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THE VELOPHARYNGEAL MECHANISM: AN ELECTROMYOGRAPHIC STUDY

by

FREDERICKA BELL-BERTI

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,
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Fredericka Bell-Berti

New York, New York
April, 1973

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Chapter I: Introduction

The pharynx provides a common structure for several basic life functions: respiration, swallowing, and speech. A survey of the existing literature about the functions of this region reveals that several questions of importance to those interested in the problems of individuals with anomalous mechanism (e.g., cleft palate) as well as to those interested in a physiologically accurate linguistic description of speech remain unanswered. In this paper I shall be concerned with questions about the physiology of this region with regard to normal speech function.

Anatomy

The pharynx may be divided into three parts: the nasopharynx, the oropharynx and the laryngopharynx. The nasopharynx is the superior portion of the cavity, behind the nasal cavities and above the soft palate. Immediately inferior to the nasopharynx is the oropharynx, whose superior boundary is formed by the elevated soft palate; when the palate is not elevated, the oropharynx is continuous with the nasopharynx. Laterally and posteriorly the oropharynx is bounded by the muscular pharyngeal walls. The anterior boundary of the oropharynx is formed, superiorly, by the faucal pillars and, inferiorly, by the base of the tongue. The inferior border of the oropharynx is at the level of the epiglottis and hyoid bone. Below the oropharynx is the laryngopharynx which extends from the level of the hyoid bone, superiorly, to the orifice of the esophagus and larynx inferiorly. The velopharynx is that region which is associated with constricting the port between the nasopharynx and oropharynx, and consists, therefore, of the superior portion of the oropharynx and the inferior portion of the nasopharynx. I shall, however, refer to the entire oropharynx and the velopharyngeal port area as the velopharynx, so as to deal with the entire region as it is concerned with normal speech function.

The Muscles

The soft palate is a shelf of musculoaponeurotic tissue extending posteriorly from the edge of the hard palate. The palatine aponeurosis, the fibrous central connective tissue mass of the soft palate, forms its skeletal core. The aponeurosis and tendon of the tensor palatini comprise the bulk of the tissue of the anterior third of the soft palate, the major portion of the palatal muscles inserting into the middle third of the palate (Hollinshead, 1954).

levator veli palatini. - The main muscular bulk of the soft palate is the levator veli palatini (Figures 1, 2, 3) (Hollinshead, 1954), arising from the inferior surface of the petrous portion of the temporal bone (Hollinshead, 1954; Dickson and Maue, 1970) and, also, from the lower part of the Eustachian tube cartilage (Hollinshead, 1954). It courses downward and medially from its origin, curving to enter the soft palate between the musculus uvulae and the anterior portion of the palatopharyngeus, the fibers from both sides meeting in the midline (Hollinshead, 1954). Dickson and Maue (1970) report that the levator veli palatini enters the soft palate at an angle of approximately 45 degrees postero-anteriorly. The same authors report that the most anterior fibers extend into the anterior third of the soft palate. Oldfield (1922) described the levator veli palatini as the "middle segment" of the soft palate.

The levator is innervated by the pharyngeal plexus (Broomhead, 1951), with the motor fibers deriving from the vagus nerve and reaching the levator through the bulbar roots of the spinal accessory nerve (Hollinshead, 1954).

Vidič's (1964) report that glossopharyngeus nerve fibers join the vagus nerve fibers to the levator, is cited by Fritzell (1969).

Contraction of the levator veli palatini lifts the soft palate posteriorly and superiorly toward the posterior pharyngeal wall. Its angled entrance into the soft palate may also result in the lateral pharyngeal walls' medial and posterior movement (Dickson and Maue, 1970).

palatoglossus. - The fibers of the palataglossus (Figure 1) are the most superficial muscle fibers of the inferior surface of the soft palate (Hollinshead, 1954). The palatoglossus fibers course downward and insert into the lateral margin of the tongue (Hollinshead, 1954; Dickson and Maue, 1970). The fibers form the muscle mass of the anterior faucal pillars (Hollinshead, 1954; Dickson and Maue, 1970). Fritzell (1969) reports that Luschka (1868) found the palatoglossus to be 1.5 mm thick and 3 mm broad at the level of the anterior pillar.

Broomhead (1951) reports that motor innervation is by fibers of the pharyngeal plexus.

The palatoglossus may act as an antagonist to the levator veli palatini, lowering the soft palate (Dickson and Maue, 1970). Hollinshead (1954), suggests that the joint action of the palatoglossus and palatopharyngeus is to draw down the soft palate, narrowing the pharyngeal and faucal isthmi.

palatopharyngeus. - The palatopharyngeus (Figure 1) has two origins arising from the infero-anterior surface of the palate, running between the tensor veli palatini and levator veli palatini,and from the supero-posterior section of the soft palate. The anterior fibers course downward, are joined by the posterior muscle bundle, and form the muscle mass of the posterior faucal pillar. From the posterior pillar the fibers fan out and attach to the pharyngeal aponeurosis and posterior border of the thyroid cartilage (Hollinshead, 1954; Dickson and Maue, 1970).

Broomhead (1951) reports that motor innervation of the palatopharyngeus is via the pharyngeal plexus.

Fritzell (1969) reports that one may consider as commonly accepted that the palatopharyngeus is active for velopharyngeal closure during speech. Hollinshead (1954) also reports that the palatopharyngeus acts to narrow the faucal and pharyngeal isthmi, thus aiding in velopharyngeal closure. Dickson and Maue (1970), however, suggest that the palatopharyngeus acts in swallowing to narrow the lower pharynx and also acts to lower the soft palate. Obviously, these two descriptions of function for speech are incompatible.

superior pharyngeal constrictor. - The superior pharyngeal constrictor (Figures 1, 2, 3) forms the superficial muscle layer of the upper pharynx (Fritzell, 1969). The fibers run circumferentially and insert into each other at the medial pharyngeal raphe (Hollinshead, 1954). The muscle is classically divided into four parts: pars pterygopharyngea, the most cranial inserting to the hamulus and the lower third of the medial pterygoid plate, and the section most important to velopharyngeal closure; pars buccopharyngea, inserting into the pterygomandibular raphe; pars mylopharyngea, inserting to the inside of the posterior portion of the mandible; and pars glossopharyngea, inserting into the tongue (Fritzell, 1969; Dickson and Maue, 1970).

Broomhead (1951) reports that motor innervation is via the pharyngeal plexus.

Contraction of the superior pharyngeal constrictor will narrow the upper pharynx, assisting in lateral pharyngeal wall movement (Fritzell, 1969; Dickson and Maue, 1970), and perhaps may assist in posterior movements of the tongue. Passavant (1863) advocated the importance of the superior pharyngeal constrictor in achieving velopharyngeal closure, although others (e.g., Calnan, 1953) have disputed the primacy of its role in achieving closure.

middle pharyngeal constrictor. - The middle pharyngeal constrictor (Figure 3) is a fan-shaped muscle arising from the median pharyngeal raphe and inserting to the greater and lesser hyoid cornua and the inferior portion of the stylohyoid ligament (Hollinshead, 1954; Dickson and Maue, 1970). For part of its extent it lies external to, and overlaps, the superior pharyngeal constrictor (Dickson and Maue, 1970).

Motor innervation is via the pharyngeal plexus (Hollinshead, 1954).

Contraction of the middle pharyngeal constrictor will narrow the pharynx during swallowing and may draw the hyoid bone posteriorly (Dickson and Maue, 1970).

sternohyoid. - The sternohyoid (Figure 4) is a thin, broad, flat muscle arising in the postero-superior region of the sternum and inserting near the midline of the lower border of the hyoid bone (Hollinshead, 1954; Dickson and Maue, 1970).

Motor innervation of the lower portion of the sternohyoid is via branches of the ansa hypoglossi. Additional motor innervation is via nerve fibers from the cervical plexus (Hollinshead, 1954).

Contraction of the sternohyoid will draw the hyoid bone inferiorly (Dickson and Maue, 1970).

Research Techniques

It is possible to observe articulator movements associated with speech gestures at two levels. The first of these, which I shall call direct viewing, involves direct measurement of articulator displacement, e.g., the height of the soft palate. The second method, which I shall call indirect viewing, involves measurements of the cause or result of articulator displacement, implying but not specifying articulator movements, as, for example, electromyographic potentials. The research techniques which have been applied to the study of the velopharyngeal region are described below within these two categories.

Direct Viewing Techniques

Description of the oropharynx during speech articulation requires that observations be made of that region during speech. Great strides have been made in the development of techniques for the direct viewing of articulator movements since the mid-nineteenth century observations of patients with orofacial anomalies (Hilton, 1836). Fritzell (1969) reports that it was through such openings that investigators were able to observe the velar region during speech, breathing,and deglutition (Hilton, 1836; Bidder, 1838).

Possibilities for direct viewing of the velopharyngeal region were expanded with the development of posterior rhinoscopy (Passavant, 1863) and, at the end of the nineteenth century, the discovery of X rays. The development of radiographic techniques revolutionized the study of the speech mechanism. It became possible to observe and make a permanent record of the positions of the articulators, first for isolated, sustained phoneme productions and, later, with high-speed motion pictures, for running speech (Bzoch, 1970).

More recent technological advances have produced additional direct viewing instruments. One of these, the Taub oral panendoscope (1966) allows the observer to view the oral aspect of the velopharyngeal port during sustained vowel production and oral occlusion. The bulk of the panendoscope, however, precludes observations of high vowels and occlusions formed anywhere save the lips (where the occlusion is formed around the panedoscope). Another direct viewing instrument of recent development is a fiberoptic endoscope (Sawashima and Hirose, 1968; Sawashima and Ushijima, 1971), which consists of two bundles of very fine,flexible glass fibers, one image conducting and one light conducting. Inserting the fiberscope through the nasal cavity, one may observe, and photograph, the nasal surface of the soft palate during running speech (Berti and Hirose, 1972; Ushijima and Sawashima, 1972). Pulsed ultrasound has also been used to monitor articulator movements (Minifie et al., 1970).

Indirect Viewing Techniques

Fritzell (1969) reports that in the late 1850's aerodynamic measurements were in use for determining the efficiency of velopharyngeal port closure (Brucke, 1856; Czermak, 1857, 1858, 1869). Alternative indirect measurements were mechanical in nature (Czermak), the degree of palatal elevation (and closure) being estimated from resulting positional changes of materials placed in the nasopharynx.

Recent strides in instrumentation have resulted in many new, sophisticated techniques for indirect viewing of the velopharyngeal port. A transillumination technique for determining the presence of velopharyngeal opening has been described by Ohala (1971). He introduces a DC light source into the pharynx at the epiglottal level and places a sensor above the soft palate.

Another technique for studying articulatory mechanisms, electromyography, records the electrical activity that corresponds to muscle contraction. Within the domain of electromyography, several methods are available for detecting differences in electrical potential: electrodes may be placed on the epidermal covering of the muscle under study, or needles or fine wires may be implanted in the muscle. In both situations, the recorded signal is the potential difference generated by the contracting muscle fibers, rather than some physical measure of the contraction itself. Hence, the electrical activity precedes the articulatory gesture in time. In addition, overall electrical activity is related to the distance over which the articulator must move per unit of time.

History

The observations of soft palate elevation, velopharyngeal port size and posterior pharyngeal wall movements during speech, by Passavant (1863) and his predecessors, established the framework for all subsequent research on velopharyngeal function. In the mid-nineteenth century (Hilton, 1836; Bidder, 1838), reports were made of the soft palate observed from above during swallowing and speech in subjects with orofacial anomalies. The soft palate was observed to be elevated during speech, oral breathing and deglutition (Hilton, 1836).

Fritzell (1969) reports studies by Bruckë(1856) and Czermak (1857, 1858, 1869) which employed indirect indicators of velopharyngeal closure during speech. Bruckë used a candle flame to study emission of air through the nose. Czermak rested a specially designed iron wire on the floor of one side of the nasal cavity and then observed the deflection of its outer end caused by soft palate elevation. Czermak also introduced water into the nasal cavities and noted the speed with which the water passed into the lower pharynx during the production of sustained sounds. He used a cold mirror held under the nostrils to demonstrate the difference between oral and nasal vowels. Another of Czermak's techniques (1869) was the introduction of a pressure sensitive device into the subject's nostril. The results of his experiments demonstrated decreasing palatal height in the vowel series /i/, /u/, /o/, /e/, /a/.

Fritzell (1969) reports that Passavant (1863) found, using posterior rhinoscopy, that /a/, /o/, and /u/ are not always produced with complete velopharyngeal closure. By placing tubes of varying diameter in the velopharyngeal port region, he found that a velopharyngeal port cross-sectional area of 12.6 mm^2 had little effect on speech quality, but that a cross-sectional area of 28.3 mm^2 resulted in nasalization of most consonants. Passavant also reported the presence during speech, in a cleft palate subject, of a bulging in the posterior pharyngeal wall, and assumed that it is present in normal subjects above the level of velopharyngeal closure.

It is possible to discover two fundamental lines of investigation leading from these early data: (1) into the nature of oral and nasal articulation; and (2) into functional differences in velopharyngeal activity related to phonetic variations in oral contexts.

The first line concerns the dimensions of oral and nasal articulation. More specifically, is oral articulation essentially achieved by: (1) posterior movement of the velum; (2) a combination of posteriorly directed velar movement and anteriorly directed movement of the posterior pharyngeal wall (Passavant's pad); or (3) some other multidimensional action of the velopharyngeal musculature? Included in this problem is the question of the nature of nasal articulation: is nasal articulation achieved by contraction of some muscle or muscle group or is it solely the result of decreased activity in those muscles responsible for oral articulation? In either case, which muscles are responsible for oral articulation?

Studies concerned with the second question, functional variations in velopharyngeal activity conditioned by phonetic environment, may be grouped into two classes. The first category concerns variations in velopharyngeal activity with vowel color, while the second concerns variations in activity which accompany stop consonant articulation.

Oral-Nasal Articulation

1. The Passavant's Pad Question

The first question related to oral-nasal articulation, that is, whether anteriorly directed movement of the posterior pharyngeal wall plays a significant role in normal velopharyngeal closure mechanisms, has been approached by several investigators. Calnan (1957) has disputed the presence of Passavant's pad in most speakers and claimed that such a mechanism would be too sluggish and fatigable to be a reliable compensatory phenomenon in speakers with inadequate palatal musculature. Hagerty et al. (1958, 1960) measured posterior pharyngeal wall movement during isolated sustained speech sounds in normal and cleft palate subjects from lateral head X rays. They concluded that Passavant's pad is not a mechanism used by most normal speakers although post-operative cleft palate subjects tend to use more posterior pharyngeal wall movement than do normal speakers. Björk (1961) obtained cinefluorographic and tomographic films of normal children and adults and reported that although there were frequent cases of incomplete velopharyngeal closure (including instances of oral consonant articulation) the speech of these subjects was judged to be completely normal. Nylén (1961) compared groups of post-operative cleft palate subjects with Björk's normal subjects and found velar movement patterns, among those cleft palate subjects judged to have no insufficiency, which were comparable to those of the normals. A Passavant's pad was identified in eleven of twenty-seven subjects whose speech was judged insufficient in the Nylén study. After secondary palatal repair (velopharyngoplasty) only six instances of Passavant's pad were identified in seventy-one surgically repaired cleft palate individuals and in only two of these did the pad contribute to velopharyngeal closure. Carpenter and Morris (1968) examined cinefluorographic films of six surgically repaired cleft palate individuals known to exhibit Passavant's pad and concluded that it is, for some subjects, a reliable compensatory mechanism. Bzoch (1968) reported measurements made from cinefluorographic films of five adult subjects repeating the syllables /pi/, /pa/ and /pu/ and found that velar elevation, but not posterior pharyngeal wall movement, showed significant differences across the different syllables.

The consensus in this matter, then, seems to be that Passavant's pad (or use of the superior constrictor) is not a normal mechanism of velopharyngeal closure, even for subjects with repaired cleft palates. It may, however, contribute to velopharyngeal closure in a few cleft palate individuals.

2. Critical Velopharyngeal Port Size

The second line of investigation derived from the early work of Passavant, and others, is research into the physical requirements for decoupling of the nasal and oral cavities.

In 1956, House and Stevens, using oral and nasal tract analogs to produce their speech samples, varied the ratio of the driving point impedance of the velopharyngeal port to the internal impedance of the vocal tract (which increases with decreased cross-sectional area) and found that as the ratio decreased (i.e., the driving point impedance of the velopharyngeal port decreased in relation to oral cavity impedance), nasal coupling increased, with the principal effects of coupling occurring in those frequency ranges where the impedance difference is greatest, particularly in the region of F_1. They concluded that: nasal coupling leads to a differential reduction across vowels in the amplitude of F_1, with increasing formant bandwidth and an upward shift in the center frequency of F_1; there is an overall reduction in vowel amplitude with nasal coupling; and there are secondary effects on the spectrum, including the introduction of antiresonances, minimization of F_3, and the addition of spectral peaks. "Nasality" is perceived when these major spectral effects reach appropriate magnitudes. House and Stevens used five velopharyngeal port orifice sizes in their study: a completely closed port; a port size of 0.25 cm^2 (25 mm^2); a port size of 0.71 cm^2 (71 mm^2);a port size of 1.68 cm^2(168mm^2);and a port size of 3.72 cm^2 (372 mm^2). Results of perceptual tests indicated that listeners failed to judge any vowel stimuli produced with a velopharyngeal port size of 25 mm^2 as "more nasal" than those produced with closed ports, while the high vowels produced with a port size of 71 mm^2 were judged as a "more nasal" than those produced either with a closed port or with an opening of 25 mm^2.

While House and Stevens worked with oral and nasal tract analogs to determine the impedance relationships for oral and nasal articulation, other investigators used direct and indirect physiological measurements to determine the critical velopharyngeal port size above which nasal coupling would seriously interfere with oral articulations. Björk (1961) reported a tomographic and cineradiographic study of velopharyngeal function during speech. He determined velopharyngeal port areas from tomographic films and compared these area measures to the antero-posterior measurements of port size. He established that the cross-sectional area of the velopharyngeal port is a linear function of the port's sagittal minor axis, which may be determined from lateral X-ray pictures. The area may be computed by multiplying the antero-posterior dimension of the velopharyngeal port by 10 mm. Nylén (1961) obtained sagittal minor axis measurements from cineradiographic films and using Björk's (1961) computation, determined that there was an effect on speech acceptability for one subject with an antero-posterior port size of 2 mm, which corresponds to a velopharyngeal port area of 20 mm^2. Speakers in Nylén's study who had velopharyngeal port areas of greater than 90 mm^2

had speech which was always seriously affected by nasal coupling, while some degree of nasal coupling was observed for all speakers who had port areas of at least 50 mm^2. Subtelny et al. (1961) measured the distance between the soft palate and posterior pharyngeal wall from lateral skull X-rays of subjects with repaired cleft palates. They determined that there was an evident loss of speech intelligibility when the antero-posterior dimension of the velopharyngeal port was as little as 0.5 - 3.0 mm. A more serious loss of intelligibility accrued to a port size of between 3.5 and 11.0 mm, while the most serious effect on intelligibility was found for the speech of subjects with an antero-posterior port dimension of 11.5 - 18.0 mm.

Using Björk's (1961) computation on the data of Subtelny et al. (1961), which is to multiply the antero-posterior dimension of velopharyngeal port size by approximately 10 mm to determine the area of the port, one sees that speech intelligibility was affected when the area of the port was between 5 and 30 mm^2. Isshiki, Honjow and Morimoto (1968) induced velopharyngeal incompetence in their subjects by placing polyvinyl tubes of varying cross-sectional diameters in the subjects' velopharyngeal ports. They found that a port size of 19.6 mm^2 (corresponding to a tube diameter of 5 mm) is the critical velopharyngeal port area for acceptable speech. Warren (1969), using nasal air flow to estimate velopharyngeal port size, found that there is adequate velopharyngeal closure for speech when the port area is less than 20 mm^2, and that closure is inadequate when the velopharyngeal port area is greater than 20 mm^2.

All of these fairly recent data provide general confirmation of the findings of Passavant (1863) that a velopharyngeal port cross-sectional area of 12.6 mm^2 had little effect on the quality of speech, while a cross-sectional area of 28.3 mm^2 resulted in nasal coupling.

3a. Oral and Nasal Gesture Mechanisms

The third line of research to develop out of the nineteenth century observations of oral and nasal articulation is actually an extension of the Passavant's pad problem, concerning itself with the description of the detailed physiology of nasal and oral gestures. This area includes the smaller questions of how the velopharyngeal port is closed for oral articulation, the mechanism by which velopharyngeal port size is increased in order to permit nasal coupling, and the degree to which such coupling is permitted to occur in normally oral sounds (coarticulation). Research along these lines has included both indirect (electromyography and transillumination) and direct (fiberscopic and cineradiographic viewing techniques).

Electromyographic (EMG) studies of the velopharyngeal region have been performed for the past several years. Harris et al. (1962), using surface suction electrodes on the soft palate,report no activity in the palatal region for the production of /m/ and identical bursts for /p/ and /b/.

Lubker (1968) obtained simultaneous cinefluorographic films and surface palatal electromyographic recordings of isolated vowels and CV syllables, where C = /p/, /b/, /t/, /d/, /m/, and V = /i/, /æ/, for five normal adult subjects. He found a high correlation between velar position and velar EMG activity, with lower EMG activity and velar position for nasal syllables than for oral syllables, and with high vowels showing greater EMG activity and velar height than did low vowels.

In a major study reported in 1969 Fritzell presented the findings of an electromyographic and cineradiographic study of the muscles of the velopharynx during speech. He recorded from electrodes inserted into: the levator palatini below and behind the tensor palatini; the tensor palatini lateral to the levator in an area posterior to the medial pterygoid plate; the superior pharyngeal constrictor at the estimated level of velopharyngeal closure; the palatopharyngeus and palatoglossus in the posterior and anterior pillars of fauces, respectively. Subjects were required to repeat a series of eighteen VCV utterances and three sentences.

He concluded, based on the electromyographic recordings, that the levator palatini is the most important muscle involved in velopharyngeal closure in normal speech, its pattern being more consistent and uniform across subjects than that of any of the other muscles[1] in his study. He confirms that the previously reported increase in velar height was reflected in increased levator palatini activity in the series from /a/ to /i/ and /u/. Superior constrictor activity was similar in pattern to that of the levator palatini. The palatopharyngeus was not active in all subjects during speech. When it was active, it showed no differences between oral and nasal articulation. Palatopharyngeus activity was greater for /a/ than for any other vowel, although the greatest activity occurred during swallowing. Fritzell believes, from the recordings of the palatoglossus, that its major role is the lowering of the soft palate both for nasal phones and the end of phonation. He feels, too, that it may also be active in positioning the soft palate at the onset of phonation. Recordings during the production of /g/ and /ŋ/ would also indicate that the palatoglossus is active in elevating the middle and posterior parts of the tongue. The palatoglossus was also active during nasal breathing with the mouth open. My own reinspection of Fritzell's EMG traces for the palatoglossus for the VCV syllables leads me to the conclusion that there is little evidence of palatoglossus activity for nasal sounds except for /η/ (pp. 38,40). On the contrary, activity appears to correspond to backing and raising of the posterior part of the tongue, with activity evident for /a/, /u/, /g/ and /η/: the activity patterns appear nearly identical for the utterance pairs /əPa/-/əNa/, /əPu/ - /αNu/, and /əPi/-/əNi/, where P is/b,d/ and N is /m,n/. Peaks occurred during vowel articulation for the pairs /əPa/-/əNa/ and /əPu/ - /əNu/, with no peaks of activity in the pair /əPi/ - /əNi/. It is possible that the activity peaks before and after phonation are associated with nasal breathing with the mouth open.

Another part of Fritzell's study involved synchronized cinefluorography and electromyography of the levator palatini and palatoglossus muscles. He found a striking similarity between the shapes of the velar movement curves obtained from frame-by-frame measurements of the cinefluorographic films and the curves of the rectified EMG signal of the levator palatini. The curves of palatoglossus activity appear to correspond to velar descent, although there were bursts of activity occurring at other times (i.e., for production of /a/ and /η/). An alternate possibility, which is consistent with the observed data, is that palatoglossus activity occurs for low back vowels, which also exhibit decreased levator palatini activity and velar height.

Fritzell also reported confirmation of the findings of Moll (1962) and Lubker (1968), discussed below, that there is a clear difference in velar height for low and high vowels. (The correlation between velar height and EMG activity varied from 0.46 to 0.94 among subjects). Fritzell concluded that the motor signals to the levator palatini operate along a continuum rather than in a two-mode (i.e., on-off) fashion (Moll and Shriner, 1967).

In a closely related study, Lubker, Fritzell and Lindquist (1970) obtained electromyographic recordings from the levator palatini and palatoglossus muscles of seven native speakers of Swedish. The study reports data for one of the subjects for whom successful palatoglossus recordings were obtained. They investigated high and low vowels, "pressure" consonants, and nasals in order to examine palatal coarticulation. They report decreasing levator palatini activity in the series /t, s, d, i, ɑ/ with greater levator activity for consonants and vowels which followed nasals than for those which preceded nasals. Consonants following low vowels showed greater levator activity than consonants following high vowels. The nasal /n/ was always accompanied by a marked reduction in levator palatini activity. The palatoglossus was reported to be active for nasals, although the strongest burst of palatoglossus activity occurred for /u/. The authors concluded that:

> "...Palatal elevator activity during speech might be described as being grouped according to certain phoneme categories, a possible example being voiceless consonants, voiced consonants, relatively close vowels, relatively open vowels and nasal-rest. Thus palatal musculature would be predicted to contract as forcefully as necessary to move the soft palate from wherever it is to wherever it must be to prevent excessive nasal coupling."
> (p. 16)

They added that while the palatoglossus, for this subject, is active in palatal lowering maneuvers, no predictable pattern of activity is discernible from the relatively small body of data yet available.

3b. Nasal Coarticulation

In addition to describing the mechanisms of oral and nasal articulation, studies of nasal coarticulation have been aimed at defining the extent of velopharyngeal opening in phones in nasal environments and the articulatory parameters which limit the coarticulation. Ohala (1971), using a transillumination device, has reported that: vowels preceding nasals show greater coarticulation effects than do vowels following nasals; palatal lowering begins as soon as closure is no longer necessary (as it is for obstruent articulation); and velopharyngeal closure is incomplete for the articulation of low vowels.

Ushijima and Sawashima (1972) obtained high speed (50 frames/sec) motion picture films of the nasal surface of the soft palate and, subsequently, of the velopharyngeal port during oral and nasal consonant and vowel articulations. They found that the greatest velar elevation occurs for oral consonants preceded by nasals. A vowel in a nasal environment shows lower velar height than does the same vowel in an oral environment, with velopharyngeal port closure being incomplete in the former case. Velar height was found to increase with vowel height.

In a study of the timing of velar movements Moll and Daniloff (1971) found that movement toward velopharyngeal release in CVN and CVVN sequences began during articulator movement toward the first vowel, and that some velopharyngeal opening was observed for all such vowels. In NC and NCN sequences, movement toward closure began during the nasal preceding the consonant, and in all cases, contrary to Björk's findings, complete velopharyngeal closure was observed at least 15 msec prior to the consonant release. In NVC sequences, movement toward closure was found to be quite similar to NC sequences, although movement toward closure begins a bit later in the former and closure may not be complete during the vowel. In addition, no closure gesture was seen when the vowel was followed by /w/ or /l/. The observed coarticulation effects (figure 5) were found to occur across word boundaries. In a study of Hindi, Dixit and MacNeilage (1972) concluded that nasal coarticulation will be unrestricted both to the left and right of the nasal [i.e., will be unlimited in both anticipatory and postcipatory conditions if: (1) there is no pause; (2) no obstruents or liquids are involved (the latter being contrary to the findings of Moll and Daniloff, 1971);[2] and (3) there is no loss of contrast (as between nasal and nonnasal vowels)]. They also found that vowels preceding and following nasals will have equivalent coarticulation effects (contrary to the reports of Moll, 1962; Ohala, 1971) if their surrounding phonetic environments are equivalent. Additionally, they report finding velar leakage for all voiced sounds, though the degree increases from low to high and from anterior to posterior articulations.

In summary, then, we know that the levator palatini functions to raise the soft palate and draw it posteriorly for the production of oral speech sounds, and that there is suppression of activity in the levator palatini for the production of nasal consonants. The superior pharyngeal constrictor shows a pattern similar to that of the levator palatini, while the activity pattern of the palatopharyngeus has not been established. In addition, we know that vowels which precede nasal consonants show decreased activity in those muscles responsible for velopharyngeal closure, and, concomitantly, velar height is reduced in such cases. The mechanism by which the soft palate lowers to facilitate nasal coupling is, however, not clear. My own feeling is that evidence that the palatoglossus is active in velar depression is not satisfying: it seems to correlate as well with tongue body movements as with soft palate lowering gestures.

Nonnasal Phonetic Variation

1. Vowels and Velopharyngeal Variation

Closely related to the question of how the velopharyngeal port is closed to achieve oral articulation is the question of how tightly the port must be closed (i.e., how high the velum must be) for different phonemes in order to prevent nasal coupling. This latter question also concerns, quite obviously, the matter of the effect of phonetic variations upon velar height. Moll (1962) used cinefluorographic observations to investigate the relationship between velopharyngeal closure and vowels in varying consonant contexts. He concluded that: closure is greater for high vowels than for low vowels; closure is incomplete for vowels in nasal environments, with anticipatory effects being greater than postcipatory ones; various nonnasal consonants show no significant differences in their effect on vowel closure but that vowels in context tend to have greater closure than do isolated vowels.

Other researchers (Lindblom, 1963; Stevens and House, 1963) proposed that observed variations in articulatory positions may not imply similar variations at higher physiological levels, but that the articulatory positions may vary due to the mechanical constraints of the system and the timing relationships among control signals. Moll and Shriner (1967) used cinefluorographic films to investigate possible explanations for the observed variations in velar height with tongue height, which might be explained as different levels of activity corresponding to the palatal elevation necessary to preclude nasal coupling (House and Stevens, 1956). Moll and Shriner concluded (as did Lubker and Curtis, 1966, on the basis of EMG and cinefluorographic films), that a simple on-off theory of muscular activity will not suffice: while the velum does lower from its oral articulation level for nasal consonants it does not reach its rest level for such articulations. In light of this, they propose a minimum of two levels of muscular activity during speech; a lower level, corresponding to nasal articulation, in which the velum is raised slightly from its rest position;and a much higher level,which elevates the palate to a maximum height limited only by mechanical constraints on the system. The palatoglossus muscle, which inserts into both the tongue and velum, might, according to this theory, act to lower the velum from its maximum elevation for low vowels by resisting stretch. This theory, however, is based on observations of movement and not of muscle activity and, as the authors state, requires further observations of velar movements and velar muscle activity to test its validity. Lubker (1968)found a high correlation between velar position and velar EMG activity for vowels of different height, with greater velar height and EMG activity for the high vowel included in his study than for the low one. Lubker therefore found it necesary to modify the Moll-Shriner (1967) theory in light of these data, in which he found a greater force of contraction in phonetic contexts which have high oral cavity impedance in relation to the resistance to air flow of the velopharyngeal port. He concluded that greater effort may be required for production of high vowels to produce speech which is nonnasal in quality. Bzoch (1968) found that velar elevation varies with vowel height, a finding which confirms those of Moll (1962), Moll and Shriner (1967), and Lubker (1968). The range of differences in velar elevation which he reported, however, is in the range of his own reported errors of measurement. Fritzell (1969) confirmed the findings of Moll (1962), Lubker (1968) and Bzoch (1968), finding clear differences in velar height for different vowel heights, with greater velar height for high vowels than for low vowels. Minifie, Hixon, Kelsey and Woodhouse (1970), using pulsed ultrasound, monitored lateral pharyngeal wall movement in speech. They used three normal speakers who produced the six English stop consonants combined with five vowels. Lateral pharyngeal wall movement was greatest on low vowels, least on high vowels. Lateral wall movement during consonant production depended on vowel environment. Movements of up to 5 mm on one side were measured.

2a. Voicing and Velopharyngeal Variation: Phonological Theories

Variations in velopharyngeal activity as a function of consonantal environment have been reported in, or may be culled from, still other studies of this region.

A question of particular interest for this report is the relation between the voicing condition of oral consonants and pharyngeal activity.

In 1924, Rousselot postulated that the primary difference among the homorganic stops (for French) was one of tension in the peripheral articulators used for the gesture. Researchers looking for this tension difference have found it elusive (see above, Harris et al., 1962, 1965; Fromkin, 1966; Malécot, 1966a, 1966b; Lubker and Parris, 1970). By introducing pulses of air into the oral cavity and having subjects respond to varying degrees of intraoral air pressure thus produced (Malécot, 1966a) as well as to mechanical pressures applied to the lips, Malécot (1966b) determined that the difference limen for the externally applied mechanical pressure were nearly exactly those for the internally applied air pressure. When subjects are asked to describe minimal pairs of English utterances situated on the "tense-lax" continuum, they easily divided the sounds into tense (voiceless) and lax (voiced) categories. Malécot (1971), suggesting that the feature "tenseness" must have some reality since naive subjects so readily respond to it, believes that intraoral air pressure differences account for the distinction, but only indirectly. That is, the fortis-lenis (tense-lax) distinction is a synesthetic interpretation of the evident air pressure differences. In light of Lisker's (1970) data, however, this view needs modification: the shape of the function of pressure growth may be the cue for the tense-lax distinction.

In 1964(a), Lisker and Abramson recorded samples of twelve languages and measured the timing of voice onset (i.e., the onset of glottal pulsing) relative to the release of stop consonants occurring in word-initial position, and concluded that there are three major categories of voice-onset-time across languages: 1) voicing precedes stop release by approximately 50-75 msec; 2) voicing coincides with stop release; 3) voicing begins 30-100 msec after stop release. They concluded 1964(b) that:

> "...in general this feature of relative onset time serves very effectively as a means of separating stop categories quite independently of whether they are said to be distinguished solely by voicing or solely by aspiration or by a combination of the two features; the only categories clearly not distinguishable on this basis are the so-called voiced aspirates and voiced inaspirates of Hindi and Marathi." (pp. 390-391).

Further research (1967) has led them to conclude that it was context effects which caused the length of the "voicing lag" (the time from stop release to the onset of glottal pulsing) in English voiceless stops to vary, with the lag increasing as stress increases. When voiced stops occur in noninitial positions the glottal pulsing of the preceding environment tends to continue into the occlusion. In 1971, in response to a criticism that their data actually shows two degrees of voicing lag, the same authors stated:

> "We might then group together the Korean stop with moderate voicing lag and English /ptk/ as a type with first-degree aspiration; the voiceless aspirates in languages such as Cantonese would have second-degree aspiration; and third-degree aspiration would be exemplified by the very strongly aspirated stops found in Korean. Our data would then suggest at least five types of stops occupying different ranges of values along the dimension of voice onset timing." (p. 772)

Some contemporary phonologists believe that since minimal contrasts are binary distinctions (something is either x or y, either /pæt/ or /bæt/) then the features which describe phonological systems must also be binary (which the voice-onset-time dimension, for instance, is not). A fairly recent set of binary features said to distinguish among the stop consonants has been put forth by Chomsky and Halle (1968). They propose four features which, taken together, determine the timing of the onset of glottal pulsing:

1. Tense-Nontense: "...the differences between tense and lax consonants...involve a greater versus a lesser articulatory effort and duration. The greater effort is produced by greater muscular tension in the muscles controlling the shape of the vocal tract." p. 325.
2. Heightened subglottal pressure: "...it is usually observed that tense sounds are produced with greater subglottal pressure...this fact accounts for the well-known presence of aspiration in the tense voiceless stops of many languages... heightened subglottal pressure may be used without involving tenseness..." p. 326.

3. Voiced-Nonvoiced: "In order for the vocal cords to vibrate, it is necessary that air flow through them. If the air flow is of sufficient magnitude, voicing will set in, provided only that the vocal cords not be held as widely apart as they are in breathing or in whispering." p. 326-327.
4. Glottal Constriction: "Glottal constrictions are formed by narrowing the glottal aperture beyond its neutral position. Such constrictions may accompany many different types of supraglottal articulatory configurations. Glottal constrictions... commonly involve total closure. There are, however, instances where glottal constrictions of lesser degree occur." p. 315.

The feature [± tense] has been assigned by the authors to the pharyngeal cavity, on the basis of Perkell's (1969) cineradiographic study of the vocal tract, with less activity in the pharyngeal wall musculature for [-tense] phones than for [+ tense] phones, which would allow the pharyngeal walls to retract, enlarging the pharynx, thus decreasing supraglottal pressure, a requirement for the continuation of glottal pulsing during the stop occlusion.

2b. Voicing and Velopharyngeal Variation: Physiological Studies

The myoelastic-aerodynamic theory of voice production stipulates that glottal pulsing can occur when there is a transglottal pressure difference, a condition easily met when the vocal tract is not occluded, when supraglottal pressure is equal to atmospheric pressure and subglottal pressure is greater than atmospheric pressure. Once the vocal tract is occluded, however, pressure equalization will rapidly occur. In order to sustain pulsing it therefore becomes necessary to reduce the supraglottal pressure after occlusion has occurred. One way of achieving this pressure drop across the glottis is to enlarge the pharyngeal cavity.

Rothenberg (1968) has calculated possible pharyngeal enlargement volumes for each of the several different possible enlargement mechanisms. He suggests that the base of the tongue may be expected to move anteriorly 0.5 cm along an axial path (over a 6 cm length, 3 cm width), resulting in a 6.0 ml. enlargement. Lowering the larynx up to 0.5 cm (acting over an area of 4 cm^2) would result in a 2.0 ml increase in pharyngeal volume. Retraction of the lateral and posterior walls of the pharynx would add up to another 2.0 ml. The maximum possible expansion of the pharynx, then, would be about 10.0 ml. As each 1.0 ml will allow glottal pulsing to continue for an additional 10 msec, one arrives at a figure of 100 msec (for a 10.0 ml expansion) as the maximum possible duration of glottal pulsing during stop occlusion as a result of pharyngeal cavity expansion. Another possibility suggested by Rothenberg is that the velum is sufficiently depressed for voiced stops to allow nasal escape of air during stop closure.

Perkell (1969) presented data from frame-to-frame cinefluorographic films of one speaker for thirteen syllables of the form /hə'CV/, where seven dissyllables were of a subset of /hə'tV/, with V=/i/, /I/, /ɛ/, /æ/, /u/, /ʊ/,/ɑ/ and the remaining six were of a subset /hə'Cɛ/, with C = /d/, /s/, /z/, /n/, /k/, /p/. He reports that velar height is greatest for high vowels, although there is some deformation of the velum for the articulation of /u/ and /ʊ/, possibly caused by contraction of the palatoglossus (postulated to be active in pulling the tongue dorsally), but without affecting velar closure. Pharyngeal width (anteroposteriorly) is greater for high vowels than low vowels. Comparison of velar heights for the various consonants studied shows the velum to be lower throughout /hənɛ/ than for any other /hə'Cɛ/ utterances. Inspection of the movement curves during stop consonant occlusion, however, shows that velar height is greater during [d] occlusion than [t], showing a gradual rise through the period of occlusion.

Perkell also reports that pharynx width is greater for [d] than for [t] and that the larynx is lower for [d] than for [t], both of which are findings which fit Rothenberg's suggested patterns for pharyngeal enlargement for voiced stops.

Kent and Moll (1969) wished to determine whether English stop cognates differ in supraglottal characteristics, and performed many of the same measures as Perkell. They reported that velopharyngeal closure for voiceless stop consonants preceded by nasals begins earlier and is executed more rapidly than is the same gesture for voiced stop consonants in half of their samples; in the other half, no difference was seen between the stop cognates. When the stop preceded the nasal, they state that their results were contradictory across subjects. The authors report, also, that the supraglottal cavity is larger during voiced than during voiceless stops, with increased hyoid bone depression and tongue-pharynx width for the voiced stop. While Perkell assigns the increased pharynx width for voiced stops to a lower tension of the muscles comprising the pharyngeal walls, Kent and Moll feel that the enlarged pharynx must be due to the dynamic action of pharyngeal and/or extrinsic laryngeal musculature, acting to pull down the hyoid bone, pulling the mass of the tongue forward, increasing pharynx width. Inspection of Lubker's (1968) data reveals that velar height and electromyographic activity were of equal magnitude for, or were greater for, voiced stop consonants when they were contrasted with their voiceless cognates. The authors note that each of their three subjects had at least one voice break during the production of /g/.

Several studies have been conducted to determine whether there are electromyographic differences, mechanical pressure distinctions, or aerodynamic differences between voiced and voiceless stop cognates at the place of vocal tract occlusion. Harris et al. (1965), Fromkin (1966) and Lubker and Parris (1970) report finding no consistent difference in the EMG signal recorded from the orbicularis oris for the articulation of /p/ and /b/. Tatham and Morton (1969) have reported small but consistent differences in the same EMG signals, with /p/ activity being somewhat greater than /b/ activity.

Malécot (1966a) devised a pressure transducer designed to measure differences in labial pressure between /p/ and /b/, and found that naive subjects demonstrated no differences in that pressure. Similar results were reported by Lubker and Parris (1970). In addition to the mechanical pressure measurements, Malécot has reported (1955, 1966b, 1970) intraoral air pressure differences for the stop cognates with greater pressure for /p/ than /b/. Equivalent results have been reported by Arkebaur, Hixon and Hardy (1967), Netsell (1969) and Lubker and Parris (1970). Lisker (1970), however, has shown that peak intraoral air pressure is not sufficient for categorizing post-stress English stop cognates, as the peak pressures reached are quite similar. What is distinctive, however, is the function of the growth in pressure, with the pressure rise being nearly instantaneous after closure for the voiceless stops and being a step-function for the voiced stops (incrementing with each glottal pulse) up to the same pressure level achieved for the voiceless stops. Netsell (1969) has demonstrated negligible differences in subglottal pressure between English voiced and aspirated voiceless stops.

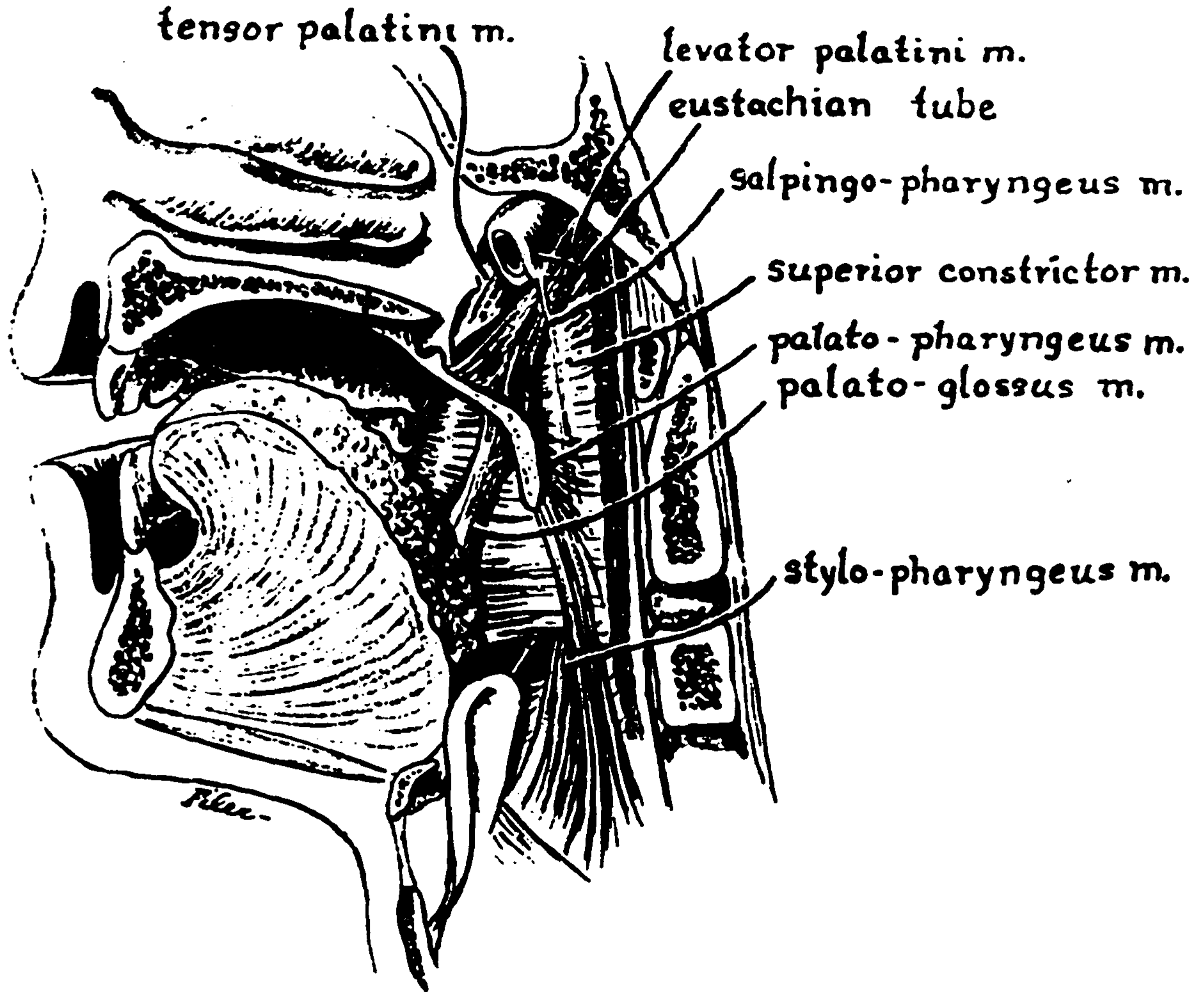
The Problem

A review of the existing literature on velopharyngeal function for oral and nasal as well as for phonetically varying articulations reveals that several problems require further clarification. The first of these involves the specification of function of all of the muscles of the velopharynx for oral articulation. The second problem, related to the first, is the specification of function of all of the muscles of the velopharynx for nasal articulation. That is, does any velopharyngeal muscle (e.g., the palatoglossus) depress the soft palate by increasing its activity? Existing data fail to satisfy either of these questions: no activity patterns for oral articulation have been specified for the middle pharyngeal constrictor or the palatopharyngeus. The data offered in support of the argument that the palatoglossus acts to depress the velum are far from convincing. Finally, there is, as yet, no thorough description of velopharyngeal muscle activity which accounts for the pharyngeal cavity volume increase observed during voiced stop consonant occlusion. The study which follows is an attempt to gain information on these questions concerning velopharyngeal physiology.

FOOTNOTES

1. In addition to the muscles whose activity patterns are described below, Fritzell also recorded from the tensor veli palatini. His results, which confirm those of Rich (1920) and of Wardill and Whillis (1936) but contradict those of Bloomer (1959), indicate that the tensor is not functional for speech. Recording from the tensor also raises technical problems concerning the location for electrode insertion, as the tensor has no muscular portion within the soft palate (Hollinshead, 1954; Dickson and Maue, 1970).

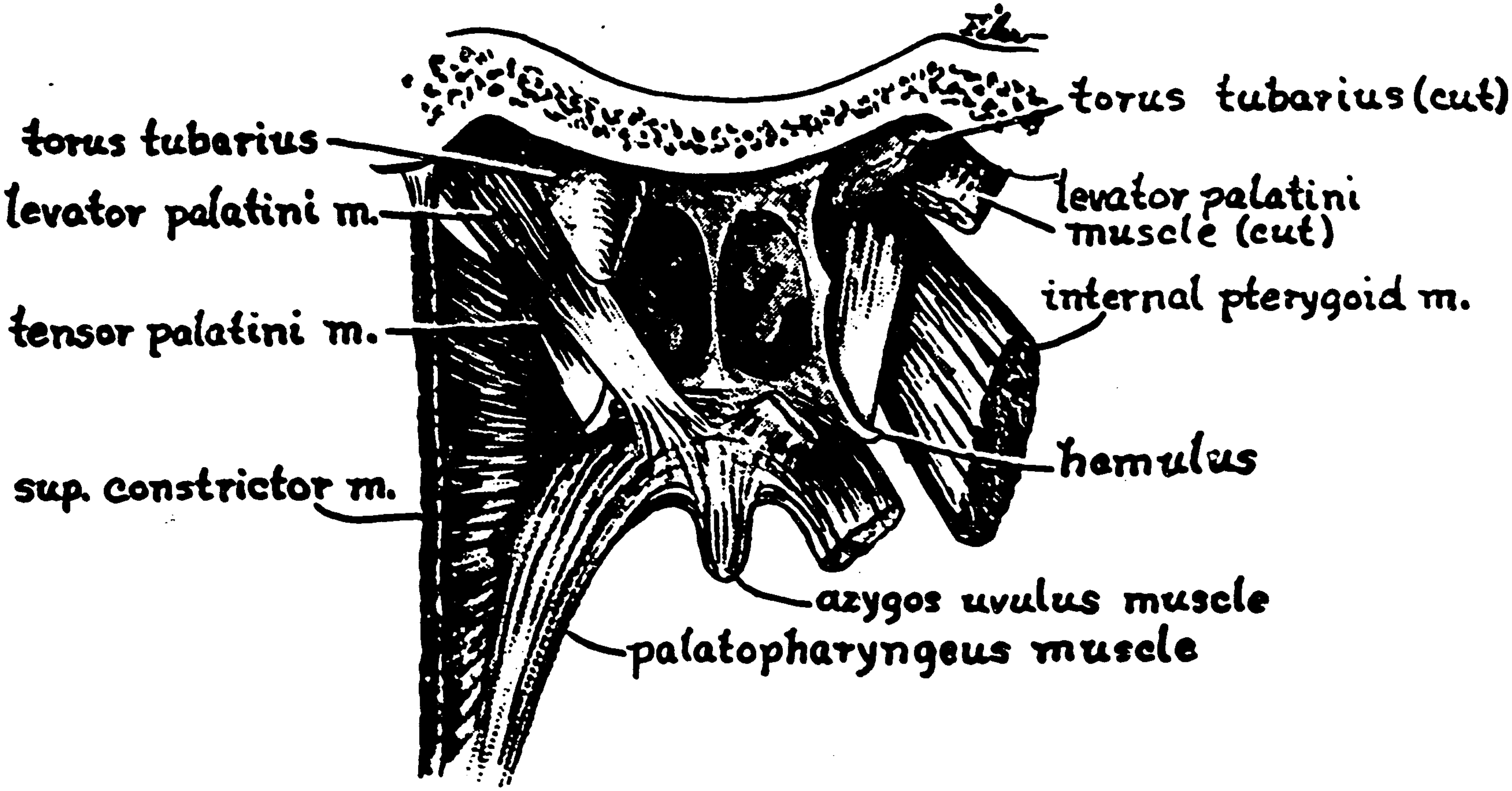
2. The Dixit and MacNeilage (1972) study involved only indirect measures of velopharyngeal closure: electromyographic recordings and acoustic recordings obtained with a nasal microphone. The Moll and Daniloff (1971) study involved direct measures of velar position. It is possible that the dimensions of velopharyngeal port size obtained by Moll and Daniloff would not have been sufficient to allow nasal coupling for /l/ and /w/, and, hence, would not have been detected by the probe used by Dixit and MacNeilage, although complete closure need not have occurred.



Mid-sagittal Section of Head (dissected)

Figure 1

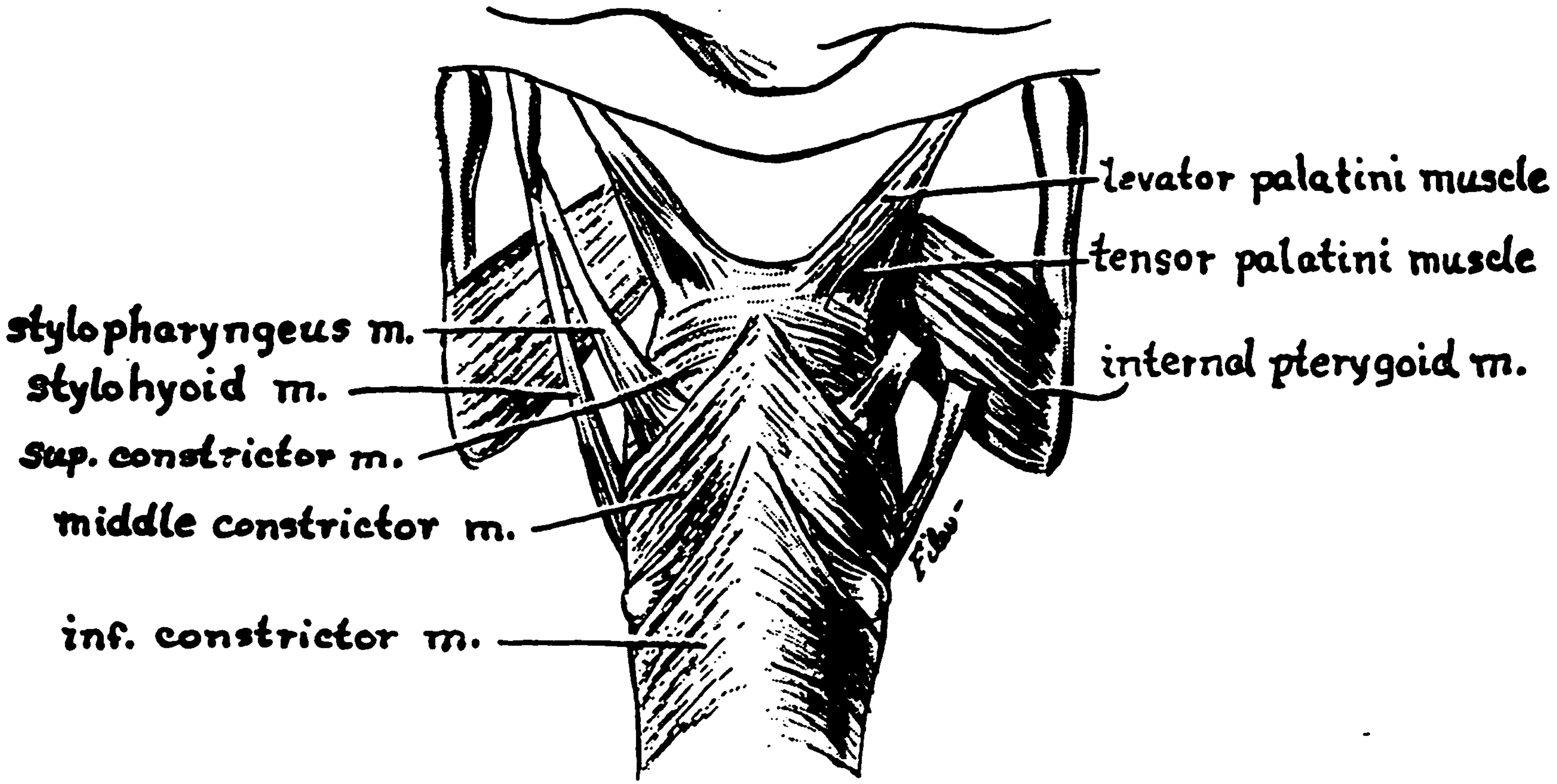
From Dickson, David Ross and Wilma K. Maue, HUMAN VOCAL ANATOMY, 1970.
Courtesy of Charles C Thomas, Publisher, Springfield, Illinois.



posterior view – dissected
Palatopharyngeal Muscles

Figure 2

From Dickson, David Ross and Wilma K. Maue, HUMAN VOCAL ANATOMY, 1970.
Courtesy of Charles C Thomas, Publisher, Springfield, Illinois.

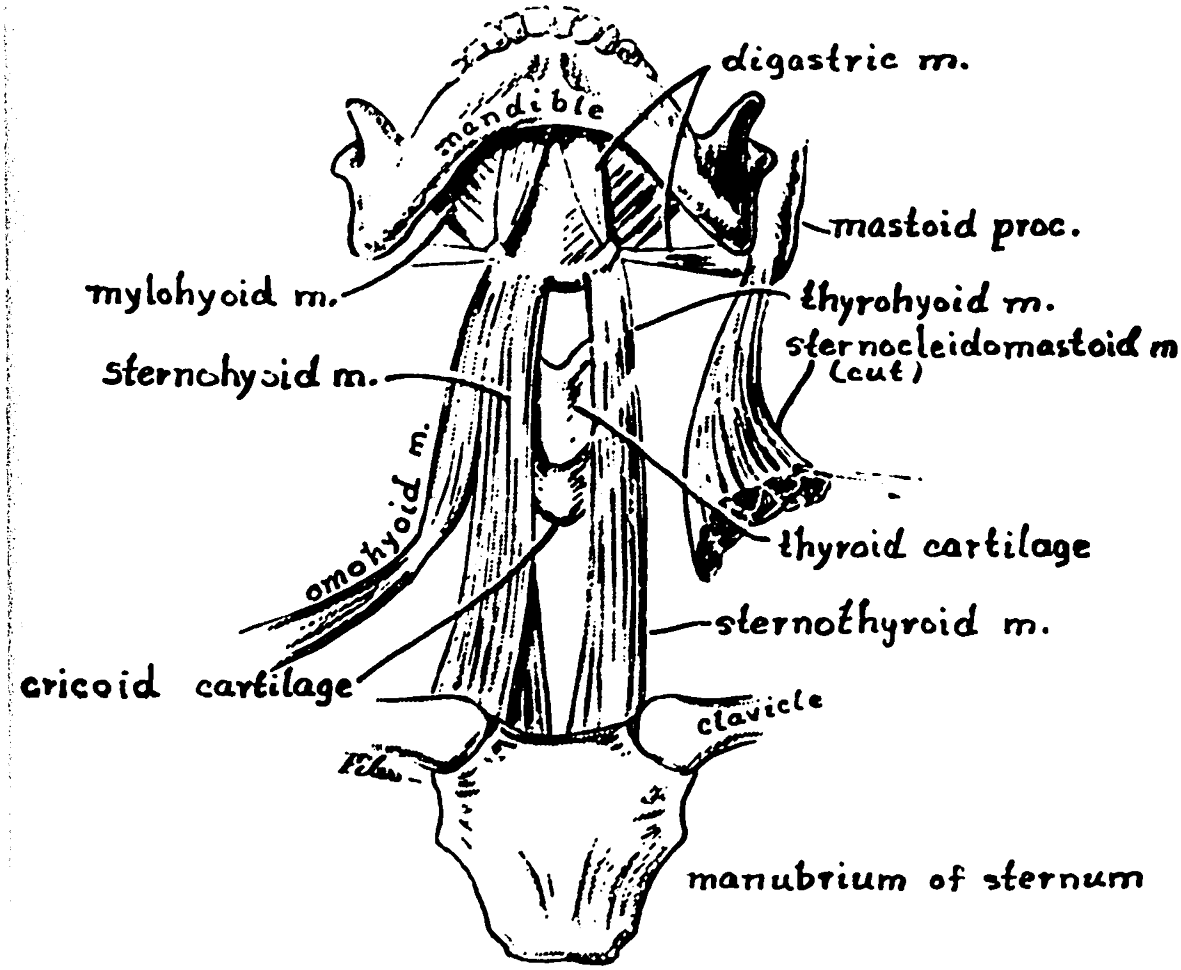


posterior view (dissected)

Palatopharyngeal Muscles

Figure 3

From Dickson, David Ross and Wilma K. Maue, HUMAN VOCAL ANATOMY, 1970.
Courtesy of Charles C Thomas, Publisher, Springfield, Illinois.



anterior view
Extrinsic Muscles of the Larynx

Figure 4

From Dickson, David Ross and Wilma K. Maue, HUMAN VOCAL ANATOMY, 1970.
Courtesy of Charles C Thomas, Publisher, Springfield, Illinois.

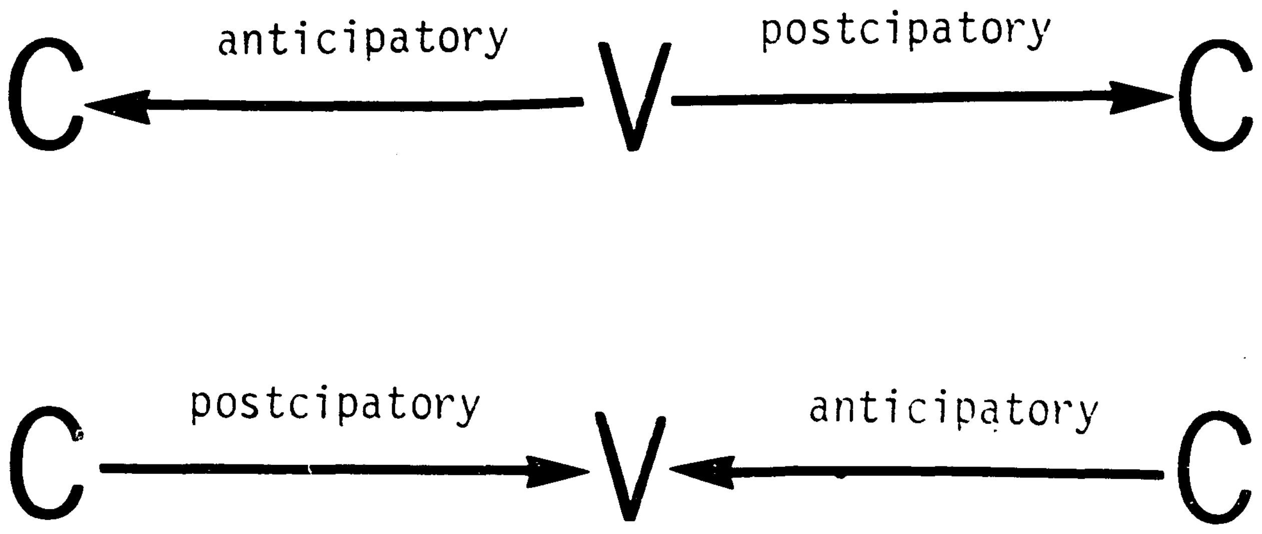


Figure 5

The arrow points in the direction of the coarticulation effect.

Chapter II: Methods and Instrumentation

The Electrodes

The electrodes and the insertion techniques employed were those described in Hirose (1971).

Electrode Preparation

Hooked-wire electrodes were used exclusively. The wire employed is a platinum-iridium alloy (90%-10%) with an Isonel (polyester) coating. The wire is of 0.002 inch diameter (Consolidated Reactive Metals, P-91). This alloy was chosen for these experiments since no chemical reaction was expected between the alloy and human tissues, and because the wire has good physical properties--it has less spring than stainless steel and is less easily crimped than copper. The electrodes were prepared in essentially the same manner as was described by Hirano and Ohala (1969) and Basmajian and Stecko (1962). In Hirose's procedure, the free ends of a length of wire sufficiently long to serve as a pair of electrodes (50-60 cm for percutaneous insertions, 80-90 cm for peroral insertions) are threaded through a hypodermic needle (26 or 27 gauge, 3/4 in. to 2 in. long) and pulled through the needle until only a small loop of wire remains at the tip of the needle. This loop is bent over the tip of the needle and cut with a razor blade, leaving two short hooks 1-2 mm in length at the tip of the needle. The loop is cut so that the two hooks are of different lengths to prevent, as far as possible, short-circuiting caused by contact of the two cut ends of the wire within the muscle. The free ends of the wire are burned in a match flame to remove the polyester insulation so that the wires may be connected to the preamplifiers of the EMG recording system. The shafts of the hypodermic needles are angulated for peroral insertions to the velopharyngeal musculature, to allow easier access to the target muscles. The needle and the wire electrodes are sterilized, prior to insertion, by high-pressure steam or antiseptic solution.

Subject Preparation

To inhibit salivation seven to ten drops of tincture of Belladonna were administered by mouth to each subject before the experimental session. A topical anesthetic, Cetacaine[1] spray was administered to the pharynx of the subject before electrode insertion. This was followed by a gargle of 2-3 ml of 2% Xylocaine[2], after which the pharynx was, if necessary, swabbed with additional Xylocaine. For percutaneous insertions the skin was disinfected, at the insertion site, with an alcohol swab. Topical administration of 2% Xylocaine through a Panjet-70 air jet (Panray)[3] at the site of the needle insertion preceded percutaneous insertions. A ground electrode (a gold earring) was attached to the left ear lobe of the subject. An oscilloscope and amplifier-speaker system were used for monitoring pertinent muscle activity during electrode insertion. After insertion into the appropriate site the electrode-bearing needle was withdrawn, leaving the electrodes hooked in the target muscle. Regardless of the position assumed by the subjects for electrode insertion and verification of placement, all data recordings were made with the subjects sitting in an upright position. Optional oscillographic monitoring of EMG recording channels was provided throughout the experimental session.

Insertions and Placement Verification

Insertions to velopharyngeal muscles were always peroral, made with an angulated needle, and with the subject in a sitting position. A pair of alligator forceps were used to hold the electrode-bearing needles. Insertions to the sternohyoid, one of the strap muscles of the neck, were percutaneous and were made with straight electrode-bearing needles.

1. levator palatini

The insertion was made into the levator "dimple" on the soft palate while the subject sustained open vowel phonation. The tip of the needle was directed latero-cranio-posteriorly approximately 10 mm from the surface of the mucosa. Verification of electrode placement was made by having the subject repeat the production of /s/. Marked activity is observed for this strong oral gesture if the electrodes are properly placed.

2. superior constrictor

The tip of an angulated electrode-bearing needle was directed cranially to reach the posterior pharyngeal wall at a position lateral to the midline at the estimated level of velopharyngeal closure. As the insertion was made under direct inspection, placement was verified if EMG activity was observed for swallowing.

3. middle constrictor

The insertion was made using an angulated needle directed caudally into the posterior pharyngeal wall near the level of the tip of the epiglottis, while the subject's tongue was protruded and held for improved visualization of the insertion site. As the pharyngeal constrictor muscles are interlayered in the transition from one to another, precise discrimination of the superior and middle constrictor fibers is, at best, difficult. We examined, under the name "middle constrictor," a topographical representation of the pharyngeal constrictor at the anatomical site described. Electrode placement was again verified if EMG activity was observed for swallowing.

4. palatoglossus

The palatoglossus was reached by inserting an angulated needle cranio-caudally or caudo-cranially into the anterior faucal pillar. As the insertion was made under direct inspection, placement was verified if marked EMG activity was observed for swallowing.

5. palatopharyngeus

We regarded the palatopharyngeus as the muscular portion of the posterior faucal pillar. The palatopharyngeus was reached by inserting an angulated needle cranio-caudally into the posterior faucal pillar. As the insertion was made under direct observation, placement was verified if EMG activity was observed during swallowing.

6. sternohyoid

When a subject in supine position is asked to raise his head from the head-rest, with his head kept extended, the sternohyoid may be palpated or even seen through the skin (unless the subject has a very short, fat neck). The insertion is made at the level of the thyroid lamina, where the contour of the sternohyoid is usually clear. At this level, also, possible contamination by other muscles is kept to a minimum. The needle was inserted lateral to the midline, parallel to the alignment of the muscle fibers, as the subject raised his head while in a supine position. The placement of the electrode was verified if strong EMG activity was observed while the subject raised his head from the supine position, opened his jaw, or produced very low-frequency phonation.

Oral and Nasal Articulation Stimuli

Nonsense disyllables were constructed to place maximum stress on the mechanisms of oral and nasal articulation (Appendix). The utterances were also designed to investigate the effect of place of articulation of both oral and nasal phonemes on velopharyngeal mechanisms. Another consideration in the design of the utterances was our interest in describing any pharyngeal cavity adjustments accompanying nonnasal phonetic variations, including both vowel color and stop consonant voicing conditions. The disyllables were designed to fill each of these requirements.

The stimuli included two subsets of utterances, the first containing a stop-nasal consonant contrast, the second containing a nasal-stop consonant contrast. The stop-nasal contrasts were expected to place maximum stress on the mechanism of nasal articulation because the nasal would follow a very strongly oral articulation. Conversely, the nasal-stop contrasts were expected to place maximum stress on the mechanism of oral articulation, with a very strongly oral gesture following a nasal one.

Both labial and velar nasal consonants were employed, the former occurring in both stop-nasal and nasal-stop contrasts while the latter occurred only in nasal-stop contrasts in which the nasal followed a vowel(/ŋ/ may occur only in syllable final position in English). All six English stop consonants were employed, providing two conditions of voicing and three places of articulation. Another consideration in constructing the stimulus set was the effect of vowel environment on oral-nasal articulation and the allophonic variants of stop consonants. To this end, three vowels were included in the stimulus set, /i/, /u/, and /ɑ/. The same vowel appears in both the first and second syllables of any given disyllable to equalize any coarticulation effects which might confuse the results. Each stop consonant was paired with each possible nasal consonant for both the stop-nasal (or oral-nasal) and nasal-stop (nasal-oral) contrasts. In addition, each stop and nasal combination was paired with each possible vowel. The result was eighteen utterance types in the oral-nasal subset and thirty-six utterance types in the nasal-stop subset (which included /ŋ/-stop contrasts).

In electromyographic investigations it is not advisable to inspect the EMG potentials of the utterance initial gesture as its timing and magnitude may both be affected by a readying of the articulators well before speech begins. Thus, as we wished to study velopharyngeal activity for vowels, the utterance format had to include an additional phoneme before the vowel under study. The labial consonant /f/ was selected to give all the utterances an initial oral articulation which did not involve lingual articulation, and so did not create any postcipatory coarticulation effects in the following vowel. In order to control the length of the final vowel, and to insure a terminal oral articulation, all of the utterances terminated with /p/, again a labial consonant to avoid lingual coarticulation effects (anticipatory, in this instance). The initial and final consonants were voiceless to facilitate the identification of the vowel onset and termination from an oscillographic record of the speech waveform, which was used to obtain the measurements of segment duration which appear on the data displays below.

An additional set of stimuli (Appendix) were specifically designed to investigate the temporal relationships among EMG signals for one of the muscles in this study (the sternohyoid) for voiced and voiceless stop consonant articulation. These stimuli do not contain contrastive medial consonant clusters. Rather, they have either a bilabial voiceless or voiced stop or nasal consonant in medial position.

The fifty-four stop-nasal and nasal-stop stimuli were divided into two groups, each with twenty-seven utterances, to correspond to the data processing programs which provide for the processing of up to thirty tokens each of thirty utterance types (Port, 1971). Four randomizations of each of these two groups of stimuli were prepared. The nine noncontrastive stimuli were included in four randomizations of an additional group of CVC utterances which were recorded for another experiment. Each group of four random lists was read four times by each subject, providing sixteen repetitions of each utterance type for the subsequent analysis.

Data Collection and Processing

The Record-Playback System

The data were collected and processed using the Haskins Laboratories EMG system (Figure 6) described by Port (1971). The electrodes are connected to differential preamplifiers with gains of 40 db. The signals are then fed to distribution amplifiers which have adjustable gains and include 80 Hz high-pass filters, with 24 db roll-off; the low frequency filtering is intended to reject hum and movement artifacts. The signals are FM recorded on one-inch magnetic tape using a Consolidated Electrodynamics VR-3300 14-channel instrumentation recorder. The acoustic signal and clock and code pulses are recorded as AM signals. A 300 microvolt (μV) calibration signal (± 1%) appears on the tape periodically. This calibration signal is used in converting the electromyographic signals into microvolts. A clock track, a 3200 Hz pulse train, is used to synchronize the tape recording and data processing. Code pulses occur every 20 msec (or with a frequency of 50 Hz), some pulses being inverted in polarity or cancelled to generate a four-digit octal code which is automatically incremented at a rate of one code per second. These codes may be read by the experimenter from an oscillographic record of the code track and by the computer from a separate channel of the tape recording.

The recorded signals are played back through the distribution amplifiers and routed through a section of the 80 Hz high-pass filter, resulting in 36 db total roll-off. The overall frequency response of the system is 80-1250 Hz. The FM channels have a signal-to-noise ratio of about 40 db.

The electromyographic, voice and code tracks are the inputs to an eighteen-channel Honeywell Visicorder, whose oscillographic records are used by the experimenter for visual editing of the signals. The EMG signals are inspected for nonphysiological spike potentials (short-circuits, for example). A point in the audio signal was selected for lining up the utterances for computer sampling and averaging. This point was the beginning of the acoustic signal for /m/ in the stop-nasal contrast stimuli, the end of the acoustic signal for /m/ and /ŋ/ in the nasal-stop contrast stimuli, and the end of the acoustic signal for the first vowel in stimuli having no contrastive medial consonant clusters. The audio trace and the code and timing markers were used to identify each utterance with a preceding octal code number. The temporal offset between the octal code and the chosen line-up point was measured to the nearest 5 msec (one-quarter of a timing interval) using the timing pulses which occurred every 20 msec. Lists were prepared of the octal codes identifying each utterance type and of their respective line-up point offsets. The remaining manual task is that of entering these lists of control information into the computer, including a specification of the number of timing markers to be sampled before and after the "zero" or line-up point.

The EMG data tape is played back on the Consolidated Electronics VR-3300 14-channel tape recorder which is under computer control. Analog EMG signals are full-wave rectified and passed through an RC circuit which performs a running integration with a time constant of 25 msec. The signals are sampled at 5 msec intervals with 12-bit precision, using a 16-channel multiplexer driven by a clock internal to the computer, consistent with the recorded clock track (3200 Hz) to within 1%. Since the playback signal-to-noise ratio is 40 db, only the seven most significant bits, of the twelve delivered by the analog-to-digital converter, are used in the subsequent averaging. (An increment of one bit in signal amplitude is equal to 6 db, so that an increment of seven bits is equal to 42 db.) The stored digital sample values are converted to microvolt values by comparison with a 300 μV calibration signal. The conversion factors are calculated and stored on the digital tape along with the control data and the digital sample values for the experiment. The sums and sums of squares for each utterance type are computed and stored on magnetic tape. The means and standard deviations divided by the means are calculated and printed out for the 5 msec intervals at which the analog data were sampled.

The Programs

The data processing programs (Port, 1971) provided for an experimental size of up to thirty tokens each of thirty utterance types. The maximum sample duration for any token is two seconds. As many as eight channels of electromyographic data may be processed for any thirty utterance-type experiment. The sampling and averaging programs, which use magnetic tape storage and up to three data disc units and one monitor system disc unit, provide for sampling of all eight channels of data for all utterance tokens included in one experiment on one pass of the EMG data tape. The fifty-four stop-nasal and nasal-stop utterances were divided into two groups of twenty-seven utterance types each in order to conform to the maximum experiment size of thirty utterance types imposed by the data processing programs. The nine stimulus types which do not have contrastive medial consonant clusters were included in an additional set of CVC utterances recorded for another experiment.

The data are measured, averaged, and plotted, by the computer, using several programs which each do a part of the processing job.

ESEL:	The control information is entered and stored in memory and on magnetic tape. The individual utterance-type lists are merged, so that the order of the entries corresponds to the order of the individual tokens on the EMG data tape. It is also with this program that the channels to be sampled and the number of sample points before and after the line-up point are specified.
ECHK:	This program is used to check the control information and to set the input analog levels. A print-out of the maximum digital value for each token of each utterance type is available and inspection of these values for a given utterance type allows detection of obvious line-up errors.

ERIT:	This program samples, digitizes, and stores the EMG data in one pass of the original data tape.
E$MGSUMS:	This program sorts and averages the digitized EMG samples and prints the averages, sample point by sample point, for each utterance type, on a line printer.
E$MGPAGE:	This program permits inspection of the sample curves of each token of each utterance type, to check for errors in line-up identification and the presence of nonphysiological spike potentials. The individual tokens are compared with the averaged curve on a Tektronix storage scope. Scale values (in microvolts) may be set for each channel.
E$MGPLOT:	This program produces a hard-copy output of the averaged EMG curves, channel-by-channel and utterance-by-utterance, on a strip chart recorder.
E$MGDISP:	This program permits inspection and comparison of the averaged EMG curves for up to eight data channels for twelve experiments of thirty utterance types each, allowing inter-comparison of all data for this experiment. The EMG curves are displayed on a Tektronix storage scope. The curves are displayed with their line-up, or zero, points aligned. Scale values may be set for each channel each time that channel is selected.

Subjects

Four volunteer subjects were used in this study, each a native speaker of American English. Data for one of the four original subjects will not be considered as they are sketchy at best. This subject did not adapt well to the experimental procedure, and was troubled by both a strong gag reflex and a persistent cough. He was unable to refrain from touching his face and mouth and, in so doing dislodged three of the six electrode pairs, which precluded processing of the data collected from the muscles involved. We felt that this subject would probably not tolerate the experimental conditions with any greater ease on subsequent dates and so he was abandoned as a source of information on the nature of the velopharyngeal mechanism. The remaining three subjects each spoke a different dialect of American English, a fact dictated by experimental convenience and not experimenter choice.

Each of the final three subjects served twice, with the two experimental sessions for each subject separated by six months to one year. The result was a total of six experimental sessions. At the first session for two of the subjects an attempt was made to record from each muscle included in the experiment. For the third subject, the middle constrictor was omitted because of a limitation in available EMG channels at that session. The second experimental session was used to obtain satisfactory recordings from muscles whose earlier data were unsatisfactory, and then to duplicate data from as many muscles as there were remaining recording channels. Table 1 presents an evaluation of each attempted recording for each subject at each experimental session.

The peak value from a given channel depends on the total number of firing fibers, and on the distance of the electrode tips from the active units. In general, if the peak value from a given channel is high, the recording is of high quality. Channels with lower peak values are more likely to show noisy data. However, since there are differences in the peak values to be expected from insertions into different muscles, "high" and "low" must be redefined for each muscle, so that low absolute peak values do not necessarily mean a recording of poor quality.

FOOTNOTES

1. Cetacaine (trade name) is packaged in a 50 ml aerosol bottle and contains the following: ethyl aminobenzoate, 14%; butylaminobenzoate, 2%; benzalkonium chloride, 0.5%; cetyldimethylethyl ammonium bromide, 0.005%. A one-second spray releases 0.1 ml of solution, and usually three to four seconds of spray are needed to anesthetize the oral and pharyngeal mucosa. (Gaskil and Gillies, 1966).

2. Recent studies (Shipp, 1968; Zemlin, 1969) revealed no discernible effect of topical anesthesia on normal laryngeal behavior.

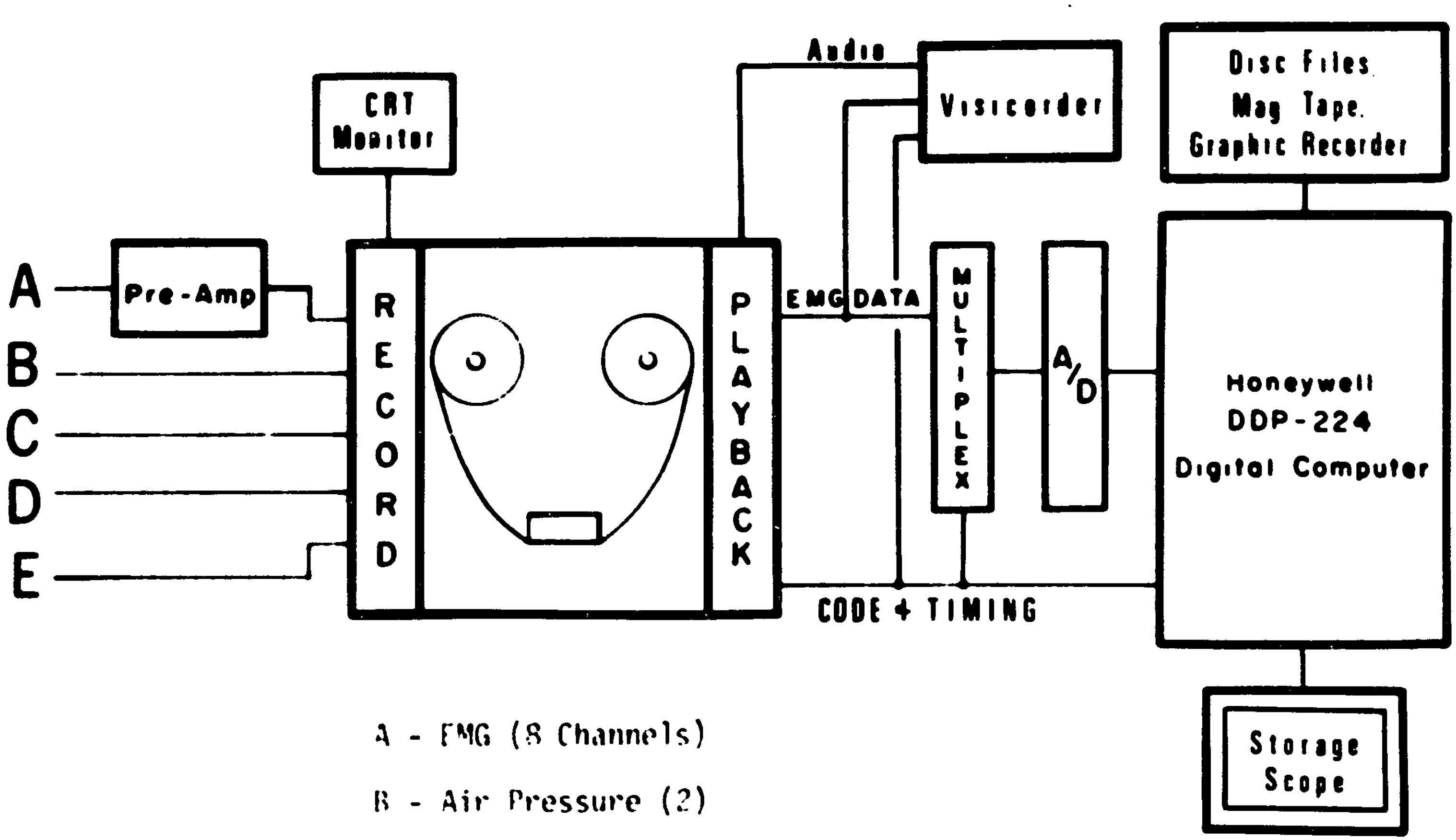
3. Panjet-70 delivers approximately 0.1 ml of the anesthetic solution to a circumscribed intradermal depth up to 6 mm penetration.

Table 1

Evaluation of acceptability of EMG recordings, with maximum peak values in microvolts.

Subject	FBB		KSH		LJR	
Session	I	II	I	II	I	II
Date	30 Dec.1970	6 Dec.1971	5 April 1971	10 Feb.1972	25 June 1971	16 Dec. 1971
levator palatini	√ (337)	√ * (660)	√ * (407)	x (86)	√ * (528)	x (86)
superior constrictor	√ * (276)	x (71)	x (26)	√ * (53)	√ (107)	√ * (41)
middle constrictor		√ * (132)	x (118)	√ * (43)	x (96)	√ * (49)
palato-glossus	√ (79)	√ * (117)	x (25)	√ * (83)	x (11)	√ * (41)
palato-pharyngeus	x (56)	√ * (170)	√ * (91)		√ (360)	√ * (197)
sterno-hyoid	√ (216)	√ * (140)	√ (91)	√ * (154)	√ (454)	√ * (112)

√ : good quality
x : poor quality
blank: this placement not attempted
* recording used for figures and tables



A - EMG (8 Channels)

B - Air Pressure (2)

C - Voice

D - Banter

E - Digital Code & Timing

Figure 6

Chapter III: Results

Preliminary

Concerning the oral-nasal contrast it was remarked in Chapter I that there is some question which muscles participate actively in velopharyngeal closure and whether any muscle participates actively in velopharyngeal opening. The data of this study speak to these questions since we may identify as muscles of velopharyngeal closure those that display greater EMG potentials for oral articulation than for nasal, and as muscles of velopharyngeal opening those that display greater EMG potentials for nasal articulation than for oral. The present data also bear on vowel color and stop consonant voicing, because these phonetic variations are associated with variations in the volume of the pharyngeal cavity (Perkell, 1969; Kent and Moll, 1969). This volume is increased by contraction of the palatal muscles, decreased by contraction of the muscles of the pharyngeal walls. Since greatest palatal height and transverse pharyngeal diameter occur for high vowels, smallest palatal height and transverse pharyngeal diameter for low vowels, greater activity is to be expected in the palatal muscles, less in the muscles of the pharyngeal walls for /i/ or /u/ than for /ɑ/. Since, furthermore the largest pharyngeal cavity size occurs for /i/ (Perkell, 1969), muscle potentials from the pharyngeal wall muscles should be smallest for /i/. Similarly, if voiced stop consonants are associated with an increase in volume of the pharyngeal cavity (see page 26), we should observe greater activity in the levator palatini and the sternohyoid, and less activity in the lateral and posterior pharyngeal wall musculature, for these elements than for their voiceless cognates.

No detailed expectations may be stated concerning variations in velopharyngeal muscle function with variations in the place of stop consonant articulation. However there are general grounds for expecting palatoglossus activity to be implicated in velar articulations.

Data are available from all three subjects for each of the six selected muscles for each utterance type. Data were recorded from each subject on two days, at least six months apart. We tried to record from all six muscles at both sessions. We were not successful in this, but we did obtain at least one reasonably good recording from each muscle for each subject in at least one of the two sessions. The data presented below for each subject therefore represent two different recording sessions. The patterns (though not, of course, the observed levels) of EMG activity remained reasonably constant within a subject over the two sessions (see, for example, Figures 7, 8, 9).

Segment durations for the vowels and the nasal and medial stop consonants were measured from an oscillographic record of the speech waveform. Beneath each set of EMG data curves (Figures 10 to 79)[1] is a record of the segment durations for the utterances having the vowel /i/. This record represents an average of the vowel, nasal and medial stop durations. That is, segment durations were averaged for minimal pairs differing only in the place of stop consonant articulation. One record, Figure 10 for example, contains the averaged first vowel, voiceless stop, nasal and second vowel durations for /fipmip/, /fitmip/, /fikmip/. The solid bars at the bottom of each figure represent the /i/ segments. The dotted bars represent the nasal segments. The blank spaces represent the medial stop segments. Average segment durations for stimuli containing each of the three vowels included in this study are found in Table 2. The V_1 rows show durations of the first syllable vowels. The V_2 rows show durations of the second syllable vowels. Durations for voiceless and voiced stop consonants are found in the C_{vl} and C_{vd} rows, respectively. The durations of the nasal segments are found in the /m/ and /ŋ/ rows.

Oral-Nasal Articulation

Levator Palatini

Inspection of the averaged EMG potentials recorded from the levator palatini muscles of each of the three subjects in this study reveals a peak of activity associated with the articulation of the initial consonant (/f/) of each utterance, occurring in the region of -600 to -500 msec (Figures 10-18). Vowels occurring in oral environments, that is in the first syllable of stop-nasal contrast utterances and in the second syllable of nasal-stop contrast utterances, generally show lower EMG potentials than do their neighboring oral consonants. Further inspection of the data reveals two basic patterns, one for the eighteen stop-nasal contrast utterances (e.g., /fipmip/) another for the thirty-six nasal-stop contrast utterances (e.g., /fimpip/).

In the stop-nasal contrasts a peak of activity corresponding to stop consonant articulation between -200 and -150 msec. This burst of activity is followed by suppression of levator palatini activity, which reaches a minimum at 0 msec, the point corresponding to the onset of nasal consonant articulation. There is a subsequent increase in levator activity in all utterances, although the point of onset of the increase varies with the height of the vowel following the nasal consonant: the increased activity begins earlier for the high vowels /i/ and /u/ than for the low vowel /ɑ/. All of the averaged EMG curves reach their terminal baseline level between +400 and +500 msec. Place of articulation does not appear to have any systematic effect upon the peak height achieved for oral stop consonant articulation.

In utterances of the nasal-stop contrast type the initial peak at -500 msec is followed by a steady decline in EMG activity level, whose minimum point varies slightly, across the three subjects, from -200 msec to -100 msec. This minimum is followed by a steep increase in potential which reaches a maximum peak value at 0 msec, corresponding to the end of nasal consonant articulation (or, alternatively, to the beginning of stop closure for the medial stop consonant). The timing of the levator palatini suppression and subsequent activity burst is unaffected by the place of articulation of either the nasal (bilabial or velar) or the stop (bilabial, alveolar, or velar) consonant.

The peak activity levels associated with the medial stop consonants vary systematically with the direction of the nasal and stop consonant contrast. Peak activity for stop consonants preceding nasal consonants (e.g., /fɑpmɑp/) is lower than peak activity for stop consonants immediately following nasal consonants (e.g., /fɑmpɑp/). This result can be shown clearly by tabulating peak height, subject by subject. Each of the six stop consonants in this study occurs in each of three vowel environments. Each stop also participates in both a stop-nasal and a nasal-stop articulation contrast. The latter condition is twice as frequent as the former because two different nasal segments (/m/ and /ŋ/) precede each stop-vowel condition. Comparing peak heights for each stop in the nasal-stop contrast with the peak height for its minimal stop-nasal contrast pair results in 36 possible comparisons for each subject. Table 3 displays these comparisons and permits us to determine how many of them reveal higher potentials for stop consonants in the nasal-stop condition than for stop consonants in the stop-nasal condition. For subject FBB, 35 go in this direction, for subject KSH 36, and for subject LJR 32.

The finding of greater peak EMG potentials for stops which follow nasals than for stops preceding nasals transcends the place of the stop consonant occlusion. If one compares all voiceless stop consonant peaks in stop-nasal contrasts, in each vowel environment for each subject, with all voiceless stop consonant peaks in nasal-stop contrasts, 54 comparisons are possible for each subject. An additional 54 comparisons are available for each subject if all voiced stop peaks are similarly compared. In total, then, 108 comparisons are possible for each subject or 324 comparisons for the three subjects. The comparison succeeds (that is, the stop-nasal peak is less than the nasal-stop peak) in 306 of the 324 comparisons. All 18 failures occur in the environment of back vowels: 12 in the environment of /ɑ/, six in the environment of /u/ (Table 4).[2]

Inspecting the data curves for utterances without contrastive medial consonant clusters one sees that, in every case, the EMG potentials are higher for the medial oral consonants than for the nasal consonants (Figures 19, 20, 21).

Superior Constrictor

Recordings from the superior constrictor were of generally low amplitude for two subjects, KSH and LJR, and failed to reach a maximum peak value of 100 μV. Both these subjects showed peaks of activity corresponding to oral consonant production. The third subject, FBB, produced peak values of better than 250 μV and shows activity corresponding to vowel articulation for both directions of stop-nasal contrast.

For subject LJR (Figures 27, 28, 29) small peaks of activity corresponding to stop consonant articulation appear in stop-nasal contrast utterances between -200 and -100 msec. Similar small peaks may be seen in nasal-stop contrast utterances at 0 msec. Subject KSH (Figures 24, 25, 26) presents peaks at +300 msec in stop-nasal contrast utterances, apparently corresponding to terminal stop consonant articulation. In nasal-stop contrast utterances, she presents two peaks of activity, one at 0 msec, the other at +250 msec, both apparently corresponding to stop consonant articulation. Subject FBB (Figures 22 and 23) presents two peaks for each utterance type, one for each syllable. Her curves separate according to vowel color: the peaks are largest for /ɑ/ and smallest for /u/, with the /i/ curve parallel to, but smaller than the /ɑ/ curve (Table 5). This separation is not found for KSH (Table 6) or LJR (Table 7). A few small peaks of superior constrictor activity may be seen in the data curves for subject FBB for stop consonants in the vowel environment /u/ (/fupmup/, /fubmup/, /fumpup/, /fumbup/, /fumtup/, and /fumdup/).

When utterances lacked contrasting medial consonants, subject LJR (Figure 32) showed small peaks of activity near 0 msec (the end of the first vowel as determined from an oscillographic record of the acoustic signal). These peaks are apparently related to stop consonant articulation, since they are absent in utterances with medial nasal consonants. Similarly, subject KSH (Figure 31) shows activity near 0 msec for utterances containing oral stop consonants in the medial position, no medial activity for utterances containing medial nasal consonants and a rise for the final stop consonant. Subject FBB (Figure 30) again shows activity of each syllable nucleus with suppression of activity in the vicinity of 0 msec.

Middle Constrictor

The EMG recordings obtained from middle constrictor electrode placements parallel those obtained from the superior constrictor placements. All three subjects gave recordings of generally low amplitude, with a maximum peak of 132 μV. Again, two subjects, KSH and LJR, show peaks of activity for oral consonants, while the third subject, FBB, shows activity for vowels.

Although poor recordings were obtained from the middle constrictor for subject KSH, small peaks of activity may be observed in both stop-nasal and nasal-stop contrast utterances between -500 and -400 msec and near +250 msec, apparently corresponding to initial and final oral consonant production (/f/ and /p/) (Figures 36, 37, 38). Small peaks for medial oral stop consonant articulation may be found near -100 msec in those stop-nasal contrast utterances having voiceless stop consonants. Very small peaks occur for the voiced cognate utterances at 0 msec. These peaks do not seem to be associated with the oral consonant production; their articulatory correlate is unknown. Occasional small peaks are found in nasal-stop contrast utterances around -100 msec and for stop articulation in those stimuli without contrastive medial consonant clusters (Figure 43).

Recordings from the middle constrictor for subject LJR, although of small magnitude, reveal activity corresponding to oral articulation (Figures 39, 40, 41). Activity begins near -500 msec and continues, in stop-nasal contrast utterances, until it peaks near -100 msec. The peak is followed by suppression of activity which reaches a minimum at 0 msec and then again begins to increase. First syllable activity is of lower amplitude in nasal-stop contrast utterances than in stop-nasal contrasts. The nasal-stop contrast show peaks of activity at 0 msec, apparently corresponding to stop consonant articulation. A similar pattern is found in the noncontrastive utterances, with one peak at -200 msec and another at 0 msec (Figure 44).

For subject FBB the pattern of middle constrictor activity parallels that of superior constrictor activity, where the peaks are related to vowel articulation and the suppression of activity is related to consonant articulation (Figures 33, 34, 35, 42). The greatest middle constrictor activity is seen for /ɑ/, while activity for /i/ parallels the curves for /ɑ/ at a lesser magnitude. Little, if any, vowel associated-activity is seen for /u/ since the tabulated values are close to baseline for this muscle (Table 8). A few consonant peaks are seen in the EMG curves for those utterances having the vowel /u/ (/futmup/, /fudmup/: Figure 33; /fumtup/, /fumkup/, /fumdup/, /fumgup/: Figure 34; /fuŋtup/, /fuŋdup/: Figure 35).

Subjects KSH and LJR demonstrate little activity for vowels (Tables 9 and 10).

Palatoglossus

Subjects KSH and FBB demonstrate vowel-associated peaks of palatoglossus activity for vowels and suppression of activity for consonant articulation (Figures 45 through 50; Tables 16, 17, 19). The minimum points in the EMG curves are between -100 and 0 msec for both the stop-nasal and the nasal-stop stimuli. There are no peaks for either general oral or nasal consonant articulation. The peaks seem, rather, to be associated with vowel color and the place of articulation of the nasal consonant; first syllable peaks are of greater magnitude and duration when the nasal is /ŋ/ (Figures 47, 50) than when the nasal is /m/ (Figures 46, 49). In those stimuli not having a contrastive medial consonant cluster, there is a tendency for utterances with a medial nasal to show less activity than those with medial oral consonant (Figures 54, 55).

Palatoglossus activity for subject LJR appears to be entirely related to the place and not at all to the manner of articulation (Tables 18, 19; Figures 51, 52, 53). Peaks of palatoglossus activity may be seen, for example, at -200 msec for /fukmup/ (Figure 51), and at -50 msec for /fumkup/ (Figure 52).

That is, the palatoglossus peak occurs earlier in /fukmup/, where the /k/ precedes /m/ than in the utterance in which the /k/ follows /m/. Since a similar pattern appears in the voiced cognate utterances and peaks are seen for the velar nasal at the same time as the peaks in /-km-/ and /-gm-/ utterances, we may take the palatoglossus peak to be associated with velar articulation rather than with nasal articulation.

Palatopharyngeus

All three subjects evince patterns of palatopharyngeus activity associated with oral articulation (Figures 57 through 65). The patterns basically follow those of the levator palatini (Figures 10 through 18), although palatopharyngeus peak magnitudes are somewhat more susceptible to the effects of vowel color. There is a peak of activity between -200 and -100 msec for stop-nasal contrast utterances (Figures 57, 60, 63), followed by suppression of activity reaching a minimum at, or just before, 0 msec. This suppression is followed by an increase in activity whose steepness varies across the subjects. The rise of palatopharyngeus activity after 0 msec is steepest and earliest for subject FBB (Figure 57). Inspection of the nasal-stop contrast utterances (Figures 58, 59, 61, 62, 64, 65) reveals peaks of activity near -400 msec, 0 msec and, for two subjects, near +300 msec. Subject FBB demonstrates the lowest first syllable EMG peaks of the three subjects.

Sternohyoid

The sternohyoid was included in this study for determination of its role in pharyngeal cavity adjustments conditioned by phonetic variations and, as was expected, showed no activity pattern related to oral-nasal articulatory contrasts.

Nonnasal Phonetic Variation

Levator Palatini

As was noted previously, when a vowel follows a nasal consonant (in stop-nasal contrast utterances), there is a difference in timing of EMG activity depending on vowel color, but not a difference in the amount of that activity for all three subjects. That is, EMG activity increases rapidly when the vowel is /i/ or /u/ but is slow to increase when the vowel is /ɑ/. All three subjects show this effect. (Figures 10, 13, 16). But when the vowel precedes or follows the medial stop the three subjects show different patterns with respect to amount of activity. Subject FBB shows no separation of EMG curves for the vowels /i/, /u/, and /ɑ/ whether they precede or follow the medial oral consonant (Figures 10, 11, 12; Table

11). Subject KSH shows some separation of the three vowels. The EMG potentials are geatest for /u/ and lowest for /ɑ/, with the potential for /i/ being either of equal magnitude or slightly greater than those obtained for /ɑ/ (Figures 13, 14, 15; Table 12). Subject LJR shows separation of the EMG curves, with /i/ larger than /u/ more often than not, his /ɑ/ potentials lower than those for the two high vowels (Figures 16, 17, 18; Table 13).

The three subjects also differ in their patterns of peak values for voiced and voiceless stop consonant articulation (Table 3 and 4). Subject FBB shows greater levator palatini potentials for the voiced stop consonants than for their voiceless cognates. At the first recording sessions, the voiced stop had greater potentials than its voiceless cognate in each possible comparison, while the second recording session provided greater potentials for the voiced stop than for its voiceless cognate in 93% of the possible comparisons. Subject LJR provided greater peak levator palatini potentials for the voiced stop than for its voiceless cognate in only 28% of the possible comparisons from the first recording session. Successful recordings from the levator palatini were not obtained at the second recording session for LJR. Subject KSH provided greater EMG potentials in the levator palatini for the voiced stop than for its voiceless cognate in 74% of the possible comparisons from the first recording session. Again, we failed to achieve successful recordings from the levator palatini for KSH at the second recording session.

Examination of utterances without contrastive medial consonant clusters reveal higher EMG potentials for voiceless than for voiced stops for subjects KSH and LJR (Figures 20 and 21). Subject FBB demonstrates no such difference (Figure 19).

Inspection of the EMG values for the stop consonant peaks (Table 4) reveals no pattern of activity associated with the place of stop consonant articulation.

Superior Constrictor

For vowels in medially contrastive utterances no consistent patterns of EMG potentials were observed for subjects KSH and LJR (Tables 6 and 7), although LJR sometimes displays a lower curve for /u/ than for /i/ and /ɑ/ (/fukmup), /fudmup/, /fugmup/) (Figure 27). Subject FBB, however, demonstrates consistent and clear differences in superior constrictor activity with variations in vowel color (Figures 22, 23, 24; Table 5). The EMG potentials are of greatest magnitude for /ɑ/, with /i/ having a pattern similar to that of /ɑ/ but at a lower amplitude. There are no clear vowel-related peaks for /u/.

For vowels in utterances without contrastive medial consonant clusters similar results emerge for subjects KSH and LJR. That is, they display no systematic variation in activity with variations in vowel color. The results for subject FBB (Figure 30) are at a slight variance with the results reported for those utterances with contrastive medial consonant clusters; here the peaks are greatest for /i/, with /u/ and /ɑ/ having little activity.

For the two values of stop consonant voicing consistent differences also fail to emerge in subjects FBB and KSH, while LJR usually shows greater potentials for voiceless stops than for voiced stops.

Inspection of the EMG values for the stop consonant associated peaks (Table 14) reveals no pattern of superior constrictor activity associated with the place of stop or nasal consonant articulation.

Middle Constrictor

The pattern for the three subjects for the three vowels is the same for the middle constrictor as for the superior constrictor.

Subject KSH does not show any consistent variations in middle constrictor activity with variations in vowel color (Figure 36, 37, 38; Table 9). Subject LJR, however, presents some separation of curves with those for /i/ and /α/ coursing together and those for /u/ tending to be of lower amplitude than those for /i/ (Table 10). Subject FBB shows clear peak separation with changes in vowel color. She exhibits the same activity pattern in the middle constrictor (Figures 33, 34, 35) as was observed in the superior constrictor. The amplitude of the EMG curves is greatest for /α/ and lowest for /u/, with the amplitude of the curves for /i/ falling between these extremes (Table 8).

Inspection of peak EMG values associated with stop consonant voicing (Table 15) fails to reveal any pattern of activity related to stop consonant voicing condition for subjects FBB and LJR, while subject KSH normally shows greater EMG potentials for voiceless stops than for their voiced cognates.

In addition, in the utterances which do not have contrastive medial consonant clusters (Figure 42, 43, 44), subjects FBB, KSH, and LJR show greater peak amplitude in those utterances having voiceless stops than in those having their voiced cognates.

The place of stop articulation affects the peak stop consonant associated EMG values differently for each subject (Table 15). Subject FBB produces greater middle constrictor potentials for the alveolar stops than for the labial or velar stops. Subject LJR tends to produce greater middle constrictor EMG potentials for the velar stops than for the labial or alveolar stops. Subject KSH shows no pattern of differences associated with the place of stop consonant articulation.

None of the three subjects presents variations in peak EMG values associated with the place of nasal consonant articulation.

Palatoglossus

Palatoglossus activity appears to be related to vowel color for subjects FBB and KSH. The most consistent peaks, which are also those of greatest magnitude, occur for the vowel /α/ (Figures 45, 46, 47, 48, 49, 50; Tables 16, 17). There is little or no activity associated with vowel articulation (Figures 51, 52, 53; Table 18) for subject LJR.

Subject FBB presents several averaged potential curves in which palatoglossus activity is of equal magnitude for /i/ and /u/, but in those instances in which they are separated, /u/ is generally of greater amplitude than /i/ (Table 16). Small peaks for velar stop articultion may be seen when the stop is preceded or followed by /u/ (Figures 45, 46, 47). In nasal-stop contrast utterances in which the nasal consonant is velar palatoglossus activity for the first syllable may be of greater amplitude than it is when the nasal consonant is bilabial (Figures 46, 47). Subject KSH demonstrates some activity for /i/ and /u/, in addition to that observed for /α/. The activity for /i/ and /u/ is either of equal magnitude or /i/ is of greater magnitude than /u/ (Table 17).

Subject FBB and KSH show no consistent pattern of activity associated with the place of stop consonant articulation, although subject KSH tends to have peaks of greatest magnitude associated with velar stop production (Table 19). Subject LJR shows palatoglossus activity for velar consonants, regardless of their oral or nasal manner of articulation (Figures 51, 52, 53; Table 19), as well as some smaller peaks associated with back vowel production (Table 18). No peaks are found for velar consonant production in the environment of /i/, possibly because the allophones of velar consonants occurring in the environment of /i/ do not have their maximum constriction as posteriorly as do these allophones occurring in the environment of /u/ and /α/.

None of the three subjects shows any pattern of palatoglossus activity corresponding to stop consonant voicing condition.

Palatopharyngeus

There is some separation of palatopharyngeus activity levels with variations in vowel color for all three subjects. /ɑ/ generally displays the greatest potential amplitude, although subject FBB presents greater potentials for /i/ than for /ɑ/ in the nasal-stop stimuli (Figures 58, 59). In all cases, /u/ has the lowest EMG potentials of the three vowels (Tables 20, 21,22).

Subject FBB generally presents greater peak palatopharyngeus potentials for voiced stops than for their voiceless cognates (Table 23). Subject LJR presents lower peak palatopharyngeus potentials for voiced stops than for their voiceless cognates (Table 23; Figures 63, 64, 65). Subject KSH presents lower peak potentials for voiced stops than for their voiceless cognates in stop-nasal contrast utterances and presents equivocal results in nasal-stop contrast utterances (Table 23).

No systematic effect of the place of stop consonant articulation upon peak EMG values is evident for any of the subjects. The stop consonant peaks for subject LJR are lower, however, in utterances containing velar nasals than in utterances containing labial nasals (Table 23).

Sternohyoid

The sternohyoid was included in this study to determine its role in pharyngeal cavity expansion for voiced stop consonants and not its role in jaw opening. Consequently, no tables of vowel-associated sternohyoid activity were compiled.

The greatest EMG activity in the sternohyoid is generally found for the vowel /ɑ/. The peaks for /ɑ/ are equal to those for /i/ for subject KSH, with /u/ clearly smaller although all of the peaks recorded for this subject are broad and poorly defined. The peak for the first syllable of each utterance is of greater magnitude and duration than is the peak for the second syllable (Figures 71, 72, 73).

Data for subject FBB and LJR show clear, well-defined peaks for /ɑ/ in the first syllable and for all vowels in the second syllable (Figures 68, 69, 70, 74, 75, 76).[2] Subject LJR presents nearly equal potentials for all three vowels in the second syllable, although the magnitude of the EMG potentials may be slightly lower for /u/ than for /i/ and /ɑ/. Subject FBB presents potentials of equal magnitude for /u/ and /ɑ/ in the second syllable, while the magnitude of the EMG potentials for /i/ is somewhat lower than that found for /u/ and /ɑ/.

Sternohyoid activity also varies, for subjects FBB and LJR, with the condition of stop consonant voicing. Wherever sternohyoid activity occurs during the first syllable of stop-nasal contrast utterances, that activity is of greatest duration for utterances having voiced stop consonants in the medial cluster than for those having their voiceless cognates (Figures 68, 74). In the same utterance types, the second burst of sternohyoid activity increases more rapidly in utterances with voiced stops than in utterances with their voiceless cognates. In nasal-stop contrast utterances, sternohyoid activity begins 50 to 100 msec earlier in those that have voiced stops than in those that have their voiceless cognates (Figures 69, 70, 75, 76). In utterances without a medial contrastive consonant cluster, sternohyoid activity for the voiced stop, and for the nasal consonant, again begins 50 to 100 msec prior to the onset of activity in those utterances having voiceless medial stops (Figures 77, 79). In general, for subjects FBB and LJR, sternohyoid activity is greater for the voiced stop than for the voiceless stop at the time of peak levator palatini activity (Table 24).

In general, sternohyoid activity is greater for FBB and LJR for velar stops than for labial or alveolar stops, while KSH shows no consistent variation of pattern with stop consonant place of articulation.

FOOTNOTE

1. The figures and tables have been systematically arranged to provide a complete display of the data, independent of the text. Their numbering does not therefore always follow the order of their discussion in the text.

2. When a stop follows a nasal the palate must be moved through a greater distance than when the stop follows a vowel. The EMG values for stop consonants are greater for stops following nasals than for stops following vowels. The greater potentials for consonants following nasals than those following vowels do not indicate greater maximum velar height but, rather, the greater distance which must be covered to achieve adequate velopharyngeal closure (Berti and Hirose, 1972).

Table 2

Average segment durations (in msec).

	FBB			KSH			LJR		
	i	α	u	i	α	u	i	α	u
V_1	107	128	126	142	158	144	113	144	133
C_{vl}	128	134	121	132	134	117	122	130	136
m	45	50	69	46	38	46	73	63	75
V_2	130	138	115	159	196	163	150	156	139
V_1	165	183	168	194	207	188	182	186	175
C_{vd}	92	103	100	47	60	54	108	95	84
m	73	60	73	93	77	79	70	81	63
V_2	148	177	155	164	197	180	136	165	189
V_1	138	145	122	153	167	145	145	146	144
m	104	93	98	113	116	117	116	104	121
C_{vl}	98	103	103	68	61	68	98	99	114
V_2	126	163	128	174	199	181	171	189	148
V_1	160	147	148	158	177	150	160	153	143
m	169	125	108	132	121	144	128	129	132
C_{vd}	41	25	34	31	23	28	38	38	33
V_2	132	163	159	167	195	171	171	182	166
V_1	142	169	158	160	186	179	127	142	143
η	153	126	123	141	133	142	174	158	193
C_{vl}	95	88	98	74	102	77	105	108	118
V_2	155	178	134	179	178	181	148	170	158

Table 2 (cont'd)

	FBB			KSH			LJR		
	i	ɑ	u	i	ɑ	u	i	ɑ	u
V_1	174	165	138	168	190	172	142	151	126
η	158	155	172	142	139	166	181	124	173
C_{vd}	30	31	34	37	33	36	61	44	52
V_2	158	171	179	178	212	176	165	164	167
V_1	115	125	140	146	153	145	142	142	128
C_{vl}	127	140	120	130	132	122	110	140	125
V_2	130	175	148	169	187	172	167	188	158
V_1	170	182	185	187	208	187	180	185	162
C_{vd}	90	100	110	45	103	55	95	120	88
V_2	150	170	161	162	197	167	171	178	163
V_1	132	163	159	157	177	150	171	153	144
m	109	125	108	132	121	144	128	129	132
V_2	148	177	155	164	197	180	150	165	162

Table 3

Peak EMG values (in microvolts) from the levator palatini for the medial oral consonant in stop-nasal and nasal-stop contrasts. Peaks are tested to see if those in nasal-stop contrasts are greater than peaks in stop-nasal contrasts.

Subject	FBB				KSH				LJR			
Vowel	i	α	u	Totals	i	α	u	Totals	i	α	u	Totals
Contrast												
pm	300	410	326	1036	174	224	167	565	300	351	406	1057
mp	392	445	396	1233	326	306	407	1039	431	458	406**	1295
ŋp	374	394**	414	1182	383	326	383	1092	457	431	406	1294
tm	284	305	286	875	175	248	155	578	261	230	370	861
mt	448	355	514	1317	337	325	364	1026	458	456	494	1408
ŋt	429	433	467	1329	300	287	333	920	444	389	421	1254
km	316	350	264	930	173	176	182	531	406	442	419	1267
mk	449	424	493	1366	288	292	322	902	472	485	523	1480
ŋk	417	449	437	1303	309	276	285	870	470	431**	432	1333
bm	323	476	339	1138	160	204	213	577	353	335	363	1051
mb	565	531	660	1756	332	363	337	1032	464	357	477	1298
ŋb	466	541	512	1519	328	392	400	1120	384	353	397	1134
dm	402	443	460	1305	187	386	248	821	345	346	286	977
md	573	496	629	1698	340	384	317	1041	464	362	528	1354
ŋd	443	533	493	1469	345	327	339	1011	368	335**	328	1031
gm	266	364	200	830	162	258	205	625	343	321	352	1016
mg	517	496	580	1593	307	302	314	923	472	372	492	1336
ŋg	496	484	546	1526	315	315	357	987	423	374	375	1172
Totals	7460	7929	8016		4941	5391	5328		7315	6828	7475	

**Failing contrasts

Table 4

Peak oral consonant values for the levator palatini, in microvolts, grouped for each subject for each vowel and for each voicing condition.

Subject	FBB				KSH				LJR			
Vowel	i	ɑ	u	Totals	i	ɑ	u	Totals	i	ɑ	u	Totals
Contrast												
pm	300	410	326	1036	174	224	167	565	300	351	406	1057
tm	284	305	286	875	175	248	155	578	261	230	370	861
km	316	350	264	930	173	176	182	531	406	442	419	1267
mp	392	445	396	1233	326	306	407	1039	431	458	406	1295
mt	448	355	514	1317	337	325	364	1026	458	456	494	1408
mk	449	424	493	1366	288	292	322	902	472	485	523	1480
ηp	374	394	414	1182	383	326	383	1092	457	431	406	1294
ηt	429	433	467	1329	300	287	333	920	444	389	421	1254
ηk	417	449	437	1303	309	276	285	870	470	431	432	1333
bm	323	476	339	1138	160	204	213	577	353	335	363	1051
dm	402	443	460	1305	187	386	248	821	345	346	286	977
gm	266	364	200	830	162	258	205	625	343	321	352	1016
mb	565	531	660	1756	332	363	337	1032	464	357	477	1298
md	573	496	629	1698	340	384	317	1041	464	362	528	1354
mg	517	496	580	1593	307	302	314	923	472	372	492	1336
ηb	466	541	512	1519	328	392	400	1120	384	353	397	1134
ηd	443	533	493	1469	345	327	339	1011	368	335	328	1031
ηg	496	484	546	1526	315	315	357	987	423	374	375	1172
Totals	7460	7929	8016		4941	5391	5328		7315	6828	7475	

Table 5

superior constrictor FBB

EMG values (in microvolts) for vowel articulation in stop-nasal and nasal-stop contrast utterances. V_1 is the first syllable vowel; V_2 is the second syllable vowel.

	i		α		u	
	V_1	V_2	V_1	V_2	V_1	V_2
pm	110	177	206	224	50	86
tm	109	165	213	227	54	80
km	114	164	258	245	45	83
mp	80	155	151	215	37	55
mt	95	164	146	234	43	74
mk	84	183	152	253	43	76
bm	92	163	192	236	40	90
dm	117	193	190	234	40	89
gm	105	187	178	232	48	83
mb	86	183	126	263	36	72
md	88	166	139	256	44	81
mg	80	183	142	250	48	71
Totals	1160	2083	2093	2869	528	940

Table 6

superior constrictor KSH

EMG values (in microvolts) for vowel articulation in stop-nasal and nasal-stop contrast utterances. V_1 is the first syllable vowel; V_2 is the second syllable vowel.

	i		α		u	
	V_1	V_2	V_1	V_2	V_1	V_2
pm	22	30	31	28	26	44
tm	24	32	30	30	24	32
km	22	48	23	29	26	38
mp	23	27	22	27	22	28
mt	21	26	23	35	22	27
mk	24	26	22	25	23	27
ηp	25	27	23	25	25	29
ηt	28	41	25	27	23	27
ηk	22	27	25	29	21	25
bm	39	29	30	25	30	29
dm	34	31	31	25	30	28
gm	41	29	33	28	30	28
mb	24	33	22	29	20	40
md	25	33	24	34	23	30
mg	25	36	20	32	22	35
ηb	25	28	23	27	25	33
ηd	24	28	23	29	22	27
ηg	24	29	23	33	26	26
Totals	472	560	473	517	440	553

Table 7

superior constrictor LJR

EMG values (in microvolts) for vowel articulation in stop-nasal and nasal-stop contrast utterances. V_1 is the first syllable vowel; V_2 is the second syllable vowel.

	i		ɑ		u	
	V_1	V_2	V_1	V_2	V_1	V_2
pm	31	20	22	20	18	16
tm	33	21	27	17	21	13
km	30	18	28	30	18	22
mp	24	17	18	18	15	13
mt	26	14	14	15	18	13
mk	27	16	16	13	18	11
ŋp	23	14	22	14	18	11
ŋt	22	13	21	14	15	10
ŋk	22	14	18	13	17	11
bm	25	16	21	18	20	12
dm	23	16	26	19	14	11
gm	25	15	21	15	14	11
mb	25	24	21	20	16	18
md	27	23	20	22	13	14
mg	27	17	20	15	30	13
ŋb	21	21	20	18	16	14
ŋd	22	22	20	20	15	14
ŋg	22	21	22	14	16	15
Totals	505	322	377	315	313	230

Table 8

middle constrictor FBB

EMG values (in microvolts) for vowel articulation in stop-nasal and nasal-stop contrast utterances. V_1 is the first syllable vowel; V_2 is the second syllable vowel.

	i		ɑ		u	
	V_1	V_2	V_1	V_2	V_1	V_2
pm	61	56	115	100	32	30
tm	78	66	132	92	22	29
km	65	70	108	84	21	29
mp	41	67	70	81	39	30
mt	61	72	72	97	39	50
mk	66	60	77	88	25	36
ŋp	42	38	54	76	19	24
ŋt	46	48	60	65	25	36
ŋk	47	61	75	60	23	29
bm	44	52	58	57	22	29
dm	42	50	59	54	14	32
gm	39	53	52	53	22	27
mb	59	73	77	86	29	29
md	55	66	73	102	23	49
mg	60	75	74	100	24	40
ŋb	60	56	54	59	24	28
ŋd	38	50	60	70	23	35
ŋg	52	53	47	56	19	32
Totals	956	1056	1317	1380	445	594

Table 9

middle constrictor KSH

EMG values (in microvolts) for vowel articulation in stop-nasal and nasal-stop contrast utterances. V_1 is the first syllable vowel; V_2 is the second syllable vowel.

	i		α		u	
	V_1	V_2	V_1	V_2	V_1	V_2
pm	22	12	19	11	13	16
tm	26	15	19	14	17	14
km	23	13	17	12	14	13
mp	21	15	15	12	14	12
mt	22	14	15	13	11	14
mk	28	15	15	15	12	11
ŋp	19	12	8	8	14	9
ŋt	19	11	9	11	12	10
ŋk	23	11	9	9	10	9
bm	20	12	18	10	13	9
dm	14	11	7	13	14	13
gm	21	13	16	14	13	10
mb	21	17	12	10	15	17
md	30	18	13	12	13	14
mg	24	12	12	13	15	11
ŋb	13	9	10	9	11	9
ŋd	19	9	9	10	17	10
ŋg	18	9	9	10	10	10
Totals	383	228	232	206	238	211

Table 10

middle constrictor LJR

EMG values (in microvolts) for vowel articulation in stop-nasal and nasal-stop contrast utterances. V_1 is the first syllable vowel; V_2 is the second syllable vowel.

	i		α		u	
	V_1	V_2	V_1	V_2	V_1	V_2
pm	29	14	30	24	16	17
tm	28	15	31	24	19	22
km	24	18	26	25	18	23
mp	22	21	21	21	15	25
mt	21	17	19	18	14	16
mk	18	16	20	19	17	18
ηp	26	19	27	22	20	18
ηt	25	18	26	22	16	17
ηk	23	21	23	20	18	22
bm	25	20	26	27	23	29
dm	24	21	27	29	18	48
gm	26	24	27	27	19	18
mb	21	28	20	26	15	28
md	22	22	21	29	16	24
mg	22	35	20	26	15	25
ηb	22	27	26	27	18	32
ηd	26	28	23	22	19	23
ηg	22	25	24	26	19	26
Totals	426	389	437	434	315	431

Table 11

levator palatini FBB

EMG values (in microvolts) for vowel articulation in stop-nasal and nasal-stop contrast utterances. V_1 is the first syllable vowel; V_2 is the second syllable vowel.

	i		ɑ		u	
	V_1	V_2	V_1	V_2	V_1	V_2
pm	191	294	212	188	173	404
tm	209	237	180	145	176	381
km	234	363	199	183	174	377
mp	177	246	125	333	128	299
mt	175	277	133	248	149	291
mk	199	286	150	274	139	315
ŋp	166	207	115	240	128	252
ŋt	195	266	114	250	195	278
ŋk	193	242	117	243	121	270
bm	220	296	205	236	165	352
dm	228	352	195	173	200	320
gm	216	261	210	149	146	336
mb	144	314	124	297	119	319
md	182	321	120	307	128	329
mg	184	288	128	268	111	349
ŋb	145	290	129	301	92	272
ŋd	134	264	108	292	127	288
ŋg	153	297	109	231	92	288
Totals	3345	5101	2482	4358	2563	5710

Table 12

levator palatini KSH

EMG values (in microvolts) for vowel articulation in stop-nasal and nasal-stop contrast utterances. V_1 is the first syllable vowel; V_2 is the second syllable vowel.

	i		α		u	
	V_1	V_2	V_1	V_2	V_1	V_2
pm	140	223	121	77	175	314
tm	135	199	133	104	171	282
km	132	186	118	102	166	303
mp	122	140	89	86	142	203
mt	101	137	78	92	106	137
mk	110	142	71	94	103	182
ηp	101	142	99	98	129	177
ηt	116	132	79	106	116	183
ηk	88	127	79	97	104	186
bm	153	199	120	80	192	232
dm	168	165	122	89	224	296
gm	132	177	109	86	195	255
mb	127	139	89	116	86	180
md	108	141	66	84	86	181
mg	98	129	79	104	84	171
ηb	110	136	74	108	89	185
ηd	98	127	89	112	89	187
ηg	91	133	80	102	89	172
Totals	2130	2774	1695	1737	2346	3826

Table 13

levator palatini LJR

EMG values (in microvolts) for vowel articulation in stop-nasal and nasal-stop contrast utterances. V_1 is the first syllable vowel; V_2 is the second syllable vowel.

	i		ɑ		u	
	V_1	V_2	V_1	V_2	V_1	V_2
pm	229	277	158	236	282	294
tm	250	267	177	190	238	307
km	291	295	151	193	266	335
mp	159	229	99	152	176	196
mt	181	262	86	140	172	213
mk	194	263	96	135	195	240
ŋp	185	253	107	131	136	191
ŋt	222	192	93	114	149	188
ŋk	195	254	114	113	154	176
bm	274	295	186	215	260	338
dm	276	296	202	130	206	322
gm	278	293	184	212	243	337
mb	168	276	113	152	135	250
md	181	297	103	152	126	287
mg	171	303	113	158	139	271
ŋb	180	231	80	149	131	231
ŋd	181	255	98	155	147	192
ŋg	191	256	110	159	151	219
Totals	3806	4795	2270	2886	3306	4587

Table 14

Peak EMG values (in microvolts) from the superior constrictor for medial stop consonant articulation (chosen in the region of peak levator palatini activity) in stop-nasal and nasal-stop contrasts.

Subject	FBB				KSH				LJR			
Vowel	i	α	u	Totals	i	α	u	Totals	i	α	u	Totals
Contrast												
pm	42	27	40	109	33	28	28	89	40	33	22	959
tm	40	26	24	90	38	27	32	97	35	33	21	89
km	36	34	24	94	28	40	39	107	38	39	24	101
mp	35	17	17	69	40	46	41	127	25	30	22	77
mt	32	16	18	66	39	46	48	123	31	31	28	90
mk	32	20	15	67	38	35	35	108	40	25	25	90
ŋp	25	25	23	73	42	38	42	122	32	28	26	76
ŋt	29	25	24	78	41	36	38	115	34	28	28	90
ŋk	30	25	36	91	41	40	41	122	30	31	30	91
bm	33	37	36	106	30	27	27	84	41	27	26	94
dm	43	42	29	114	33	29	28	90	39	27	22	88
gm	31	25	29	85	34	25	29	88	37	25	24	86
mb	50	21	15	86	45	43	53	141	21	26	19	66
md	53	24	15	92	33	49	52	134	30	37	17	84
mg	43	18	14	75	52	34	37	123	26	27	19	72
ŋb	51	26	23	100	41	44	39	124	29	31	22	82
ŋd	40	25	20	85	37	40	38	115	31	30	21	82
ŋg	42	27	18	87	42	43	37	122	31	23	21	75
Totals	687	460	420		677	670	684		590	531	417	

Table 15

Peak EMG values (in microvolts) from the middle constrictor for medial stop consonant articulation (chosen in the region of peak levator palatini activity) in stop-nasal and nasal-stop contrasts.

Subject	FBB				KSH				LJR			
Vowel	i	α	u	Totals	i	α	u	Totals	i	α	u	Totals
Contrast												
pm	46	66	28	40	23	22	18	63	26	31	25	82
tm	63	129	38	230	31	20	14	65	28	31	20	79
km	60	99	39	98	32	20	24	76	34	28	30	92
mp	59	56	19	134	15	13	12	40	31	27	29	87
mt	55	49	33	137	15	20	19	54	33	31	33	97
mk	41	44	24	109	17	15	15	47	27	29	34	90
ηp	30	35	18	83	16	13	9	38	27	30	27	84
ηt	34	32	51	127	11	14	11	36	27	27	24	78
ηk	36	26	25	87	11	11	9	31	29	26	32	87
bm	24	47	22	93	16	12	12	40	25	28	26	79
dm	37	58	73	168	15	14	13	42	25	30	21	76
gm	35	44	32	111	18	9	10	37	25	25	31	81
mb	63	74	18	155	13	13	18	44	30	32	46	108
md	51	65	41	157	16	16	20	52	32	34	35	101
mg	61	63	21	145	17	15	21	53	36	42	34	112
ηb	39	45	28	112	11	12	12	35	29	30	19	78
ηd	36	41	46	123	10	13	10	33	29	29	25	83
ηg	38	56	18	112	10	9	10	29	33	35	28	96
Totals	808	1029	574		297	261	257		526	545	519	

Table 16

palatoglossus FBB

EMG values (in microvolts) for vowel articulation in stop-nasal and nasal-stop contrast utterances. V_1 is the first syllable vowel; V_2 is the second syllable vowel.

	i		ɑ		u	
	V_1	V_2	V_1	V_2	V_1	V_2
pm	64	79	117	115	81	57
tm	53	60	104	92	65	67
km	59	64	104	99	70	55
mp	50	65	77	80	86	62
mt	89	94	87	80	57	57
mk	58	56	73	89	62	50
ŋp	56	61	89	90	74	71
ŋt	62	75	82	94	86	79
ŋk	65	68	84	90	68	75
bm	71	84	99	100	74	91
dm	62	85	97	95	60	70
gm	59	85	99	90	58	72
mb	58	67	85	85	58	55
md	66	81	79	94	71	71
mg	72	77	69	98	58	50
ŋb	68	84	79	97	83	75
ŋd	74	72	86	110	79	72
ŋg	69	77	80	89	71	66
Totals	1155	1334	1590	1687	1261	1195

Table 17

palatoglossus KSH

EMG values (in microvolts) for vowel articulation in stop-nasal and nasal-stop contrast utterances. V_1 is the first syllable vowel; V_2 is the second syllable vowel.

	i		α		u	
	V_1	V_2	V_1	V_2	V_1	V_2
pm	36	30	51	47	29	20
tm	35	32	47	48	24	36
km	37	26	67	34	31	24
mp	46	41	50	50	22	31
mt	33	32	43	60	28	30
mk	49	44	40	59	25	34
ŋp	34	30	34	42	37	23
ŋt	42	32	44	55	40	33
ŋk	46	32	35	42	32	28
bm	37	40	32	44	27	26
dm	32	27	34	83	24	34
gm	54	30	50	41	27	22
mb	43	46	38	52	38	51
md	53	44	41	61	27	30
mg	42	37	39	51	40	26
ŋb	23	37	36	44	44	27
ŋd	47	26	32	65	46	22
ŋg	38	37	35	52	33	27
Totals	727	623	712	930	574	527

Table 18

palatoglossus LJR

EMG values (in microvolts) for vowel articulation in stop-nasal and nasal-stop contrast utterances. V_1 is the first syllable vowel; V_2 is the second syllable vowel.

	i		ɑ		u	
	V_1	V_2	V_1	V_2	V_1	V_2
pm	17	17	27	17	20	21
tm	18	17	19	20	20	23
km	17	16	22	17	20	20
mp	17	17	20	20	22	18
mt	18	17	19	21	18	18
mk	19	17	20	17	23	20
ŋp	16	15	16	17	18	16
ŋt	15	14	16	18	18	15
ŋk	15	15	17	16	16	15
bm	15	15	19	17	23	19
dm	14	15	18	19	17	21
gm	15	14	16	16	16	18
mb	17	18	19	19	20	25
md	18	17	20	23	19	22
mg	18	16	22	16	23	20
ŋb	16	16	17	17	19	18
ŋd	15	17	20	20	21	17
ŋg	16	15	15	13	20	17
Totals	296	288	342	323	353	343

Table 19

EMG values (in microvolts) from the palatoglossus for medial stop consonant articulation (chosen in the region of peak levator palatini activity) in stop-nasal and nasal-stop contrasts.

Subject	FBB				KSH				LJR			
Vowel	i	α	u	Totals	i	α	u	Totals	i	α	u	Totals
Contrast												
pm	62	101	59	222	51	59	45	155	19	22	26	67
tm	67	100	60	227	50	53	42	145	18	18	20	56
km	54	103	84	241	69	92	86	247	31	41	36	108
mp	59	70	43	172	36	42	36	114	17	22	19	58
mt	68	72	48	188	36	47	28	111	19	21	19	59
mk	46	62	50	158	41	76	62	179	20	31	26	77
ŋp	54	66	46	166	73	47	36	156	15	17	18	50
ŋt	54	65	66	180	33	64	27	124	17	16	16	49
ŋk	54	56	56	166	44	59	60	163	16	23	21	60
bm	54	89	52	195	34	47	47	128	17	16	24	57
dm	74	112	85	271	31	55	39	125	15	16	14	45
gm	53	98	65	216	48	57	45	150	20	33	29	72
mb	58	73	39	170	58	53	39	150	17	19	21	57
md	58	77	40	175	46	40	43	129	18	25	20	63
mg	64	64	38	166	53	66	51	170	18	27	21	66
ŋb	65	65	50	180	58	61	31	150	16	17	15	48
ŋd	54	75	62	191	49	89	27	165	17	15	15	47
ŋg	67	99	44	210	59	68	32	159	16	18	17	51
Totals	1065	1446	987		869	1075	782		326	387	397	

Table 20

palatopharyngeus FBB

EMG values (in microvolts) for vowel articulation in stop-nasal and nasal-stop contrast utterances. V_1 is the first syllable vowel; V_2 is the second syllable vowel.

	i		ɑ		u	
	V_1	V_2	V_1	V_2	V_1	V_2
pm	63	83	61	82	19	39
tm	57	73	58	58	15	34
km	59	89	49	69	21	35
mp	40	70	28	81	17	19
mt	25	75	31	72	25	36
mk	36	76	25	72	20	36
ŋp	64	93	48	101	43	44
ŋt	77	118	54	102	53	68
ŋk	114	85	56	86	42	55
bm	89	108	69	113	45	65
dm	94	107	71	105	36	60
gm	75	103	78	93	47	58
mb	28	81	31	70	19	40
md	36	83	30	76	21	45
mg	37	78	35	78	15	38
ŋb	53	113	65	109	43	53
ŋd	59	106	64	121	45	63
ŋg	69	93	50	97	47	63
Totals	1075	1712	903	1585	573	851

Table 21

palatopharyngeus KSH

EMG values (in microvolts) for vowel articulation in stop-nasal and nasal-stop contrast utterances. V_1 is the first syllable vowel; V_2 is the second syllable vowel.

	i		α		u	
	V_1	V_2	V_1	V_2	V_1	V_2
pm	65	48	53	48	46	42
tm	75	56	47	50	40	31
km	80	51	39	43	39	36
mp	66	43	54	46	42	25
mt	50	38	46	40	33	30
mk	46	34	55	41	38	33
ŋp	54	42	46	43	38	26
ŋt	46	29	42	42	36	28
ŋk	45	35	58	42	38	28
bm	55	50	50	37	30	33
dm	50	49	48	42	29	30
gm	59	50	54	47	30	30
mb	58	59	46	48	38	36
md	55	65	41	41	39	41
mg	53	57	44	53	37	33
ŋb	44	45	40	54	33	31
ŋd	49	49	42	52	35	34
ŋg	46	51	40	49	31	31
Totals	996	851	845	818	652	578

Table 22

palatopharyngeus LJR

EMG values (in microvolts) for vowel articulation in stop-nasal and nasal-stop contrast utterances. V_1 is the first syllable vowel; V_2 is the second syllable vowel.

	i		ɑ		u	
	V_1	V_2	V_1	V_2	V_1	V_2
pm	144	69	91	110	89	73
tm	138	76	111	85	82	82
km	123	91	100	118	93	92
mp	68	97	95	102	56	69
mt	83	76	82	82	81	67
mk	69	73	73	81	78	63
ŋp	101	72	105	67	76	60
ŋt	112	69	100	53	84	40
ŋk	84	55	82	51	87	57
bm	101	105	81	79	108	89
dm	96	59	90	65	92	84
gm	110	71	95	88	72	64
mb	64	90	94	110	78	82
md	58	79	76	81	87	72
mg	66	90	77	93	79	74
ŋb	70	68	102	67	78	64
ŋd	85	75	77	61	88	47
ŋg	93	75	96	63	73	61
Totals	1665	1390	1627	1456	1481	1240

Table 23

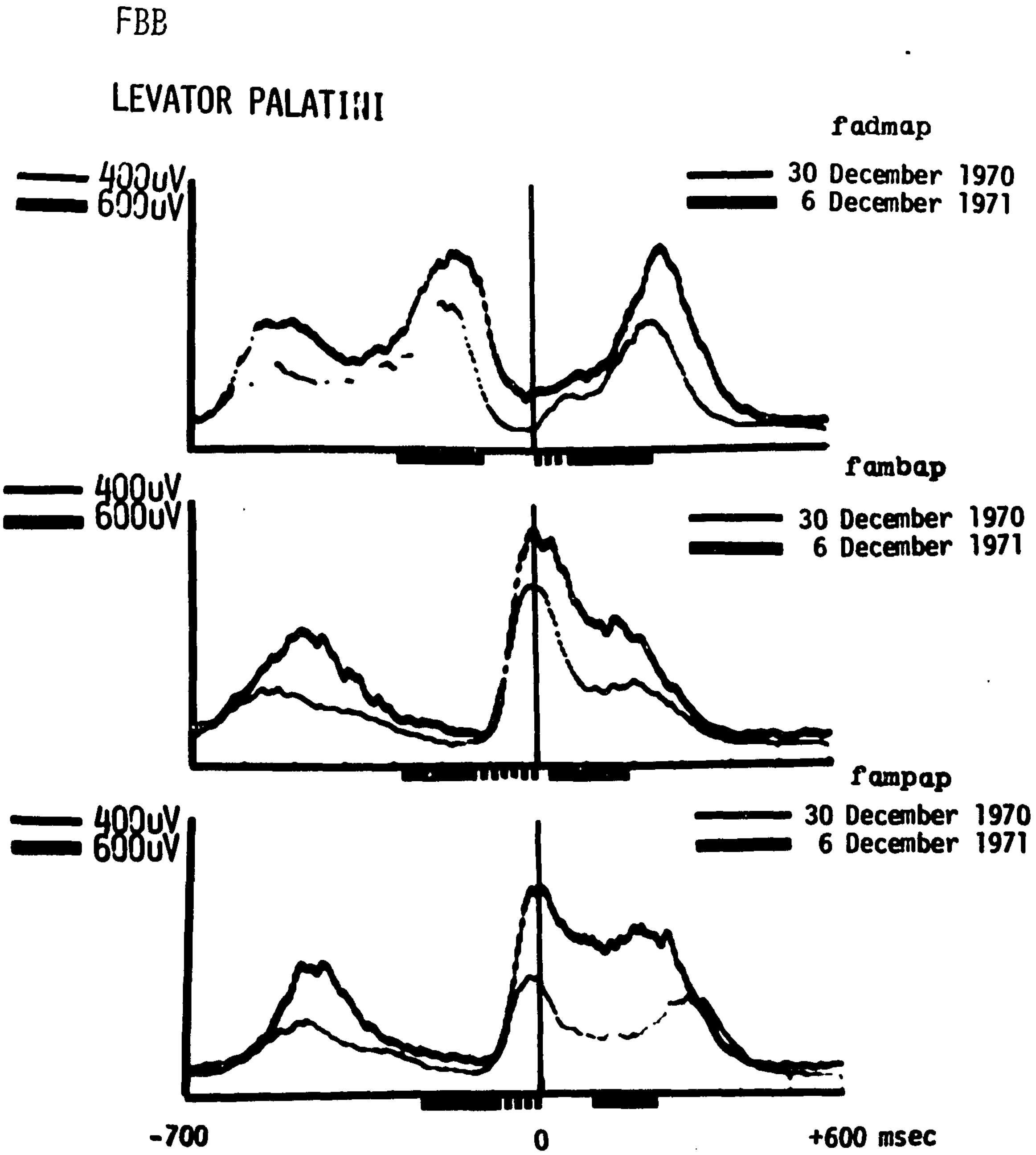
Peak EMG values (in microvolts) from the palatopharyngeus for medial stop consonant articulation (chosen in the region of peak levator palatini activity) in stop-nasal and nasal-stop contrasts.

Subject	FBB				KSH				LJR			
Vowel	i	ɑ	u	Totals	i	ɑ	u	Totals	i	ɑ	u	Totals
Contrast												
pm	111	115	60	286	62	63	61	186	147	197	119	463
tm	79	98	34	211	57	87	63	207	122	134	92	348
km	85	111	41	237	91	92	64	247	169	208	161	538
mp	79	64	35	178	80	56	52	188	158	192	125	475
mt	111	52	48	211	50	63	60	173	144	179	130	453
mk	83	34	36	153	101	66	63	230	146	162	138	446
ŋp	91	70	57	218	84	55	57	196	137	142	129	408
ŋt	101	71	78	250	44	52	53	149	144	138	118	400
ŋk	106	78	55	239	75	85	48	208	134	142	126	402
bm	85	133	70	288	53	51	38	142	126	145	133	404
dm	87	136	73	296	58	51	37	146	122	143	141	406
gm	109	114	75	298	38	45	36	119	130	159	109	398
mb	147	107	56	310	63	61	46	150	120	146	116	382
md	144	114	73	331	67	62	42	161	123	142	127	392
mg	117	85	38	240	68	55	39	162	141	147	125	413
ŋb	142	105	64	311	54	70	57	181	118	122	102	342
ŋd	123	133	75	331	53	64	47	164	120	113	101	334
ŋg	129	90	59	278	63	56	48	167	130	110	107	347
Totals	1929	1610	1027		1161	1134	911		2431	2719	2199	

Table 24

Peak EMG values (in microvolts) from the sternohyoid for medial stop consonant articulation (chosen in the region of peak levator palatini activity) in stop-nasal and nasal-stop contrasts.

Subject	FBB				KSH				LJR			
Vowel	i	ɑ	u	Totals	i	ɑ	u	Totals	i	ɑ	u	Totals
Contrast												
pm	17	17	16	50	35	33	44	112	23	18	21	62
bm	21	21	21	63	39	30	43	112	27	19	18	64
tm	20	19	15	54	31	37	28	96	17	36	21	74
dm	19	18	15	52	31	27	28	86	24	24	19	67
km	20	22	15	57	34	36	40	110	19	18	16	53
gm	21	24	14	59	31	29	31	91	29	29	18	76
mp	24	31	25	80	27	36	31	94	22	19	17	58
mb	26	41	35	102	28	37	32	97	34	34	31	95
mt	23	17	18	58	27	26	26	79	28	22	19	69
md	32	44	38	114	26	35	29	90	45	49	49	143
mk	27	34	25	86	37	43	58	138	24	27	36	87
mg	44	69	65	178	33	39	43	115	53	47	72	172
ŋp	20	27	26	73	29	30	35	94	25	31	18	74
ŋb	35	45	52	152	38	30	27	95	37	54	24	115
ŋt	23	18	21	62	30	37	30	97	32	19	23	74
ŋd	34	48	47	129	31	34	31	96	76	88	37	201
ŋk	27	30	29	86	28	30	39	97	23	29	29	81
ŋg	40	48	63	151	25	33	34	92	83	63	69	215
Totals	473	573	540		560	602	629		596	626	537	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30 December 1970
6 December 1971
fambap
400uV
600uV
30 December 1970
6 December 1971
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30 December 1970
6 December 1971
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+600 msec

Figure 7

FBB

STERNOHYOID

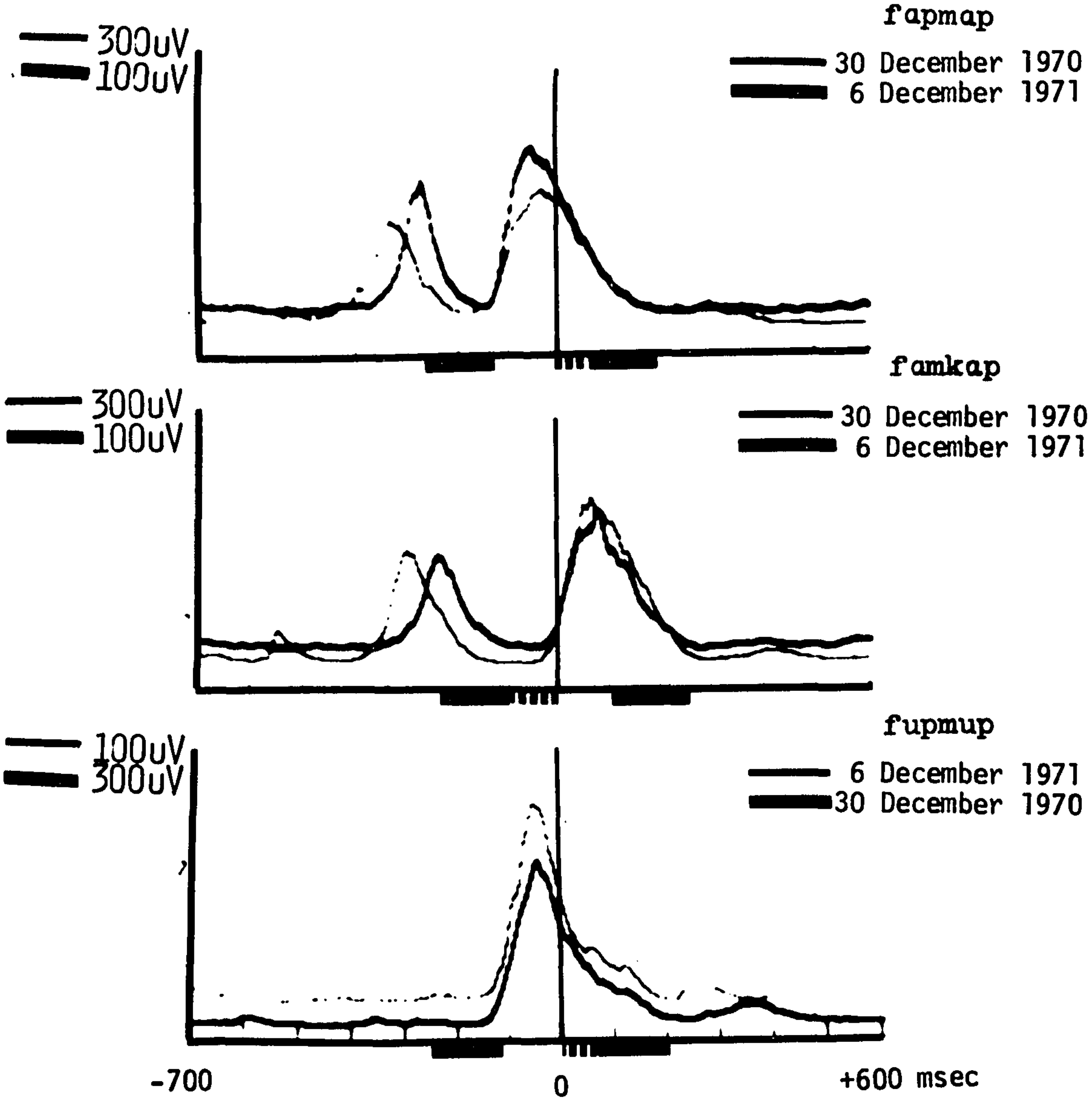
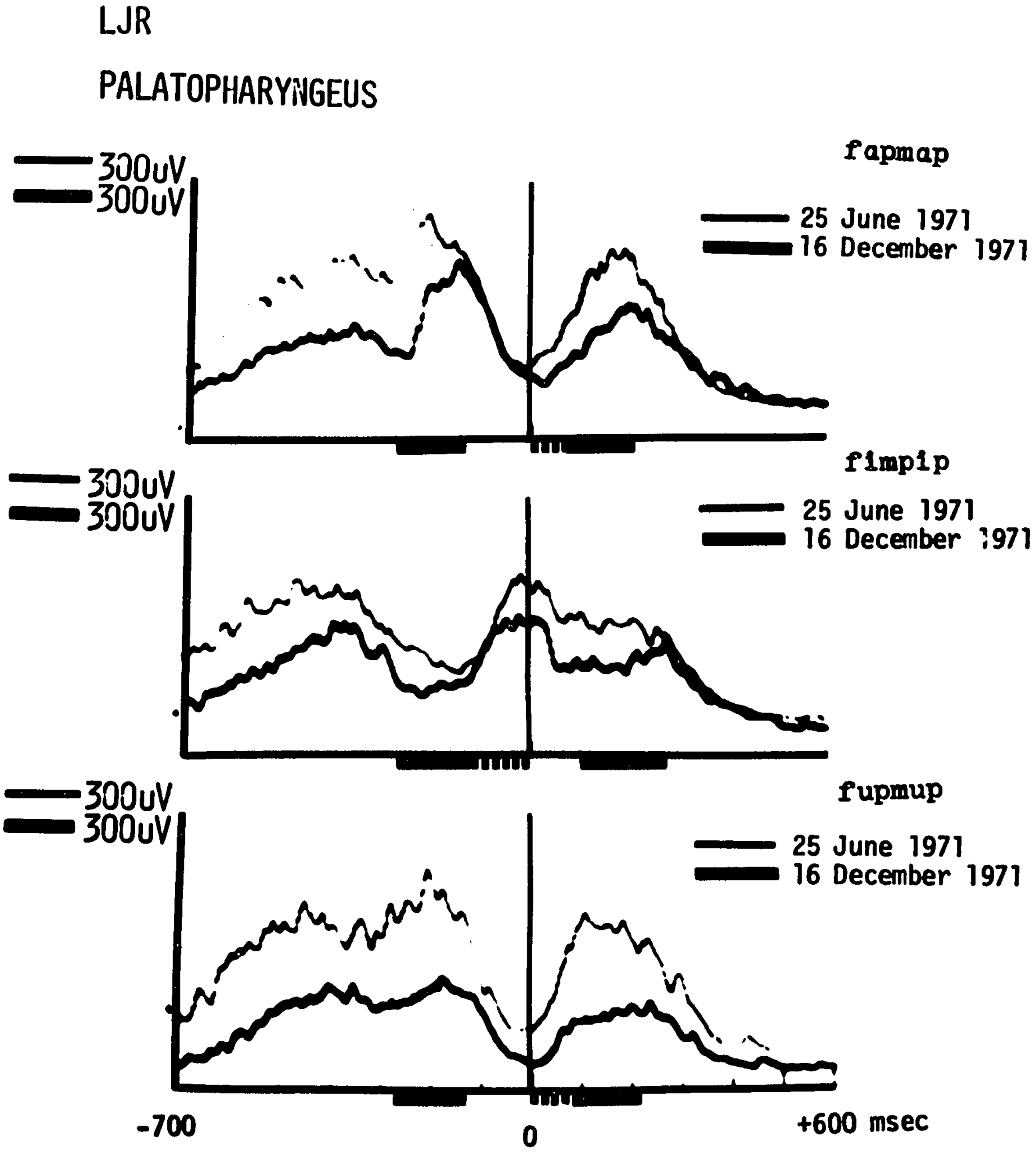


Figure 8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PALATOPHARYNGEUS
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300uV
fapmap
25 June 1971
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300uV
300uV
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25 June 1971
16 December 1971
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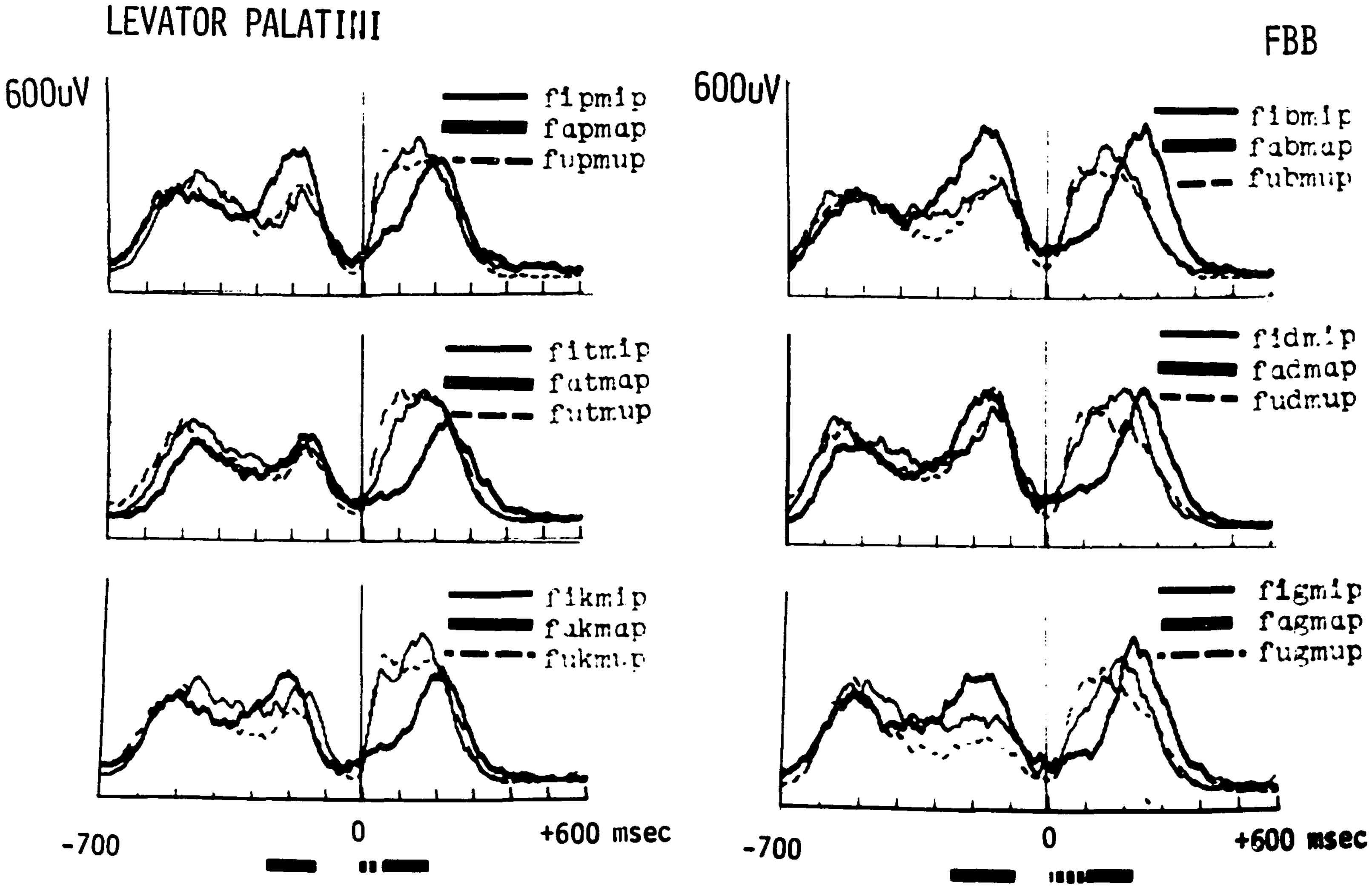
0
+600 msec

Figure 9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600uV
fipmip
fapmap
fupmup
fitmip
fatmap
futmup
fikmip
fakmap
fukmup
-700
0
+600 msec
600uV
fibmip
fabmap
fubmup
fidmip
fadmap
fudmup
figmip
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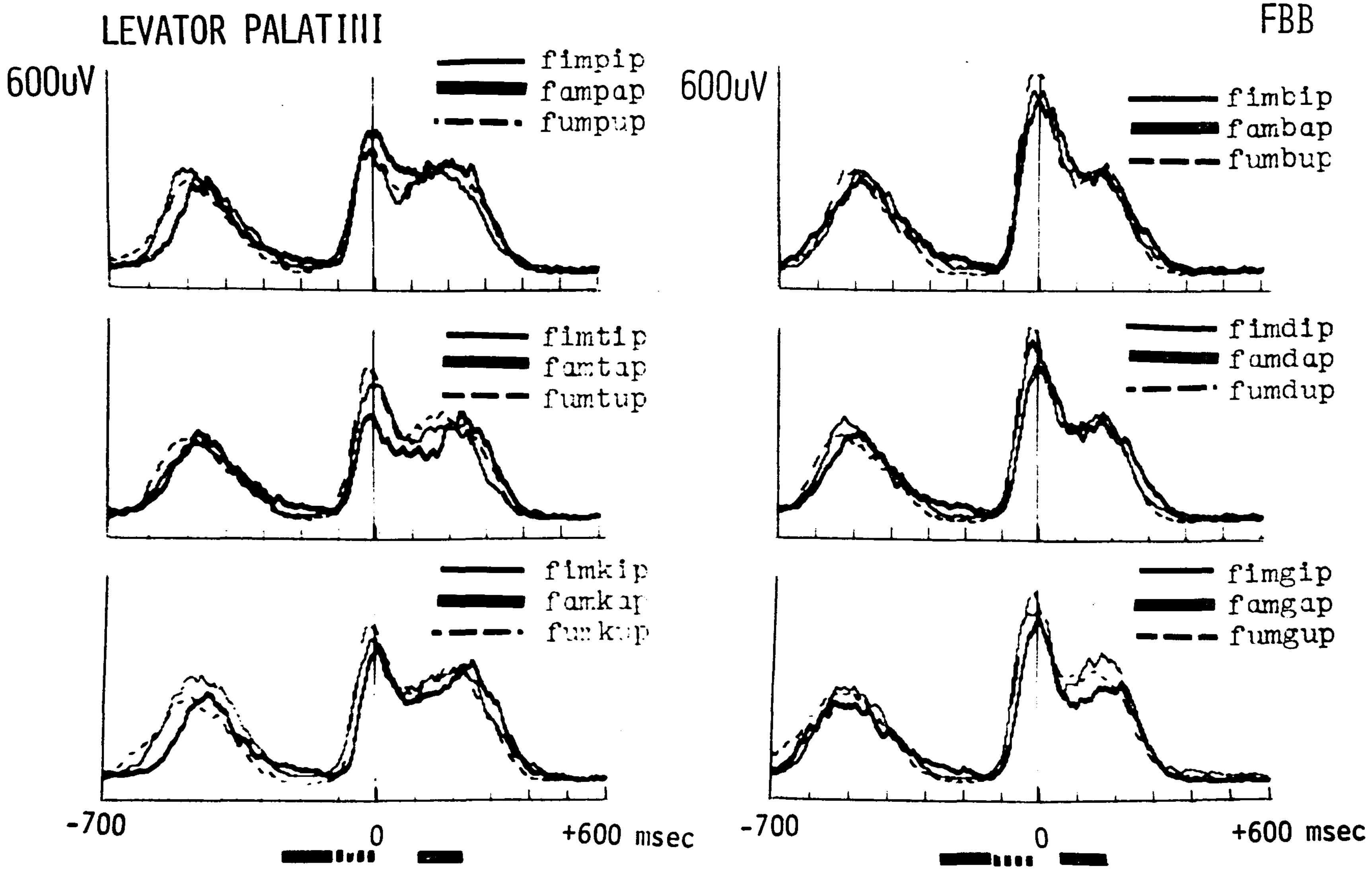
fugmup
-700
0
+600 msec

Figure 10



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fampap
fumpup
fimtip
famtap
fumtup
fimkip
famkap
fumkup
600uV
fimbip
fambap
fumbup
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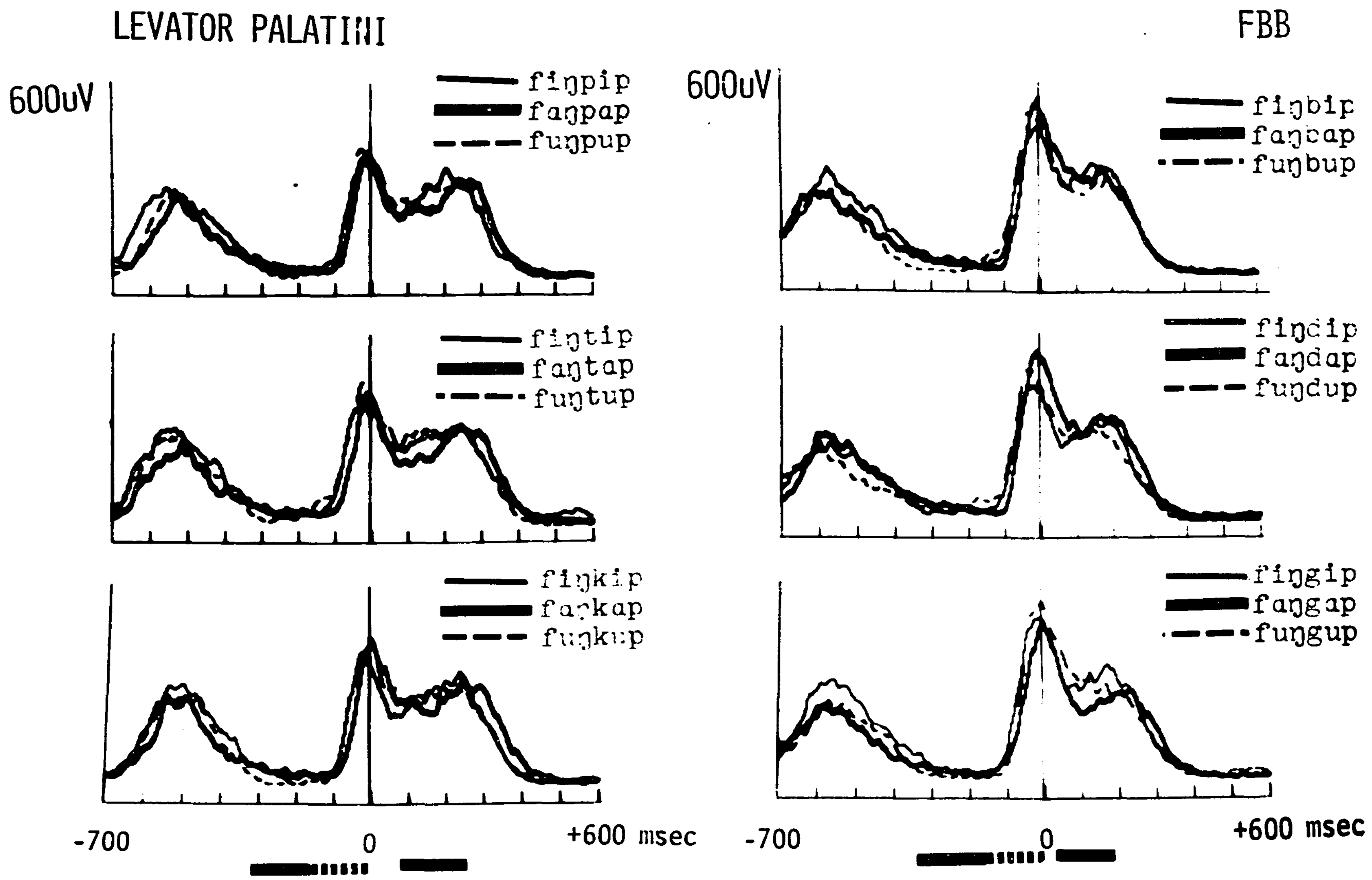
+600 msec
-700
0
+600 msec

Figure 11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fiŋtip
faŋtap
fuŋtup
fiŋdip
faŋdap
fuŋdup
fiŋkip
faŋkap
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fuŋgup
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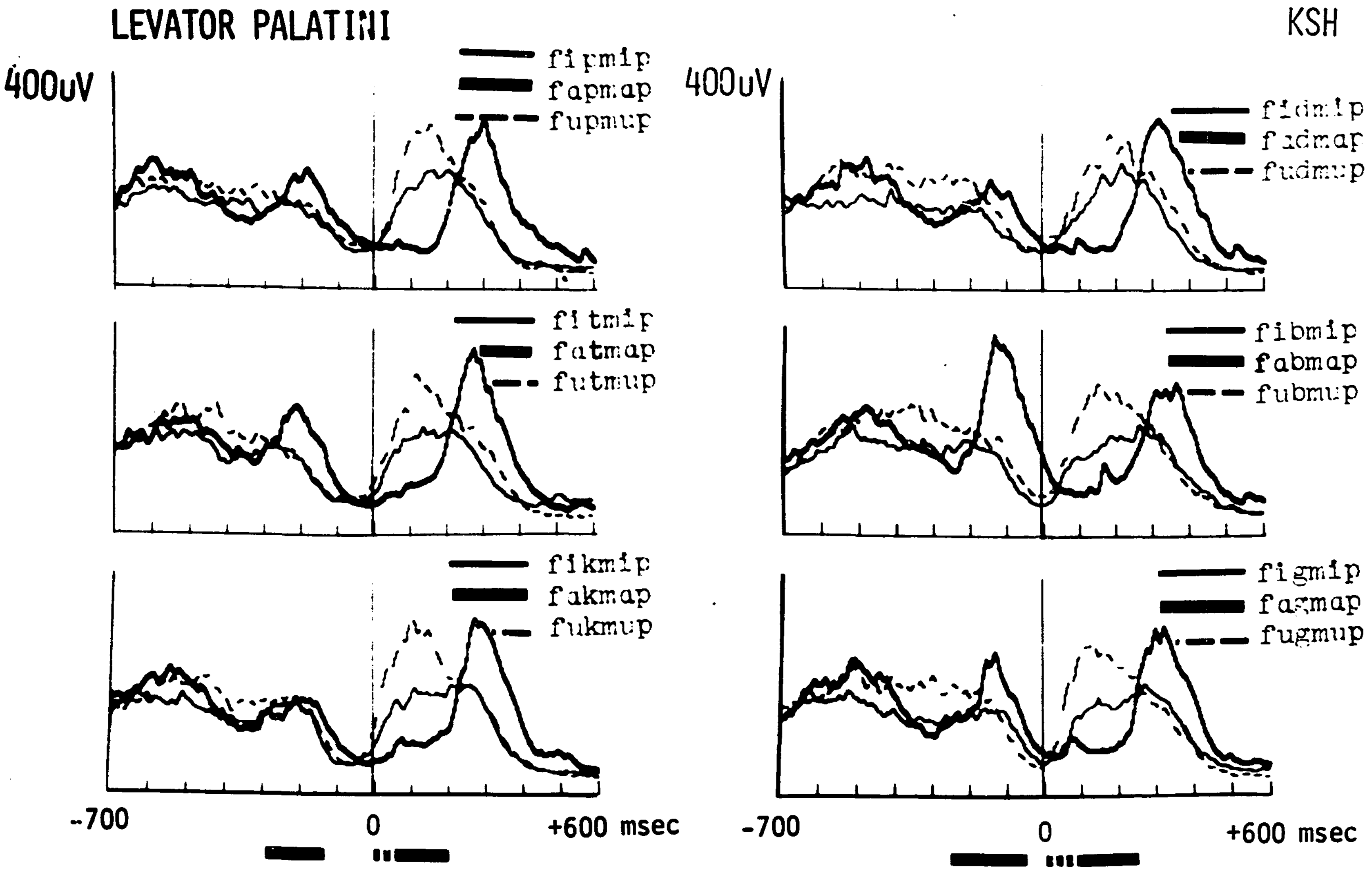
+600 msec
-700
0
+600 msec

Figure 12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fadmap
fudmup
fibmip
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+600 msec

Figure 13

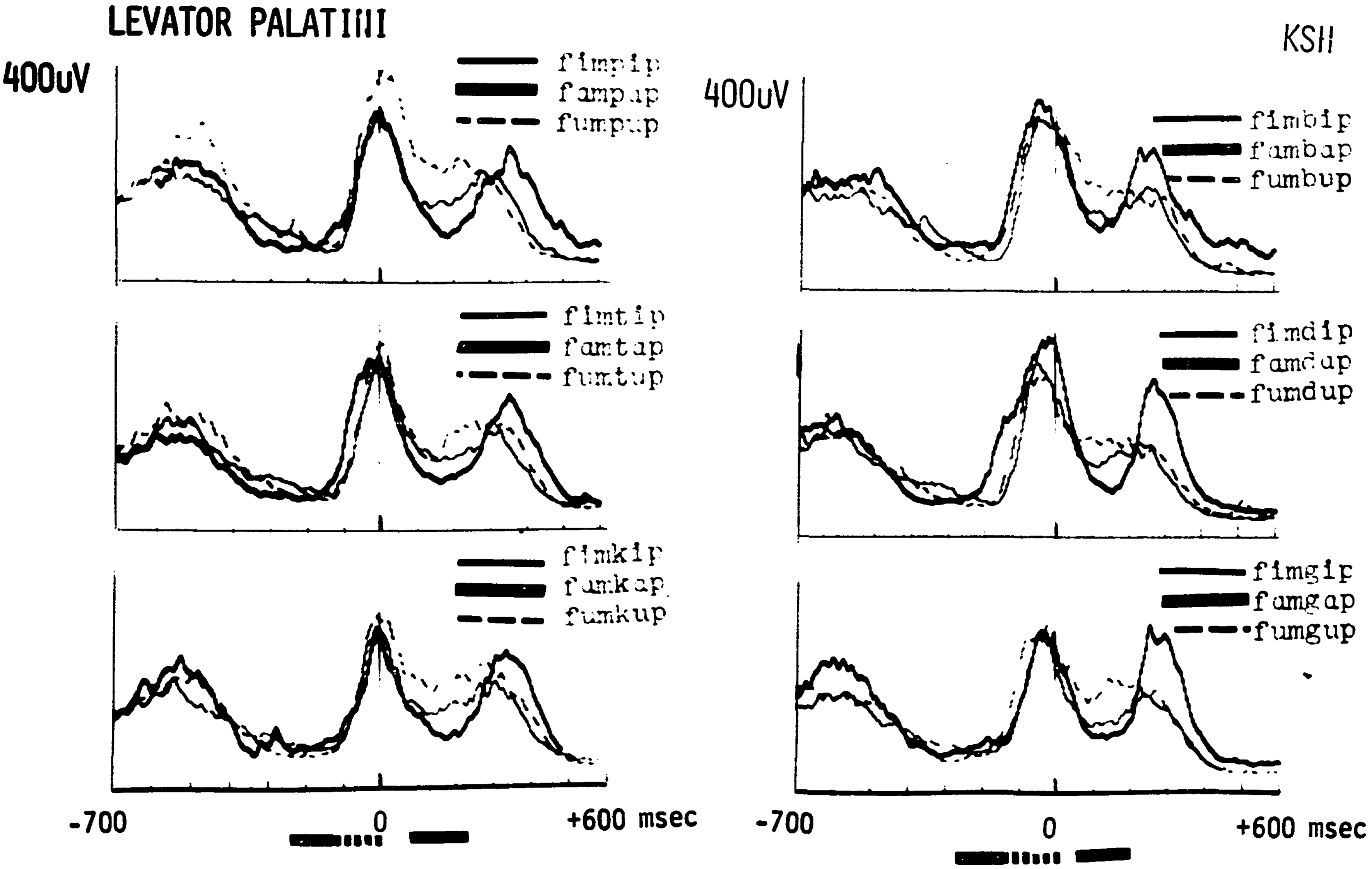
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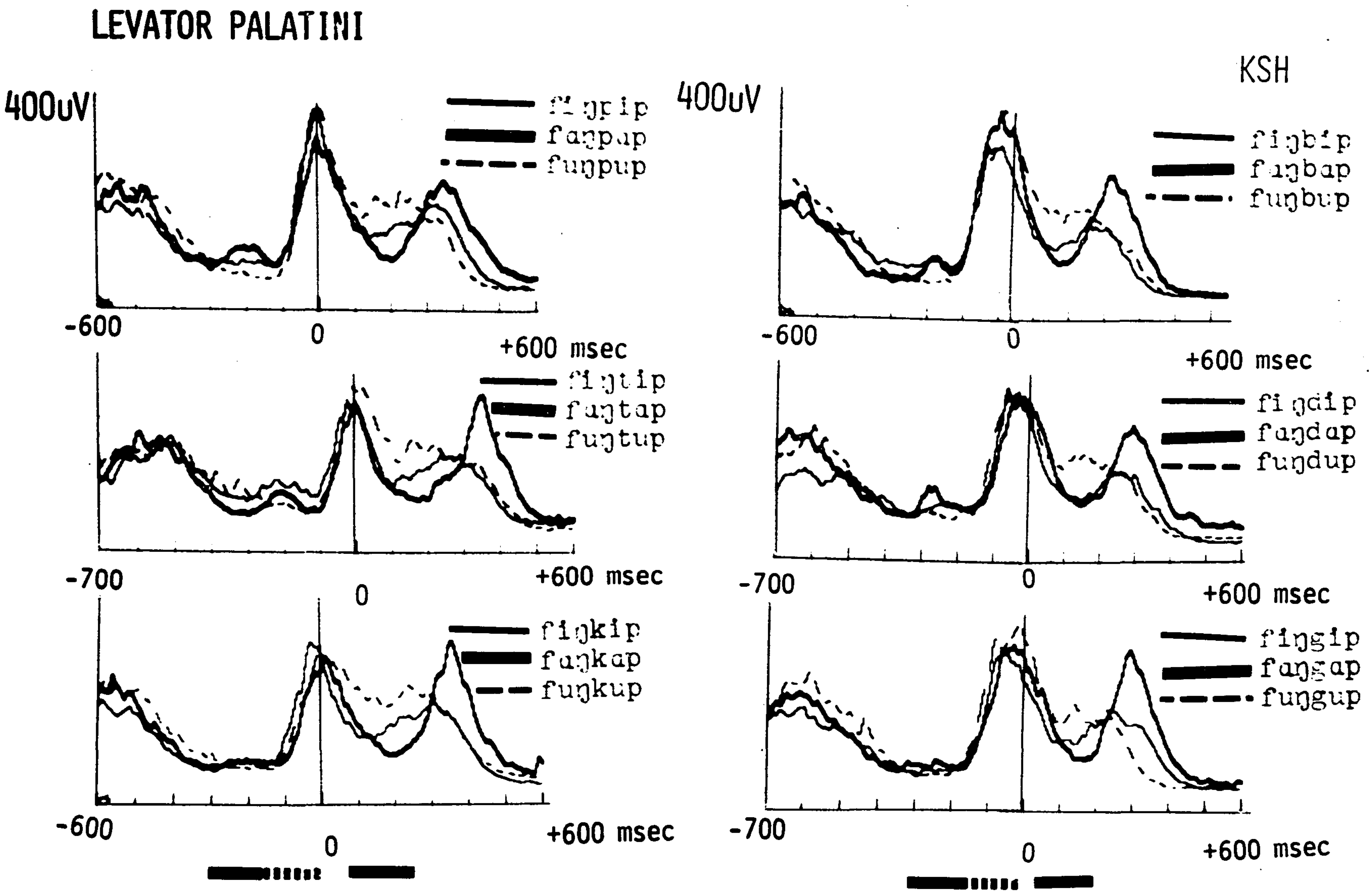
Figure 14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faŋbap
fuŋbup
-600
0
+600 msec
fiŋtip
faŋtap
fuŋtup
-700
0
+600 msec
fiŋdip
faŋdap
fuŋdup
-700
0
+600 msec
fiŋkip
faŋkap
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+600 msec
fiŋgip
faŋgap
fuŋgup
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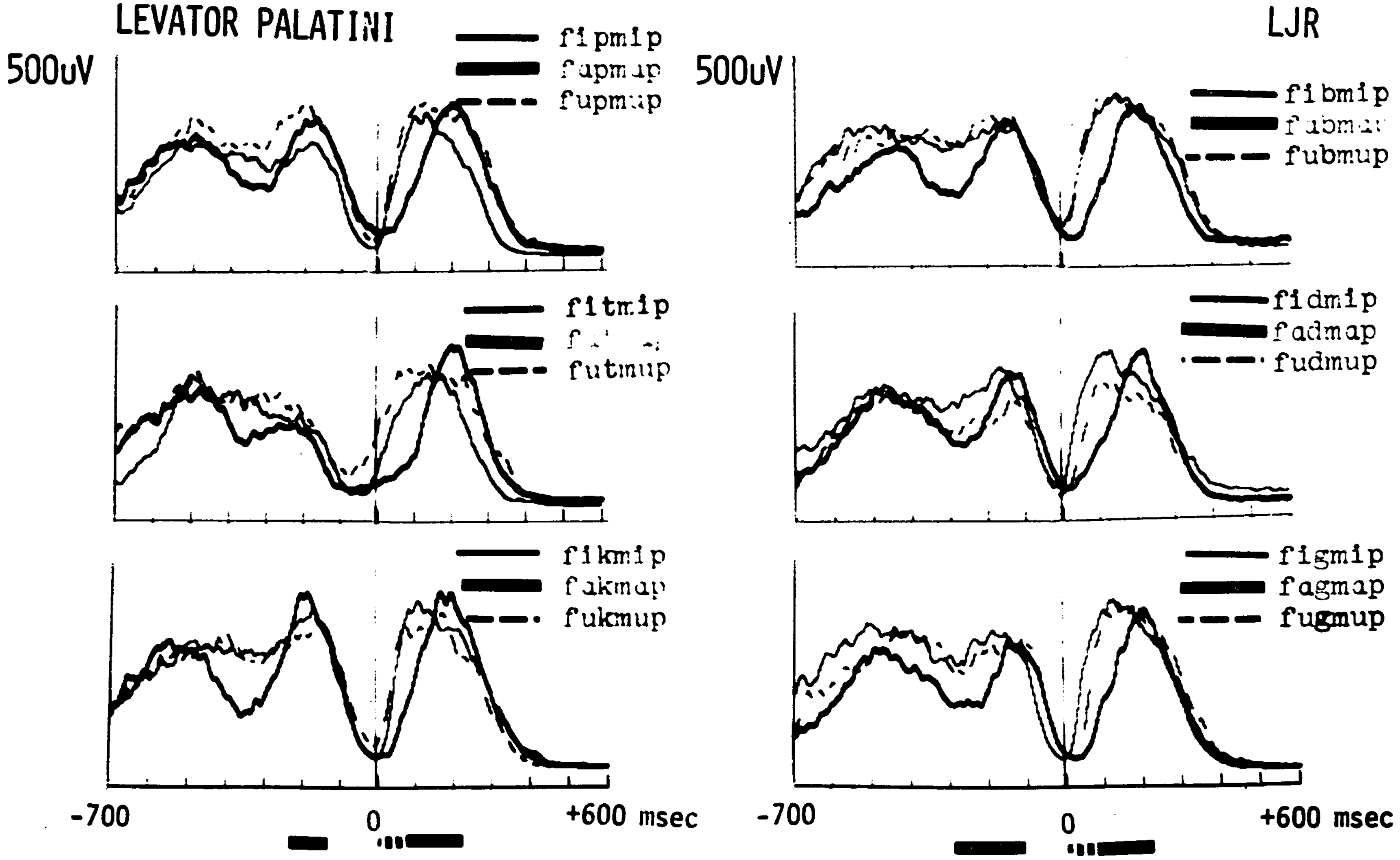
0
+600 msec

Figure 15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LJR
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500uV
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fapmap
fupmup
fitmip
futmup
fikmip
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fibmip
fabmap
fubmup
fidmip
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fagmap
fugmup
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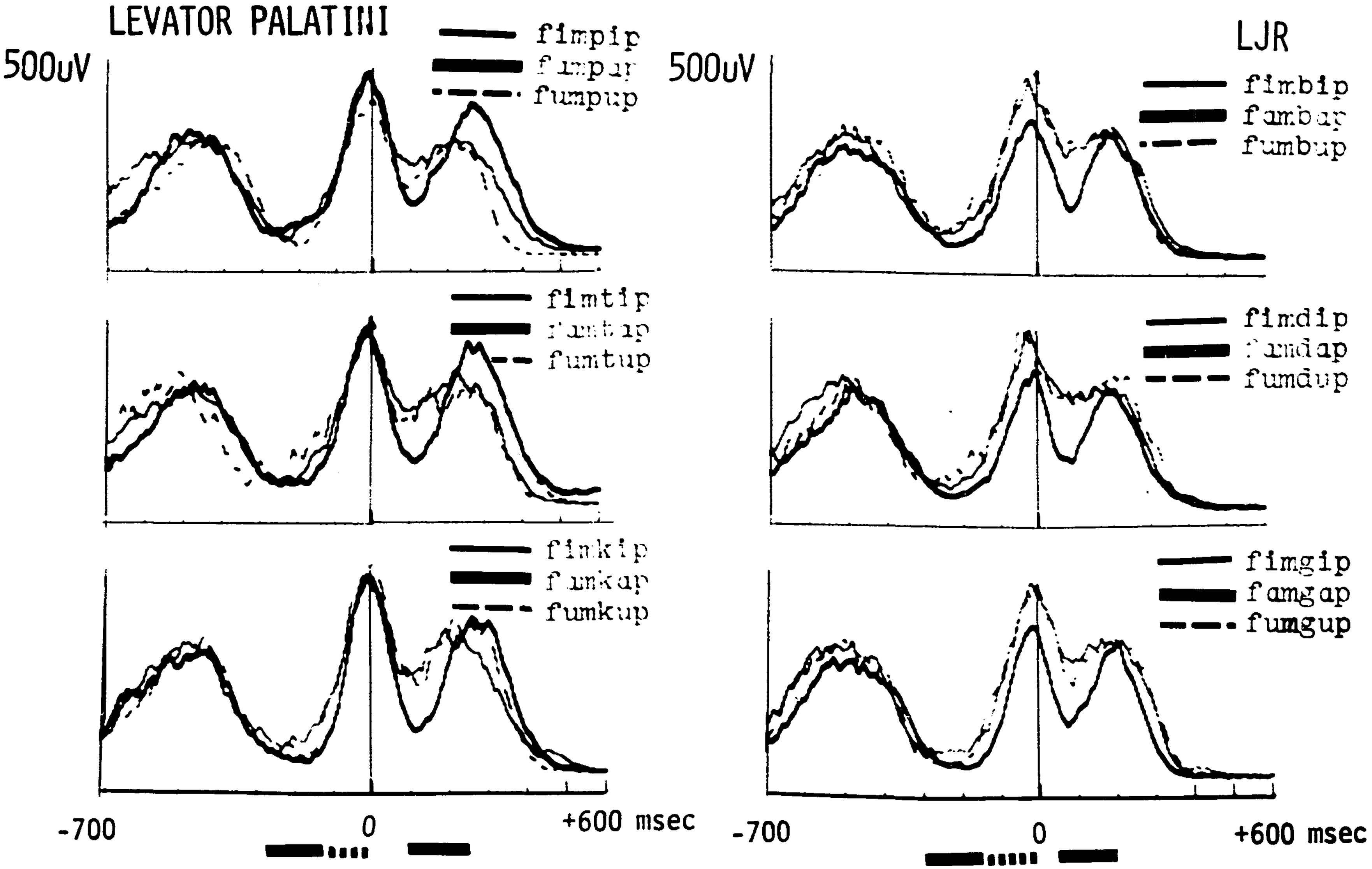
+600 msec
-700
0
+600 msec

Figure 16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fumkup
LJR
500uV
fimbip
fambap
fumbup
fimdip
famdap
fumdup
fimgip
famgap
fumgup
-700
0
+600 msec
-700
0
+600 msec

Figure 17

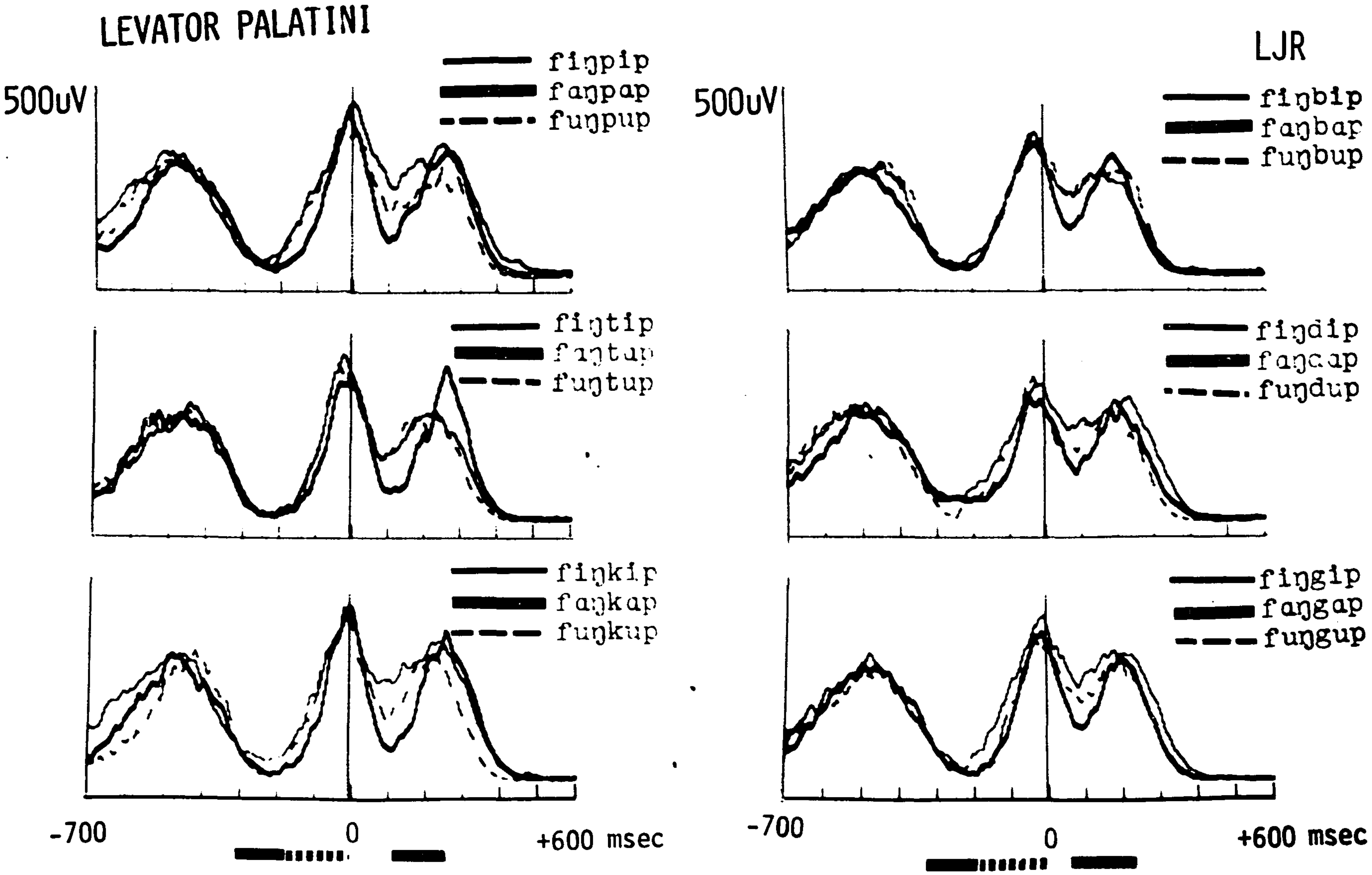

LEVATOR PALATINI
LJR
500uV
fiŋpip
faŋpap
fuŋpup
500uV
fiŋbip
faŋbap
fuŋbup
fiŋtip
faŋtap
fuŋtup
fiŋdip
faŋdap
fuŋdup
fiŋkip
faŋkap
fuŋkup
fiŋgip
faŋgap
fuŋgup
-700
0
+600 msec
-700
0
+600 msec

Figure 18

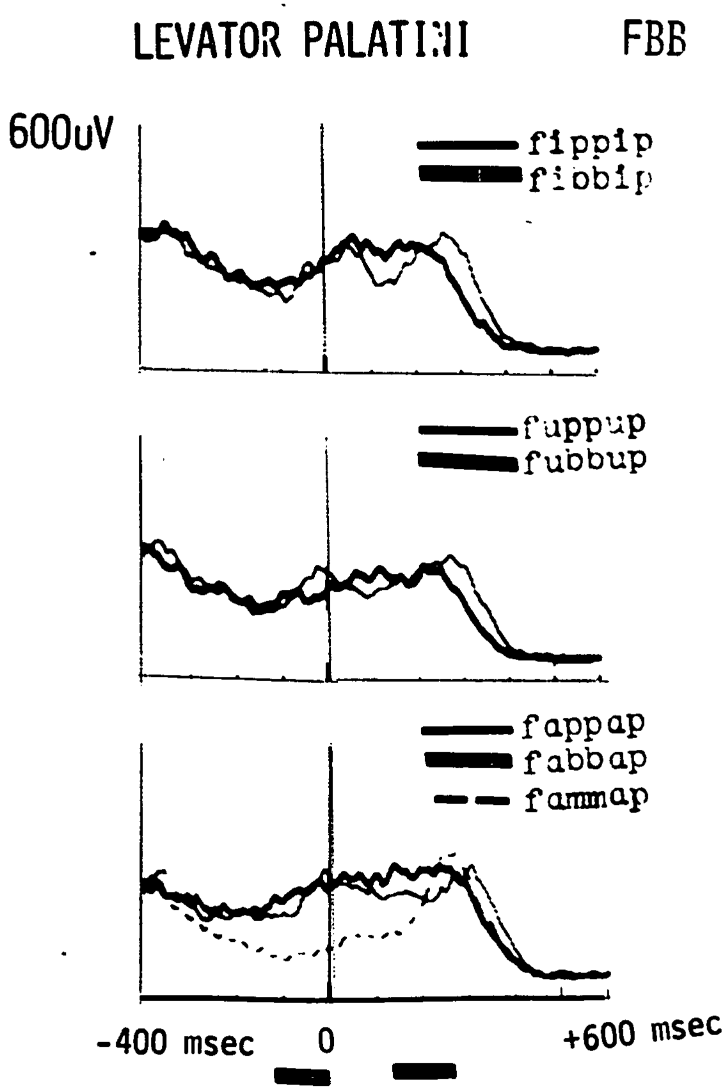

LEVATOR PALATINI
FBB
600uV
fippip
fibbip
fuppup
fubbup
fappap
fabbap
fammap
-400 msec
0
+600 msec

Figure 19

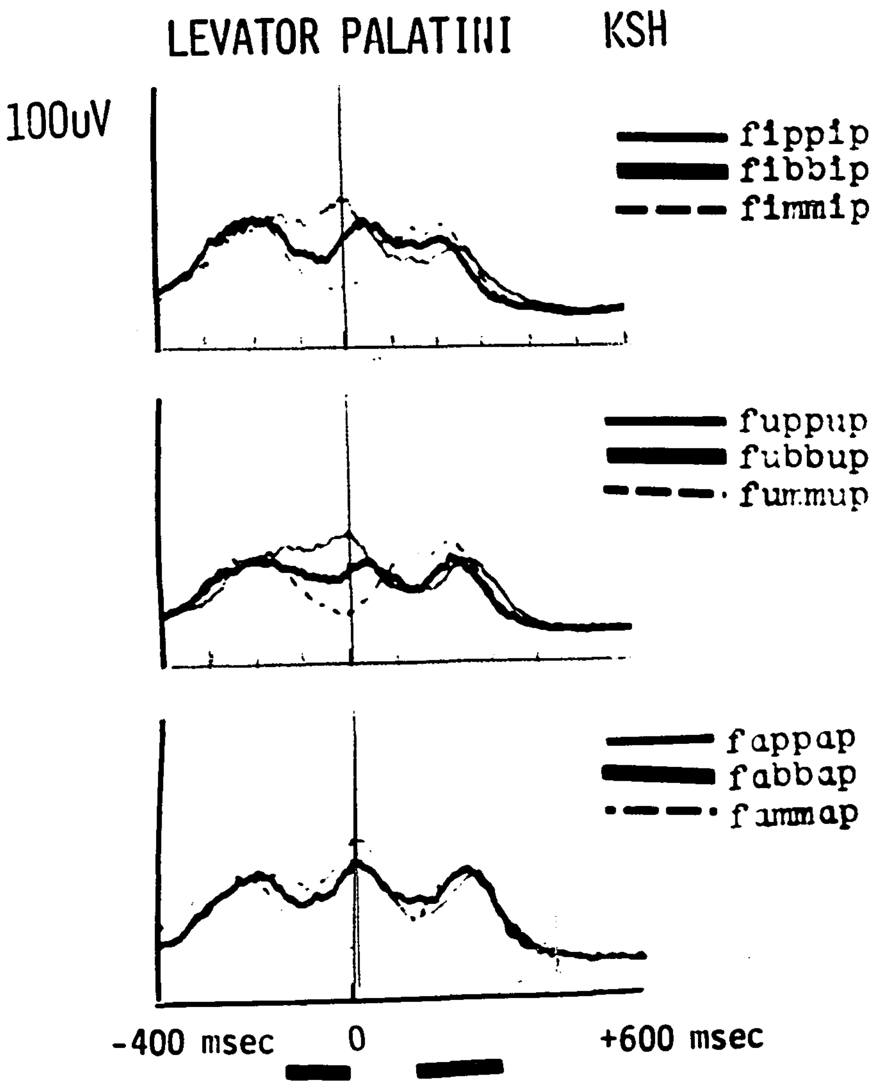

LEVATOR PALATINI KSH
100uV
fippip
fibbip
fimmip
fuppup
fubbup
fummup
fappap
fabbap
fammap
-400 msec
0
+600 msec

Figure 20

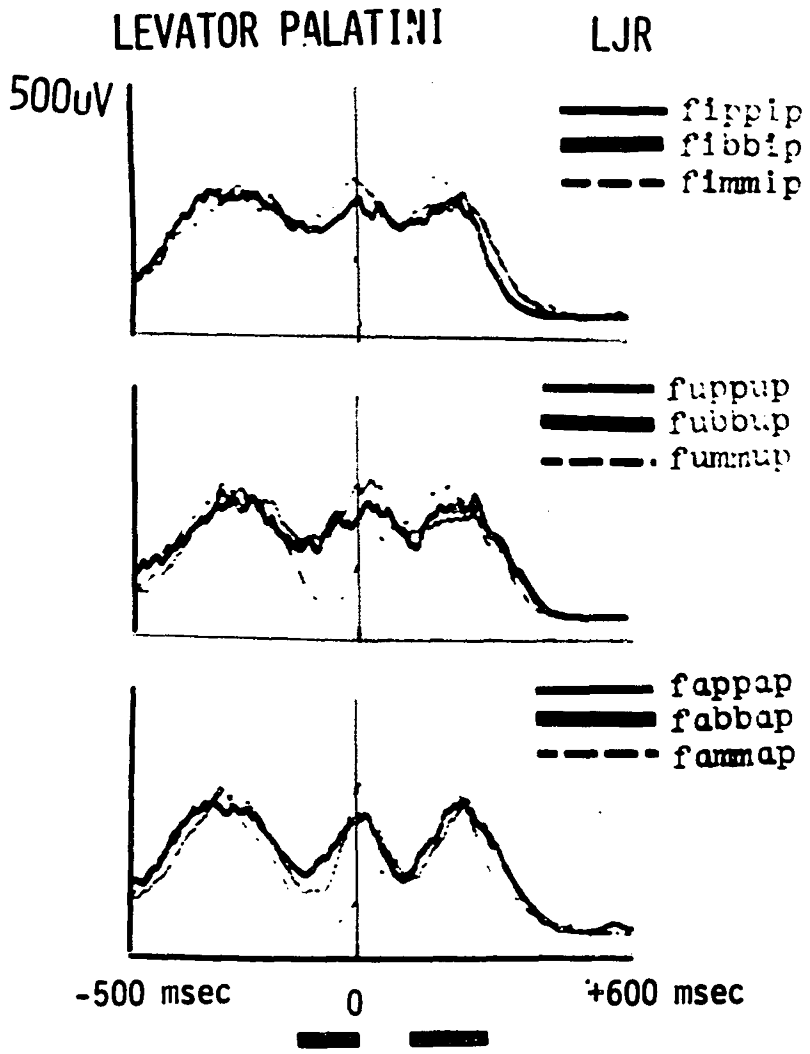

LEVATOR PALATINI
LJR
500uV
fippip
fibbip
fimmip
fuppup
fubbup
fummup
fappap
fabbap
fammap
-500 msec
0
+600 msec

Figure 21

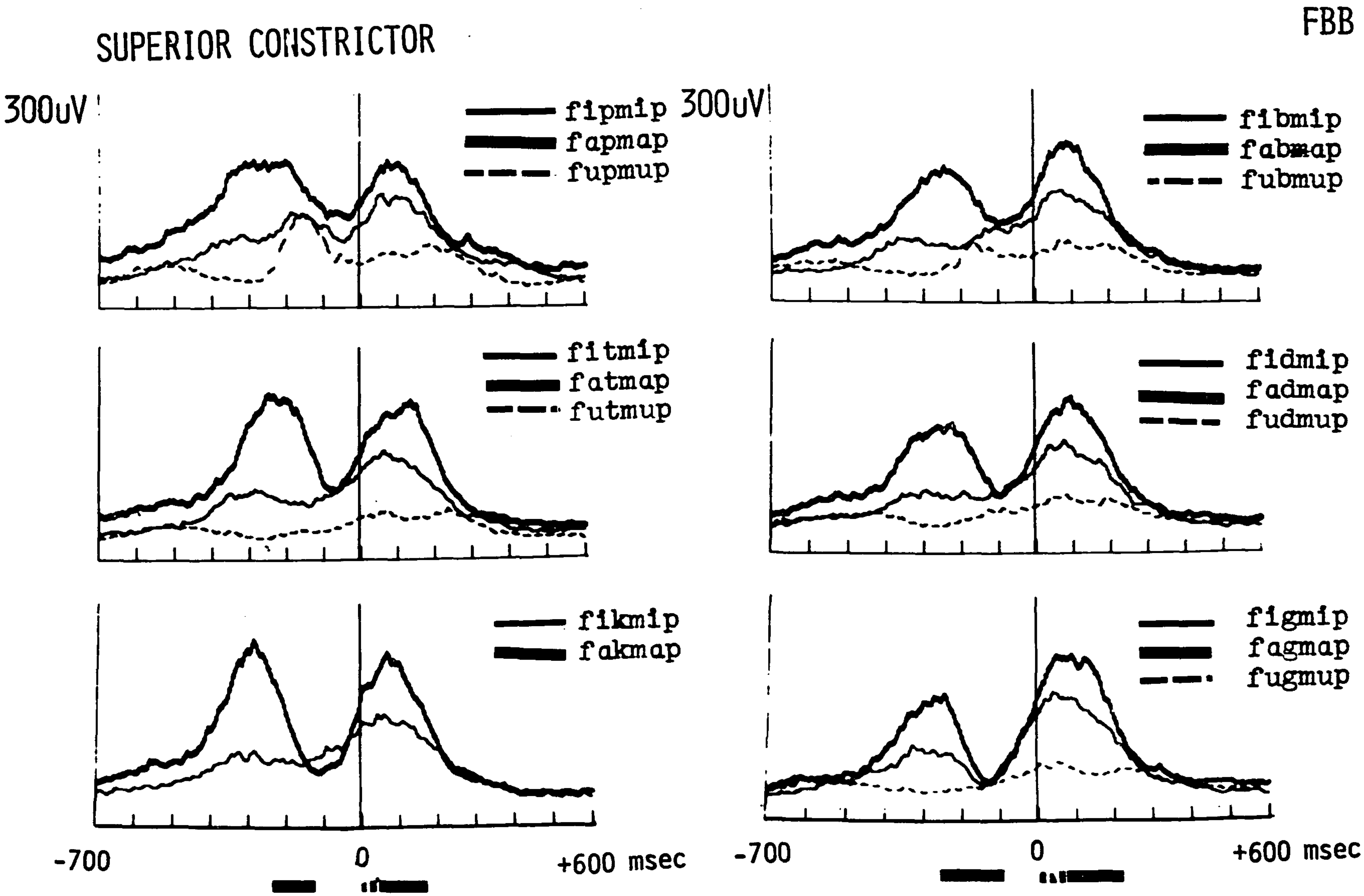

SUPERIOR CONSTRICTOR
FBB
300uV
fipmip
fapmap
fupmup
300uV
fibmip
fabmap
fubmup
fitmip
fatmap
futmup
fidmip
fadmap
fudmup
fikmip
fakmap
figmip
fagmap
fugmup
-700
0
+600 msec
-700
0
+600 msec

Figure 22

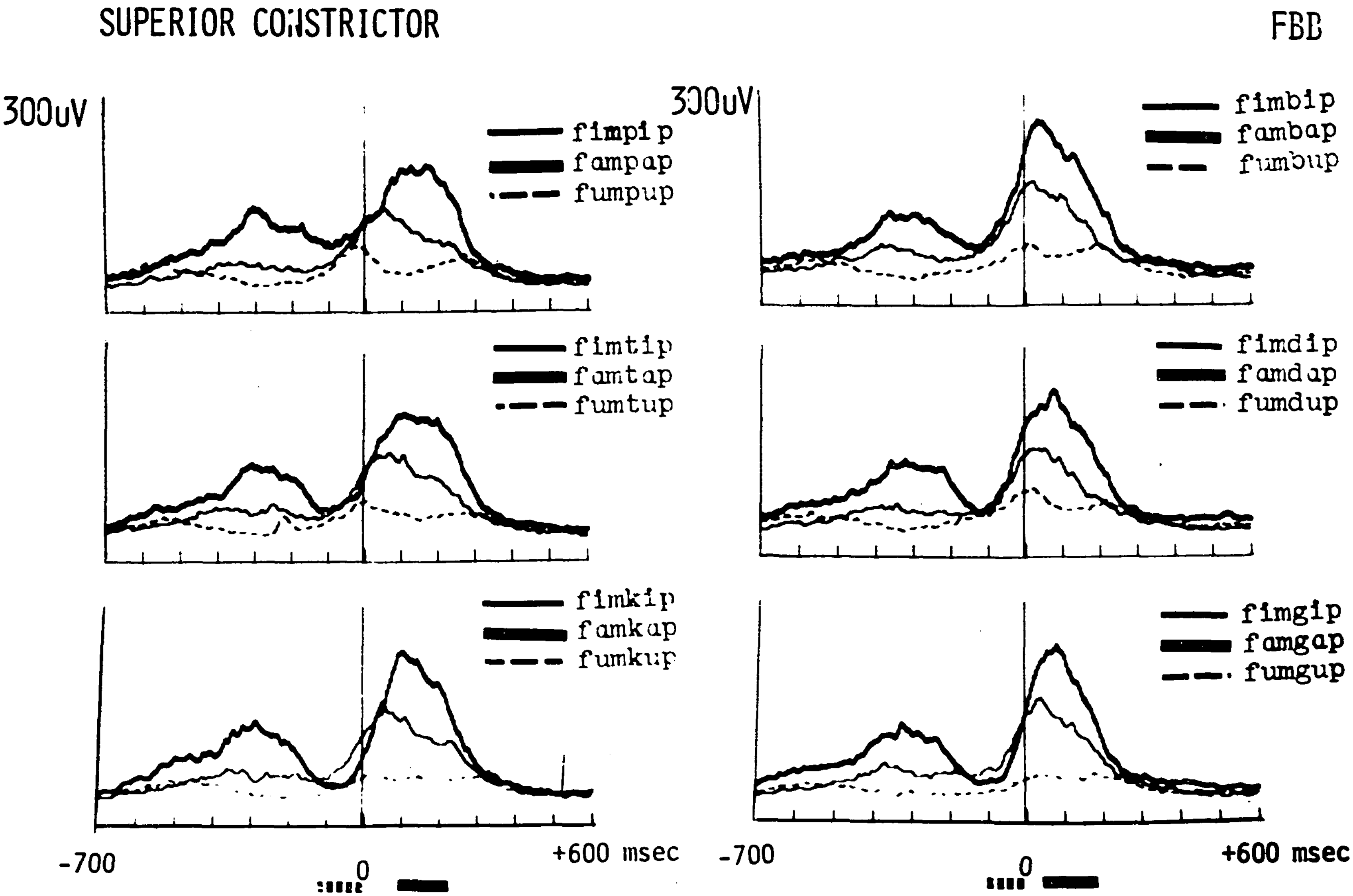

SUPERIOR CONSTRICTOR
FBB
300uV
fimpip
fampap
fumpup
fimtip
famtap
fumtup
fimkip
famkap
fumkup
300uV
fimbip
fambap
fumbup
fimdip
famdap
fumdup
fimgip
famgap
fumgup
-700
0
+600 msec
-700
0
+600 msec

Figure 23

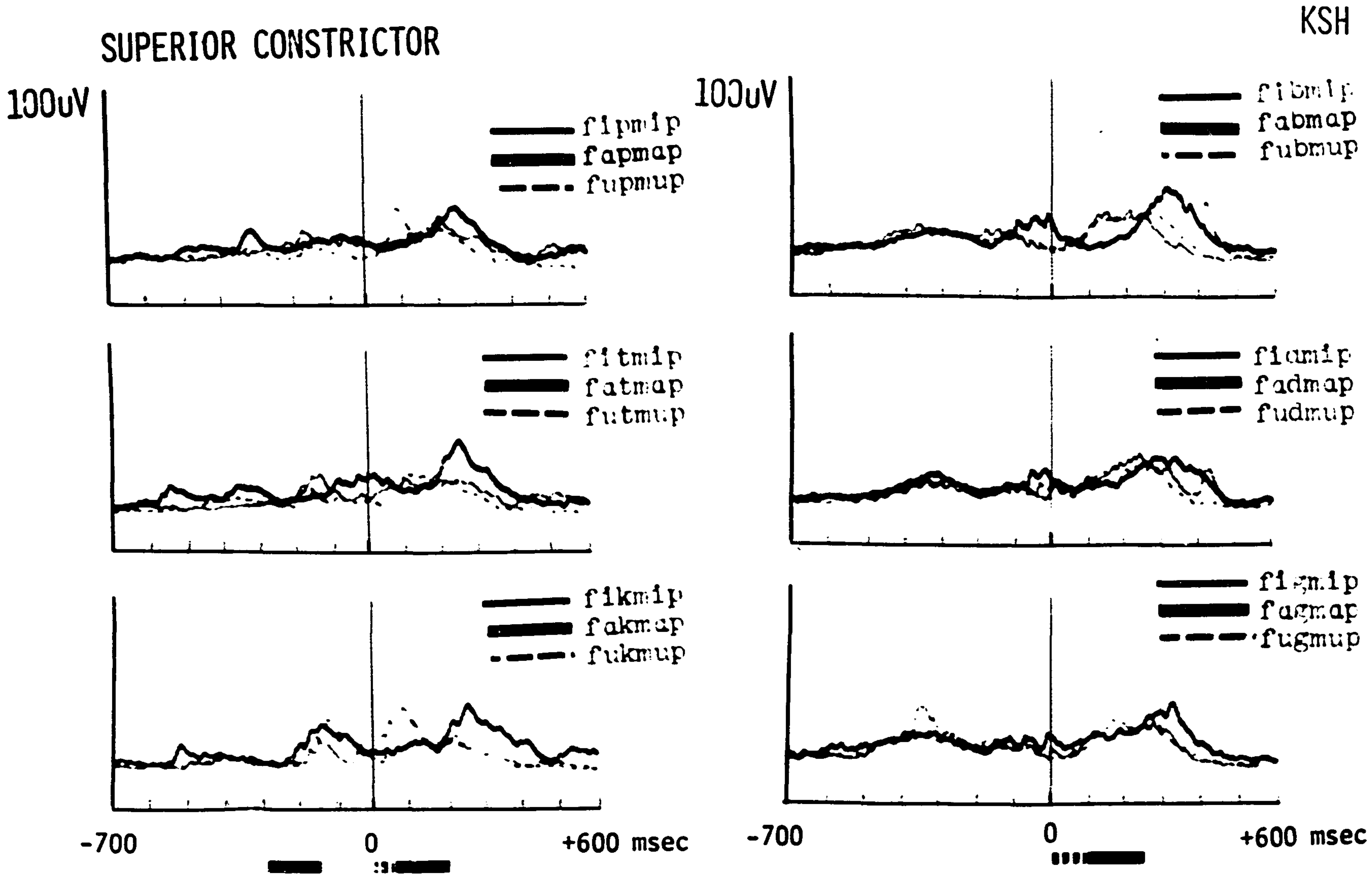

SUPERIOR CONSTRICTOR
KSH
100uV
fipmip
fapmap
fupmup
fitmip
fatmap
futmup
fikmip
fakmap
fukmup
100uV
fibmip
fabmap
fubmup
fidmip
fadmap
fudmup
figmip
fagmap
fugmup
-700
0
+600 msec
-700
0
+600 msec

Figure 24

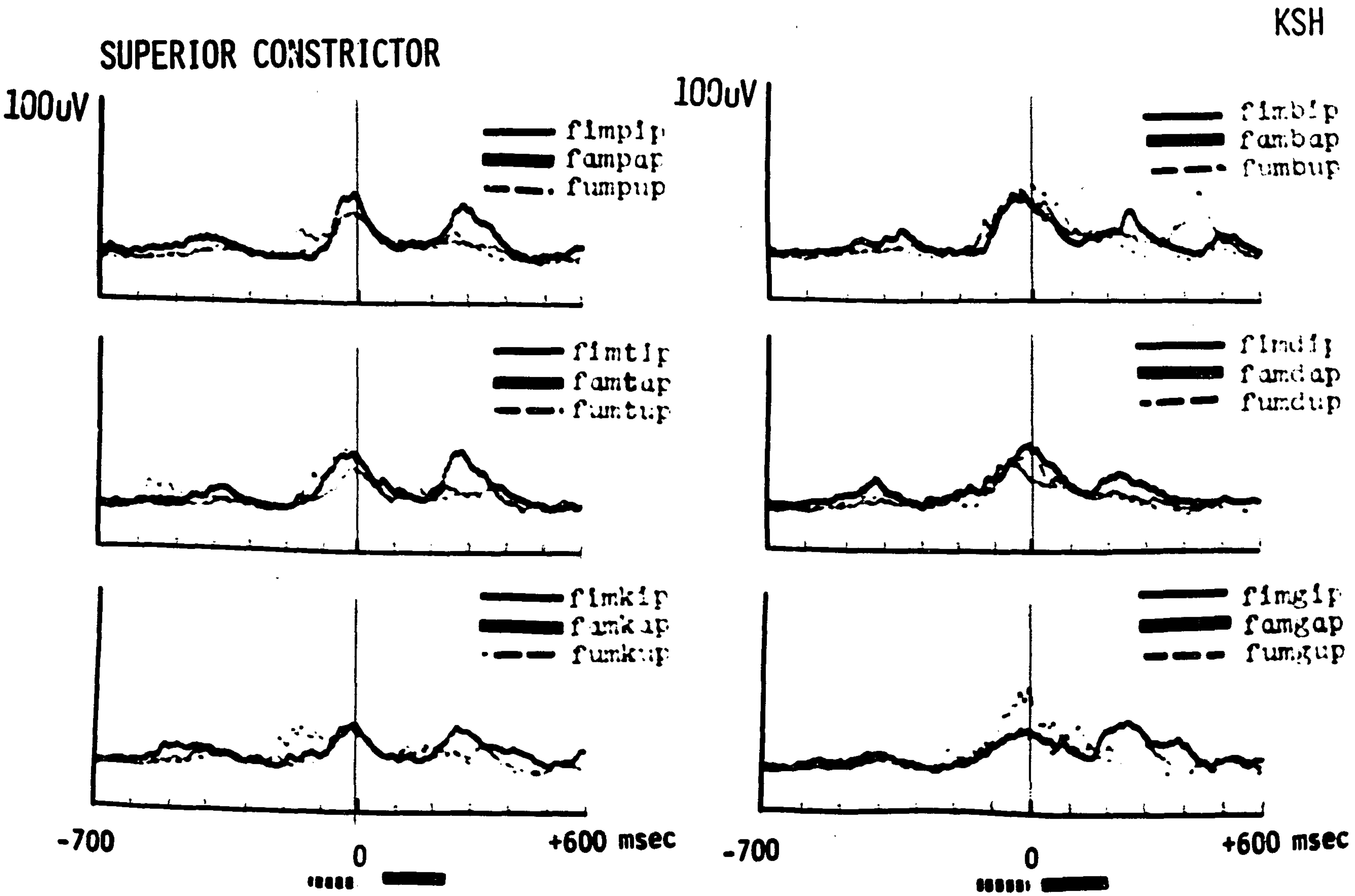

SUPERIOR CONSTRICTOR
KSH
100uV
fimpip
fampap
fumpup
100uV
fimbip
fambap
fumbup
fimtip
famtap
fumtup
fimdip
famdap
fumdup
fimkip
famkap
fumkup
fimgip
famgap
fumgup
-700
0
+600 msec
-700
0
+600 msec

Figure 25

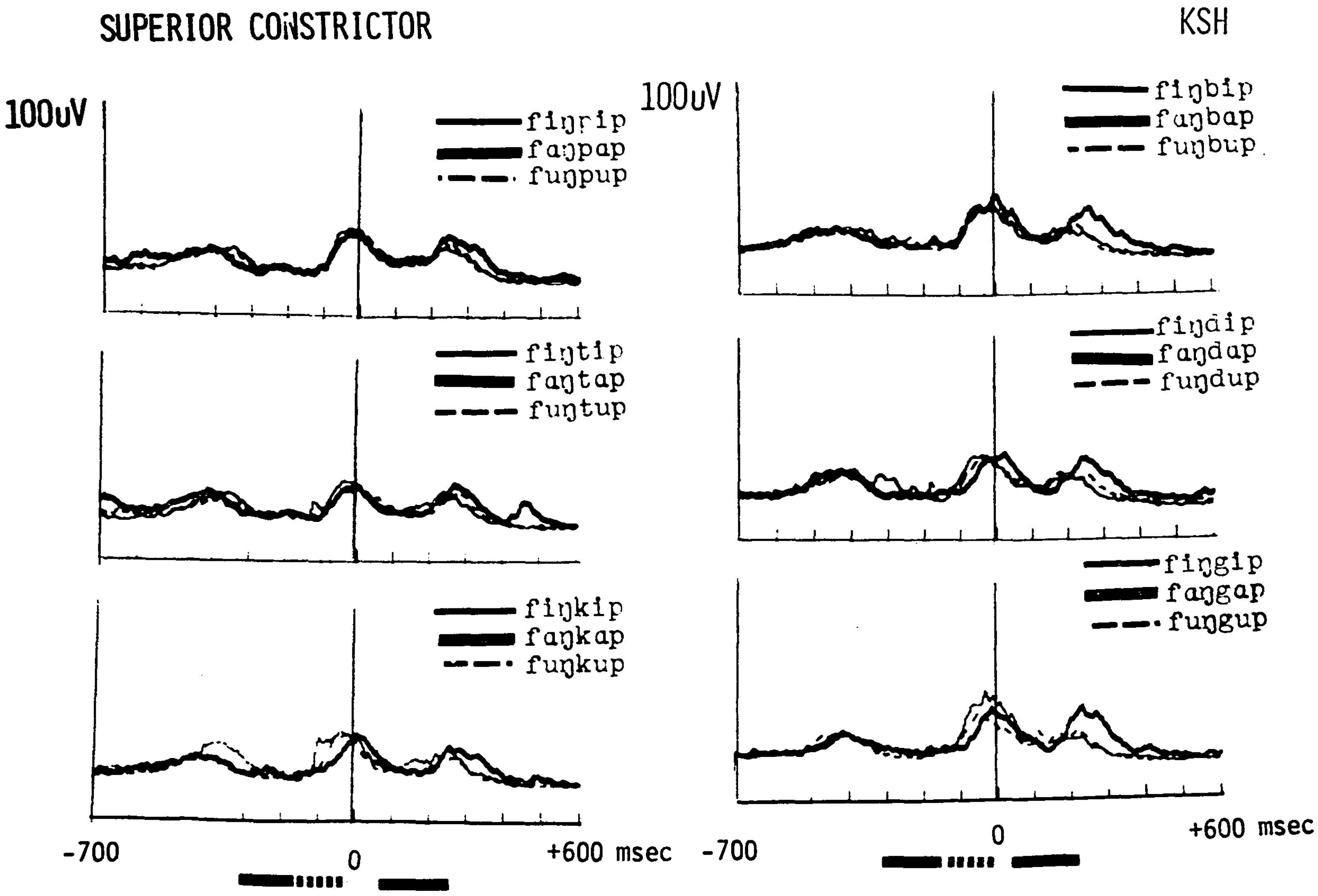

SUPERIOR CONSTRICTOR
KSH
100uV
fiŋrip
faŋpap
fuŋpup
fiŋtip
faŋtap
fuŋtup
fiŋkip
faŋkap
fuŋkup
100uV
fiŋbip
faŋbap
fuŋbup
fiŋdip
faŋdap
fuŋdup
fiŋgip
faŋgap
fuŋgup
-700
0
+600 msec
-700
0
+600 msec

Figure 26

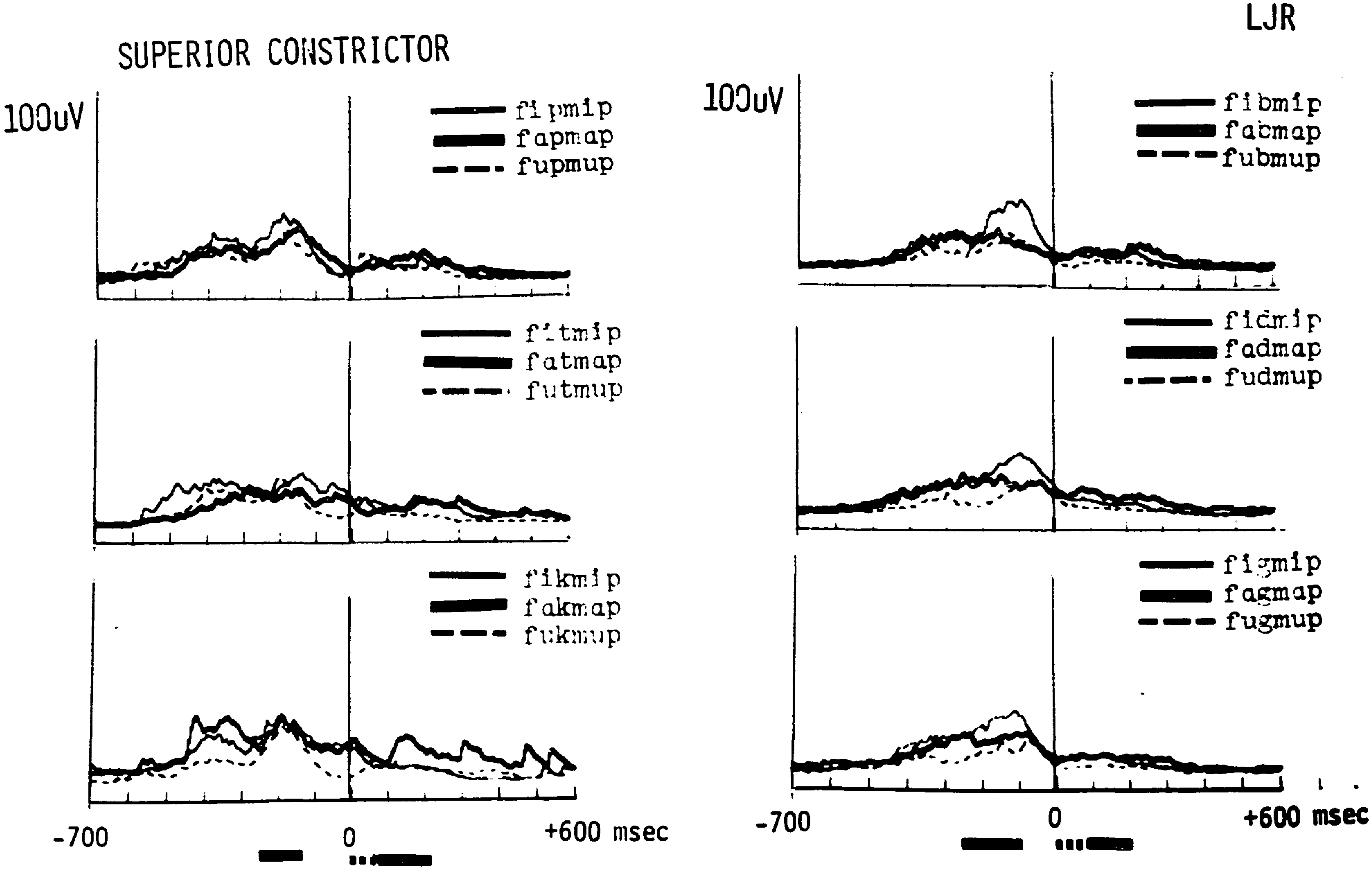

SUPERIOR CONSTRICTOR
LJR
100uV
fipmip
fapmap
fupmup
fitmip
fatmap
futmup
fikmip
fakmap
fukmup
100uV
fibmip
fabmap
fubmup
fidmip
fadmap
fudmup
figmip
fagmap
fugmup
-700
0
+600 msec
-700
0
+600 msec

Figure 27

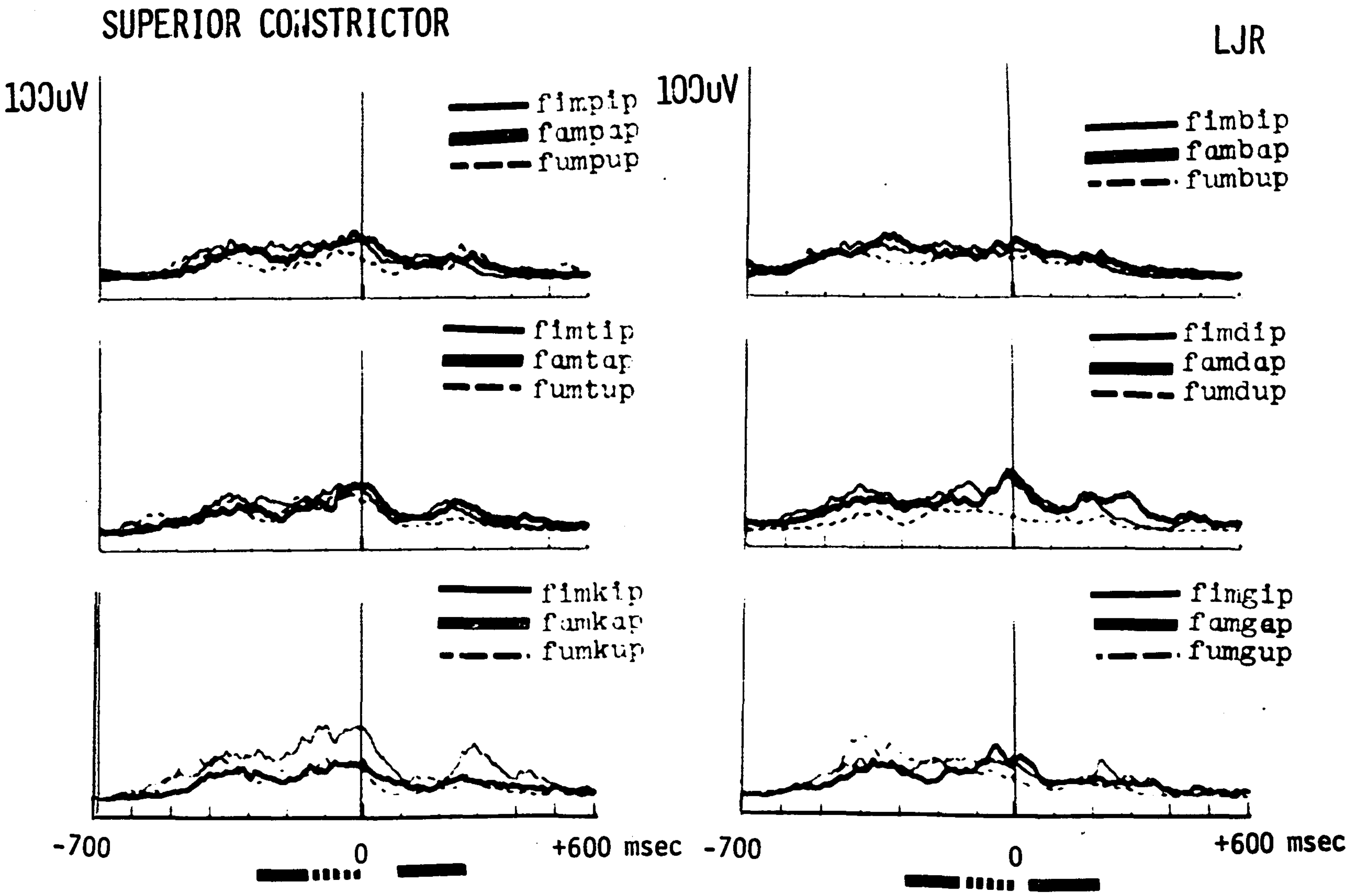

SUPERIOR CONSTRICTOR
LJR
100uV
fimpip
fampap
fumpup
100uV
fimbip
fambap
fumbup
fimtip
famtap
fumtup
fimdip
famdap
fumdup
fimkip
famkap
fumkup
fimgip
famgap
fumgup
-700
0
+600 msec
-700
0
+600 msec

Figure 28

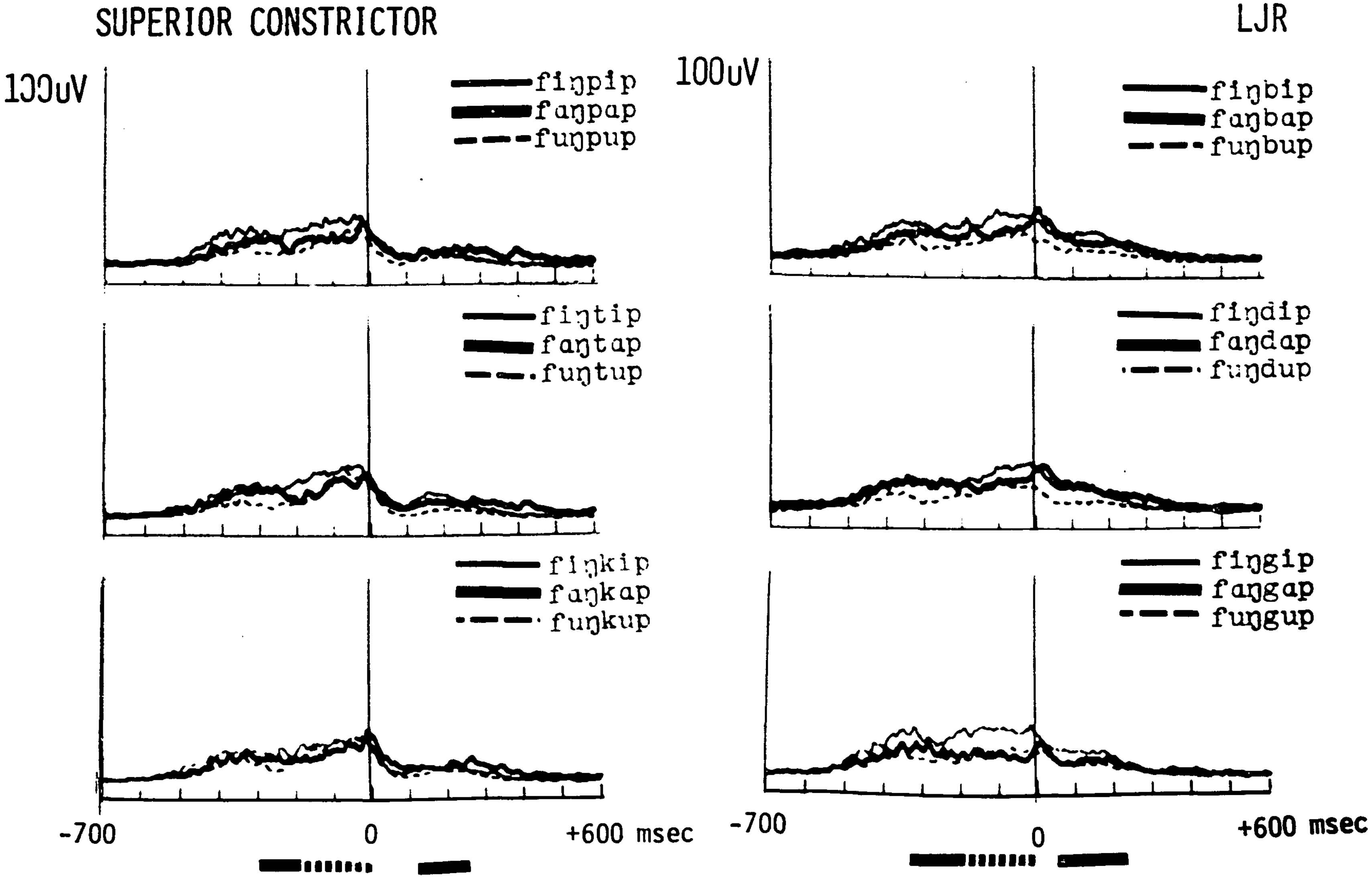

SUPERIOR CONSTRICTOR
LJR
100uV
fiŋpip
faŋpap
fuŋpup
100uV
fiŋbip
faŋbap
fuŋbup
fiŋtip
faŋtap
fuŋtup
fiŋdip
faŋdap
fuŋdup
fiŋkip
faŋkap
fuŋkup
fiŋgip
faŋgap
fuŋgup
-700
0
+600 msec
-700
0
+600 msec

Figure 29

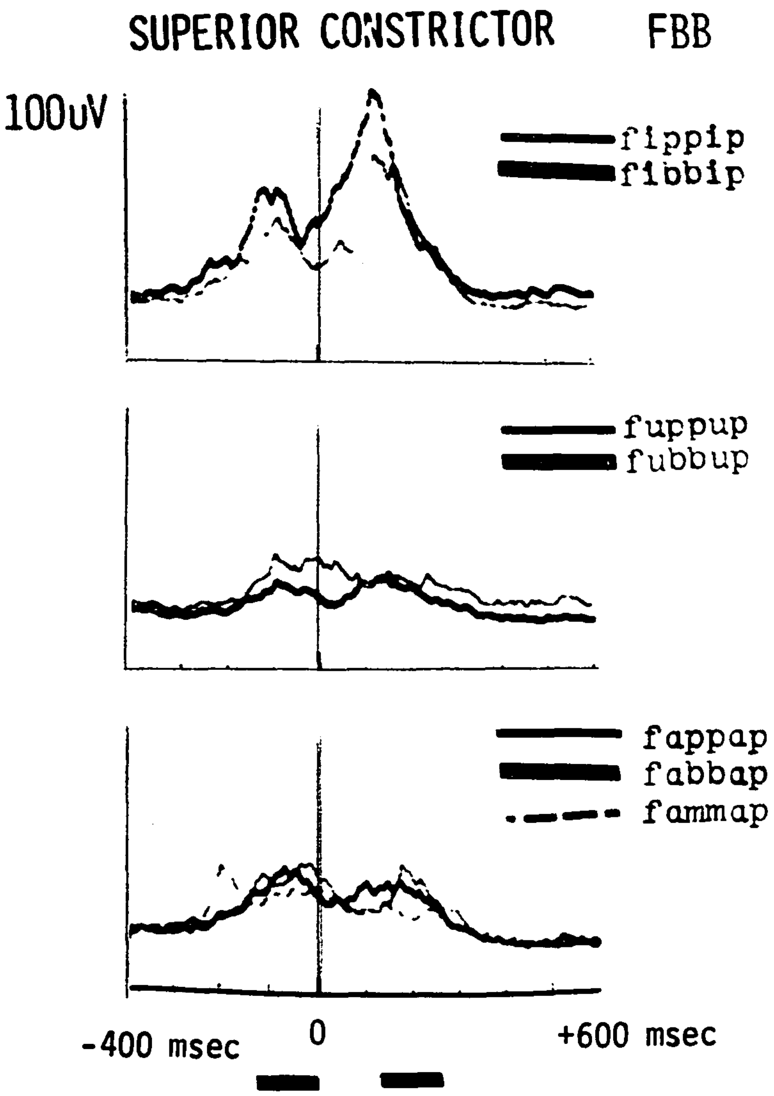

SUPERIOR CONSTRICTOR FBB
100uV
fippip
fibbip
fuppup
fubbup
fappap
fabbap
fammap
-400 msec
0
+600 msec

Figure 30

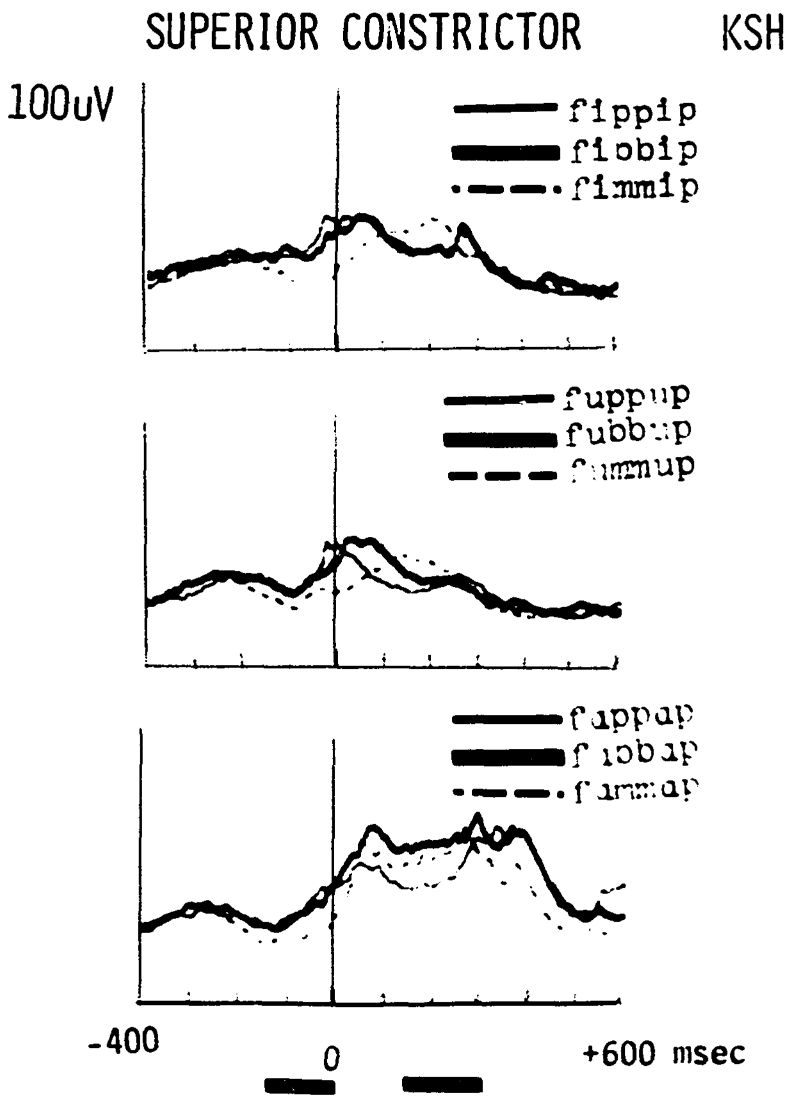

SUPERIOR CONSTRICTOR
KSH
100uV
fɪppɪp
fɪbbɪp
fɪmmɪp
fuppup
fubbup
fummup
fɐppɐp
fɐbbɐp
fɐmmɐp
-400
0
+600 msec

Figure 31

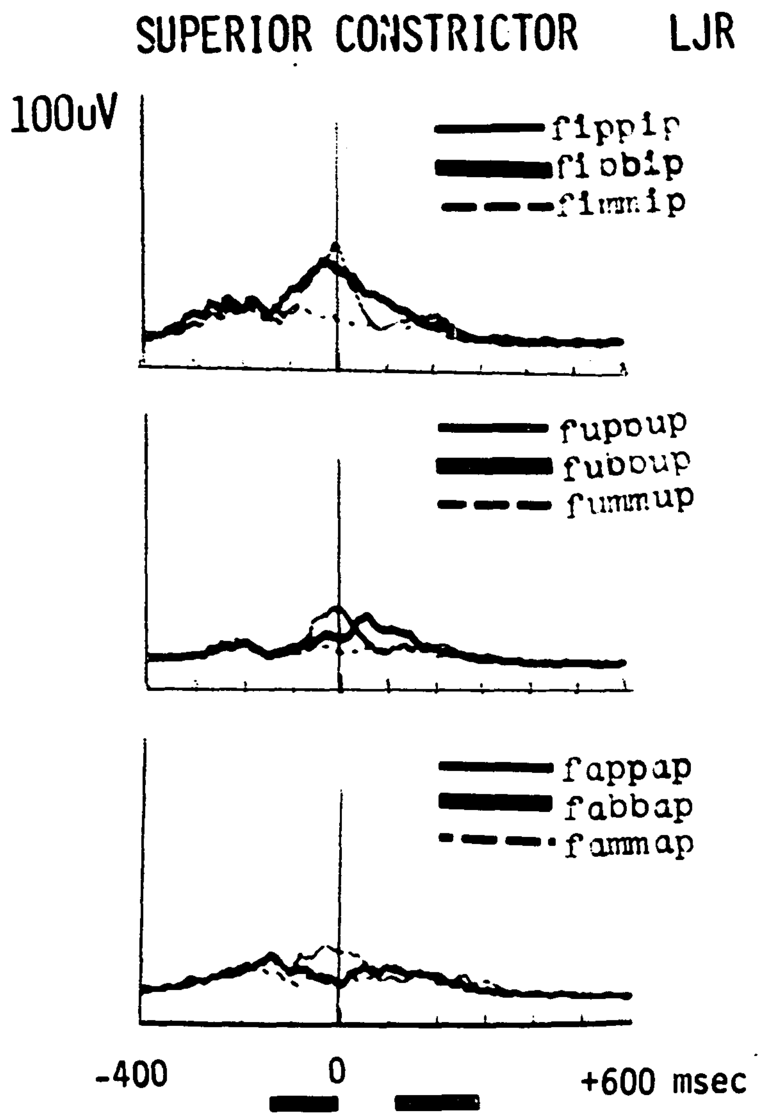

SUPERIOR CONSTRICTOR LJR
100uV
fippip
fibbip
fimmip
fuppup
fubbup
fummup
fappap
fabbap
fammap
-400
0
+600 msec

Figure 32

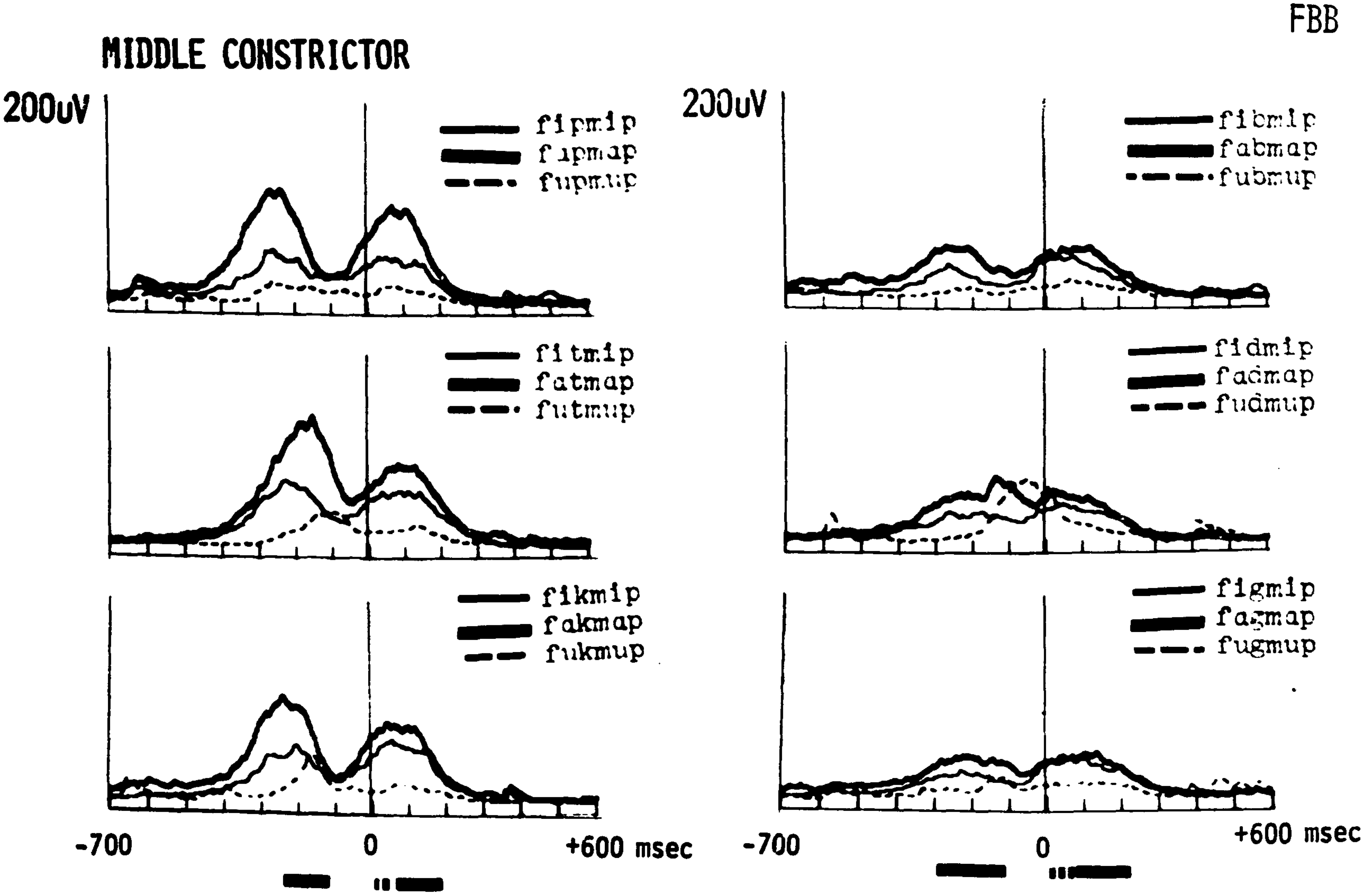

MIDDLE CONSTRICTOR
FBB
200uV
fipmip
fapmap
fupmup
fitmip
fatmap
futmup
fikmip
fakmap
fukmup
200uV
fibmip
fabmap
fubmup
fidmip
fadmap
fudmup
figmip
fagmap
fugmup
-700
0
+600 msec
-700
0
+600 msec

Figure 33

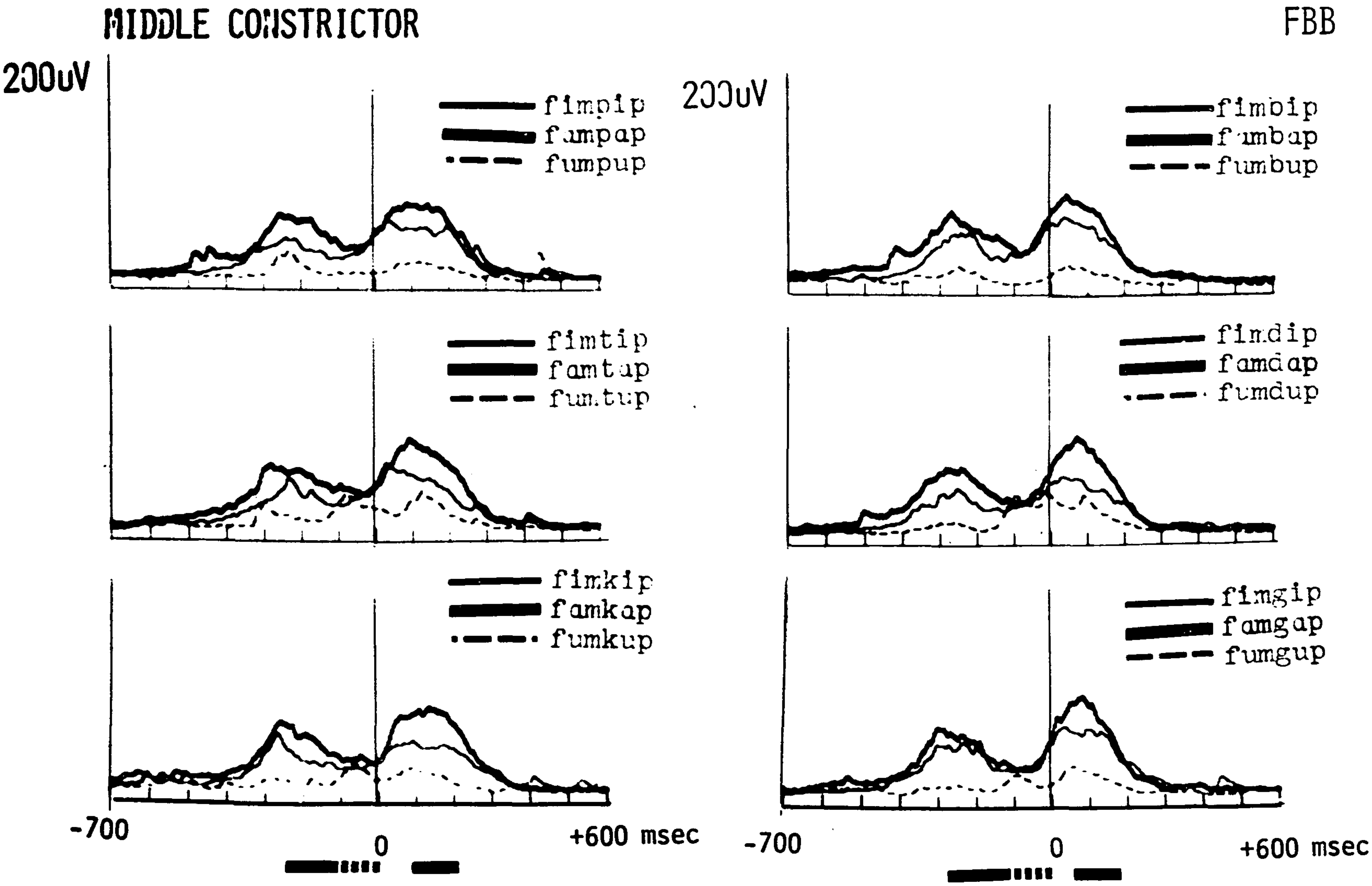

MIDDLE CONSTRICTOR
FBB
200uV
fimpip
fampap
fumpup
fimtip
famtap
fumtup
fimkip
famkap
fumkup
200uV
fimbip
fambap
fumbup
fimdip
famdap
fumdup
fimgip
famgap
fumgup
-700
0
+600 msec
-700
0
+600 msec

Figure 34

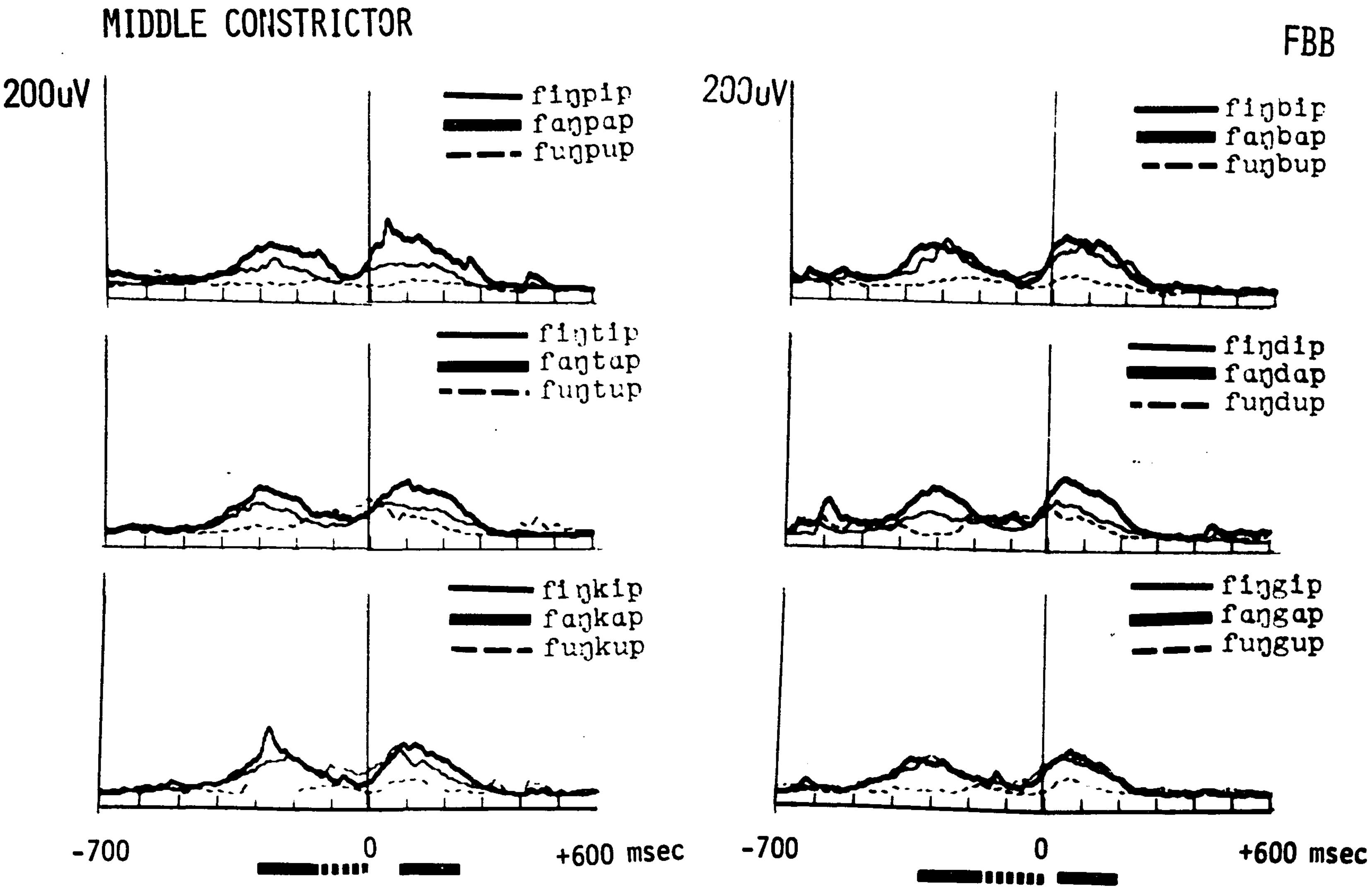

MIDDLE CONSTRICTOR
FBB
200uV
fiŋpip
faŋpap
fuŋpup
fiŋtip
faŋtap
fuŋtup
fiŋkip
faŋkap
fuŋkup
200uV
fiŋbip
faŋbap
fuŋbup
fiŋdip
faŋdap
fuŋdup
fiŋgip
faŋgap
fuŋgup
-700
0
+600 msec
-700
0
+600 msec

Figure 35

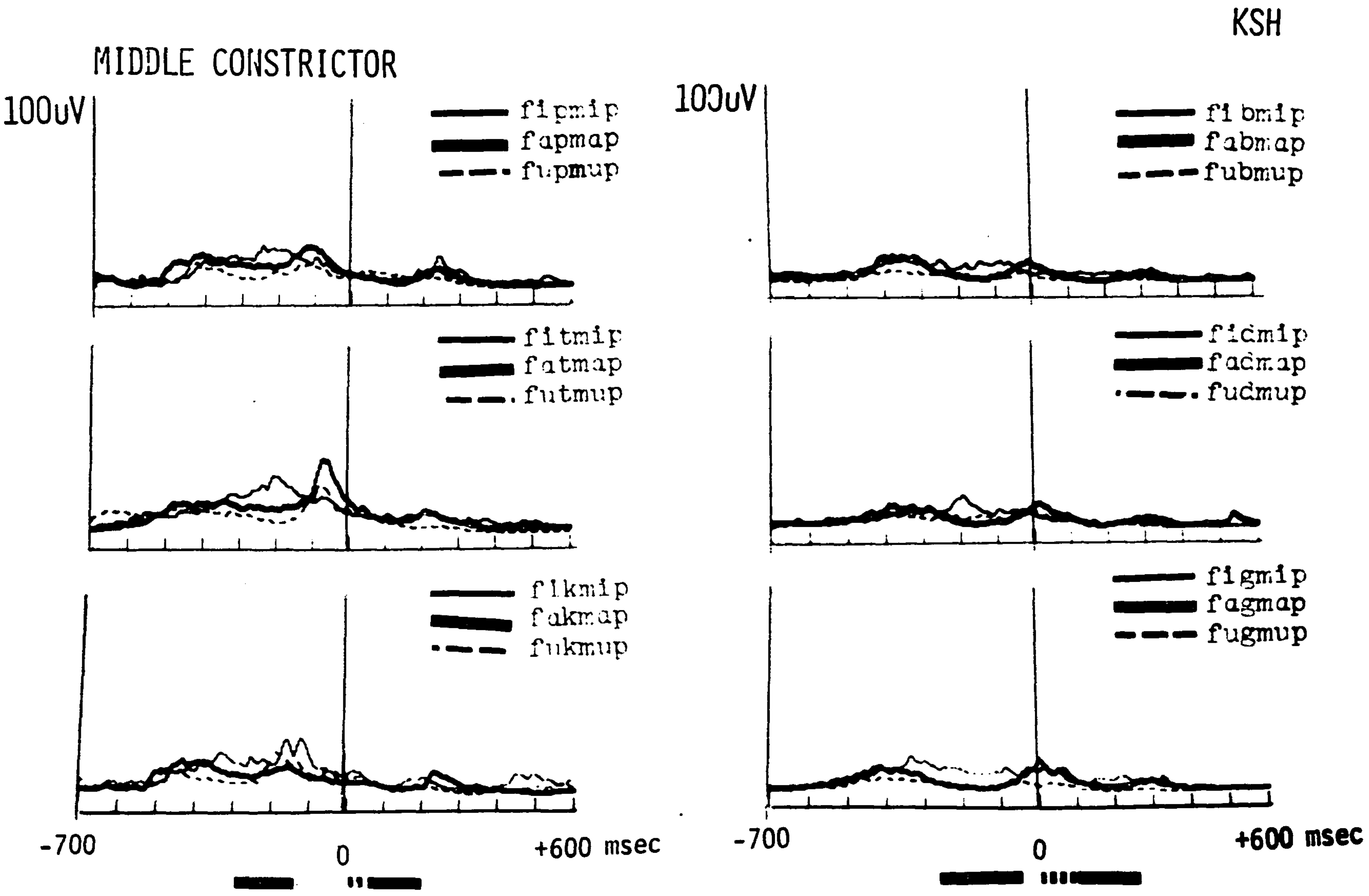

KSH
MIDDLE CONSTRICTOR
100uV
fipmip
fapmap
fupmup
100uV
fibmip
fabmap
fubmup
fitmip
fatmap
futmup
fidmip
fadmap
fudmup
fikmip
fakmap
fukmup
figmip
fagmap
fugmup
-700
0
+600 msec
-700
0
+600 msec

Figure 36

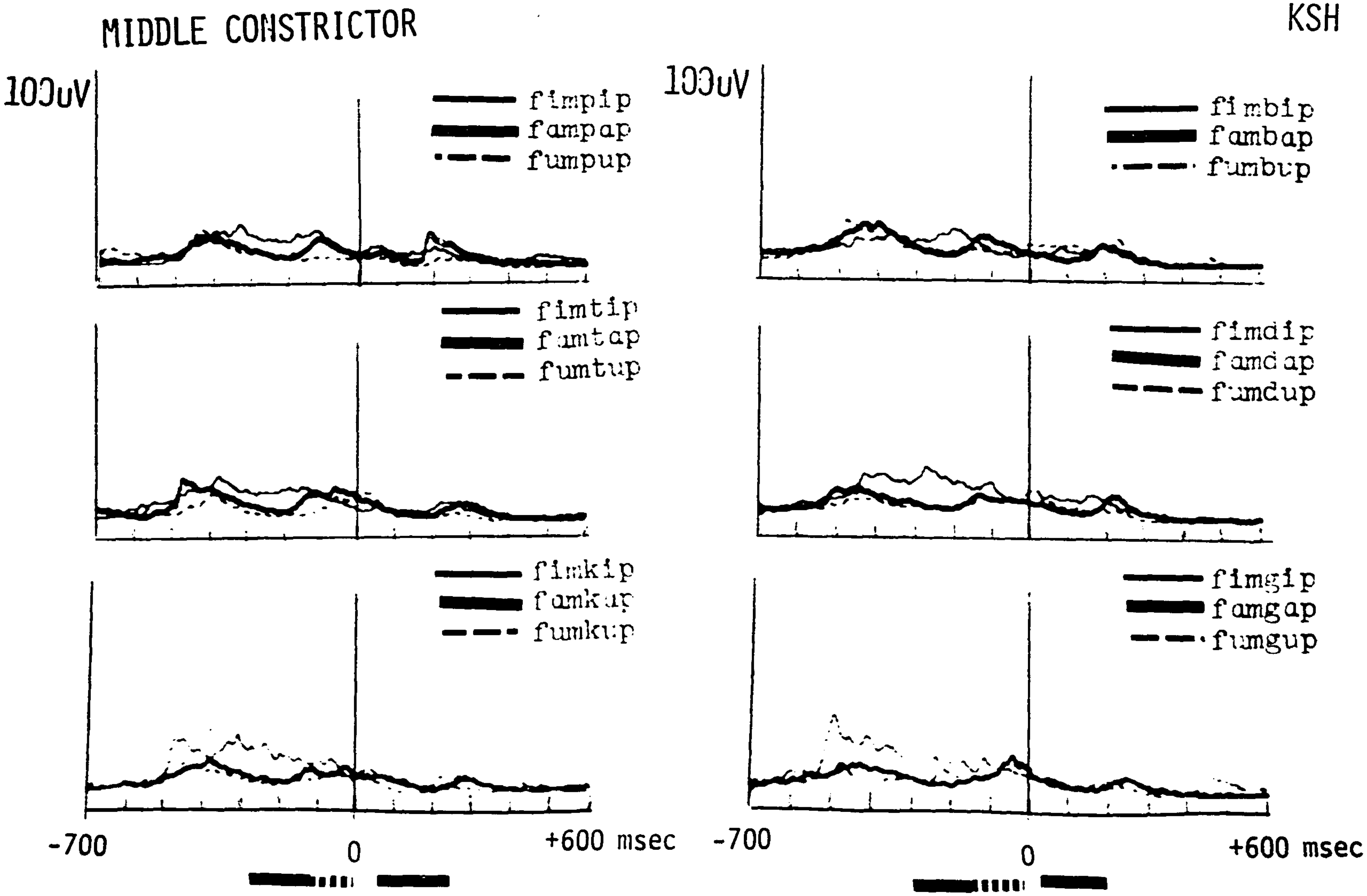

MIDDLE CONSTRICTOR
KSH
100uV
fimpip
fampap
fumpup
100uV
fimbip
fambap
fumbup
fimtip
famtap
fumtup
fimdip
famdap
fumdup
fimkip
famkap
fumkup
fimgip
famgap
fumgup
-700
0
+600 msec
-700
0
+600 msec

Figure 37

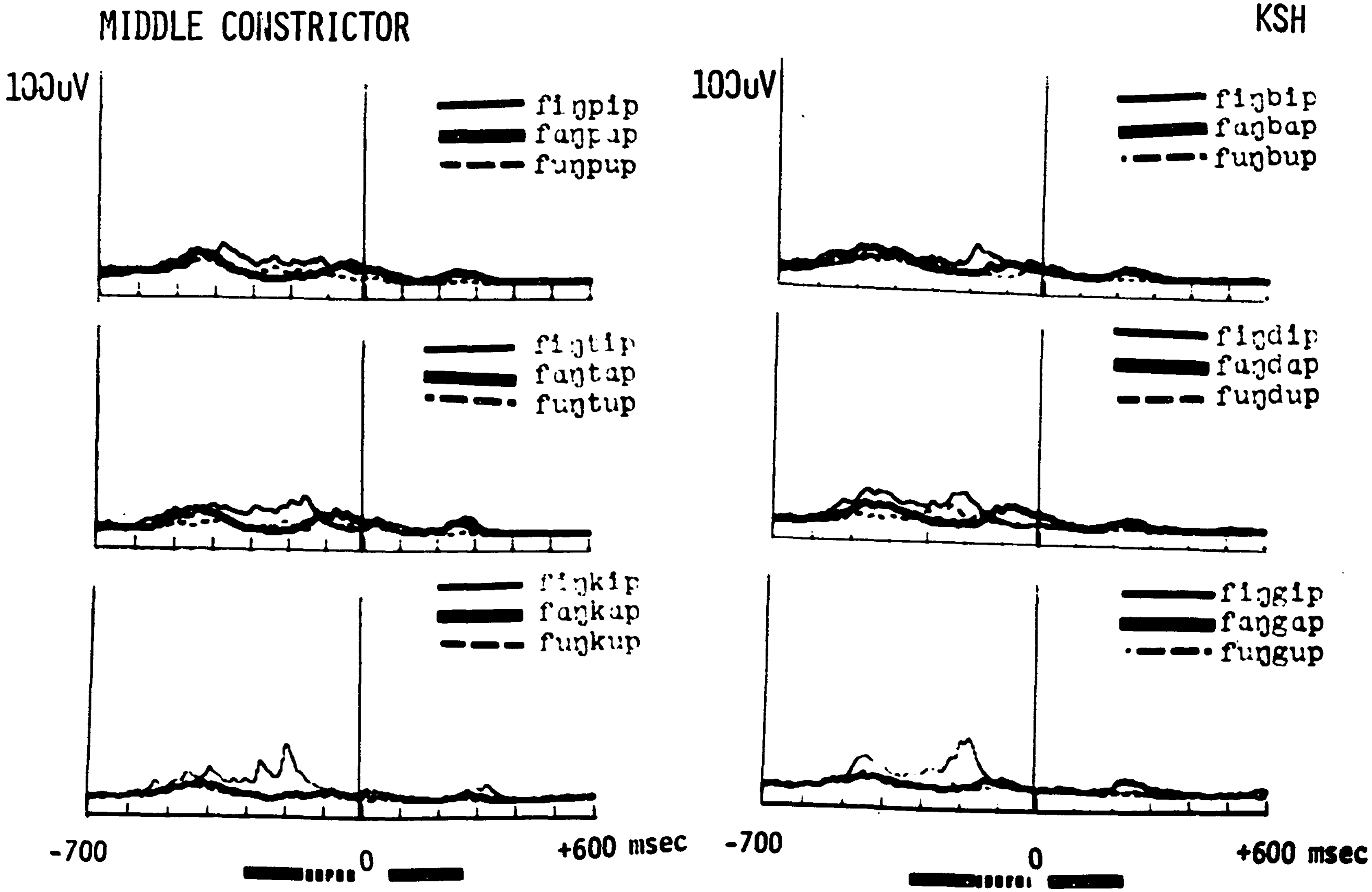

MIDDLE CONSTRICTOR
KSH
100uV
100uV
fiŋpip
faŋpap
fuŋpup
fiŋtip
faŋtap
fuŋtup
fiŋkip
faŋkap
fuŋkup
fiŋbip
faŋbap
fuŋbup
fiŋdip
faŋdap
fuŋdup
fiŋgip
faŋgap
fuŋgup
-700
0
+600 msec
-700
0
+600 msec

Figure 38

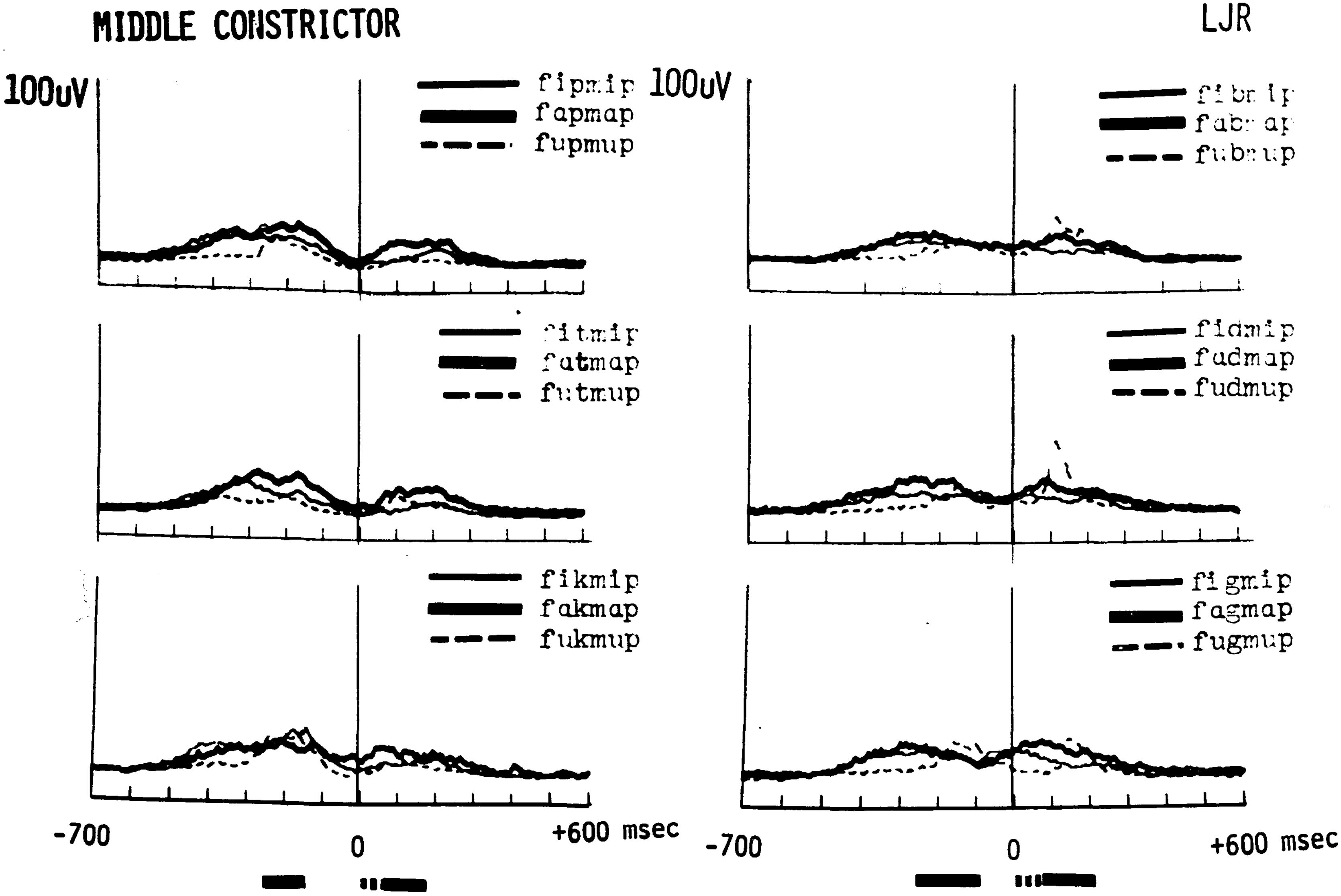

MIDDLE CONSTRICTOR
LJR
100uV
fipmip
fapmap
fupmup
100uV
fibmip
fabmap
fubmup
fitmip
fatmap
futmup
fidmip
fadmap
fudmup
fikmip
fakmap
fukmup
figmip
fagmap
fugmup
-700
0
+600 msec
-700
0
+600 msec

Figure 39

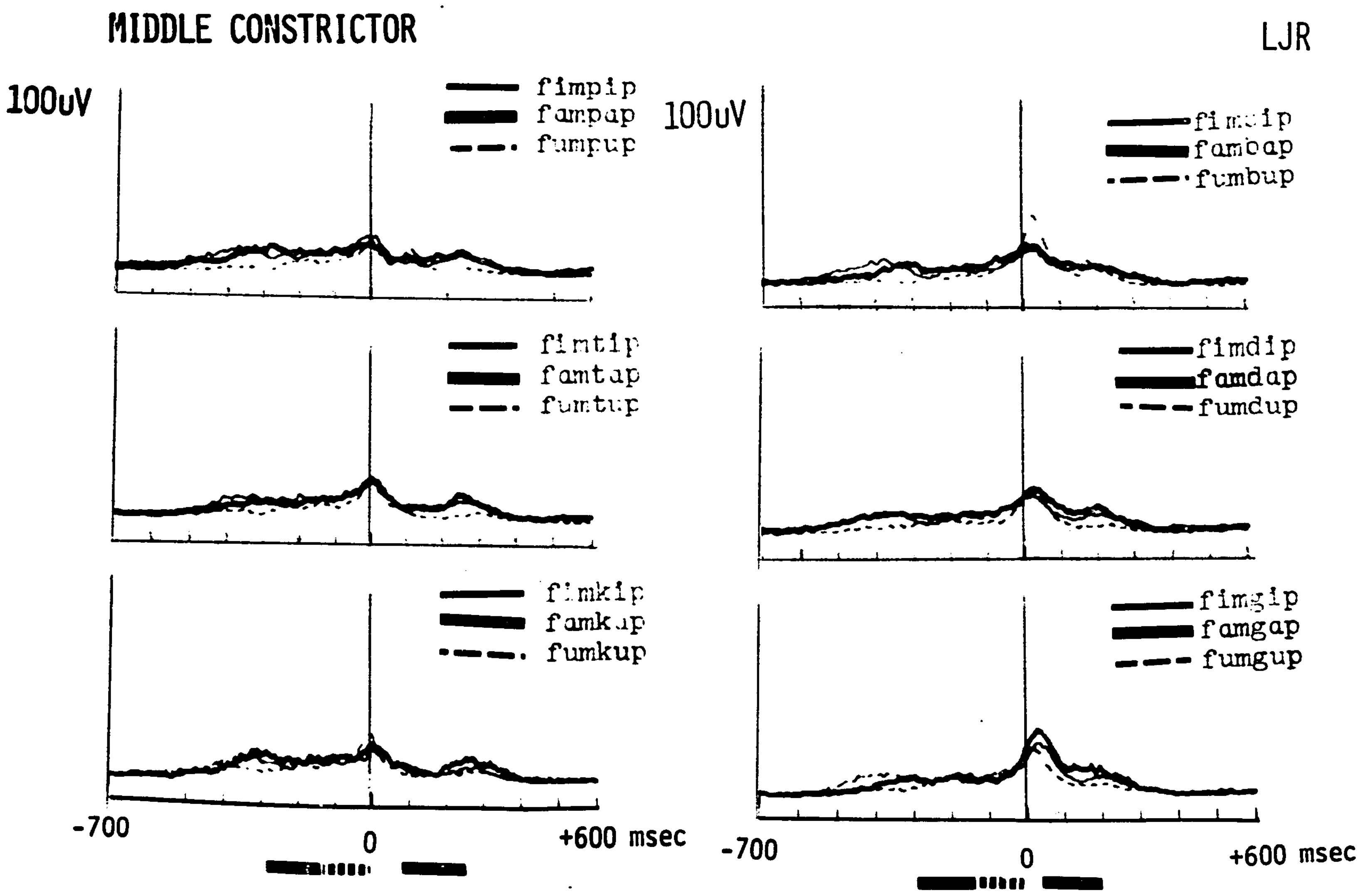

MIDDLE CONSTRICTOR
LJR
100uV
fimpip
fampap
fumpup
fimtip
famtap
fumtup
fimkip
famkap
fumkup
100uV
fimbip
fambap
fumbup
fimdip
famdap
fumdup
fimgip
famgap
fumgup
-700
0
+600 msec
-700
0
+600 msec

Figure 40

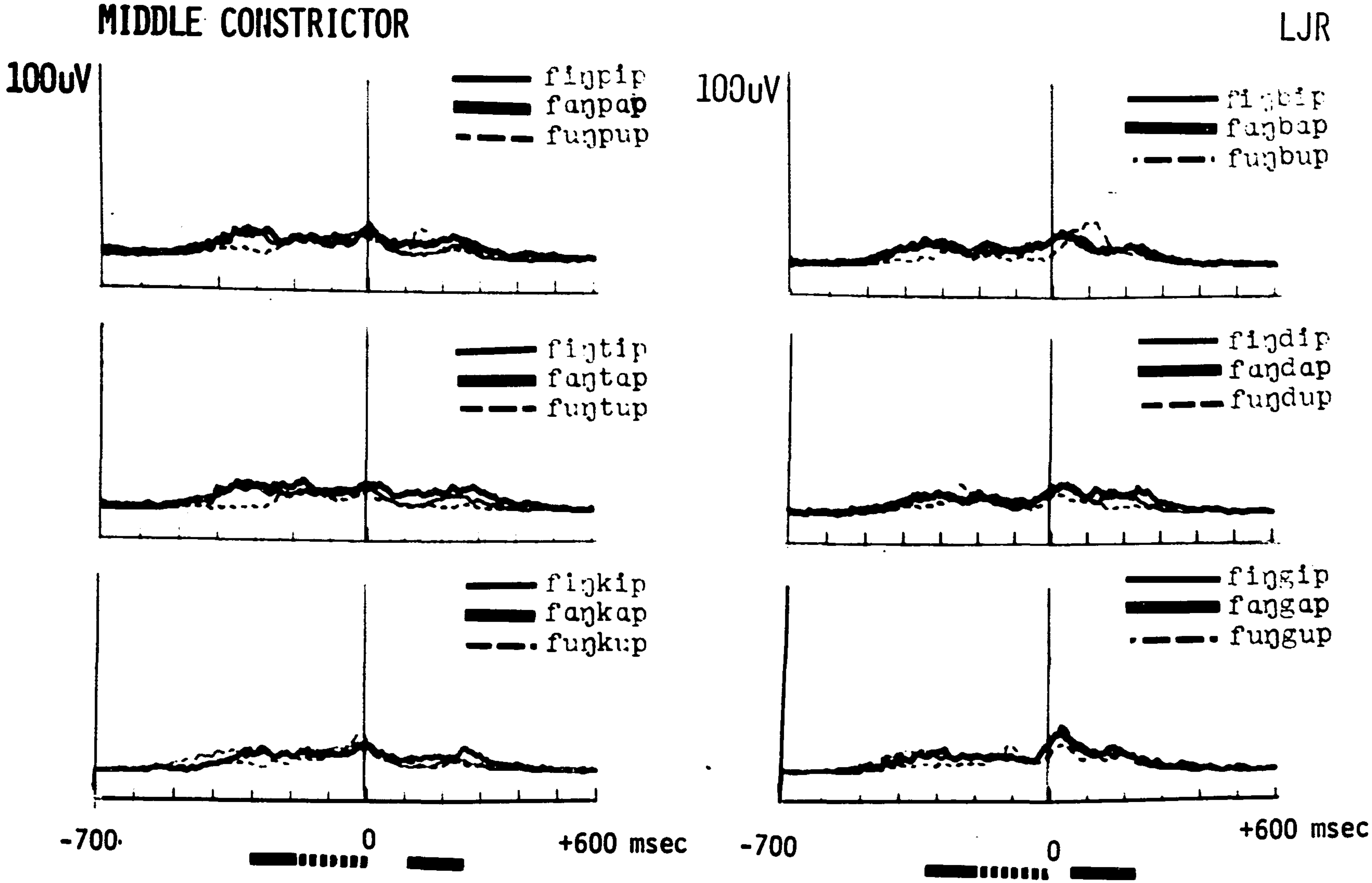

MIDDLE CONSTRICTOR
LJR
100uV
fiŋpip
faŋpap
fuŋpup
100uV
fiŋbip
faŋbap
fuŋbup
fiŋtip
faŋtap
fuŋtup
fiŋdip
faŋdap
fuŋdup
fiŋkip
faŋkap
fuŋkup
fiŋgip
faŋgap
fuŋgup
-700
0
+600 msec
-700
0
+600 msec

Figure 41

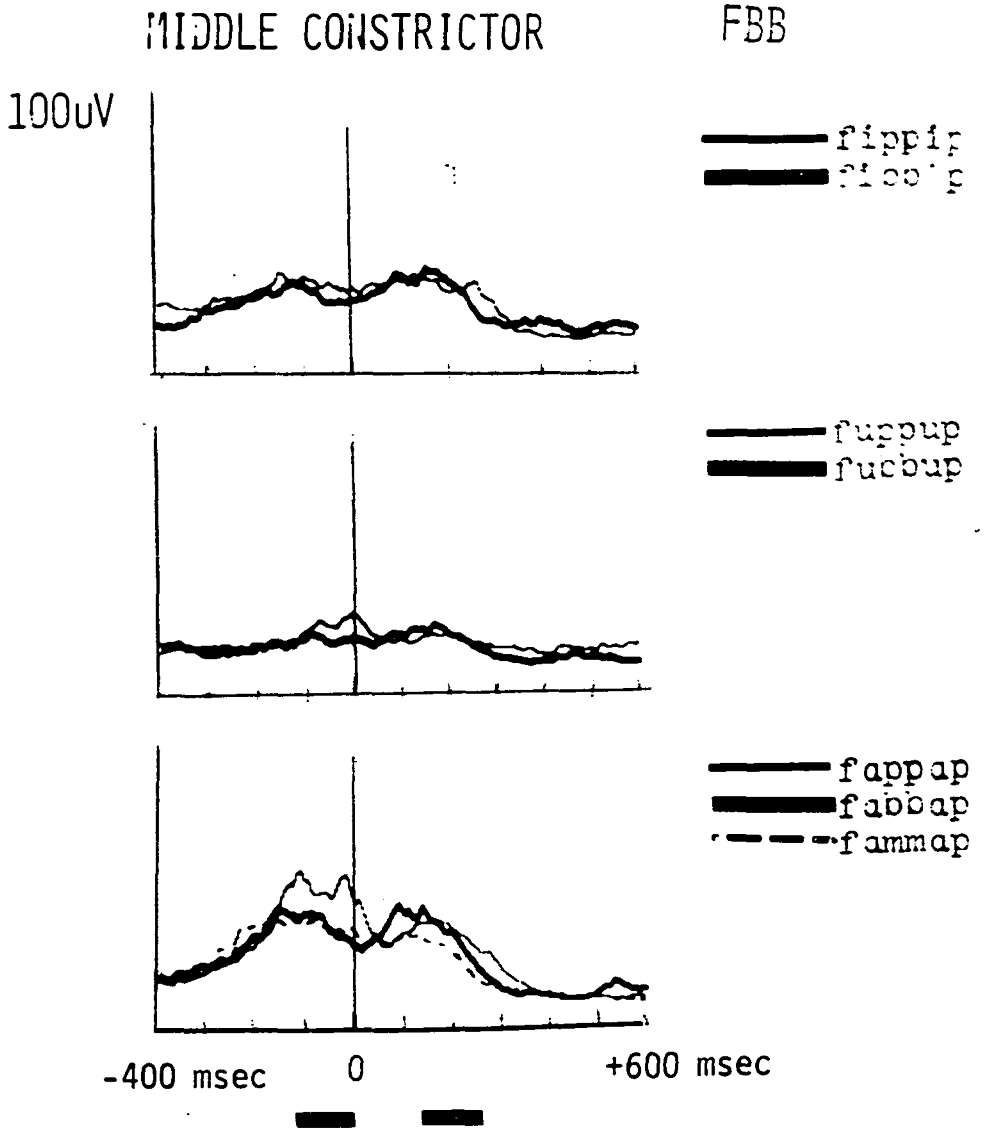

MIDDLE CONSTRICTOR
FBB
100uV
fippip
fibbip
fuppup
fubbup
fappap
fabbap
fammap
-400 msec
0
+600 msec

Figure 42

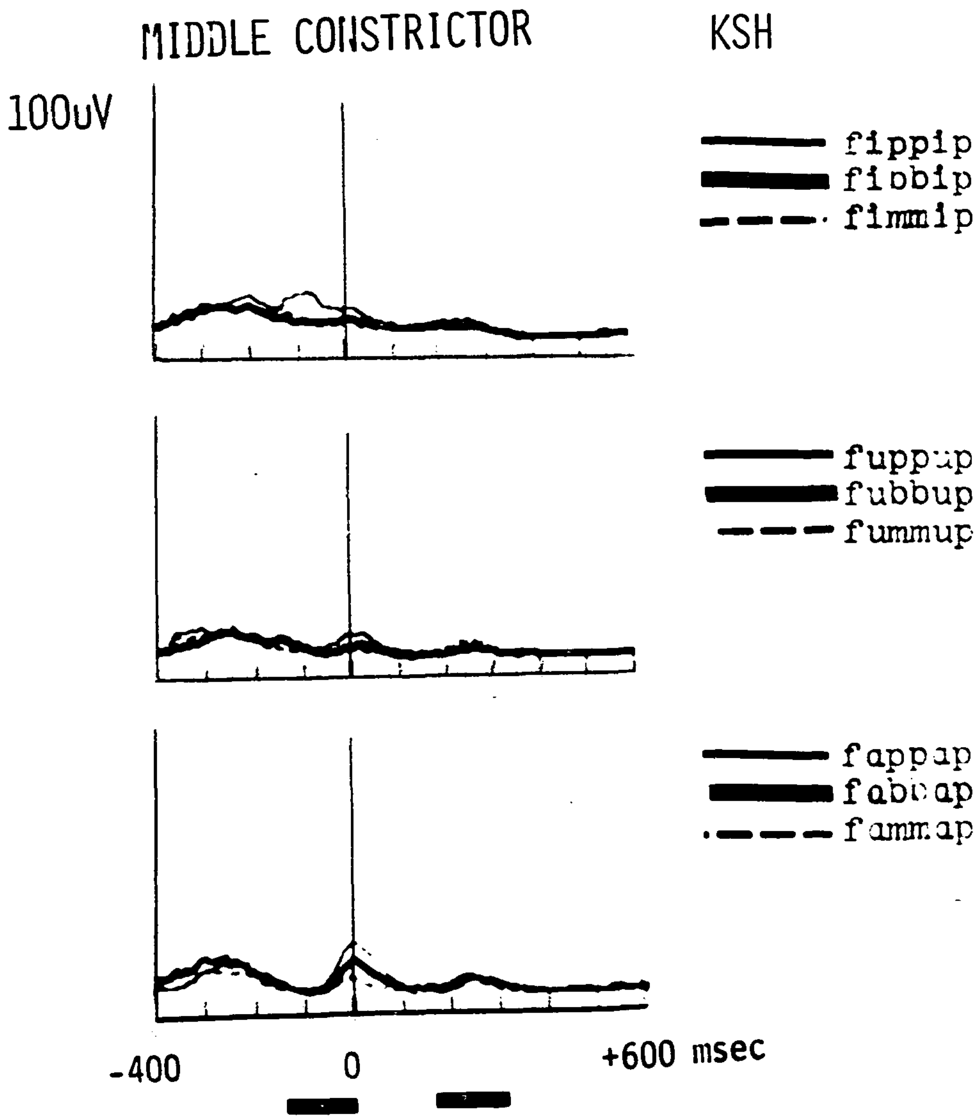

MIDDLE CONSTRICTOR
KSH
100uV
fippip
fibbip
fimmip
fuppup
fubbup
fummup
fappap
fabbap
fammap
-400
0
+600 msec

Figure 43

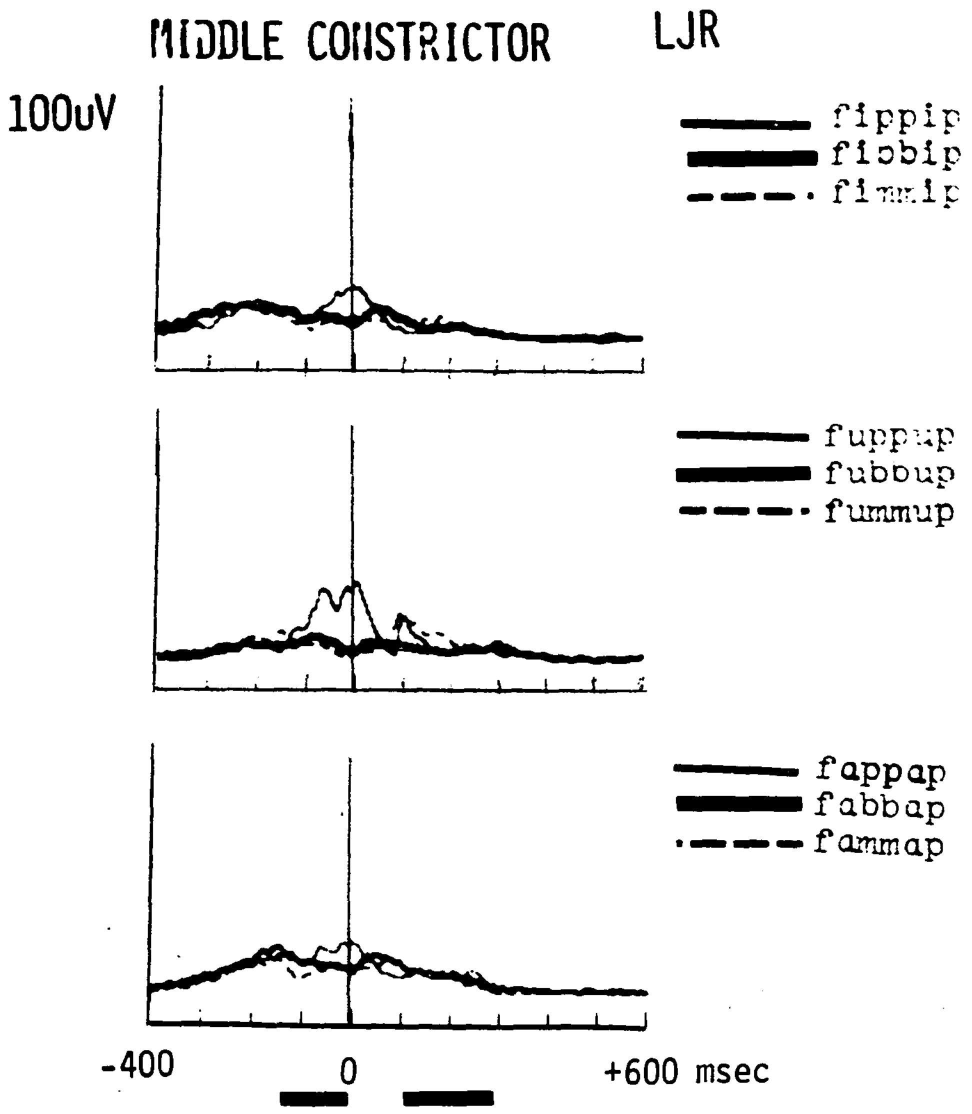
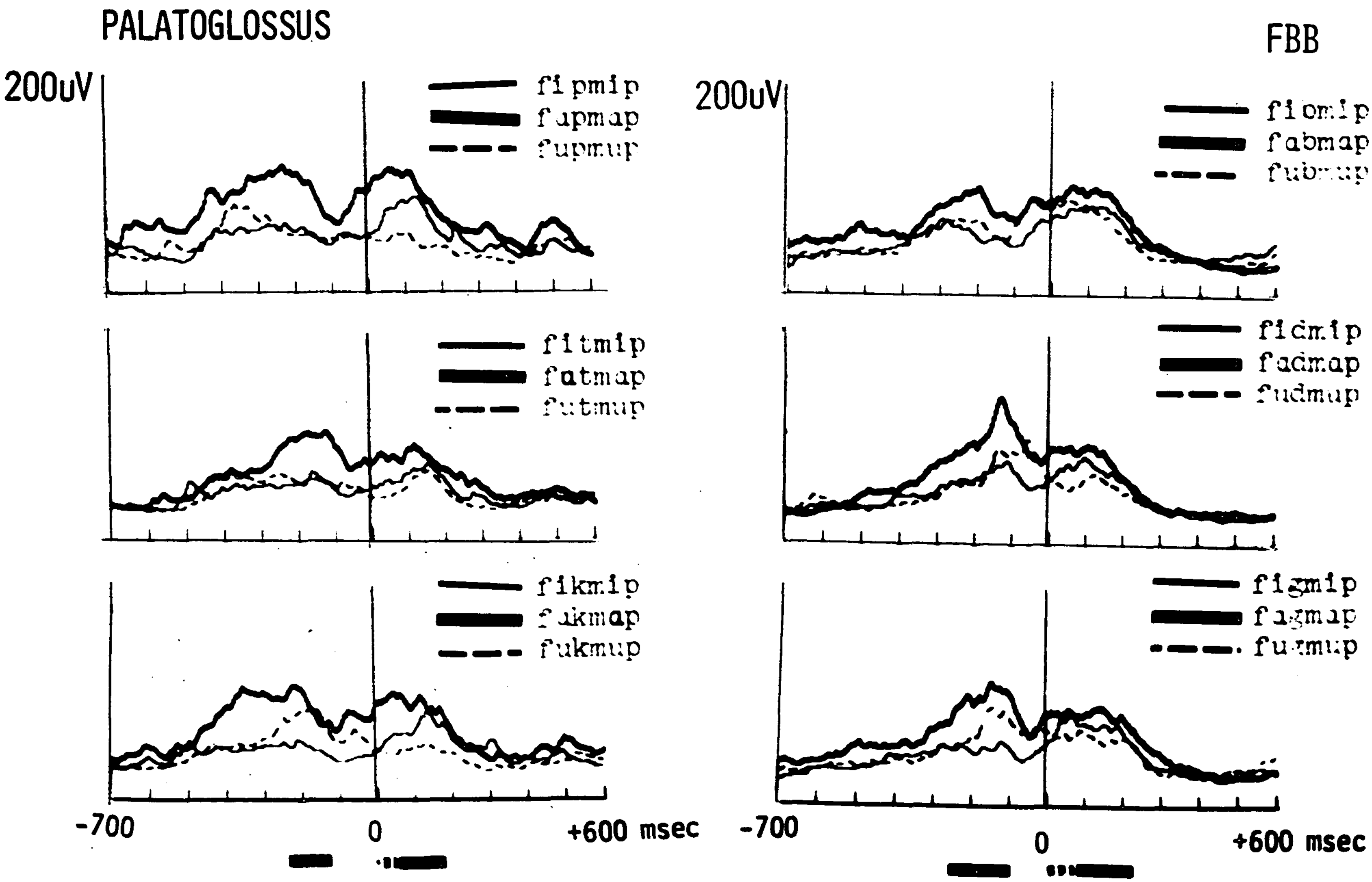

MIDDLE CONSTRICTOR
LJR
100uV
fippip
fibbip
fimmip
fuppup
fubbup
fummup
fappap
fabbap
fammap
-400
0
+600 msec

Figure 44


PALATOGLOSSUS

FBB

Figure 45

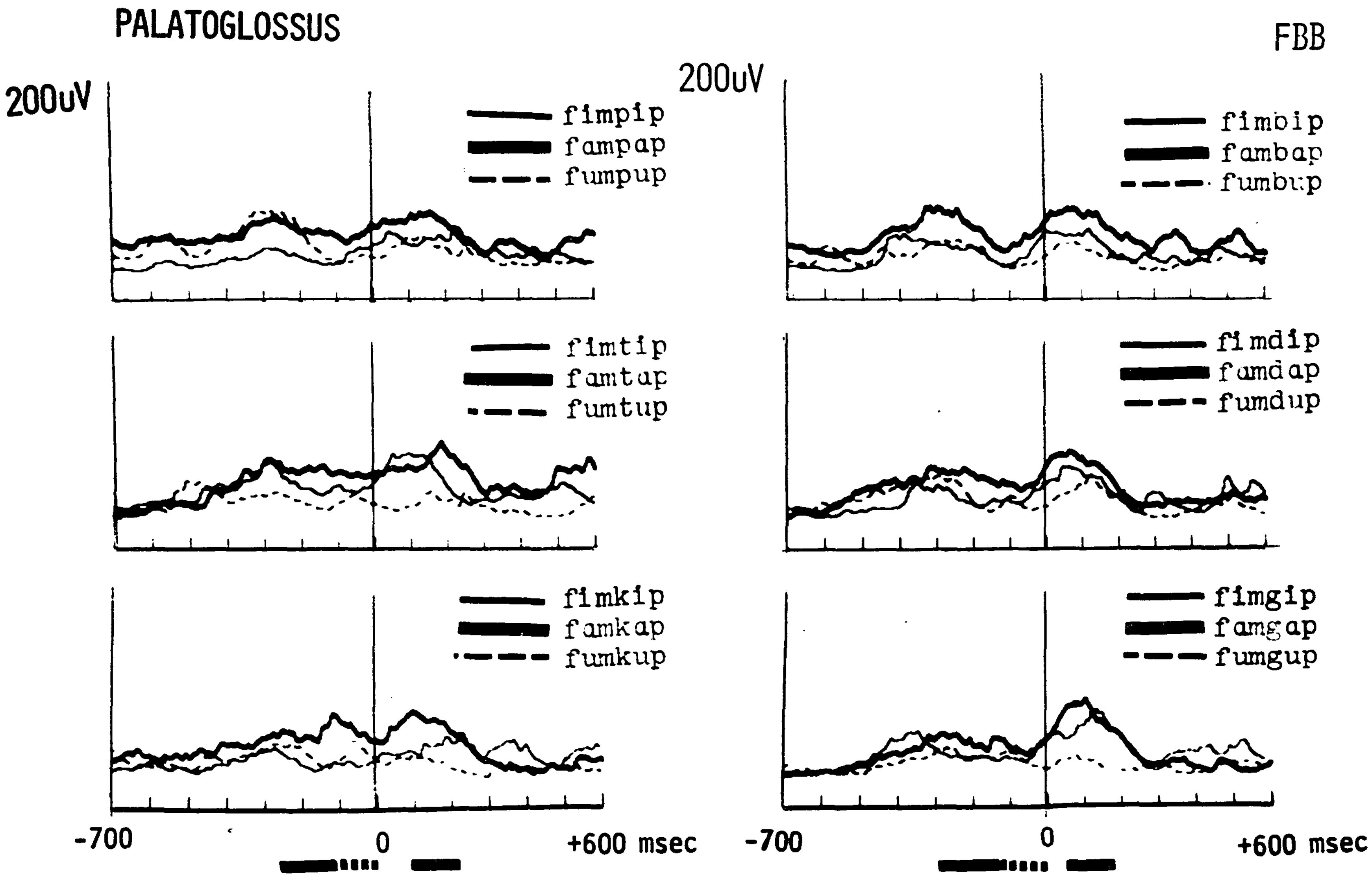

PALATOGLOSSUS
FBB
200uV
200uV
fimpip
fampap
fumpup
fimbip
fambap
fumbup
fimtip
famtap
fumtup
fimdip
famdap
fumdup
fimkip
famkap
fumkup
fimgip
famgap
fumgup
-700
0
+600 msec
-700
0
+600 msec

Figure 46

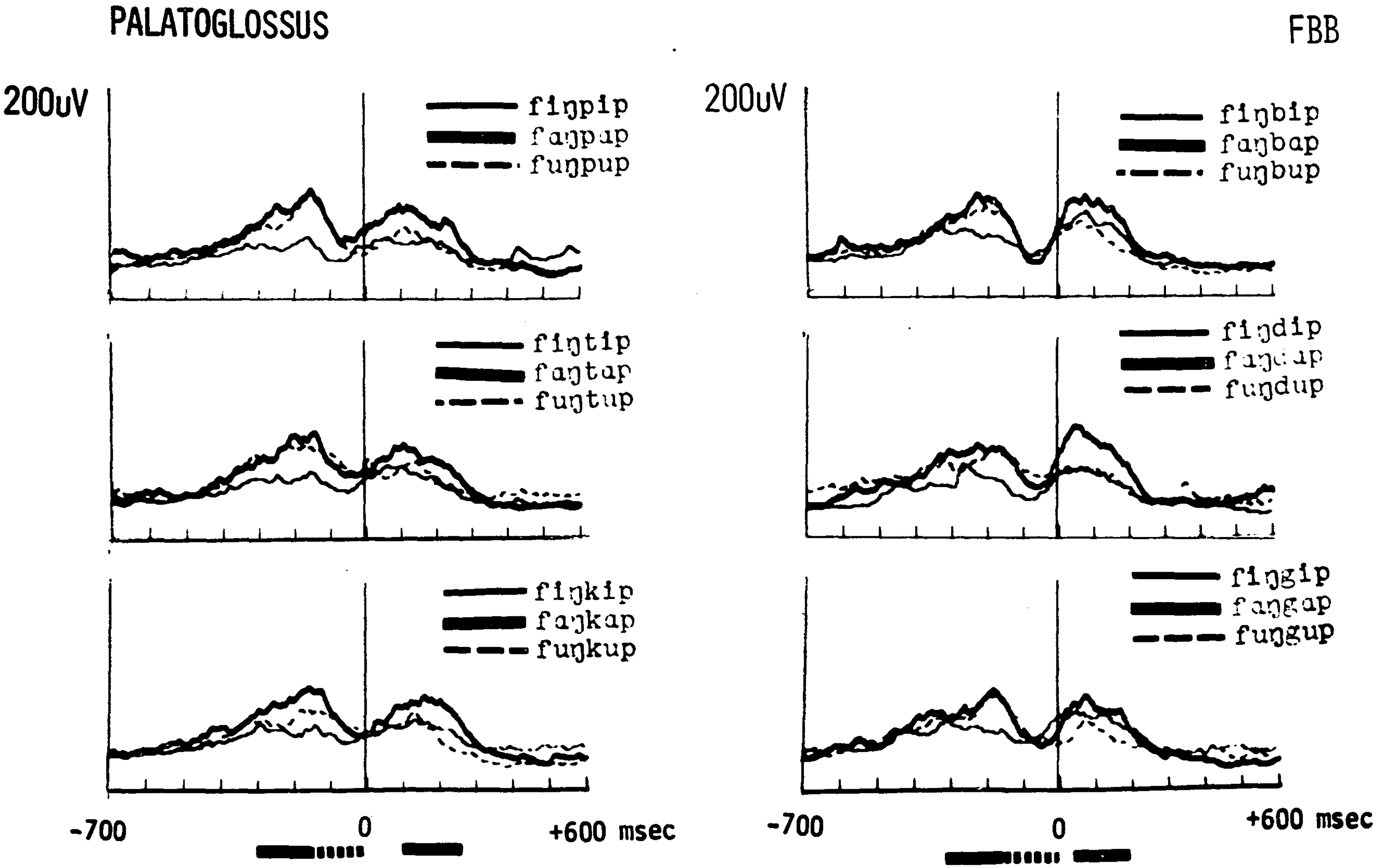

PALATOGLOSSUS
FBB
200uV
fiŋpip
faŋpap
fuŋpup
200uV
fiŋbip
faŋbap
fuŋbup
fiŋtip
faŋtap
fuŋtup
fiŋdip
faŋdap
fuŋdup
fiŋkip
faŋkap
fuŋkup
fiŋgip
faŋgap
fuŋgup
-700
0
+600 msec
-700
0
+600 msec

Figure 47

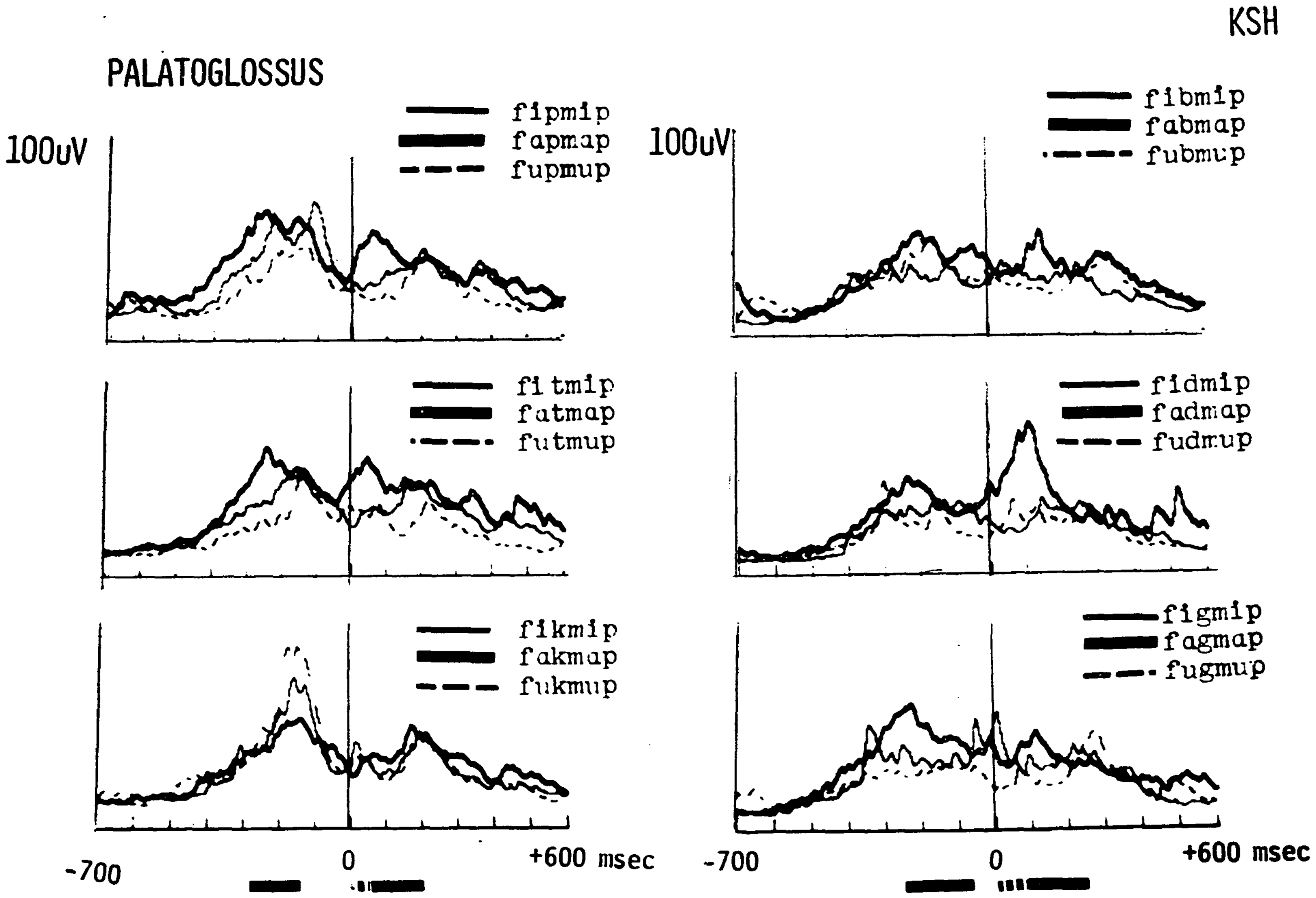

KSH
PALATOGLOSSUS
100uV
fipmip
fapmap
fupmup
100uV
fibmip
fabmap
fubmup
fitmip
fatmap
futmup
fidmip
fadmap
fudmup
fikmip
fakmap
fukmup
figmip
fagmap
fugmup
-700
0
+600 msec
-700
0
+600 msec

Figure 48

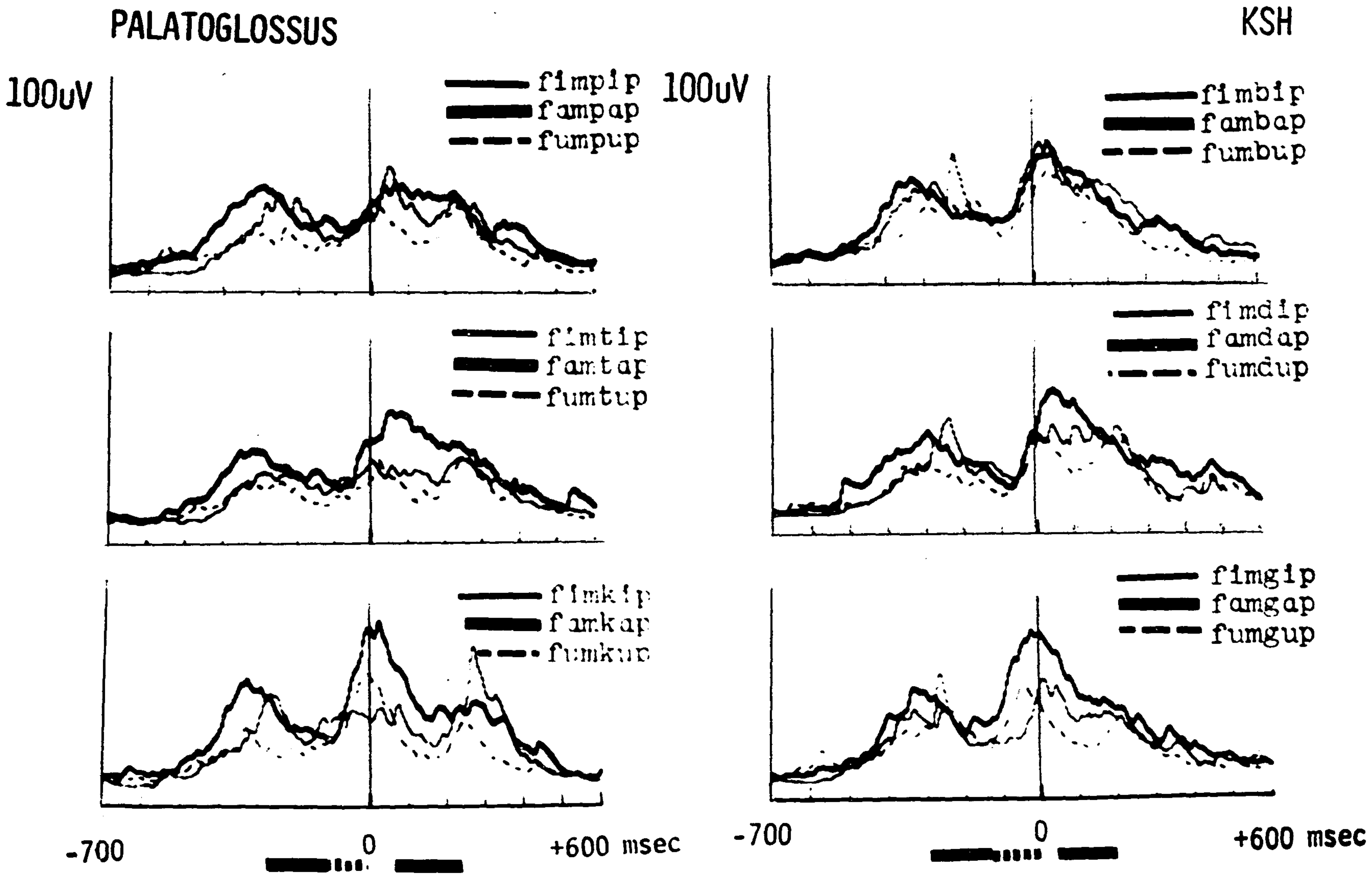

PALATOGLOSSUS
KSH
100uV
fimpip
fampap
fumpup
100uV
fimbip
fambap
fumbup
fimtip
famtap
fumtup
fimdip
famdap
fumdup
fimkip
famkap
fumkup
fimgip
famgap
fumgup
-700
0
+600 msec
-700
0
+600 msec

Figure 49

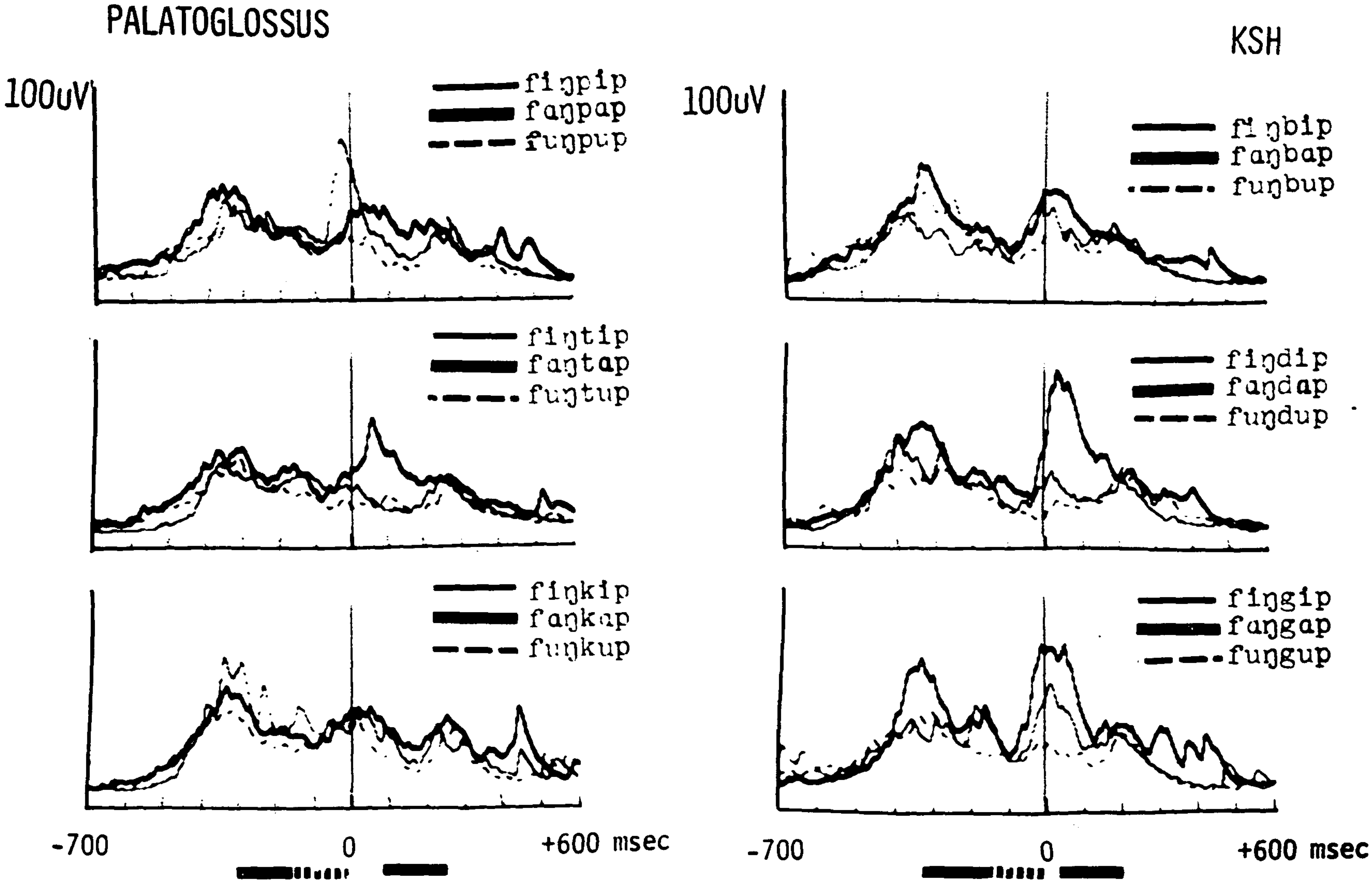

PALATOGLOSSUS
KSH
100uV
fiŋpip
faŋpap
fuŋpup
100uV
fiŋbip
faŋbap
fuŋbup
fiŋtip
faŋtap
fuŋtup
fiŋdip
faŋdap
fuŋdup
fiŋkip
faŋkap
fuŋkup
fiŋgip
faŋgap
fuŋgup
-700
0
+600 msec
-700
0
+600 msec

Figure 50

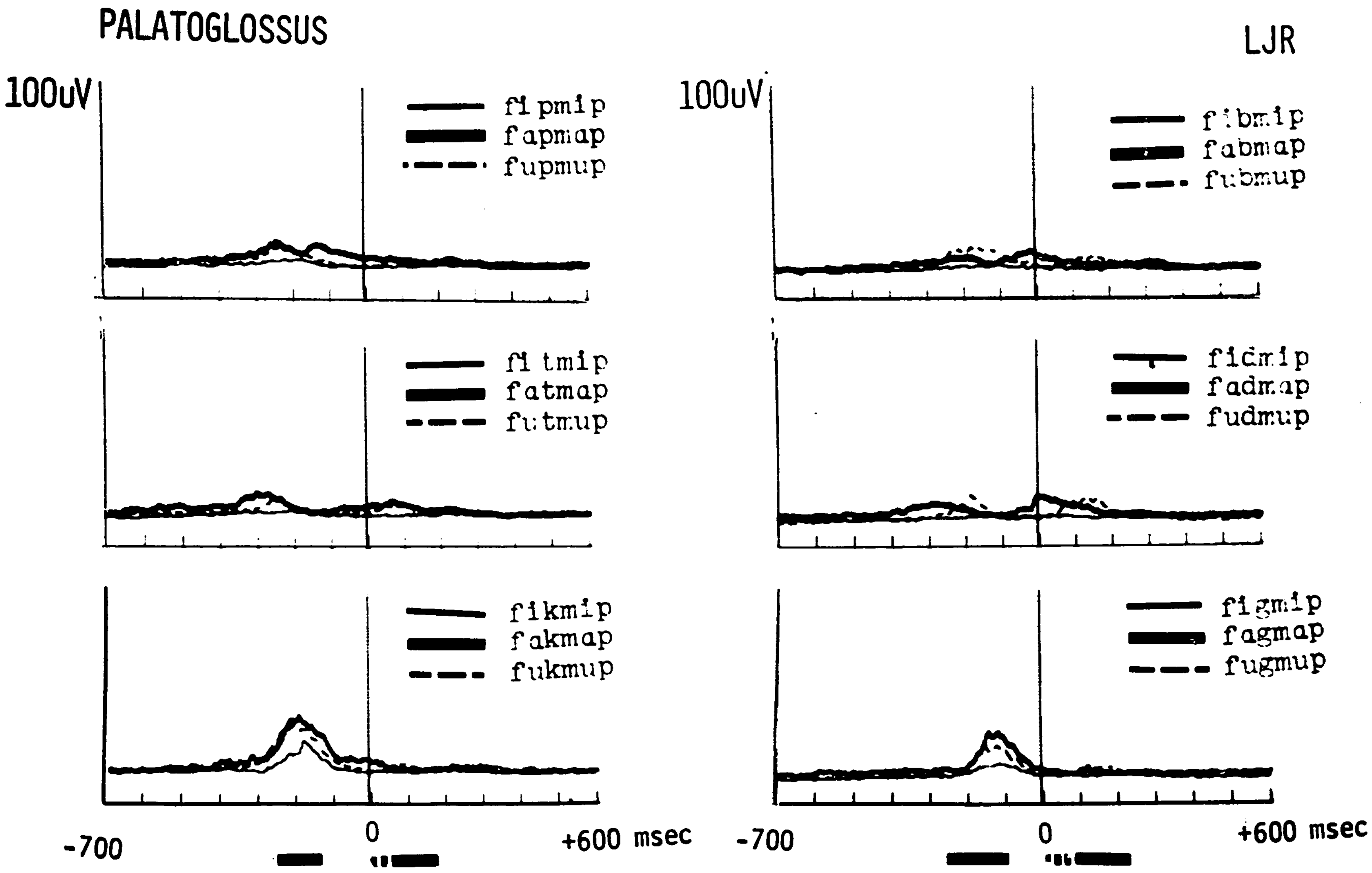

PALATOGLOSSUS
LJR
100uV
fipmip
fapmap
fupmup
100uV
fibmip
fabmap
fubmup
fitmip
fatmap
futmup
fidmip
fadmap
fudmup
fikmip
fakmap
fukmup
figmip
fagmap
fugmup
-700
0
+600 msec
-700
0
+600 msec

Figure 51

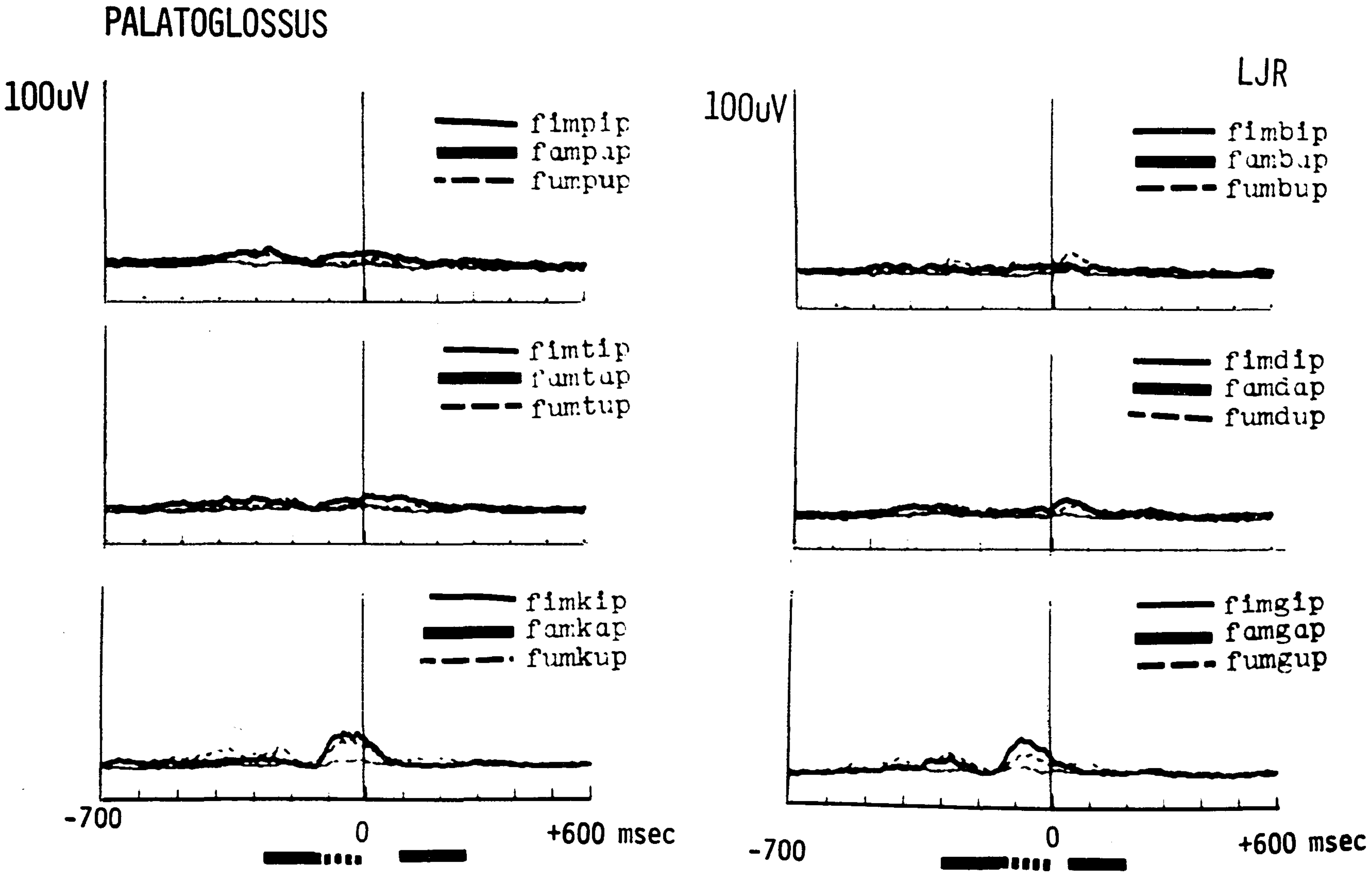

PALATOGLOSSUS
LJR
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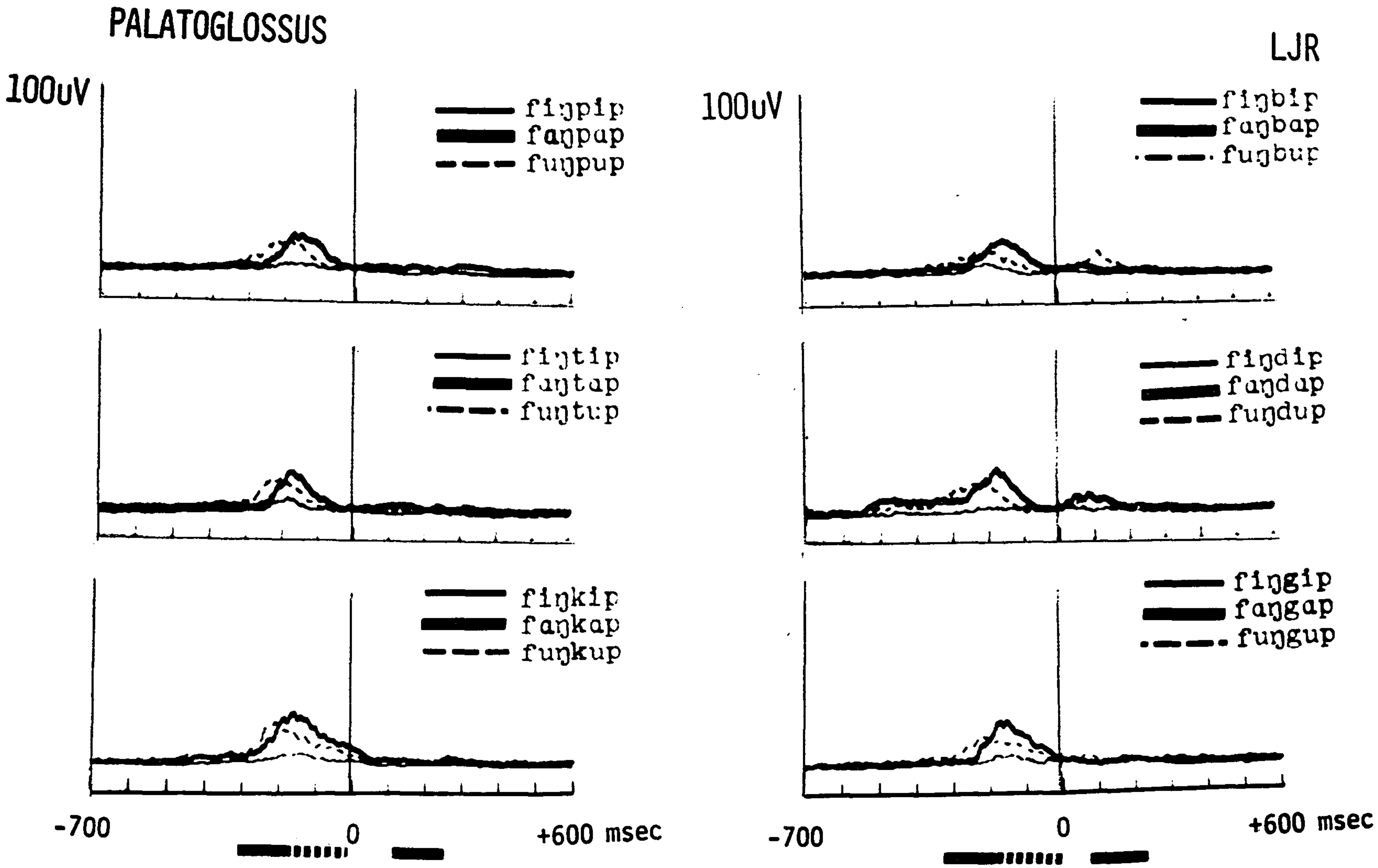
Figure 52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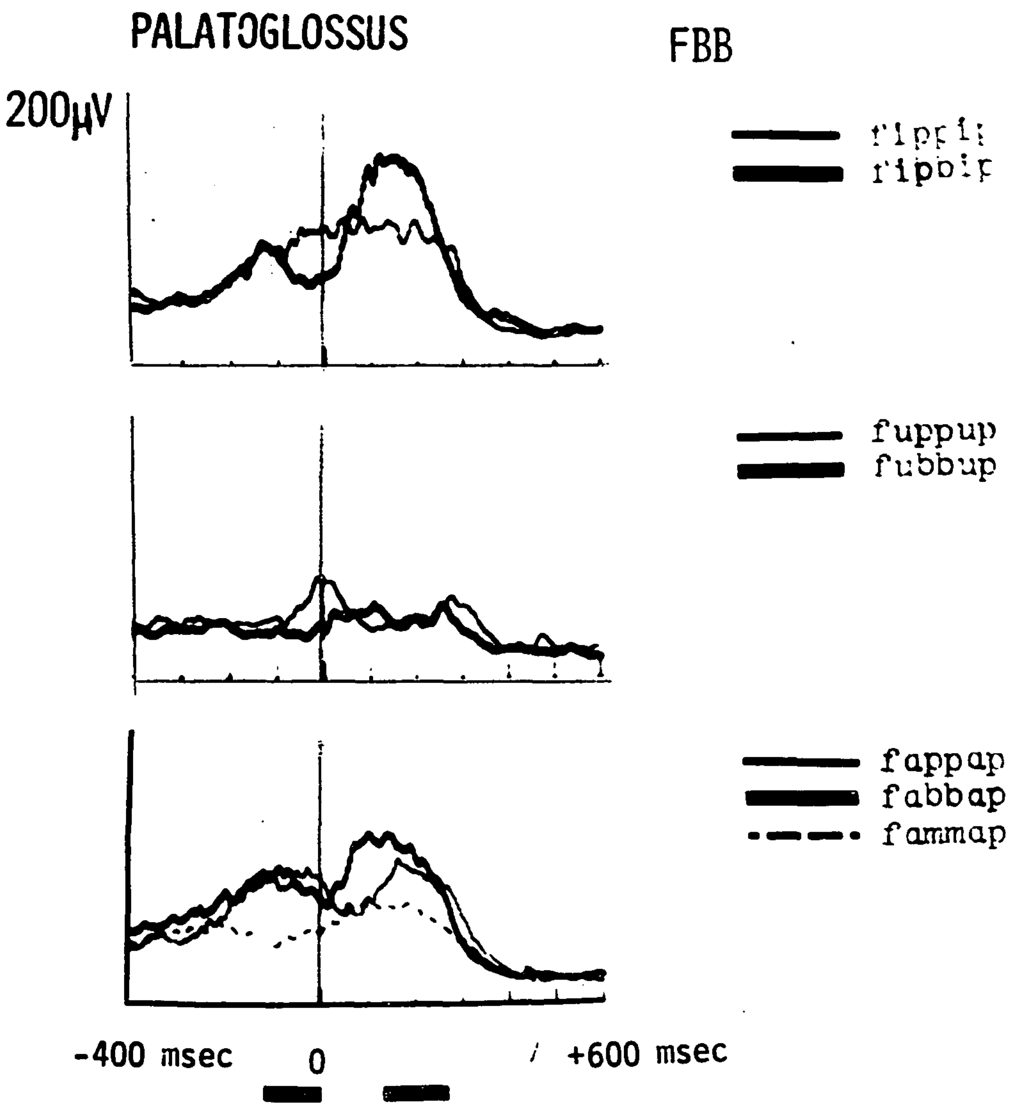
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Figure 54

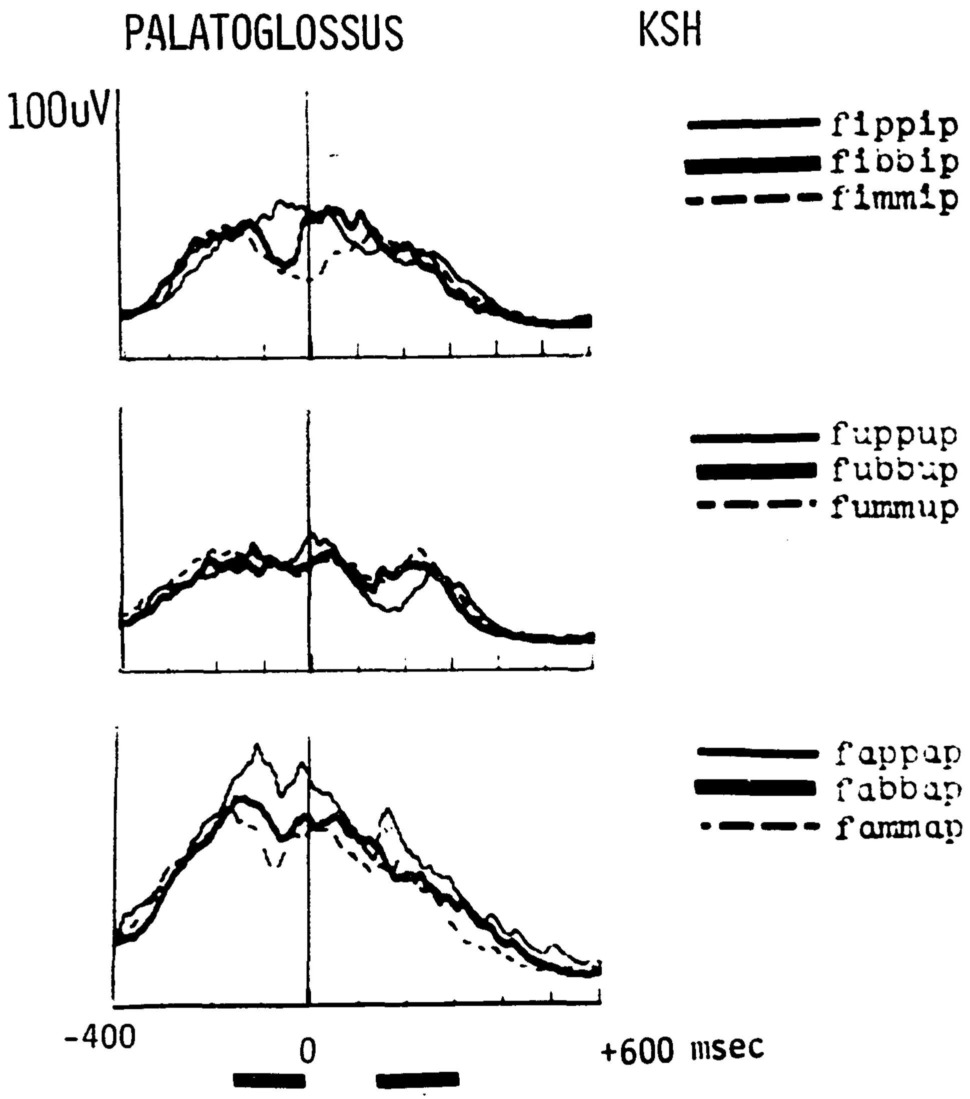
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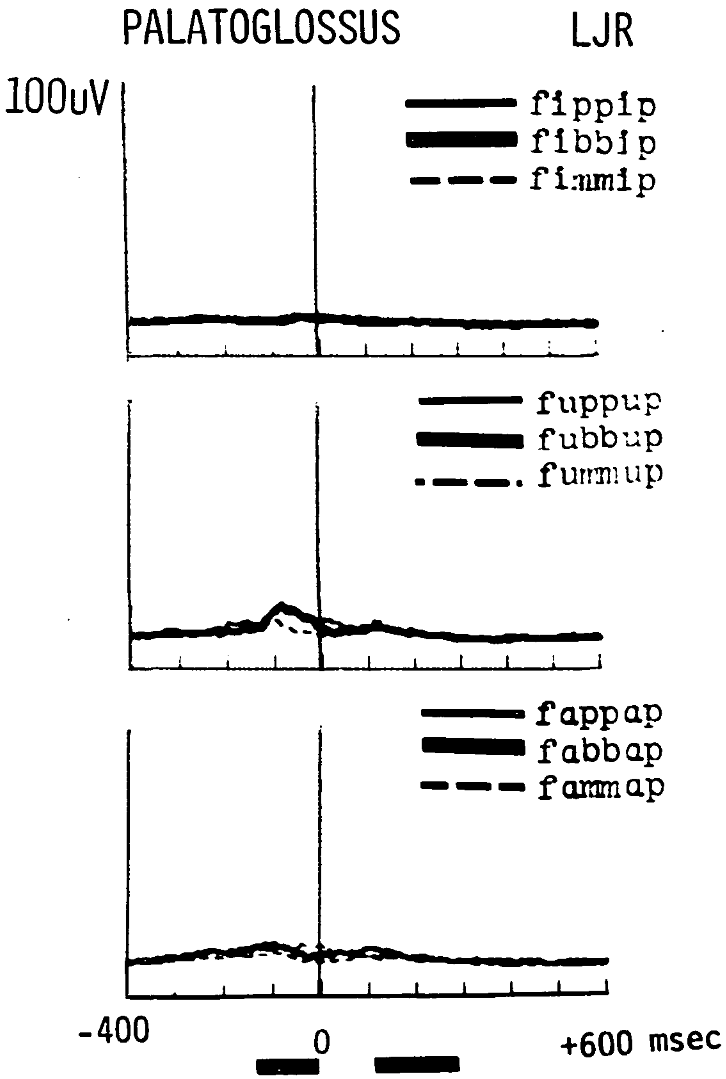
Figure 55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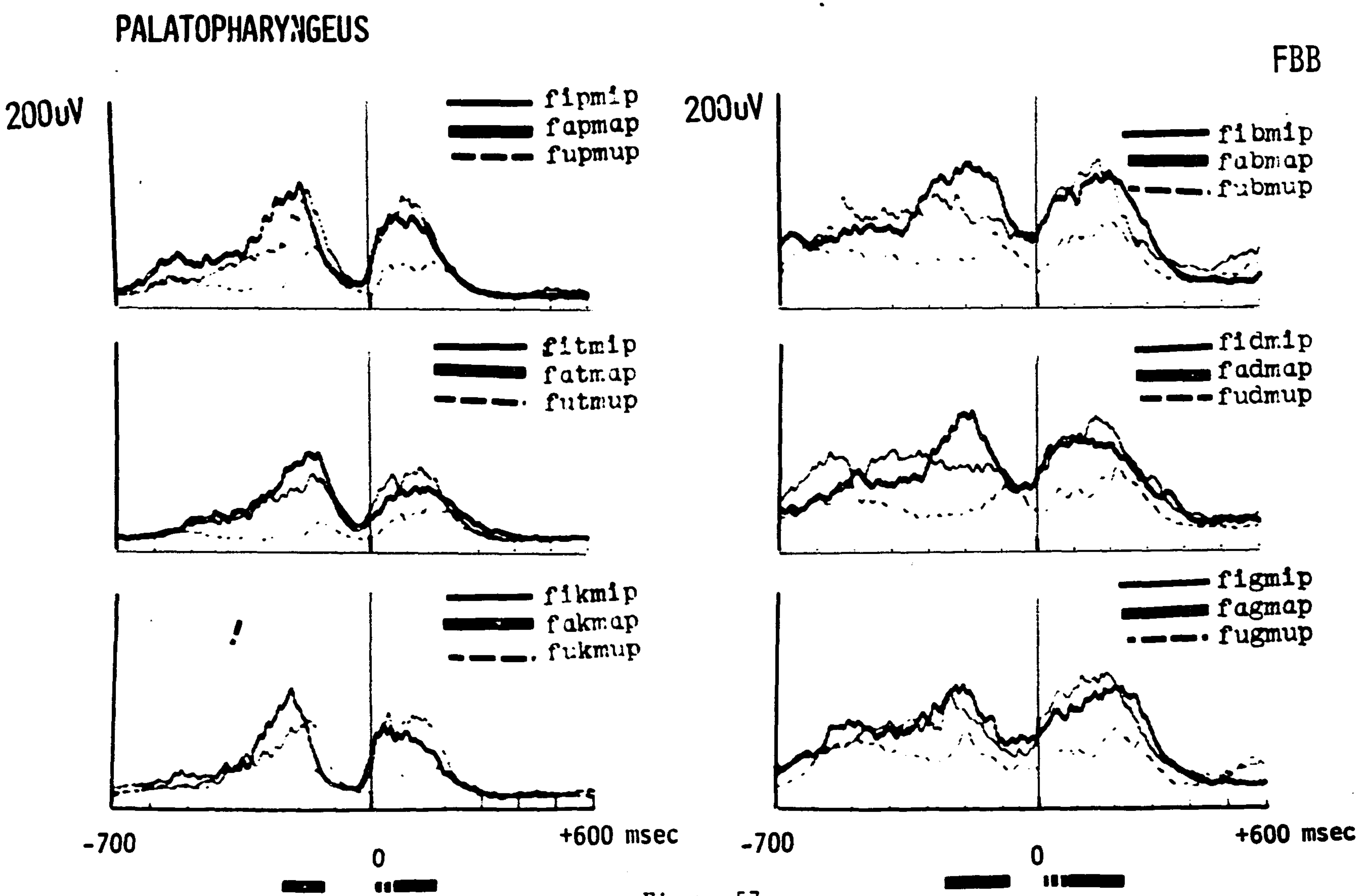
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Figure 57

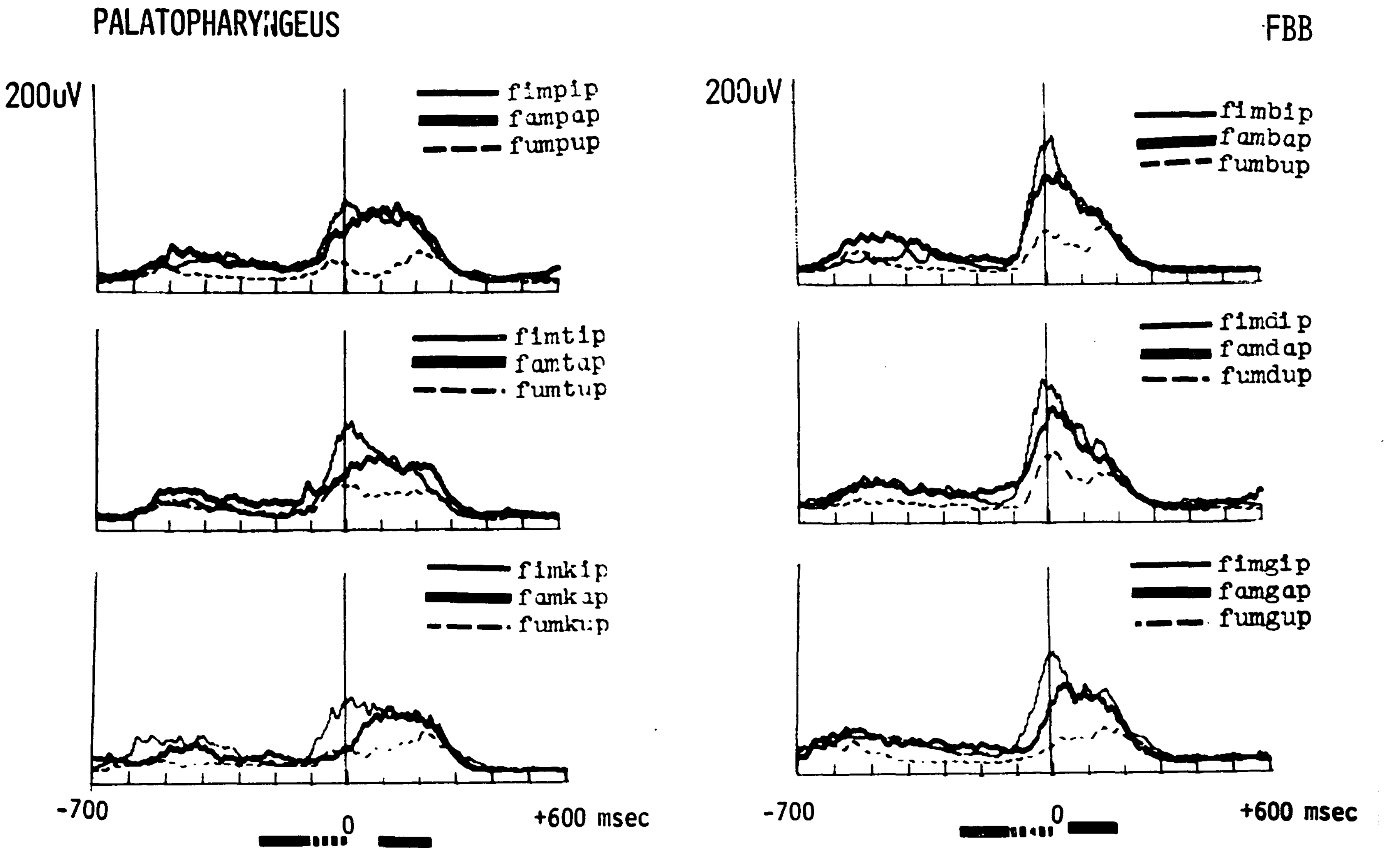
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Figure 58

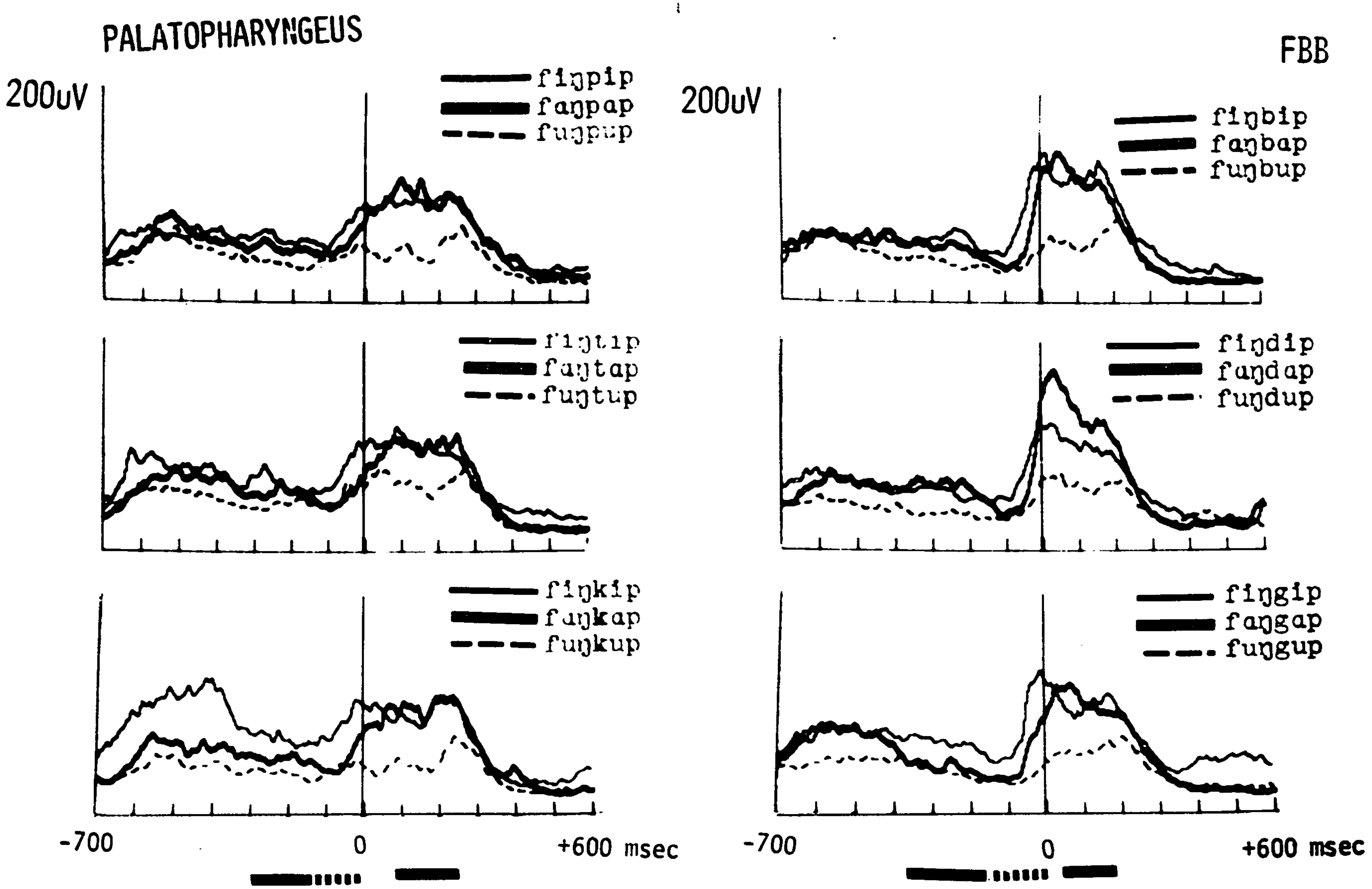
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Figure 59

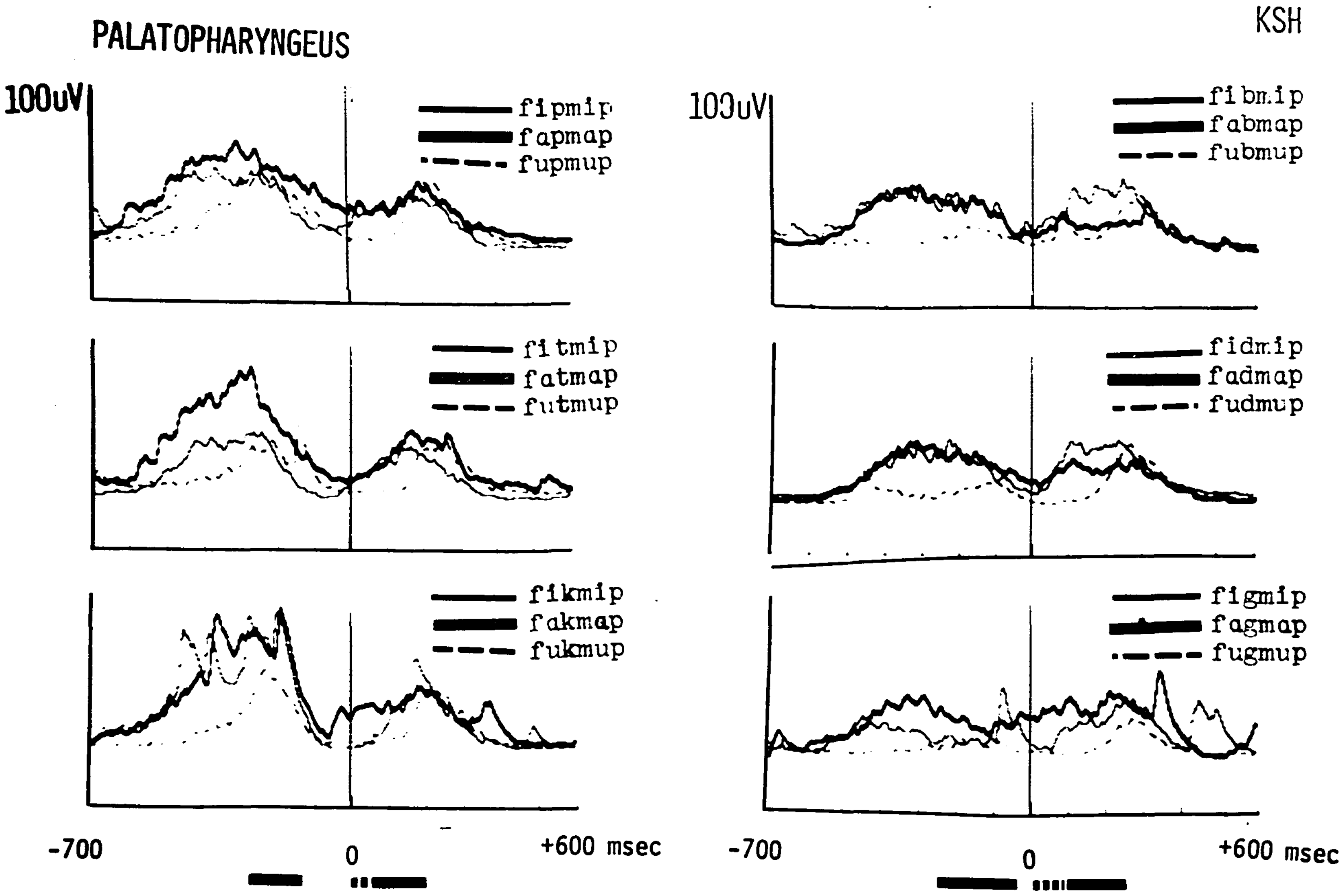
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Figure 60

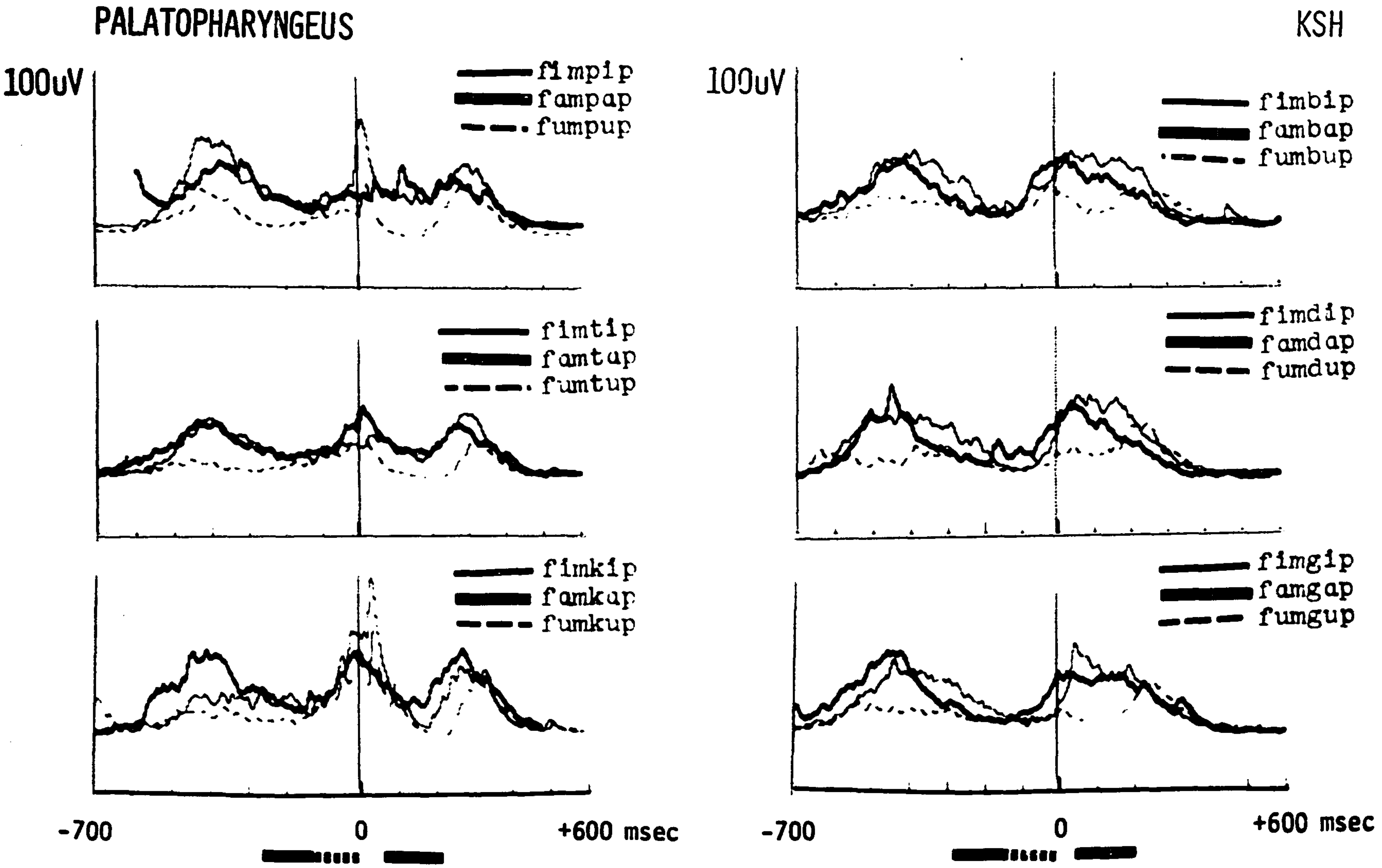
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Figure 61

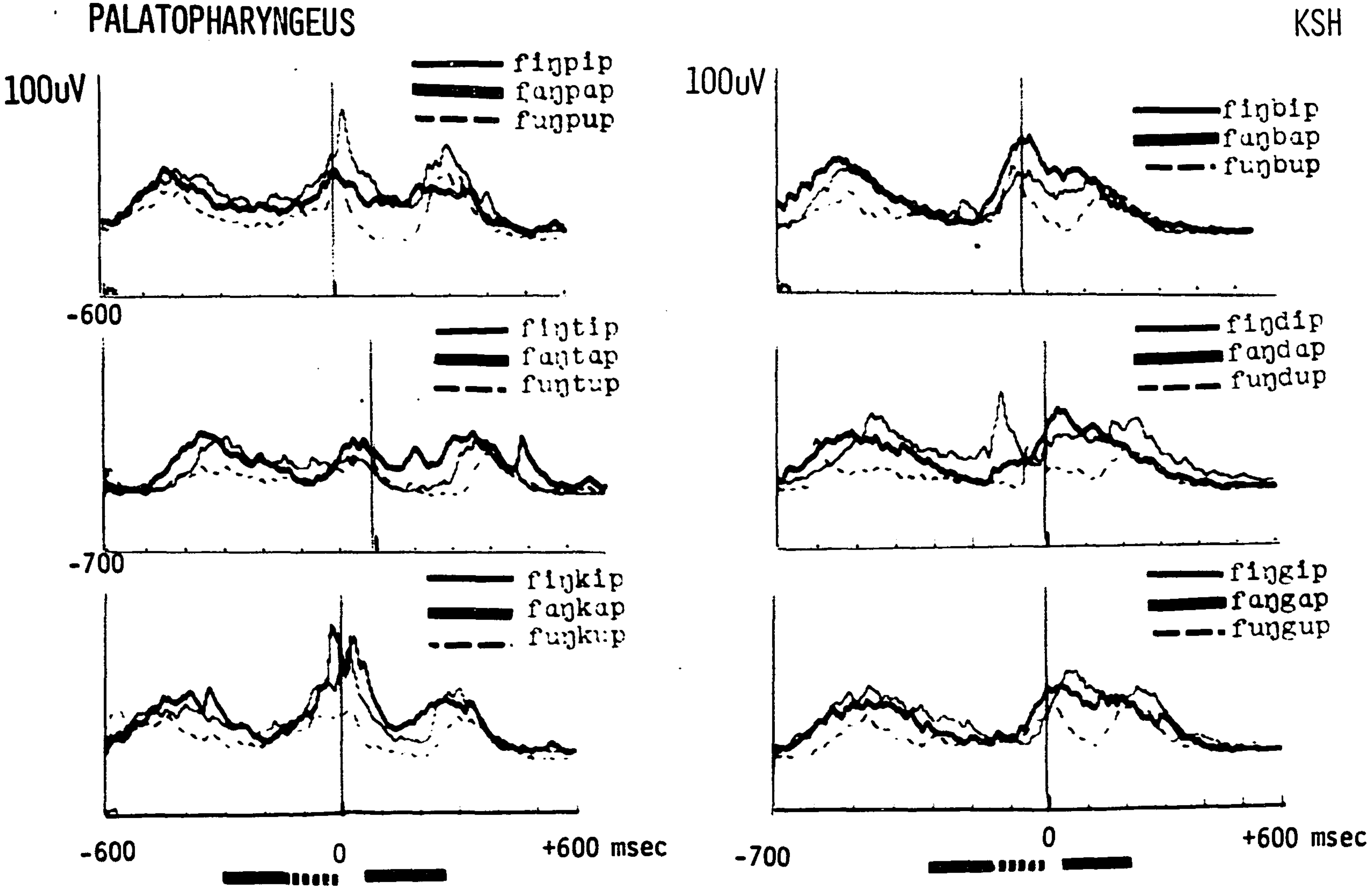
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Figure 62

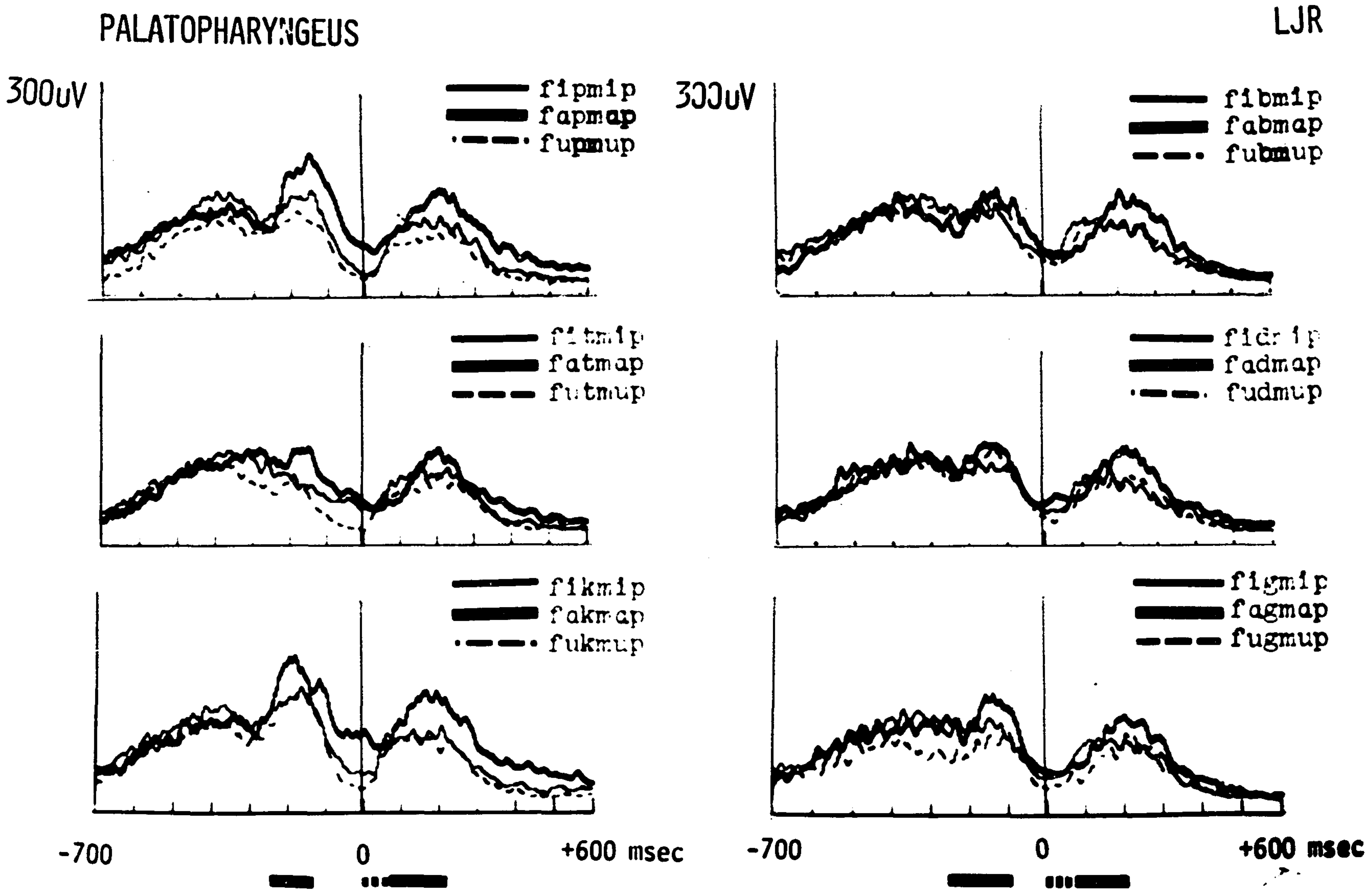
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Figure 63

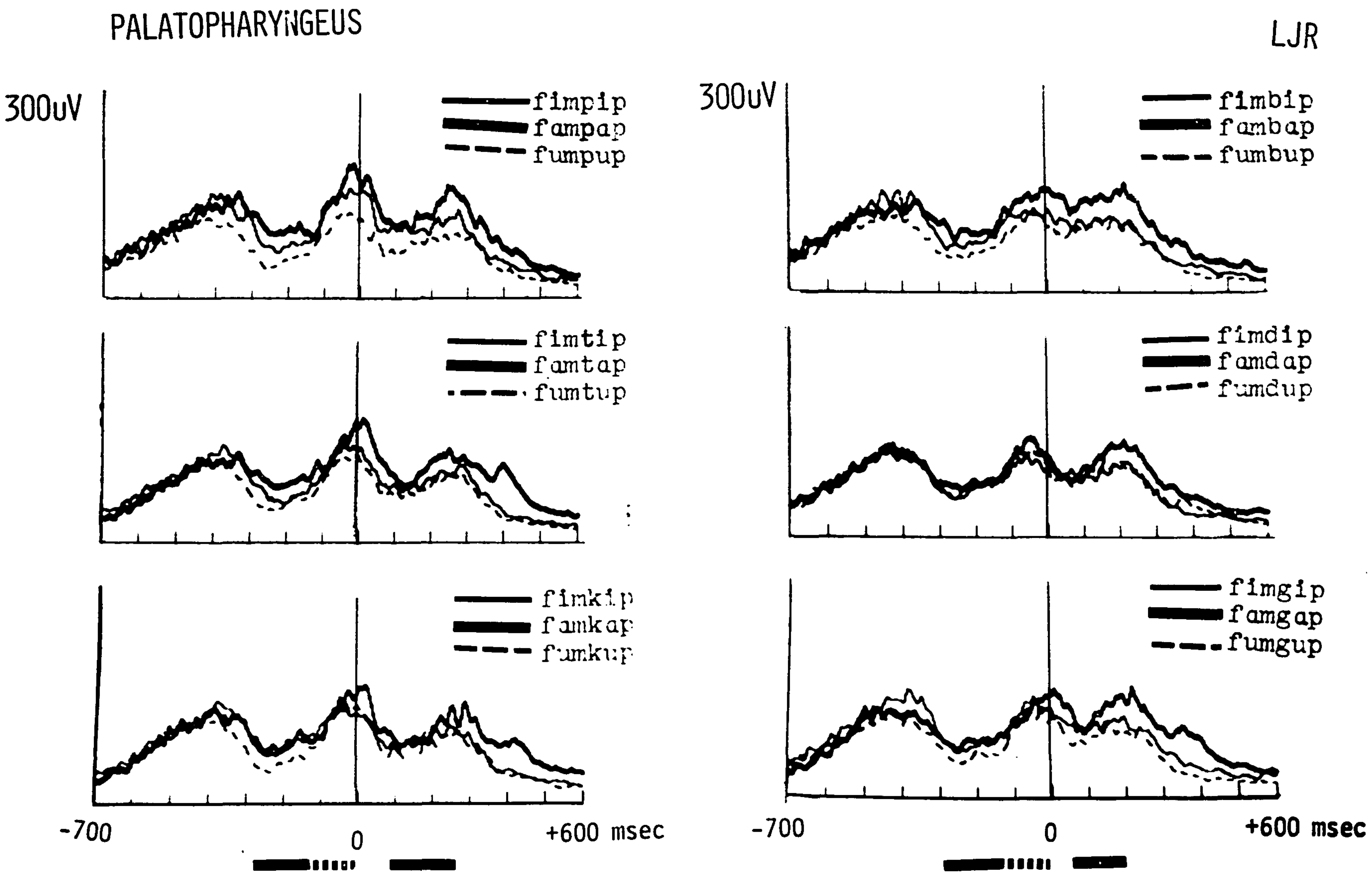
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Figure 64

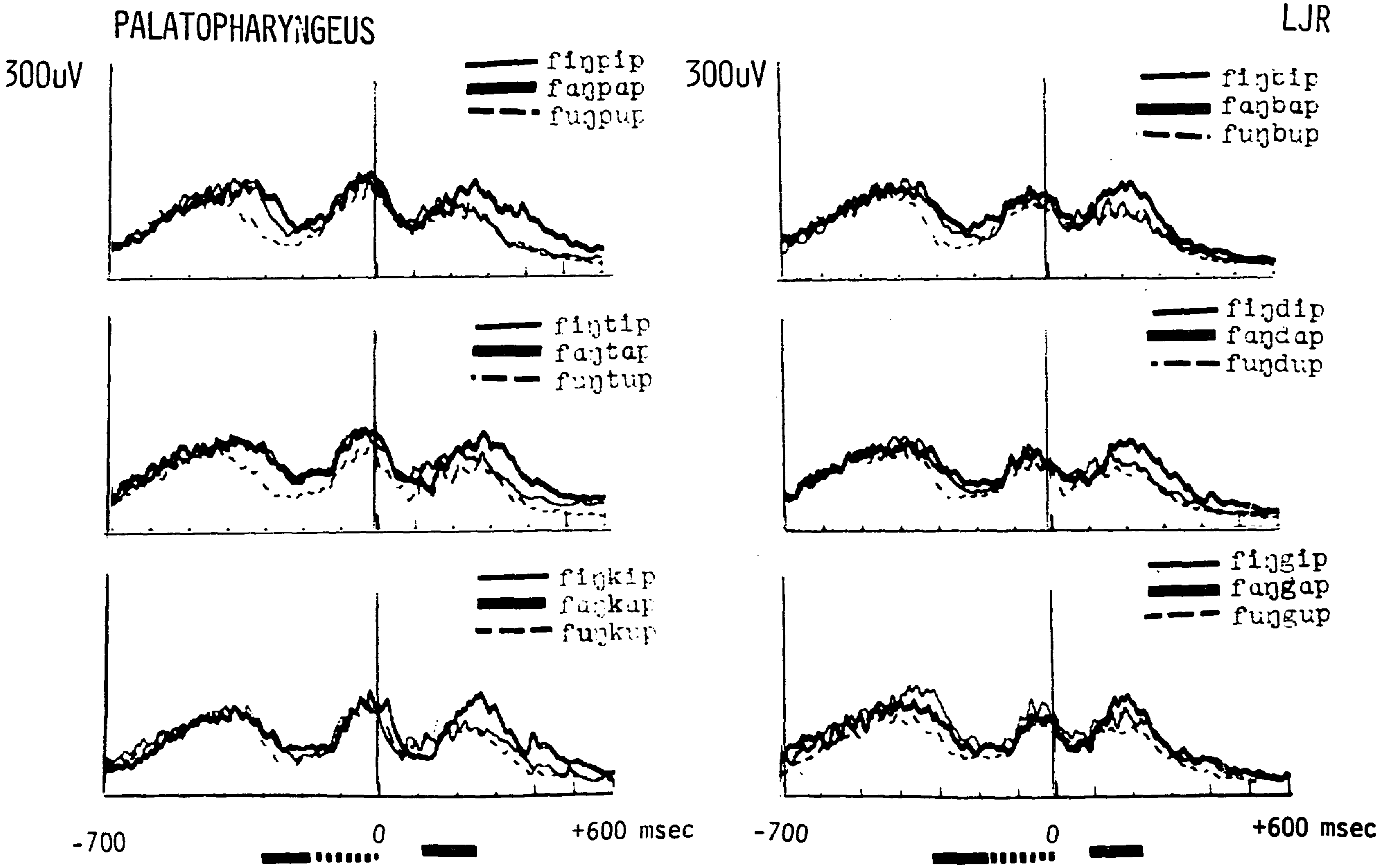
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Figure 65

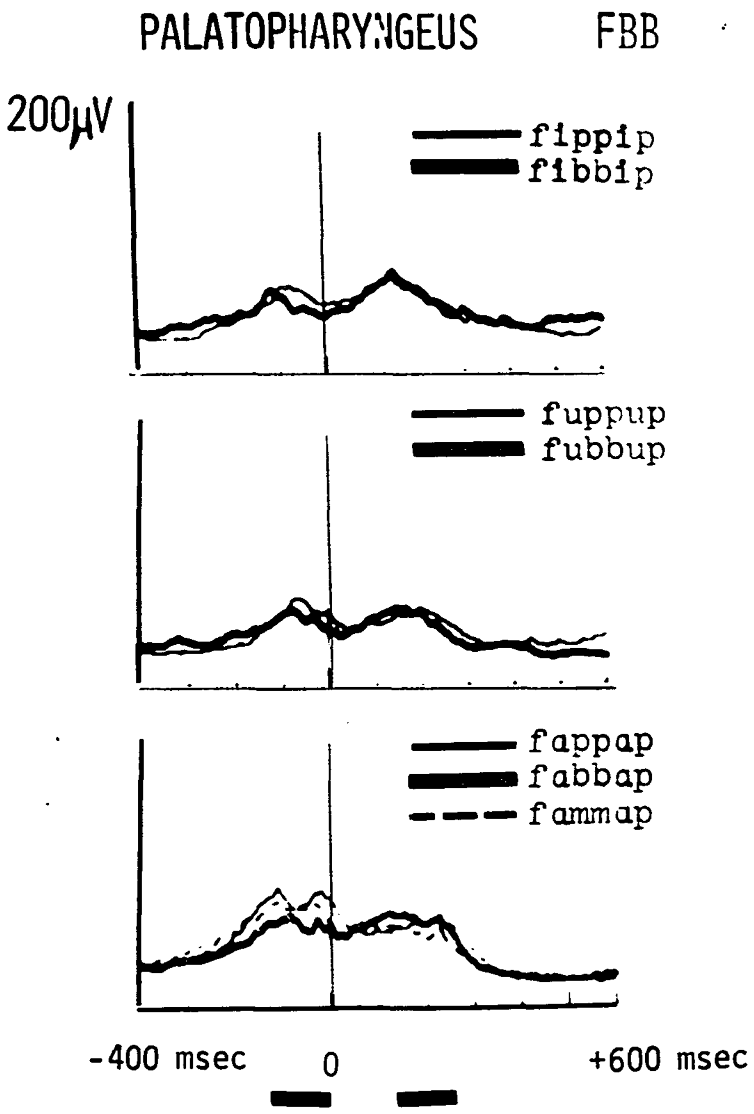
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Figure 66

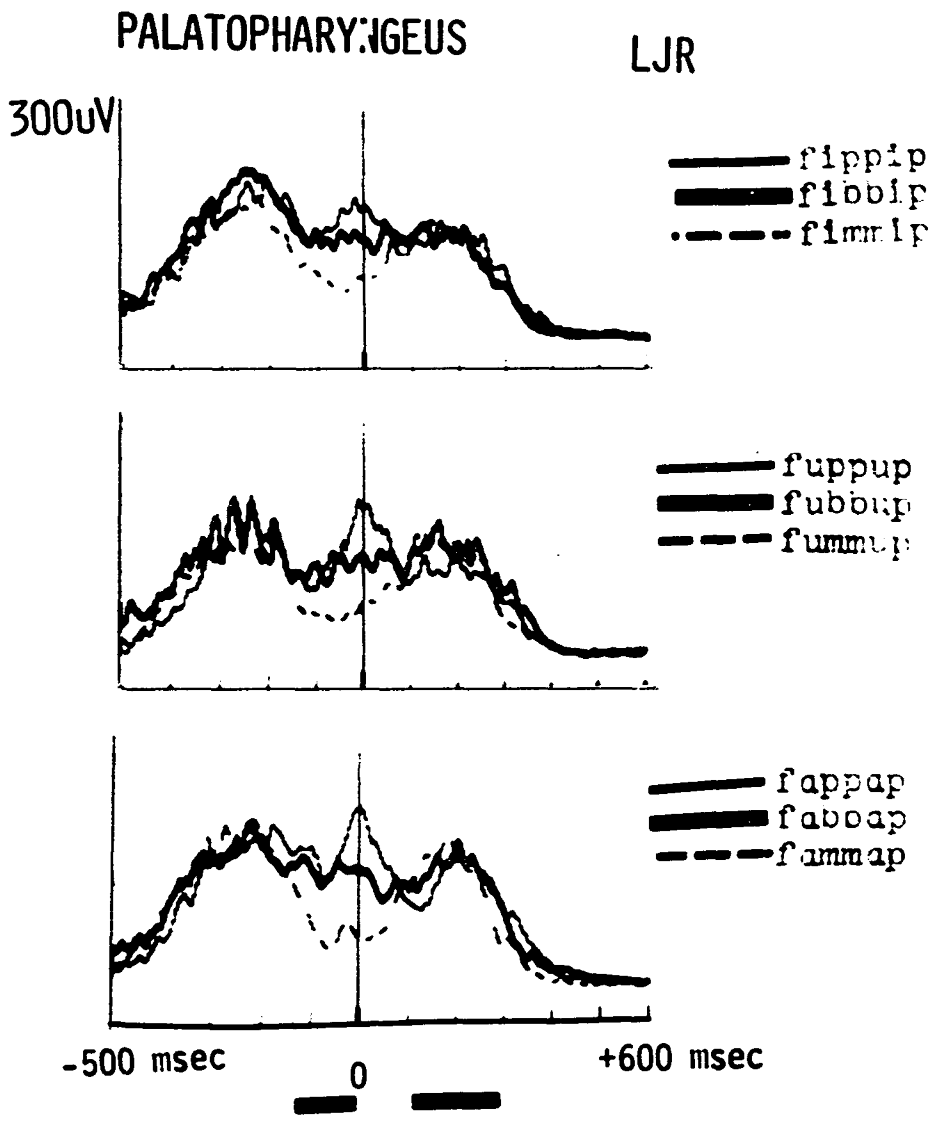
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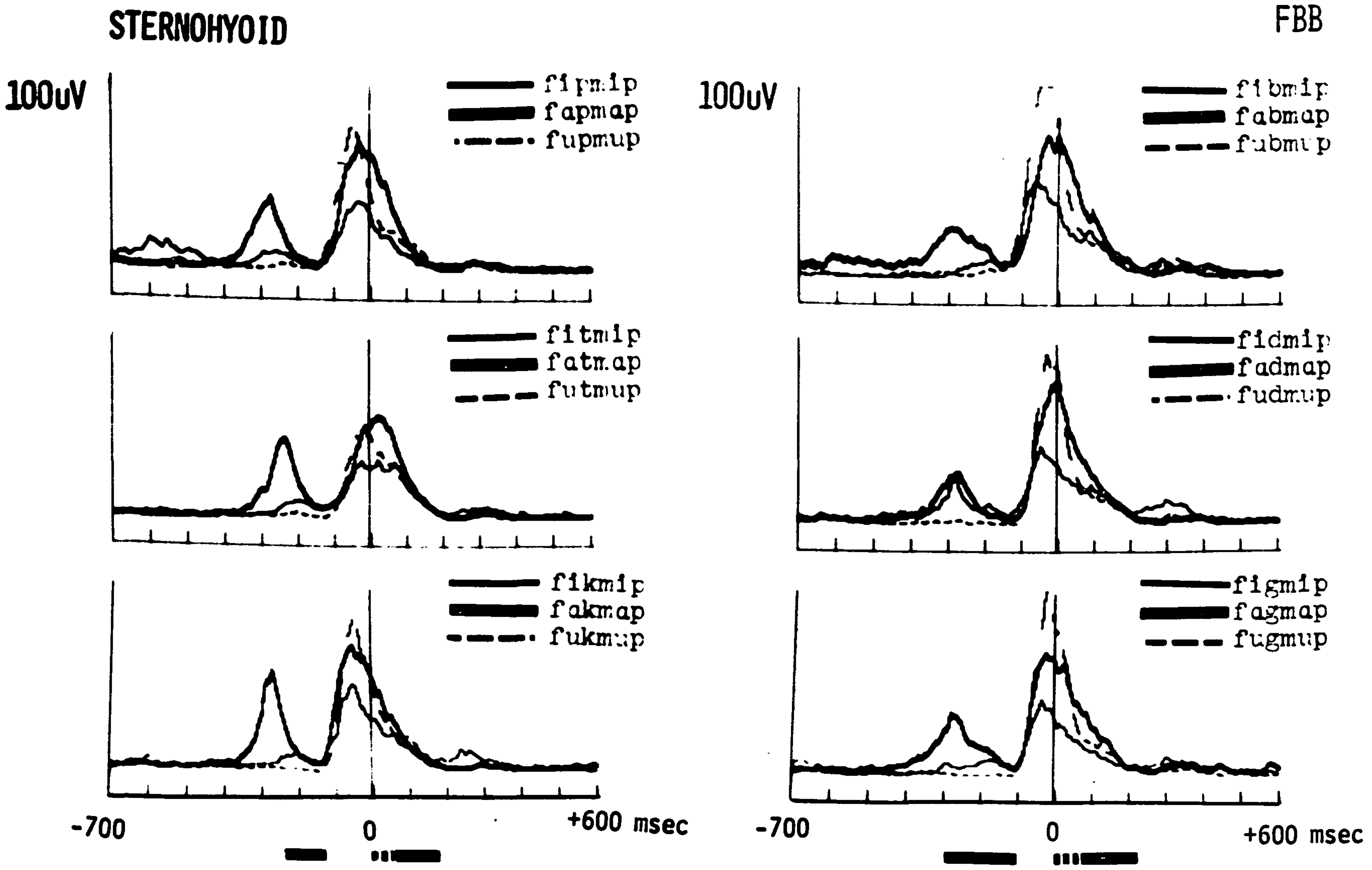
Figure 67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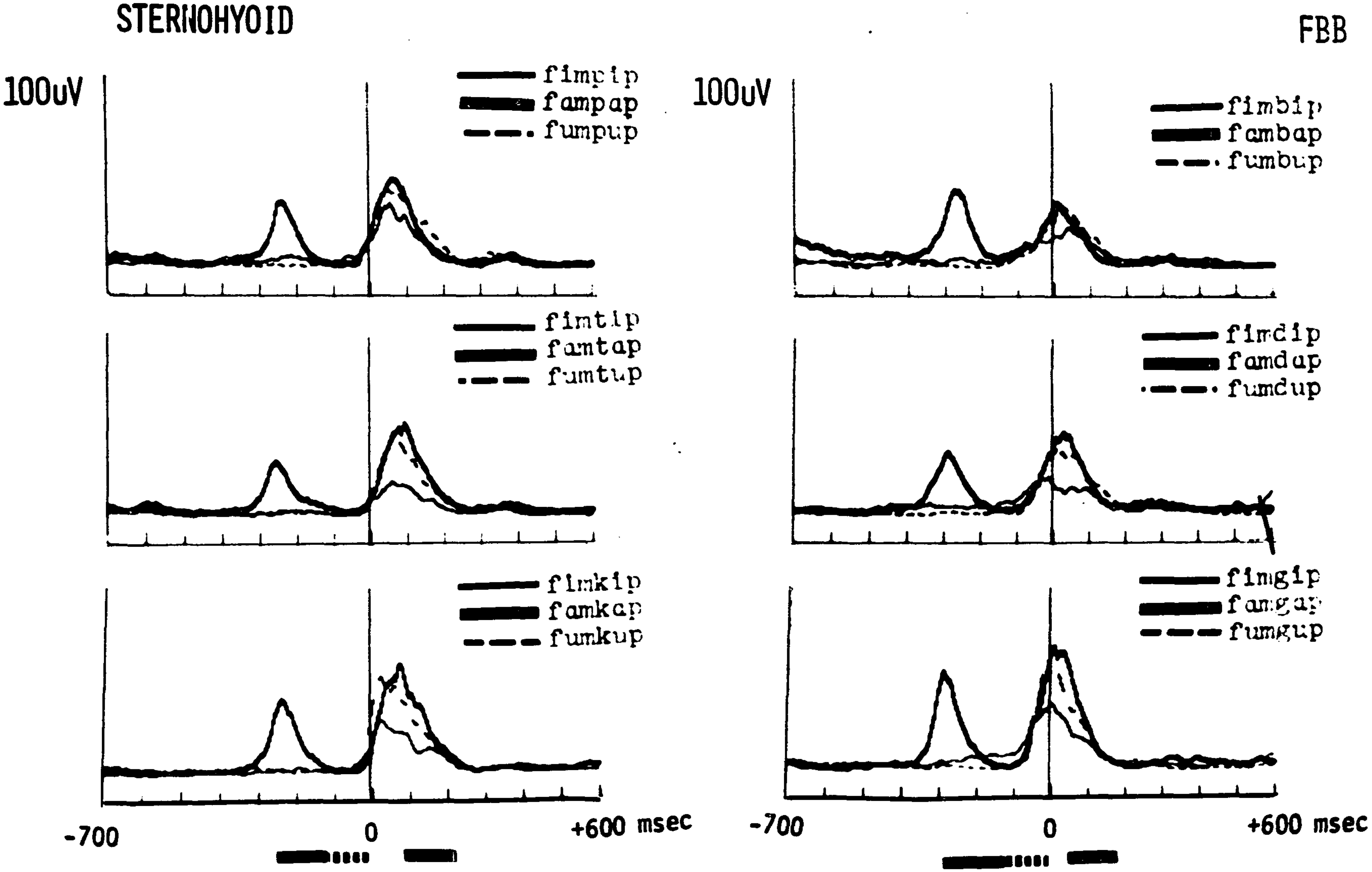
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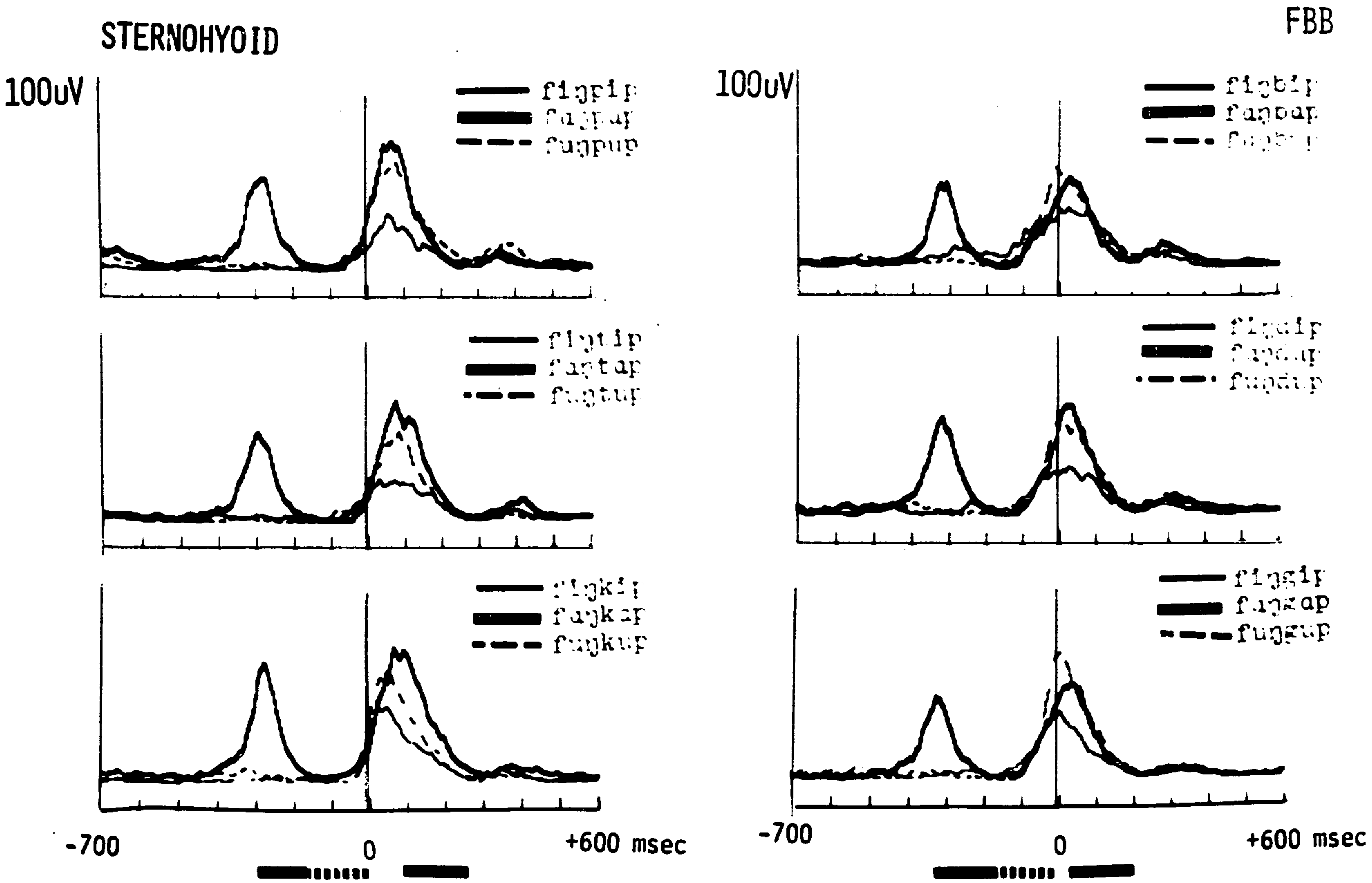
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Figure 70

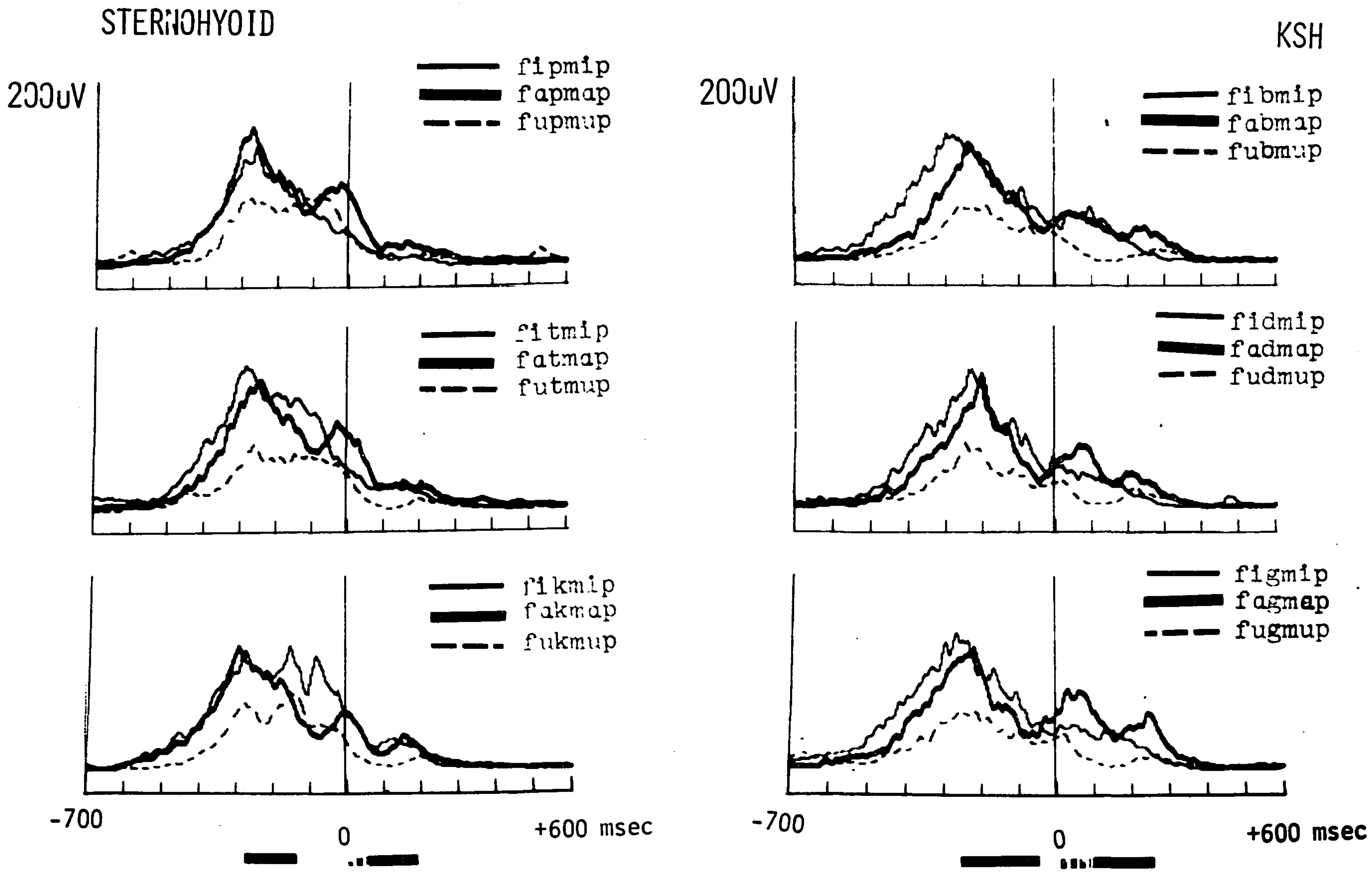
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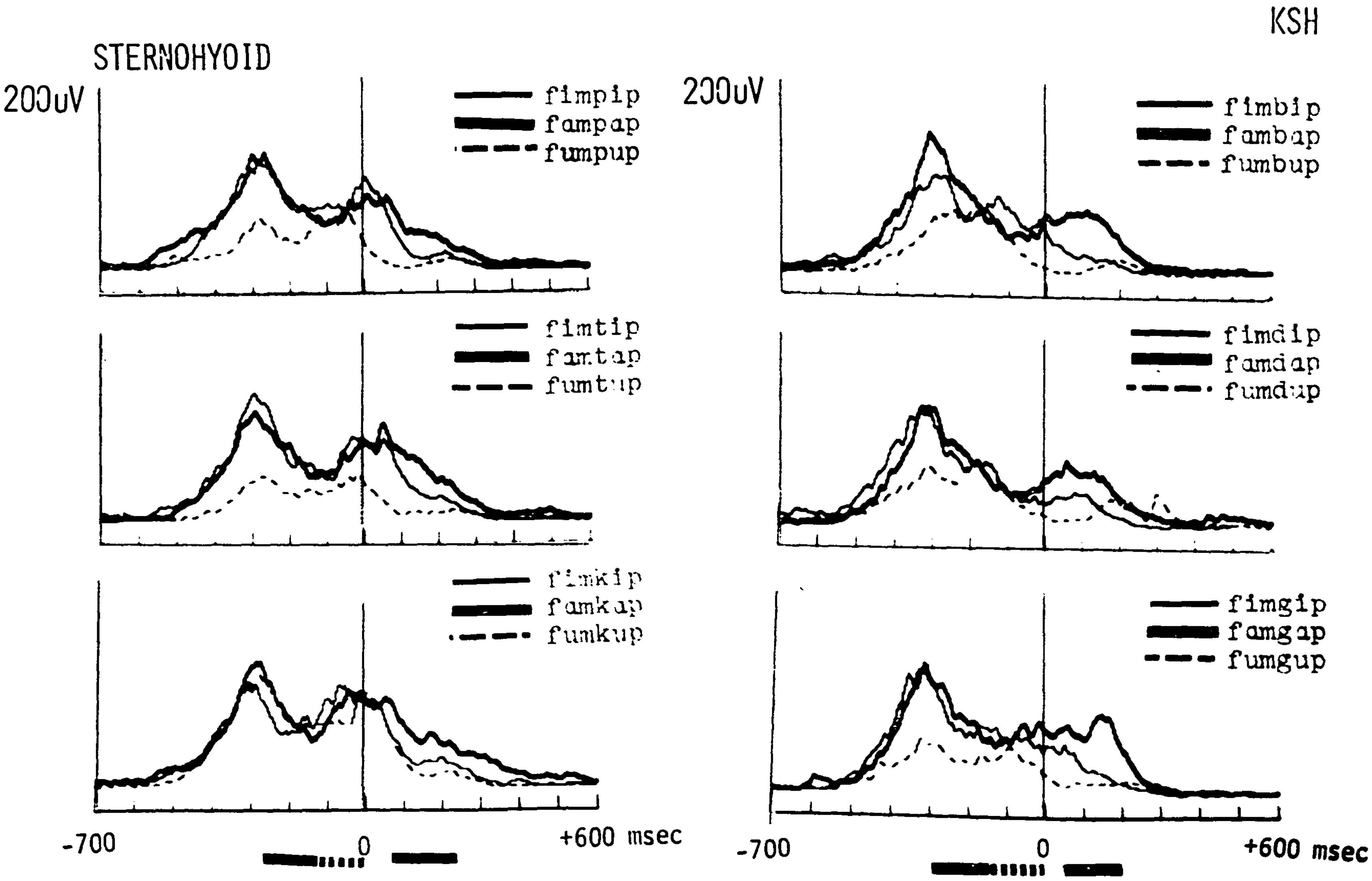
Figure 71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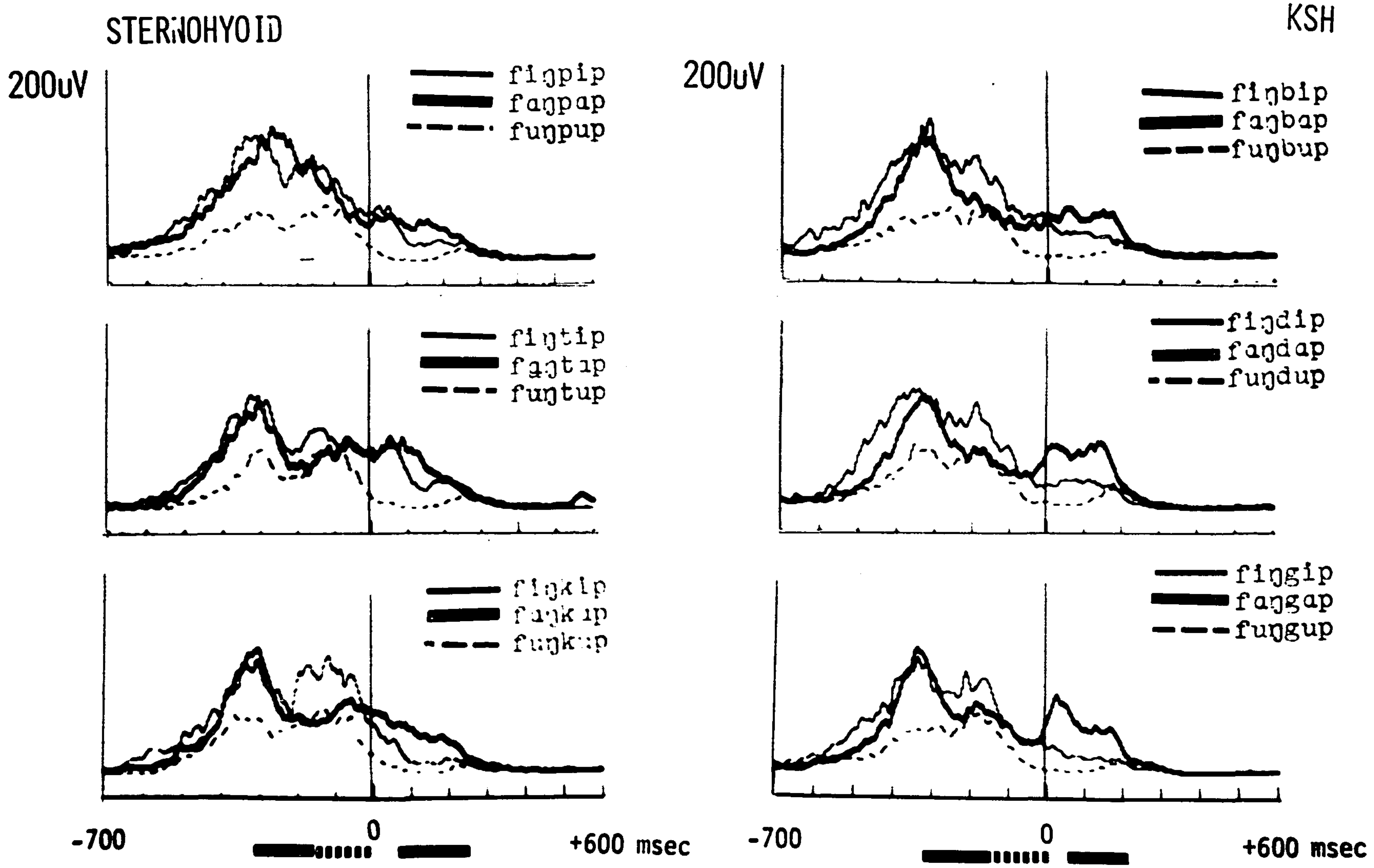
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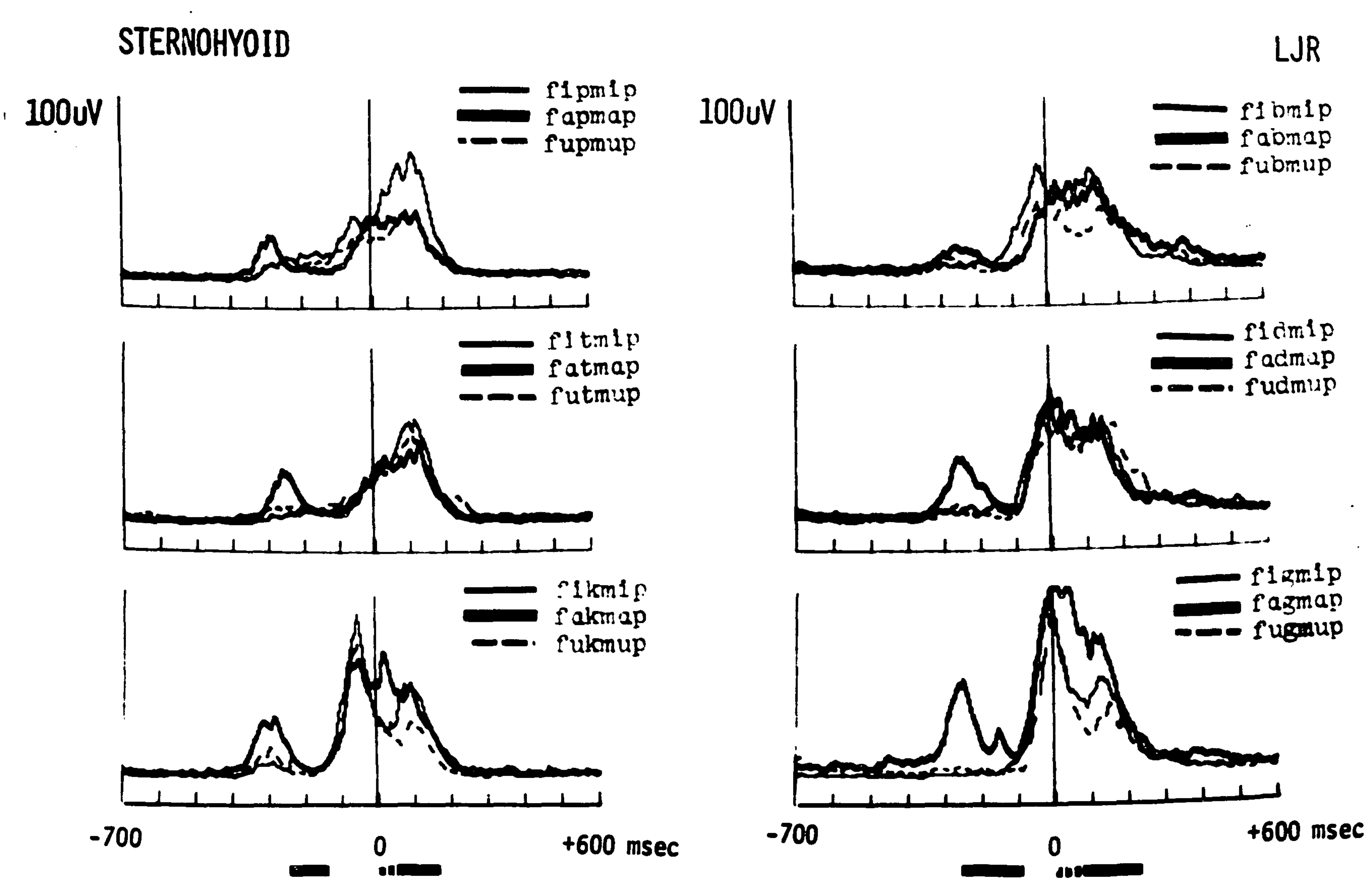
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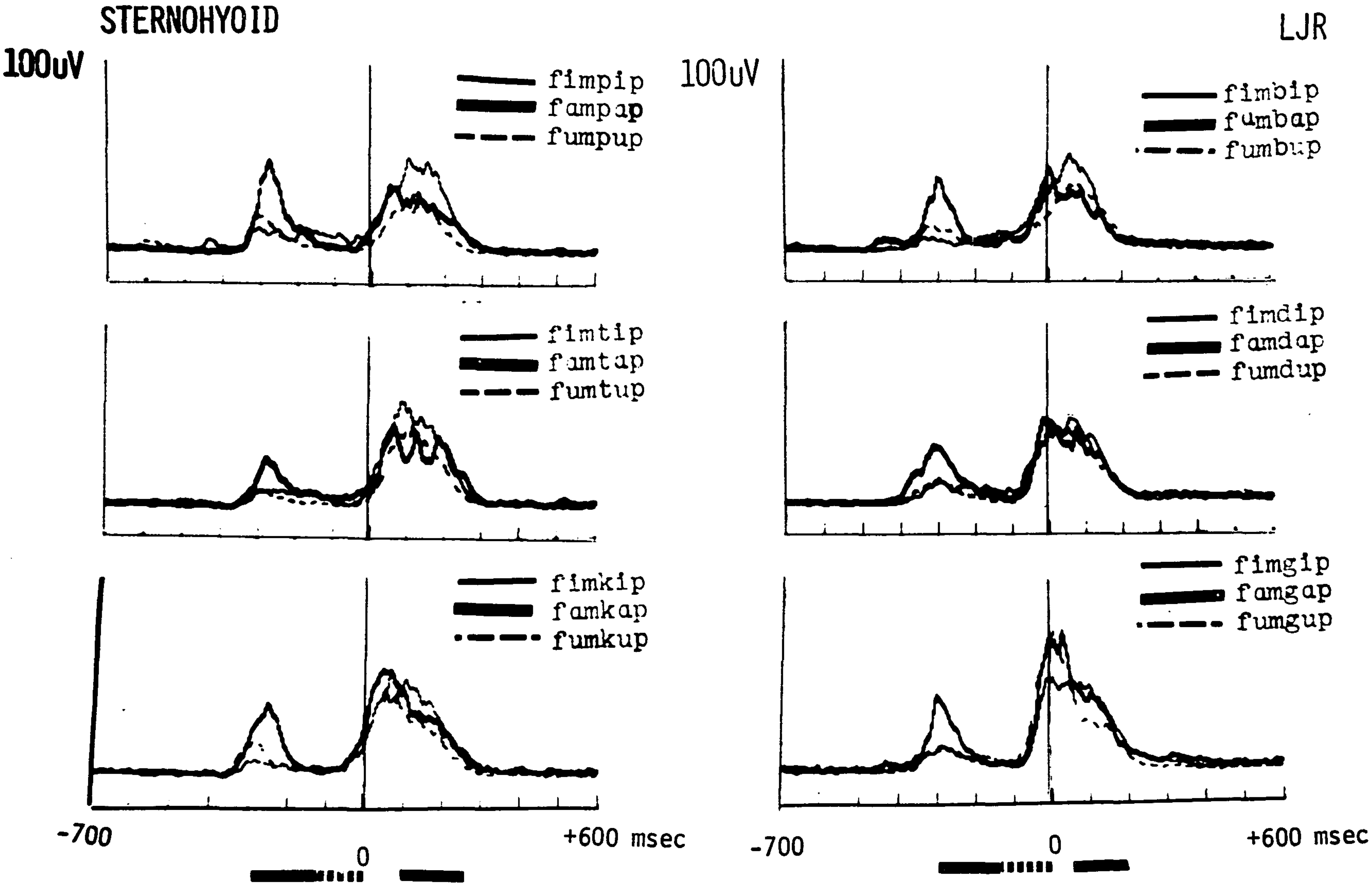
Figure 74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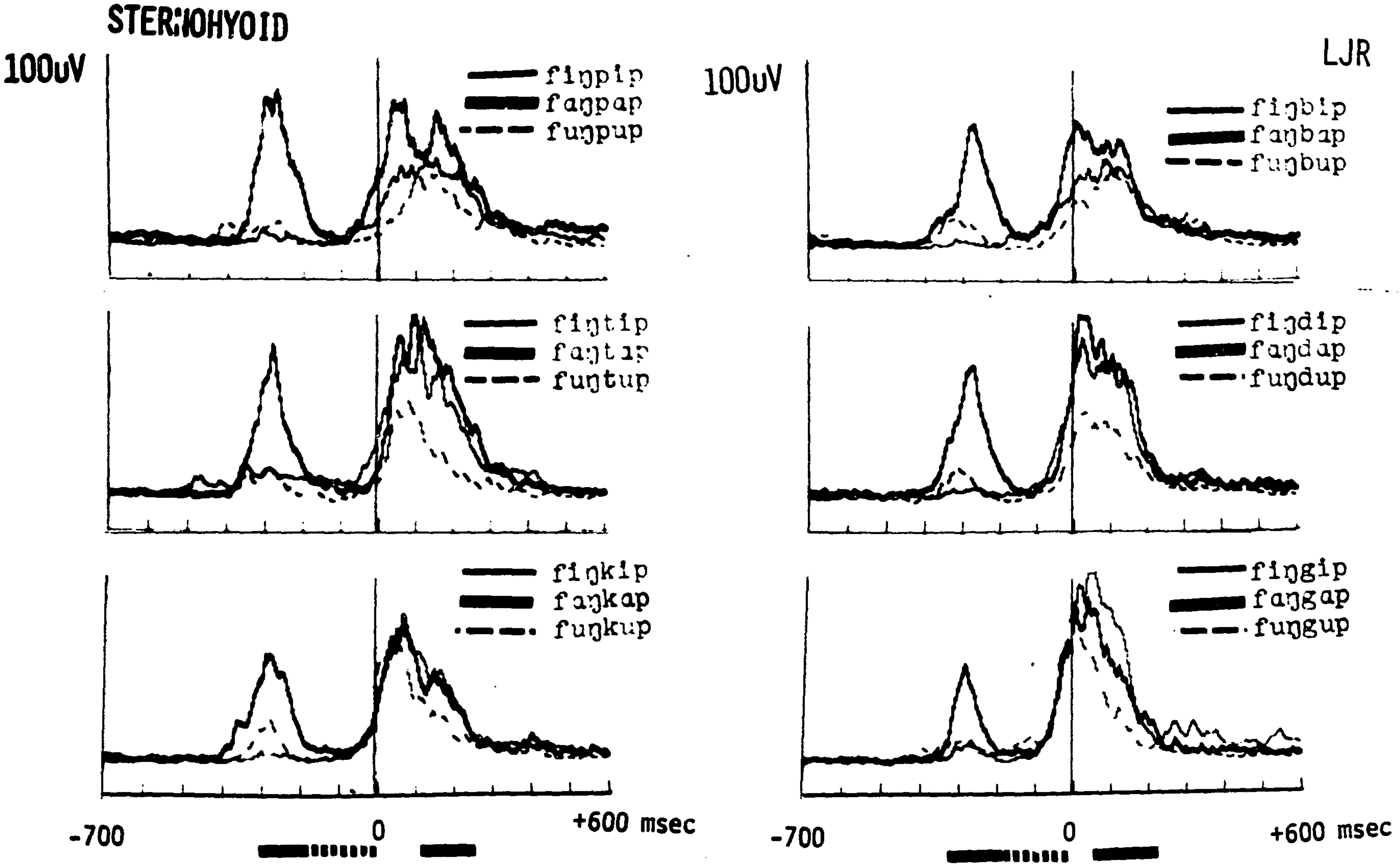
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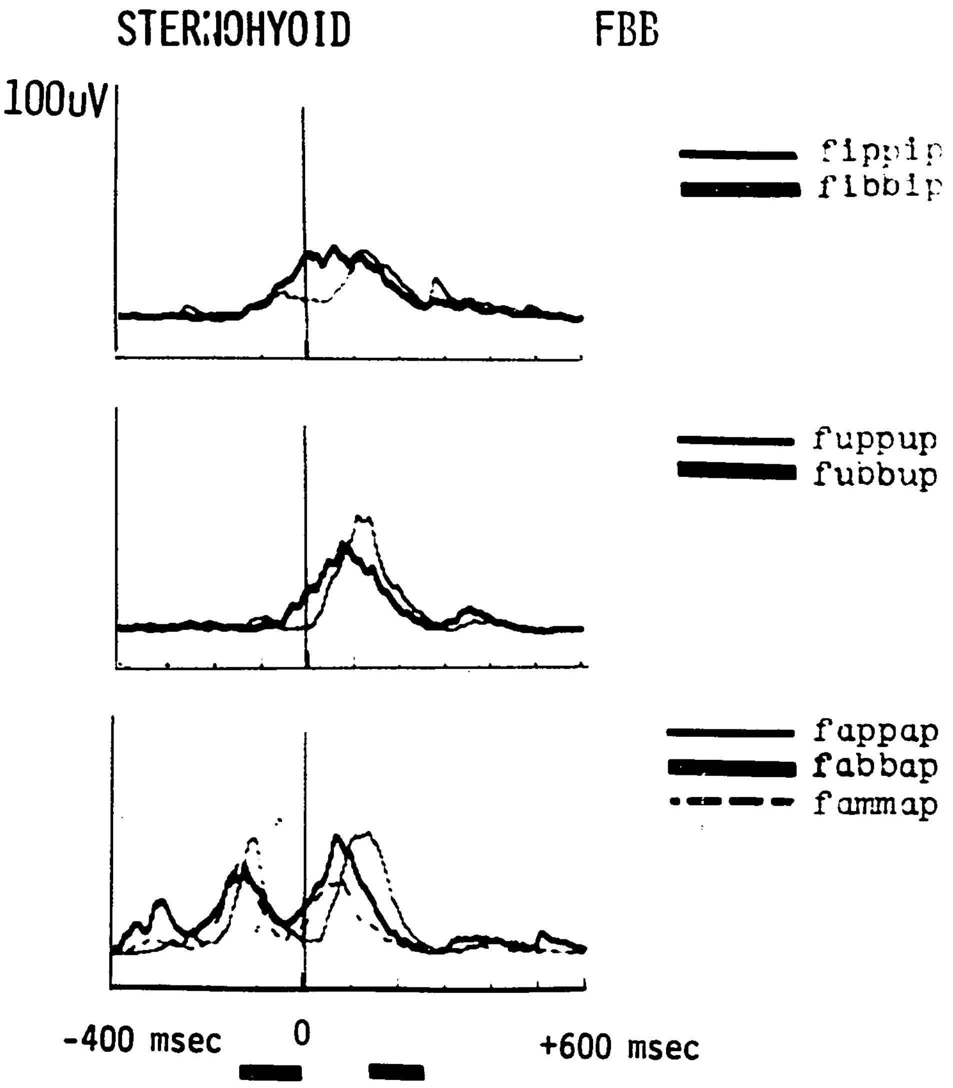
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Figure 77

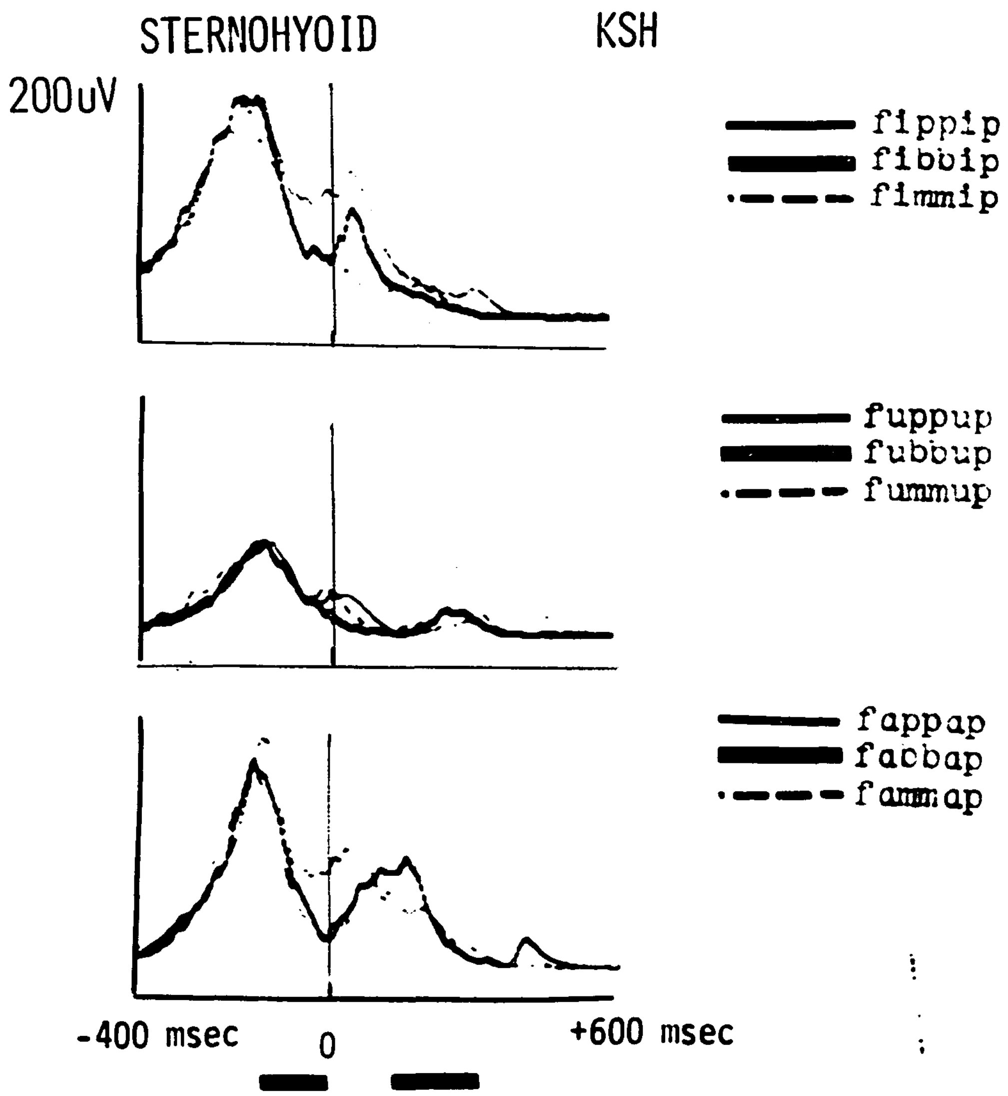

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Figure 78

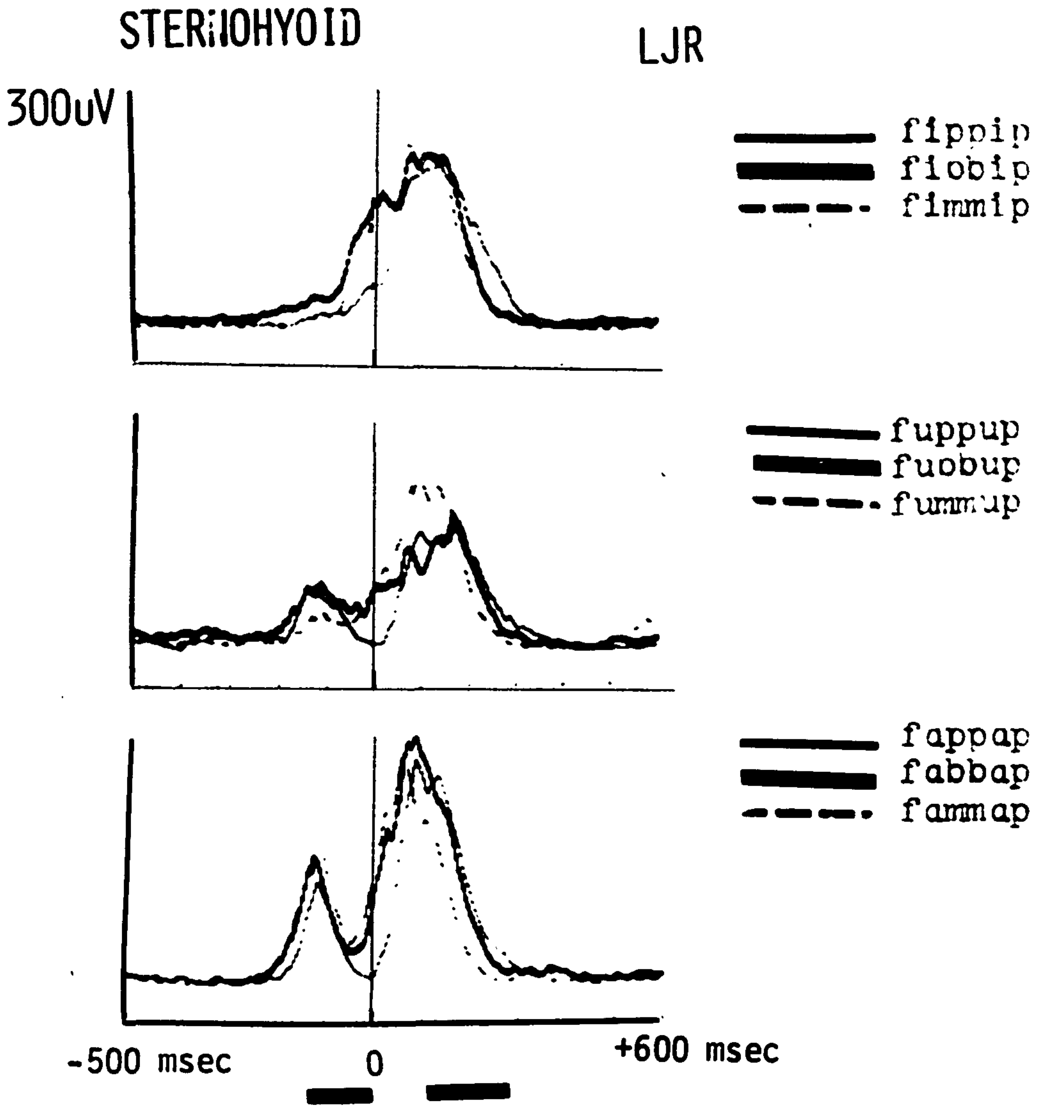
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Figure 79

Chapter IV: Discussion

Oral and Nasal Articulation

Oral articulation

The data of this study reveal a wide range of intersubject variation in the function of the muscles of the velopharyngeal region for each speech gesture studied, save one: levator palatini function for oral articulation. Uniquely, the patterns of levator palatini EMG activity for each utterance type are quite similar for all three subjects (Figures 10 through 18).

Changes in the magnitude of the EMG potentials recorded from the levator palatini, for a constant phonetic environment, correlate highly with changes in velar height (Berti and Hirose, 1972). Therefore, observations made here about EMG potential size may be considered to be commensurate with the velar height literature. Direct measurements of palatal height for the vowels in this investigation have been made by several investigators using cineradiographic and fiberoptic viewing techniques (Moll, 1962; Moll and Shriner, 1967; Lubker, 1968; Bzoch, 1968; Fritzell, 1969; Ushijima and Sawashima, 1972).

The model of levator palatini function to be applied to the present data and related to data of other investigators is that of a resistance matching device acting either to prevent or to permit coupling of the nasal and oral resonators (House and Stevens, 1956). The model provides a specific, testable prediction: variations in velopharyngeal port resistance to air flow and, hence, in levator palatini activity, are a function of variations in oral cavity impedance. The model predicts greater velopharyngeal port resistance to air flow, which implies greater levator palatini activity, for stop consonants than for vowels since oral cavity constriction, and, therefore, oral cavity impedance, is higher for stop consonants than for vowels. Furthermore, since high vowels have higher oral cavity impedances than low vowels (House and Stevens, 1956) they should have higher levator palatini potentials than low vowels. Nasal consonants, on the other hand, will be produced when oral cavity impedance is very high and velopharyngeal port resistance to air flow very low. Additional speech sounds may be fitted into the model on the basis of their relative levels of oral cavity impedance and their correlated magnitude of levator palatini potentials. We may now examine the levator palatini data on stop consonants, vowels and nasal consonants collected in this investigation within the framework of this model.

Every prediction made by the model is borne out by the data. For every subject oral consonant production is always preceded by a peak of levator palatini activity while nasal consonant production is always preceded by suppression of this activity (cf. Lubker, Fritzell and Lindquist, 1970). Furthermore, EMG potentials for vowels between oral consonants are generally of lower amplitude than those associated with oral consonant production. Finally, EMG curves for high and low vowels in oral environments or following nasal consonants, tended to differ in level with greater potentials going to the high vowels /i/ and /u/ than to the low vowel /ɑ/.

As mentioned above, this last effect seems to follow from the fact that the low vowel, /ɑ/, requires a lower velopharyngeal port resistance to air flow for the prevention of nasal coupling than do /i/ and /u/ (House and Stevens, 1956). Coupled with variations in strength, there was also an earlier increase in EMG signal strength for /u/ and /i/ following a nasal consonant than for /ɑ/ in a similar environment. The observed differences in EMG signal strength and temporal patterning for high and low vowels following nasal consonants implies a difference in the oral closure mechanism for the two observed conditions: palatal elevation begins earlier and achieves greater peak magnitude for the vowels /i/ and /u/ than for /ɑ/. While EMG activity is normally lower for low vowels than for high vowels in oral environments, the low vowels do have some EMG activity. The absence of EMG activity in low vowels following nasals, therefore, indicates a reorganization of the oral gesture for /ɑ/ in this position. This low vowel, then, exhibits postcipatory nasal coarticulation at the EMG level, whether or not coarticulation is evident at the acoustic signal level.

Nasality anticipated in vowels which precede nasal consonants has been reported in the phonetics literature (Trager and Smith, 1951; Jones, 1956). (Nasality is not distinctive for American English vowels and so its presence or absence is not critical for intelligible vowel production.) The evident suppression of levator palatini activity during the articulation of vowels which precede nasal consonants, with the implied nasalization of those vowels, regardless of the vowel color, is therefore not surprising.

While each of the subjects employs the levator palatini as the chief muscle of velopharyngeal port closure (a finding which confirms Fritzell's [1969] report) the remaining velopharyngeal musculature fails to behave as consistently as the levator palatini. Fritzell reported that the patterns of levator palatini and superior constrictor activity were similar although the amplitude of the superior constrictor signal was smaller than that of the levator. He made no observations on the middle constrictor.

It will be recalled that three subjects considered in this study presented different activity patterns in the superior and middle constrictors and the palatopharyngeus muscles. Subject FBB presented almost no activity in the superior and middle constrictors which might be identified with oral articulation. This suppression of constrictor activity occurs in the vicinity of the medial contrast and does not vary in time with the direction of the stop and nasal consonant contrast. For the other two subjects, KSH and LJR, on the other hand, constrictor muscle activity occurs essentially for stop consonant articulation. These peaks are not, however, found consistently through all fifty-four stop-nasal and nasal-stop utterance types, and they are of very low amplitude. The third subject exhibits no pattern of superior constrictor activity associated with oral closure, which is the primary function of the levator palatini.

Each subject also exhibits a pattern of palatopharyngeus activity for oral articulation, a finding at variance with that of Fritzell (1969) who reported no consistent pattern of palatopharyngeus activity. The observed activity is, however, highly subject to the influence of vowel color and so the oral articulation pattern is not as clear as the pattern observed in the levator palatini.

In summary, then, all subjects use the levator palatini as the primary muscle of oral articulation. In addition, the palatopharyngeus participates in oral articulation for all of the subjects. The superior and middle pharyngeal constrictors, on the other hand, do not behave consistently, and are active for oral articulation in only two of the three subjects.

Nasal articulation

There has been a good deal of interest in the mechanism of nasal articulation, that is, in whether nasal coupling is achieved by increased activity in some muscle or group of muscles in the velopharyngeal region or if it is achieved solely by the suppression of activity in those muscles responsible for the velopharyngeal closure necessary for oral articulation.

Moll and Shriner (1967) proposed, based upon the study of cinefluorographic films, that the palatoglossus might function to lower the soft palate. Fritzell (1969) and Lubker, Fritzell and Lindquist (1970), presenting the results of electromyographic studies of palatoglossus function, reported that palatoglossus activity is correlated with nasal articulation, occurring while the levator palatini is suppressed. The Fritzell (1969) study involved subjects who were native speakers of American English. The Lubker, Fritzell and Lindquist (1970) study reported results from one native speaker of Swedish.

Inspection of Fritzell's (1969) data reveals that palatoglossus activity occurs only for velar consonant production (both nasal and oral) and for back vowel production (/u/ and /ɑ/). When a nasal consonant occurs in a high front vowel (/i/) environment there is no evidence of palatoglossus activity. Inspection of the Lubker, Fritzell and Lindquist data on the Swedish speaker reveals that palatoglossus activity occurs for nasal consonant articulation when levator palatini activity is suppressed, and also occurs for the articulation of /u/.

The data of this experiment were, as in Fritzell's (1969) study, collected from native speakers of American English. They offer no evidence of palatoglossus activity for nasal articulation save with /ŋ/, a velar consonant. Two subjects in this study, FBB and KSH, demonstrate palatoglossus activity for vowel production, with /ɑ/ yielding the highest EMG potential in both subjects. Any palatoglossus activity correlated with consonant articulation occurs only for velar consonants, both oral and nasal. Where palatoglossus activity occurs for vowels only, the timing of the suppression of palatoglossus activity for the medial consonant production is the same for the stop-nasal and nasal-stop (where the nasal is /m/) utterances. In other words, the position of the suppression of activity does not shift with the position of the nasal consonant. Palatoglossus activity, for these two subjects, is totally unrelated to the consonantal manner of articulation but is related to tongue body movements and pharyngeal cavity adjustments. The third subject exhibits very small amounts of palatoglossus activity for back vowels, and none for front vowels. This same subject, LJR, presents his greatest peaks of palatoglossus activity for velar consonant production, in back vowel environment. In utterances having a velar stop and a labial nasal, the position of palatoglossus activity shifts in the direction of the velar stop articulation. For example, the burst of palatoglossus activity seen in /fukmup/ occurs earlier than the burst of palatoglossus activity seen in /fumkup/, indicating that the activity is related to velar articulation rather than to nasal articulation.[1]

Inspection of the EMG potentials for the levator palatini for each of the subjects reveals minima of activity for nasal consonant articulation. These minima shift, in time, with the position of the nasal consonant. When the nasal consonant appears earlier in one utterance than in another (in nasal-stop, as opposed to stop-nasal utterances, for example) the minimum point also occurs earlier. The same pattern is found in the palatopharyngeus data, where activity peaks are also associated with oral articulation. Inspection of the superior and middle constrictor data provides no evidence of increased muscle activity for nasal articulation.

The conclusion to be drawn, then, is that speakers of American English do not use increased activity in any muscle to produce nasal articulation, but rather produce such articulation by decreasing the activity in those muscles which are responsible for oral articulation.

Nonnasal Phonetic Variation

Vowel Color

A fairly lengthy account of the variations in levator palatini activity with variations in vowel height appears above, in the discussion of oral and nasal articulation. Briefly, the EMG potentials recorded from the levator palatini are of greater magnitude for /i/ and /u/ than for /ɑ/, a finding which confirms those of other workers (Lubker, 1968; Fritzell, 1969; Lubker, Fritzell and Lindquist, 1970) and which is reflected in differences in palatal height. Specifically, the velum is higher for /i/ and /u/ than for /ɑ/

(Moll, 1962; Moll and Shriner, 1967; Lubker, 1968; Bzoch, 1968; Fritzell, 1969; Ushijima and Sawashima, 1972).

Variations in velar height, however, are not the only variations to pharyngeal cavity dimensions that have been observed to occur with changes in vowel color. Perkell (1969) measured the anteroposterior width of the pharynx, from lateral cineradiographic films, at two levels: first at the level of the junction between the first and second cervical vertebrae, second at a level somewhat lower than the first, closer to the glottis. Included in that study were the vowels /i/, /u/ and /ɑ/, the three vowels which were used in this investigation. He found that /ɑ/ had the narrowest anteroposterior pharyngeal width of the vowels he studied. The widest anteroposterior pharyngeal width was observed for /i/. The pharyngeal width observed for /u/ was slightly smaller than that observed for /i/. Minifie et al. (1970) monitored lateral pharyngeal wall movements during speech using pulsed ultrasound. They found little or no medial movement of the lateral pharyngeal wall for the articulation of /i/ and /u/ and up to 5 mm of medial movement of the lateral pharyngeal wall for the articulation of /ɑ/.

Each of the three subjects in this study presents a different pattern of activity in the muscles of the walls of the velopharynx. One subject, LJR, shows slightly greater EMG activity for /ɑ/ than for /i/ and /u/ only in the palatopharyngeus, a muscle of the lateral pharyngeal wall. A second subject, KSH, presents greater EMG potentials for /ɑ/ than for /i/ and /u/ in two muscles, the palatopharyngeus and the palatoglossus. The third subject, FBB, presents greater EMG potentials for /ɑ/ than for /i/ and /u/ in the palatopharyngeus, palatoglossus, superior constrictor and middle constrictor. In each of the three subjects for each muscle except the palatoglossus, the lowest EMG potentials recorded from the muscles of the pharyngeal walls occur for the vowel /u/, but each subject also presents a different pattern of pharyngeal cavity adjustment for the three vowels. (The palatoglossus is not only a muscle of pharyngeal cavity adjustment but is also a muscle of tongue body movements.)

Obviously, then, the pharyngeal musculature of each subject follows a rule which might be stated this way: if a muscle shows differential activity for different vowel articulations, it will show greater activity for /ɑ/ than for /i/ and /u/.

There is an apparent discrepancy, however, between Perkell's (1969) report of greater anteroposterior pharyngeal cavity width for /i/ than for /u/ and the EMG potentials recorded from the superior and middle constrictor muscles of subject FBB. The inferior portion of the superior constrictor inserts into the tongue and the middle constrictor inserts to the greater and lesser hyoid cornua, the bone which forms the base of the tongue. Contraction of the superior and middle constrictor muscles should draw the tongue posteriorly, reducing the anteroposterior dimension of the pharynx.

One possible explanation for this apparent contradiction (that there are greater EMG potentials in the constrictors for /i/ than for /u/, while pharyngeal width is less for /u/ than for /i/) is that the contraction of the constrictors is more than offset by the strong contraction of the genioglossus and anterior suprahyoid muscles which act to draw the tongue body anterosuperiorly for the production of /i/ (Harris, 1971; Raphael, 1971a; Raphael 1971b).

Voicing distinctions

Glottal pulsing occurs when the vocal folds are adducted and subglottal pressure is greater than supraglottal pressure, a condition easily met when the oral cavity is not occluded. If the oral cavity is occluded, however, and the velopharyngeal port is closed the transglottal pressure differential is rapidly reduced. Glottal pulsing during an oral cavity occlusion, a condition existing for the production of voiced stop consonants in medial position by English speakers, necessitates the maintenance of a transglottal pressure differential. The transglottal pressure differential might be maintained by expansion of the pharyngeal cavity.

The pharyngeal cavity might be expanded by the movement of any of four structures: the lateral and posterior pharyngeal walls might move outward; the base of the tongue might move inferoanteriorly; the larynx might move inferiorly; the velum might move superiorly. The first of the expansion modes listed above, which I shall call passive pharyngeal enlargement, would be characterized by less activity in the pharyngeal wall musculature for voiced stops than for their voiceless cognates. The three remaining expansion modes, which I shall call active pharyngeal enlargement, would be characterized by increased activity in the infrahyoid musculature and the levator palatini (Figure 80).

Measurements of pharyngeal cavity size from lateral cineradiographic films, during stop consonant occlusion, by Perkell (1969) and by Kent and Moll (1969), reveal pharyngeal cavity enlargement during voiced stop consonant occlusion. There is an increase in the anteroposterior width of the pharynx at the level of the base of the tongue as well as a lower larynx position for voiced stop articulation than for voiceless stop articulation. Perkell (1969) hypothesized that the pharyngeal expansion occurs because of decreased tension of the muscles of the pharyngeal walls. Kent and Moll (1969) hypothesized that the pharyngeal enlargement is caused by increased activity in the infrahyoid musculature, which would act to depress the hyoid bone. Depression of the hyoid bone would result in inferoanterior movement of the base of the tongue and inferior movement of the larynx.

The EMG data for this study were inspected for consonant associated

EMG peaks, which were compiled in tables for each muscle for each subject (Tables 4, 14, 15, 19, 23, 24). When obvious peaks could not be found for some muscles, the EMG values for each of those muscles were taken at the time of peak levator palatini activity. The EMG peak values for each voiced-voiceless minimal pair were compared. When the muscle was one for which the passive enlargement mode was expected (the superior and middle constrictors, palatoglossus and palatopharyngeus), muscle activity for voiced stops was expected to be lower than muscle activity for voiceless stops. When the muscle was one for which the active enlargement mode was expected (the levator palatini and sternohyoid)[2] muscle activity for voiced stops was expected to be greater than muscle activity for voiceless stops. If the comparison of peak EMG values for a minimal contrast pair (e.g., /fimpip/ - /fimbip/) met the expectations as to the direction of the peak size difference a value of "1" was assigned to the muscle for that contrast pair. If the difference in peak heights was opposite to the direction expected a value of "0" was assigned for the contrast pair. If the peak values were equal a value of "1/2" was assigned to the muscle for that contrast pair. The total of successful comparisons was then summed for each subject for each muscle.

The results of this analysis are presented in Figure 81. It is evident that each subject employs a different pattern of muscle activity for enlarging the pharyngeal cavity for the maintenance of voicing during the production of voiced stop consonants. Subject FBB uses the levator palatini and sternohyoid muscles for active enlargement of the pharynx in nearly all instances, while she fails to use the superior and middle constrictors, palatopharyngeus and palatoglossus muscles for passive enlargement of the pharynx in more than half of the cases. Subject KSH uses greater activity in the levator palatini for the voiced stops than for the voiceless stops in nearly three-fourths of the comparisons, while using the sternohyoid for active pharyngeal enlargement in fewer than half of the comparisons. This same subject uses the pharyngeal wall muscles for passive pharyngeal enlargement in half to three-fourths of the comparisons. Subject LJR uses the sternohyoid for active pharyngeal enlargement in 87% of the comparisons while using the levator palatini for active pharyngeal enlargement in only 31% of the comparisons. This same subject uses three of the four muscles of passive pharyngeal enlargement in 65% to 87% of the comparisons.

Earlier inspection of the EMG data curves for the sternohyoid revealed that subjects FBB and LJR showed significant differences in the temporal pattern of EMG activity between voiced and voiceless stop consonant articulation. That is, EMG activity began 50 to 100 msec earlier in utterances with voiced stops than in utterances with voiceless stops, acting to draw the hyoid bone inferiorly during the consonant occlusion.

When the successful comparisons for both of the muscles of active pharyngeal enlargement and for the four muscles of passive pharyngeal enlargement are averaged, a picture is obtained of the overall use of the active and passive enlargement modes by each subject. Figure 82 presents the results of this analysis. Subjects LJR and KSH each use the active enlargement mode in 60% of the possible comparisons, while subject FBB used the active enlargement mode in 90% of the possible comparisons. Passive pharyngeal enlargement is used by subjects LJR and KSH in 68% and 62% of the possible comparisons,respectively, a rate just slightly above that computed for their use of the active pharyngeal enlargement mode. Subject FBB, on the other hand, uses the passive pharyngeal enlargement mode in only 37% of the possible comparisons.

One may conclude, then, that subject FBB makes predominant use of active pharyngeal enlargement while subjects KSH and LJR use a balance of active and passive enlargement modes, although they use different muscles for the active pharyngeal enlargement.

Chomsky and Halle (1968) postulated that one of the features of the stop consonant voicing distinction was that of pharyngeal wall tension, with greater tension for voiceless stop articulation than for voiced stop articulation (see Chapter I, above). Kent and Moll (1969) postulated that increased pharyngeal cavity volume was caused by an active lowering of the larynx and hyoid bone. It appears from the data presented here, however, that an adequate description of pharyngeal cavity enlargement for voiced stop consonant articulation is neither an exclusively active nor an exclusively passive one. Each speaker uses both modes of enlargement, with each speaker apparently favoring one mode over the other. That is, each subject shows more consistency across the muscles involved within one mode than within the other. It is also apparent that the feature [± tense] is inadequate for describing the activity of the pharyngeal cavity concomitant with voicing distinctions, since this feature at best explains the larger portion of some speakers' pharyngeal enlargements and never explains the full measure of enlargement.

[± tense] appears, in the Chomsky - Halle system, as a feature orthogonal to vocal cord adjustment in the explanation of the "voiced-voiceless" dimension. The picture of pharyngeal cavity adjustment offered here suggests that pharyngeal cavity adjustments are made in parallel with laryngeal adjustments. A final decision between parallel and orthogonal alternatives must wait on more cross-language studies.

Place of articulation

Place of stop consonant articulation influenced consonant associated EMG values for only three muscles in this study: palatoglossus, middle constrictor and sternohyoid.

The palatoglossus and the middle constrictor do not present consistent patterns of activity across subjects for particular places of articulation. Velar articulation (including velar nasal articulation) increases the peak EMG values of the palatoglossus and middle constrictor for one subject, LJR, indicating a possible general constriction of the pharynx for velar articulation in that subject. (It must be noted, too, however, that for this subject peaks of consonant associated EMG activity from the palatopharyngeus are lower for stops following /ŋ/ than for stops following /m/. There is, as yet, no explanation for these data.) Subject FBB presents greater peak EMG potentials from the middle constrictor for alveolar than for labial or velar stops. Perhaps the middle constrictor functions, for this subject, to stabilize the hyoid bone for lingual articulation.

Increased sternohyoid activity for velar stop articulation (for subjects FBB and LJR) points up the role of the sternohyoid in depressing the hyoid bone. The hyoid bone is higher for the velar articulation than for the alveolar or labial articulations required in this study (Perkell, 1969). A strong, sharp burst of sternohyoid activity would draw the hyoid bone inferiorly, aiding the release of the velar consonant.

Individual Differences

While the EMG recordings obtained from each subject were reliable, the three subjects exhibited different patterns of velopharyngeal adjustment for all of the articulatory parameters studied save levator palatini function for oral articulation. (It is not surprising, though, that the levator palatini functions in the same way for all the subjects for oral articulation as there is no other muscle which will raise the velum and draw it posteriorly.)

There are three possible bases for the observed individual differences in articulatory pattern: dialectal differences;

anatomical differences; or idiosyncratic behavior, where a speaker might, at the time of language learning, choose one from among several available articulatory patterns.

Dialectal difference would be eliminated as the cause of the observed intersubject variation if two speakers of the same dialect were found to have different articulatory patterns. Anatomical differences might be eliminated as a cause of the variation if two speakers having equivalent anatomical structures had different articulatory patterns. The case for idiosyncratic behavior as the cause of the observed intersubject variation would be strengthened if two speakers having different dialects and different anatomical structures had the same articulatory pattern.

Unfortunately, the data gathered for this study do not lend themselves to clarification of this problem. The three subjects have different dialects, different anatomical structures (one has a wide pharynx, one a long narrow pharynx, one a shorter, narrow pharynx) and different articulatory patterns. Further work might be aimed at looking at differences in articulatory pattern using speakers with closely matched dialects and gross anatomy.

FOOTNOTE

1. After this experiment was completed, we had an opportunity to hold an additional experimental session in which the subject was a native speaker of Swedish. This experiment was not a part of the design of the investigation for this thesis, which dealt only with speakers of American English and addressed itself to a broader series of questions than did this experiment with the Swedish speaker. The subject employed in this smaller study was the same subject whose data were reported in detail by Lubker, Fritzell and Lindquist (1970), and the results correspond to their reported findings. EMG recordings were obtained from the palatoglossus and levator palatini muscles of the subject. The data were obtained and processed using the Haskins Laboratories EMG system, described above in Chapter II. The 36 stimuli used were a subset of the stimuli of this larger experiment, involving both stop-nasal and nasal-stop contrasts, three places of stop articulation, one stop consonant voicing condition, and labial and velar nasals. In addition, nine stimuli were added to the nasal-stop group in which the nasal was alveolar. The subject BG, presents peaks of palatoglossus activity which correspond to nasal consonant articulation. In addition, however, he also presents peaks of palatoglossus activity which correspond to velar stop articulation and /u/ and /ɑ/ production. The palatoglossus activity is of greatest magnitude for /ɑ/. Palatoglossus activity is greater for velar nasals than for labial or alveolar nasals. Based on the results of the experiment with the Swedish speaker, we cannot tell whether the difference in function of the palatoglossus is one of the individual difference or language difference. In either case, Fritzell's hypothesis of a universal nasal mechanism, corresponding to a universal oral mechanism, can be rejected, since not all speakers use such a mechanism.

2. The sternohyoid is sometimes considered to be active for pitch lowering, as well as for jaw opening and hyoid and larynx lowering. However, since no measurements of fundamental frequency were made, we cannot attempt to correlate sternohyoid activity with changes in pitch.

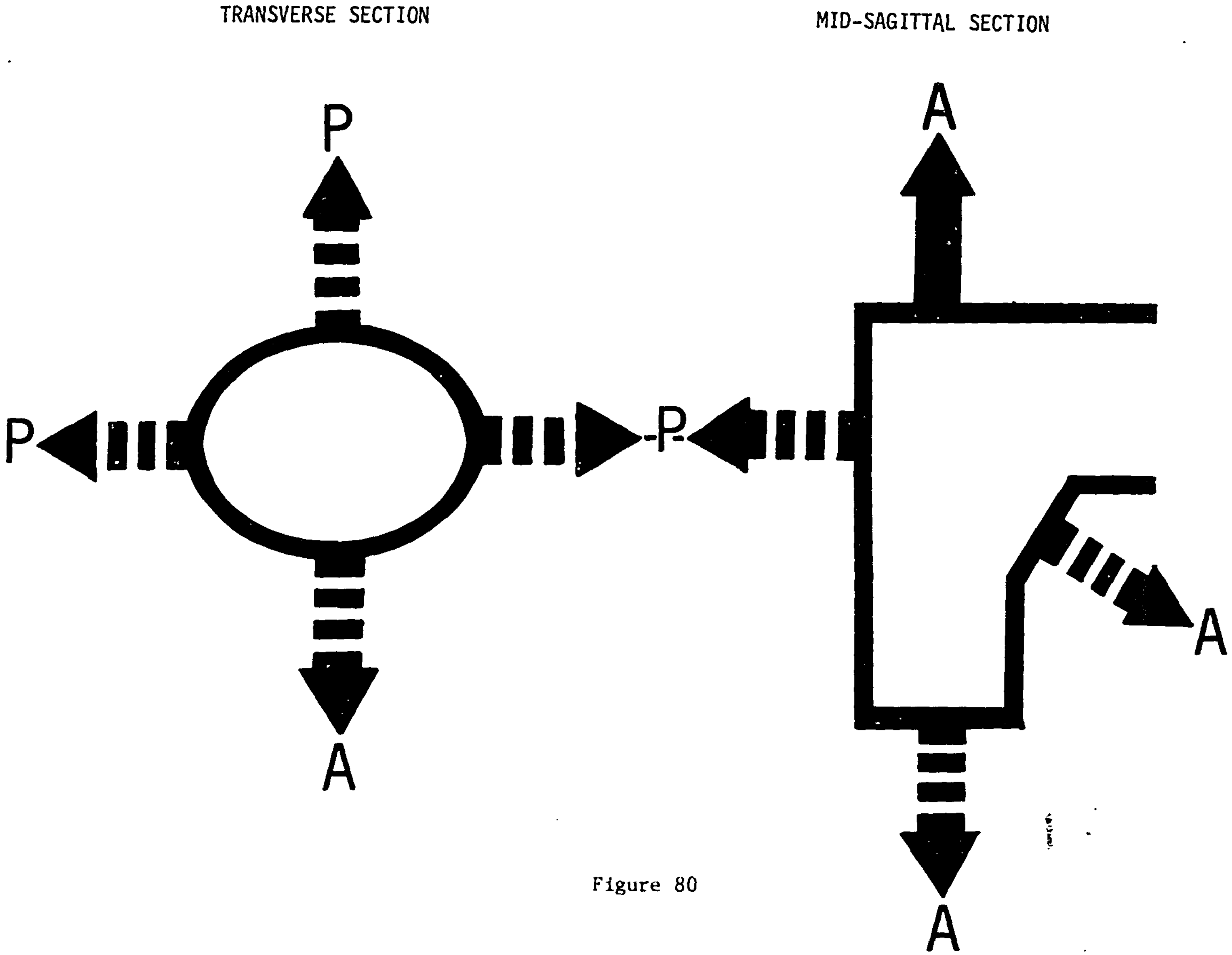

Figure 80

Schematic view of possible directions for active and passive pharyngeal cavity expansion.

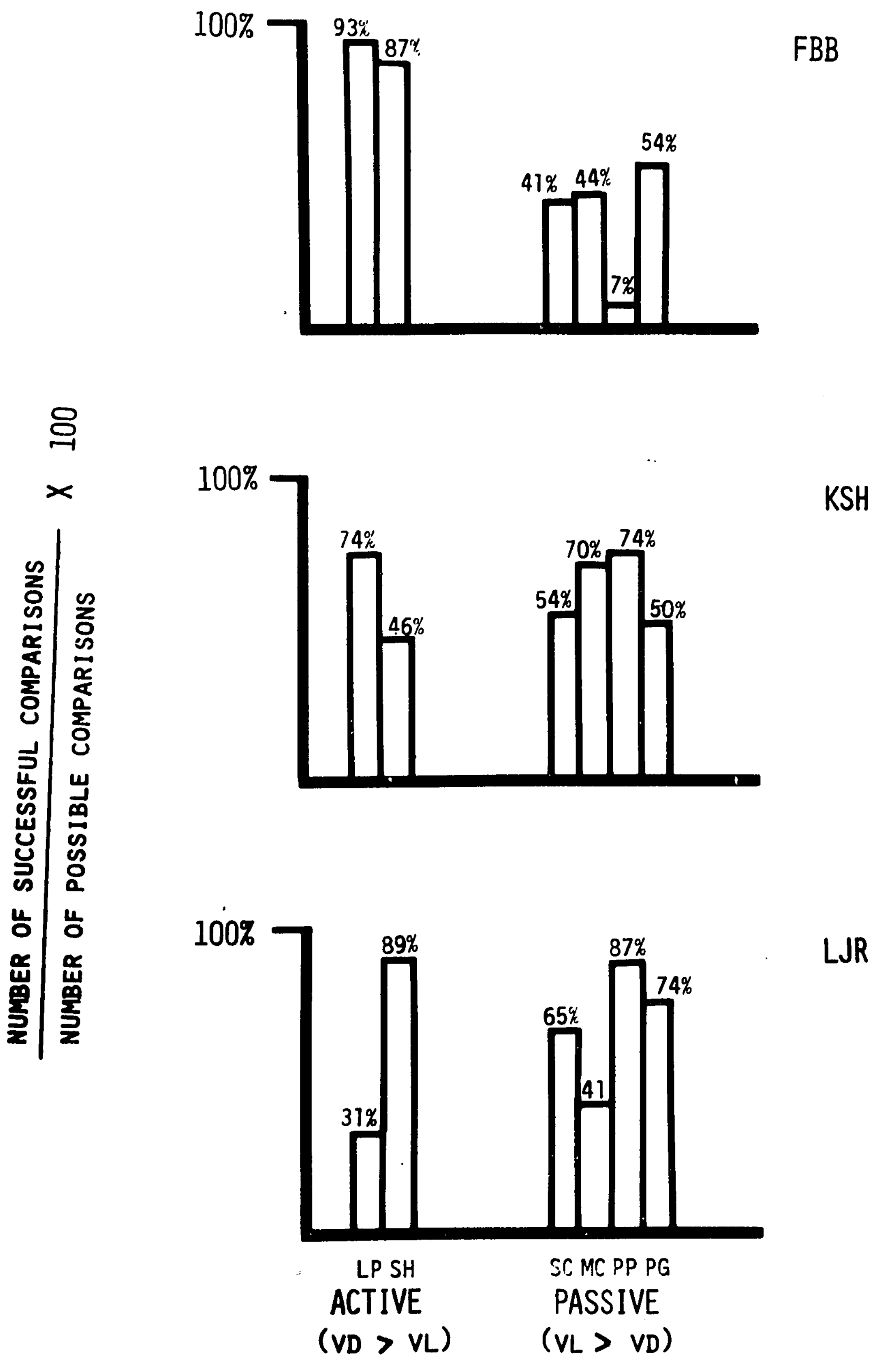
100%
93%
87%
41%
44%
7%
54%
FBB
100%
74%
46%
54%
70%
74%
50%
KSH
100%
31%
89%
65%
41
87%
74%
LJR
NUMBER OF SUCCESSFUL COMPARISONS / NUMBER OF POSSIBLE COMPARISONS X 100
LP SH
ACTIVE
(VD > VL)
SC MC PP PG
PASSIVE
(VL > VD)

Figure 81

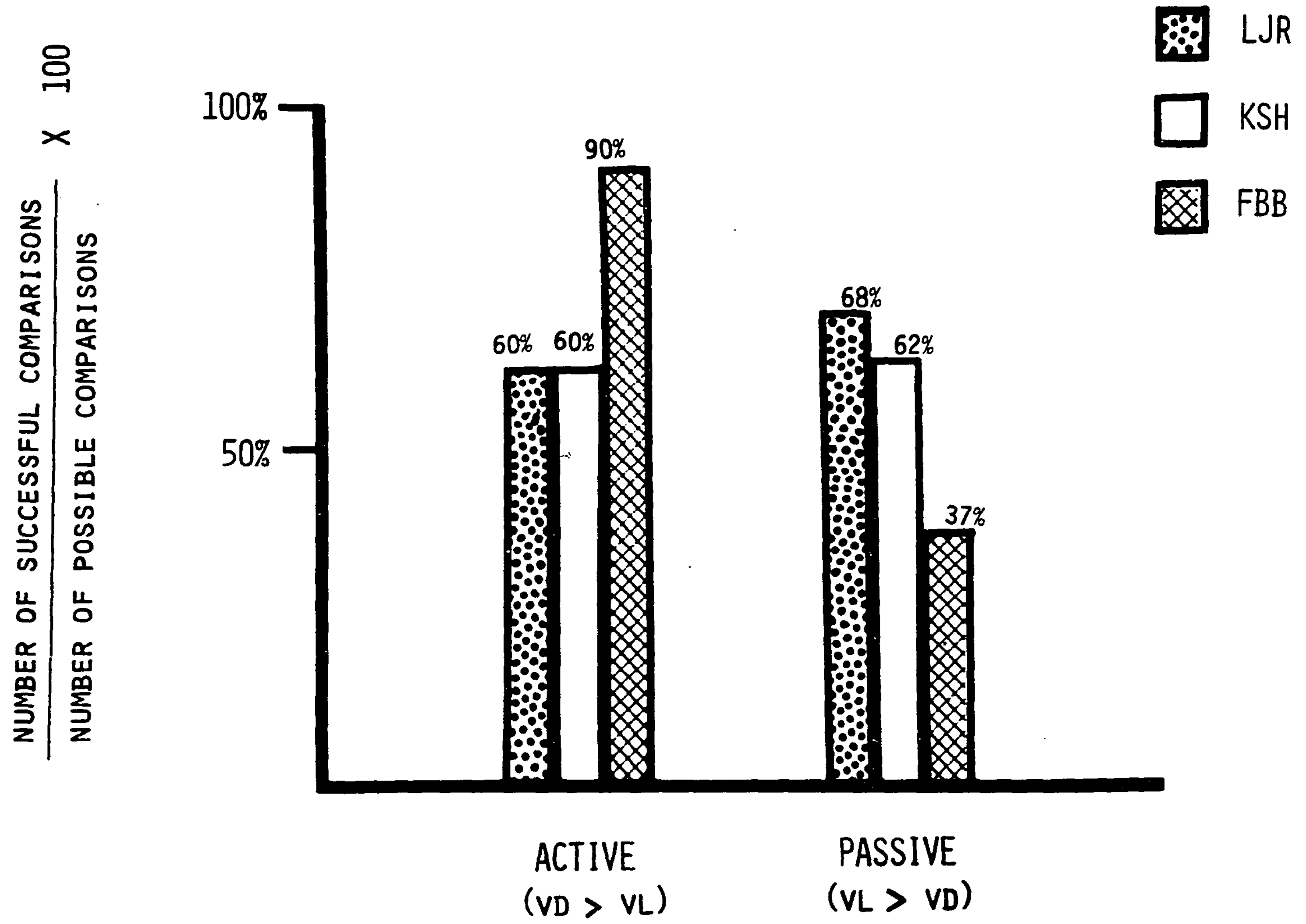
NUMBER OF SUCCESSFUL COMPARISONS / NUMBER OF POSSIBLE COMPARISONS X 100
100%
50%
60%
60%
90%
68%
62%
37%
ACTIVE
(VD > VL)
PASSIVE
(VL > VD)
LJR
KSH
FBB

Figure 82

Chapter V: Summary

This electromyographic study of velopharyngeal muscle function was undertaken to provide answers to several questions: which muscles are active in closing the velopharyngeal port for oral articulation; which, if any, muscles are active in opening the velopharyngeal port for nasal articulation; how the velopharyngeal muscles function for vowel articulation; how the velopharyngeal muscles function for pharyngeal cavity size adjustments for voiced stop consonant articulation; how the place of consonant articulation influences velopharyngeal muscle function?

Hooked-wire electrodes were used to obtain electromyographic recordings from the levator palatini, superior constrictor, middle constrictor, palatoglossus, palatopharyngeus and sternohyoid muscles of three native speakers of American English while the subjects repeated randomized sets of nonsense disyllables. The disyllables were designed to place maximum stress on the mechanisms of oral and nasal articulation, and to provide a variety of vowel and consonant contrasts. The recorded EMG signals were rectified, integrated and computer averaged.

The results provide some answers to the original questions and generate at least one additional question.

The levator palatini is the primary muscle of velopharyngeal closure for oralization, with each of the subjects showing the same pattern of activity. The amount of levator palatini activity is correlated with the oral cavity impedance of the articulated speech sound. Of the remaining velopharyngeal muscles, only the palatopharyngeus shows consistent oralization activity for each of the subjects, although palatopharyngeus activity is strongly affected by the vowel environment of the oral stop consonants. Two subjects show some constrictor muscle activity related to oral articulation.

Nasal articulation is accomplished in all subjects by suppression of EMG activity in those muscles participating in oral articulation. No muscle shows greater activity for nasal articulation than for oral articulation.

Vowel color affects the strength of EMG signals obtained from the lateral and posterior pharyngeal wall muscles. The greatest EMG potentials accompany /ɑ/ in those cases in which there is separation of the vowel-associated EMG curves, although the pattern of muscle activity varies from subject to subject.

Each subject produces a pattern of velopharyngeal activity which would provide an increased pharyngeal cavity volume for voiced (as opposed to voiceless) stop consonant production, though the three subjects use different balances of the muscles of the velopharynx.

Velar and alveolar articulations may be responsible for the increased magnitude of EMG potentials from the palatoglossus, middle constrictor and sternohyoid muscles, for two of the subjects, when such magnitude differences occur.

The question which arises from these data concerns the cause of the observed individual differences in velopharyngeal muscle function. Three possible causes are postulated for these differences: intersubject dialectal variation; intersubject anatomical variation; or idiosyncratic behavior by the subjects.

Appendix

Stop-nasal contrast stimuli (18)

/fipmip/	/fɑpmɑp/	/fupmup/
/fitmip/	/fɑtmɑp/	/futmup/
/fikmip/	/fɑkmɑp/	/fukmup/
/fibmip/	/fɑbmɑp/	/fubmup/
/fidmip/	/fɑdmɑp/	/fudmup/
/figmip/	/fɑgmɑp/	/fugmup/

Nasal-stop contrast stimuli (36)

/fimpip/	/fɑmpɑp/	/fumpup/
/fimtip/	/fɑmtɑp/	/fumtup/
/fimkip/	/fɑmkɑp/	/fumkup/
/fimbip/	/fɑmbɑp/	/fumbup/
/fimdip/	/fɑmdɑp/	/fumdup/
/fimgip/	/fɑmgɑp/	/fumgup/
/fiŋpip/	/fɑŋpɑp/	/fuŋpup/
/fiŋtip/	/fɑŋtɑp/	/fuŋtup/
/fiŋkip/	/fɑŋkɑp/	/fuŋkup/
/fiŋbip/	/fɑŋbɑp/	/fuŋbup/
/fiŋdip/	/fɑŋdɑp/	/fuŋdup/
/fiŋgip/	/fɑŋgɑp/	/fuŋgup/

Non-contrastive stimuli (9)

/fippip/	/fɑppɑp/	/fuppup/
/fibbip/	/fɑbbɑp/	/fubbup/
/fimmip/	/fɑmmɑp/	/fummup/

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