation for the reduction of both tongue and jaw displacements along the high/low dimension.

3.2. *Coarticulation*

In this section we address the following questions: what changes occur in the vowel position as a function of the consonant and of the transconsonantal vowel? Do coarticulatory effects increase in connected speech? The residual pattern allows us to infer the nature of the effects: it will be seen that the majority of the effects exerted on tongue position are reduced movements towards the target.

Jaw-y. Jaw position along this dimension for vowels is not affected by the type of intervocalic consonant, nor by the transconsonantal vowel, but is largely affected by the presence or absence of an initial consonant, as mentioned above.

Jaw-x. The position of the jaw along this dimension is instead affected by consonant type: in the context of fricatives (/z/ /ʃ/) the jaw position during vowels is more fronted than in other consonantal context. This effect occurs mainly on the post-consonantal, unstressed vowels and does not increase in connected speech. Analysis of the residuals indicates that this fronting reflects independent forward movement of the jaw. Figure 8 shows the position of jaw during V1, V2 and the intervocalic consonants; it can be seen that the effects are exerted exclusively on the unstressed vowel (V2), whose position reflects quite well that of the preceding consonant.

Tongue-y and *Tongue-x*. On the vertical dimension vowels are significantly affected by consonant type: adjacent to fricatives the tongue body position for /i/ is lower than when adjacent to other

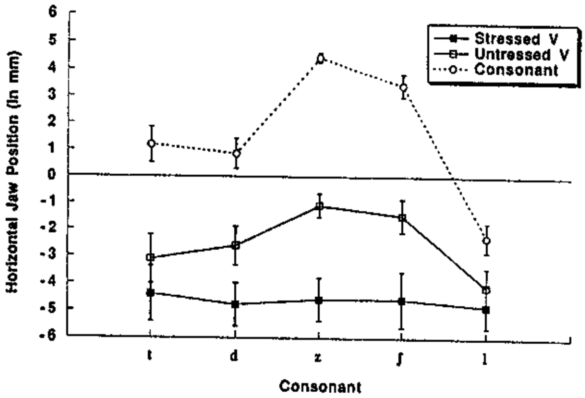


Fig. 8. Effects of consonants on horizontal jaw position for following unstressed vowels (dashed line: position for consonants; filled squares: position for V1; empty squares: position for V2).

consonants; these effects are stronger in V2 than in V1, and tend to increase in connected speech.

Figure 9 shows the consonant effects on V2, relative to tongue body measured positions (top) and to the residual pattern (bottom). The comparison between the two graphs shows that the effect of consonants mostly consists in keeping the tongue body rather low during /i/; the analysis of consonants (Faber and Farnetani, 1991) indicates that indeed the tongue body position during fricatives is lower than that of the other consonants: reminding us that the tongue coil was attached at the midline of the tongue dorsum, the present data suggest that the formation of a tongue groove for the production of fricatives must require a quite slow and precise movement which seems to start already at the point of maximum displacement during V1 and is not yet over at mid V2 (similarly (Stone et al., 1992)).

On the horizontal dimension the C-to-V effects are significant only on V2: /t/ and /ʃ/ tend to reduce the back displacement of /a/, and /l/ and /ʃ/ tend to reduce the front displacement of /i/. These effects are stronger in connected speech than in isolated words.

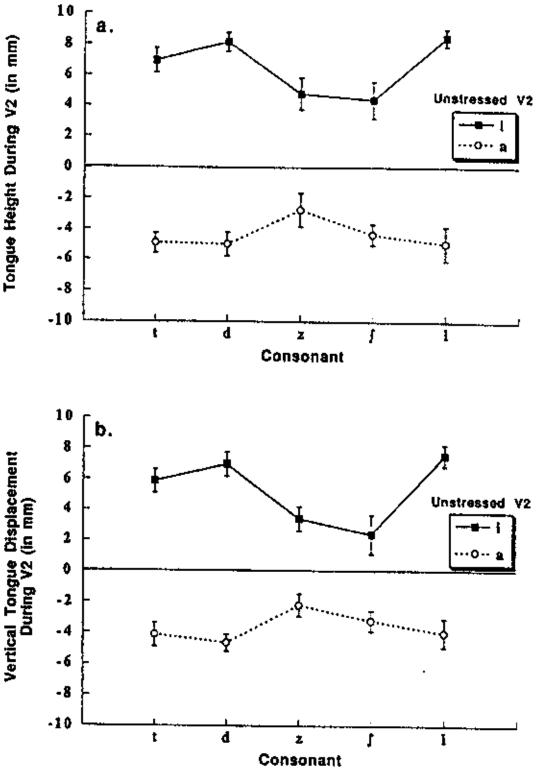


Fig. 9. Effects of consonants on tongue body along the high/low dimension for following unstressed vowels. (a) Measured tongue height; (b) independent contribution of tongue articulator to tongue body position.

The V-to-V effects were analysed by examining the position of V1 as a function of V2 and vice-versa. Globally, the carryover effects are stronger than the anticipatory effects. The anticipatory effects involve only tongue height, are exerted only by the following /i/ and, if positions of the influenced vowels are related to those of the influencing vowels, they are relatively stronger in connected speech. Thus, stressed /a/ in isolated words is higher in /a-i/ than in /a-a/ sequences; in connected speech it is already high in /a-a/, and

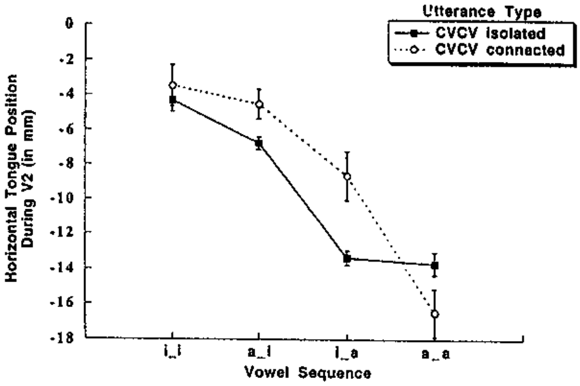


Fig. 10. Carryover V-to-V effects on horizontal tongue position in CVCVs in isolation and in connected speech.

further increases in /a-i/. Hence coarticulatory effects add to the reduction effects (the total displacement of /a/ in the context of /l/ amounts to 11.76 mm). The carryover effects involve only the front/back dimension, are exerted from both /i/ and /a/, and those exerted on /a/ appear only in connected speech. Figure 10 shows such effects, i.e. the different position of V2 as a function of V1.

The residual patterns indicate that such effects consist in limiting the forward movements during /i/ and the backward movements during /a/.

4. Discussion and conclusion

Although the present study will have to be supplemented with temporal and dynamic data, some hypotheses about linguo-mandibular coordination in vowel production in isolated words and in connected speech can be proposed on the basis of the present results. The primary question that we addressed is how the tongue and jaw are coordinated in the poduction of vowels. The global picture offered by the present results conforms to the phonetic descriptions and the experimental data available in the literature. The present data indicate, as expected, that the two articulators are largely independent of each other, and, moreover, that each of them can act along one dimension largely independently of the other dimension. This allows the articulators to perform different functions at the same time and to execute both synergistic and compensatory movements in either direction.

The jaw executes the gross movements, positioning the tongue body to perform finer shaping of the vocal tract: reduction as a function of stress and utterance type is observable in both jaw and tongue movements; coarticulation, i.e. the effect of a specific context, is much more often observed in tongue than in jaw movements, whilst compensation is observed exclusively in tongue movements.

An interesting finding is how the jaw and tongue interact in vowel reduction and in compensatory movements: the reduction of jaw displacement during /i/ makes the vowel position higher and more advanced, while the reduction of tongue body displacement makes this vowel lower and less fronted. Thus, the vocal tract configuration for high vowels results from the interaction of these two apparently contradictory movements. As a consequence, only when jaw reduction is weak and the tongue reduction is strong can we find evidence of reduced high vowels. Instead for /a/ lesser displacements of jaw and tongue body both contribute to make the vowel higher and more advanced. But, as we have seen, reduced /a/ vowels are found to be displaced backwards by an active compensatory tongue movement. This suggests that compensation aims at maintaining invariance as far as a specific tract configuration renders this possible: in the present case the strongly reducing effect of the jaw on the tongue position for the vowel could probably be compensated for only by this kind of tongue movement, which does not preserve vowel invariance but rather inter-vowel articulatory distance. The data on coarticulation, indicating that tongue body effects on unstressed V2 (as compared to the effects on V1) are mainly exerted on the horizontal axis, support the idea that front/back dimension is privileged when sounds are produced with a closer vocal tract. The finding that compensation occurs in connected speech and in reduced vowels indicates that gestures simultaneously respond to functional requirements and to economy.

Only coarticulatory effects (from the transconsonantal vowel) seem to overrule in strength the compensatory movements. Thus we can distinguish two kinds of reduced vowels: those which are reduced, but compensated for, and those which are reduced and not compensated for; only the latter can be described as simplified articulations since they are characterized by reduced displacements of jaw, and practically no displacements of tongue. The present data on this subject seem to suggest that the function of compensatory movements was to preserve the articulatory distance (hence the acoustic contrast) between /a/ and other vowel categories, rather than the gestural invariance of the vowel.

Another question we attempted to answer is how reduction and coarticulation are related. Do we have evidence that reduction itself can be the automatic response to various degrees of temporal overlap? The present data suggest that this is the case for most instances of reduction of /a/: the most evident is the case of presence versus absence of an initial consonant in isolated words which speaks not only in favor of this interpretation of reduction but also in favor of vowel-consonant coproduction (independent of timing). Another evident case is reduction in connected speech versus isolated words, which parallels both the shortening of the embedded items and the increase in C-to-V and V-to-V coarticulation. Instead reduction of unstressed final vowels, which in this subject are just slightly shorter than stressed ones (Farnetani and Vayra, 1991) is probably the outcome of a reduced amplitude of the vowel gesture in unstressed position.

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