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Effect of Speaking Rate on Labial Consonant Production

A Combined Electromyographic/High-Speed Motion Picture Study

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Abstract. This experiment used electromyography and direct, high-speed motion picture photography, in combination, to describe the effect of speaking rate on the production of labial consonants.

Electromyographic signals from a number of facial muscles were recorded simultaneously with high-speed motion pictures of the lips, from two subjects. The speech material consisted of syllables containing the consonants /p b m w/ in both CV and VC combinations with the vowels /i a u/.

The major finding of this experiment is that an increase in speaking rate is accompanied by both an increase in the activity level of the muscle as well as an increase in the speed of movement of the articulators. The data also showed certain manner effects and instances of both subject-to-subject and individual token variability. These findings are discussed in terms of theoretical models of speech production.

It is commonly known that the production of a given phone will vary a great deal depending on the supra-segmental structure in which it is placed. Recent research in this area has been concerned with the question of whether these allophonic variations, in particular those that arise from changes in stress and speaking rate, can be attributed solely to changes in the timing of commands to the articulators.

The earliest model of this type was proposed by Lindblom [1963, 1964]. In both spectrographic and cinefluorographic studies, Lindblom found that a destressed vowel, or one produced during faster speech, was accompanied by a change in color toward the neutral schwa. LINDBLOM's hypothesis was that this neutralization is a consequence of the shorter duration of the vowel and, further, is caused by a temporal overlap of motor commands to the articulators. In other words, the articulators fail to reach, or undershoot, their targets because the next set of motor commands deflect them to the following target before the first target is reached. Although some later experiments have shown similar undershoot effects for other phones [GAY, 1968; KENT, 1970], a number of other studies have produced results that imply the existence of another mechanism, articulatory reorganization, in the control of, at least, stress. For example, both HARRIS *et al.* [1968] and HARRIS [1971], in electromyographic studies of stress, found higher muscle activity peaks (greater driving forces) for phones produced in stressed, as opposed to non-stressed, syllables. A possible consequence of the electromyographic result was later observed by KENT and NETSELL [1971] in a cinefluorographic study of tongue movements. Their data suggest that the effect of increased stress is to cause the articulators to move faster, more forcefully and closer to their intended targets.

Although it is probably safe to conclude that undershoot is at least a component of destressed and faster speech, a general model of speech production based on timing changes alone is too simple. First, it is apparent from earlier experiments that reorganization of the articulatory gesture exists to enable the mechanism to respond actively to, at least some, supra-segmental demands. Second, the concept of undershoot, itself, which was originally proposed to describe vowel articulation, does not lend itself particularly well to the production of consonants, most of which involve movements towards occlusal or constrictive, rather than spatial targets. The experiment reported here was concerned with the following questions: does articulatory reorganization extend to variations that arise from changes in speaking rate, and can a mechanical model of the kind proposed by LINDBLOM [1963] apply to the production of both vowels and consonants? The specific purpose of this experiment was to determine the effects of speaking rate on the production of labial consonants spoken in various vowel environments. The experimental approach utilized the combined techniques of electromyography and direct high-speed photography in order to obtain information about both the forces that cause the articulators to move and the movements that result, simultaneously, on the same utterance.

Table I. EMG electrode locations

Subject D.L.	Subject T.G.
Orbicularis oris: superior, medial (OOSM)	Orbicularis oris: superior, medial (OOSM)
Orbicularis oris: superior, lateral (OOSL)[1]	Orbicularis oris: inferior (OOI)
Orbicularis oris: inferior (OOI)	Quadratus labii inferiorus (QLI)
Levator anguli oris (LAO)	Mentalis (MEN)
Buccinator (BUC)	Anterior belly digastric (AD)[1]
Depressor anguli oris (DAO)	
Internal pterygoid (IP)[1]	

[1] Analyzed for motion picture segment only.

Method

Subjects and speech material. Speakers were two adult males, both native speakers of American English. The speech material for one subject (D.L.) consisted of the labial consonants, /p b m w/, in both CV and VC (except /w/ which was in only CV) combination with the vowels /i a u/. Each of the syllables was placed in a word (e.g., 'keeper', 'appeal'), which, in turn, was placed in a sentence. The master list contained 21 different words. For the second subject (T.G.), a more symmetrical frame was used. Each of the consonants was placed in either [kVCə] or [kəCV] (again, except for /w/), preceded by the carrier, 'It's a ...'. Also, since the data analyzed for the first subject did not show any interesting or consistent manner differences for /m/, this consonant did not appear in the second list. For both subjects, the words were random ordered into four different lists. The lists were repeated four times, in sequence, for a total of sixteen repetitions at each of two different speaking rates. The speaking rates were either moderate or fast and were controlled by training the subject to speak at what he considered comfortable rates. The subject's performance was monitored continuously throughout the run.

Electromyography. For both subjects, conventional hooked-wire electrodes were inserted into muscles that control both lip and jaw movements. These muscles are listed in table I. Although all muscle locations showed adequate firing levels at the time of electrode insertion, some muscle locations deteriorated, at one time or another, during the run. The extent to which this occurred is also indicated in table I[1].

The basic procedures were to collect EMG data for a number of tokens of each utterance and, using a digital computer, average the integrated EMG signals at each electrode position. The EMG data were recorded on a multichannel instrumentation tape recorder together with the acoustic signal and a sequence of digital code pulses (octal format). These pulses were used to identify each utterance for the computer during processing. A more detailed description of both the data recording and data processing techniques can be found elsewhere [HIROSE, 1971; PORT, 1971].

Direct high speed photography. High speed motion pictures of lip and jaw movements were

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[1] It is interesting to note further, that for subject T.G., the internal pterygoid muscle showed only resting potentials for speech, even though correct electrode placement was ascertained for other functions (clenching, for example).

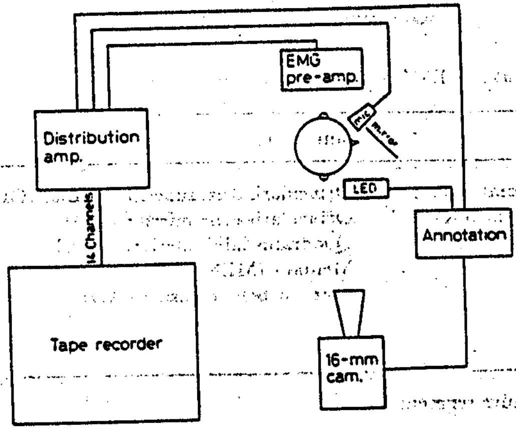

Fig. 1. Block diagram of EMG and high-speed motion picture recording system.

recorded with a 16-mm Milliken camera, set up to run at 128 fps. Both full-face and lateral views of the lips and jaw were recorded by placing a mirror, set at a 45-degree angle, beside the subject's face. The motion picture and EMG data were synchronized by an annotation system, constructed for the purpose, that displayed the octal code pulses on an LED device placed in the path of the camera. This display was also driven by a signal from the camera to count individual frames between the octal codes. A diagram of the EMG and motion picture instrumentation is shown in figure 1.

The combined EMG and high-speed motion picture data were recorded at the beginning of the run, after which the EMG part of the experiment continued. Prior to the beginning of the run, white reference dots were painted on the nose and lower edge of the subject's jaw. A ruler was also fixed to the mirror so that the lip and jaw movements could be converted to actual distances.

The films were analyzed by frame-by-frame measurements of vertical jaw opening and vertical lip opening at the midline[2]. The EMG data from the motion picture part of the run were processed separately from the remainder of the run and then compared with those data to see if the individual tokens were typical of the average. Our criteria for acceptance of the individual token were that its peak did not exceed the maximum or fall below the minimum of the averaged tokens.

Results

Electromyography. Results of the electromyographic analyses are summarized in tables II and III. These tables show the peak muscle

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[2] Lip spreading measurements (horizontal distance between the corners) were also made for /w/.

activity levels for each muscle and utterance for both subjects and both speaking rates.

The values for the OOSM, OOSL, OOI, MEN and IP represent the peak heights of muscle activity levels for the closing segment of the gesture while the values for the AD, BUC, DAO, LAO and QLI represent the peak heights for the opening segment.

For both subjects, the speech produced during the faster speaking rate condition was, on the average, some one-third shorter in duration than the speech produced during the normal condition. These differences are based on measurements made from the complete sentence, i.e., test syllable plus carrier.

One of our major concerns in combining EMG with high-speed motion picture photography was the question of whether the EMG curve for the single token motion picture run was a typical one, in other words, one compatible with the average. As the values in tables II and III indicate, this was, almost without exception, the case. For those muscles characterized by strong activity levels, the single token values followed the averaged values, in both direction and magnitude. Almost all of the other muscle locations showed the same patterns; however, since the peak values of these muscles were somewhat lower, the comparisons are not equally valid[3].

For both subjects, the major effect of an increase in speaking rate was an increase in the activity level of the muscle. Generally speaking, this increase occurred for all muscles and all utterances, in other words, for the immediate consonant gesture itself, as well as for the lip opening that extends through the adjacent vowel[4]. For those muscles characterized by strong activity levels, these increases were on the order of anywhere from 25 to 100%.

These differences in muscle activity levels indicate that the control of speaking rate requires more than just a simple adjustment of the timing of motor commands. Rather, it appears that the labial consonant gesture is also reorganized at the muscle command level. Although changes in timing are present, the primary physiological correlate of increased speaking rate seems to be a generalized increase in articulatory effort.

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[3] For subject D.L., two instances (/im. wi/ – OOI) and for subject T.G., one instance (/pu/ – MEN) occurred where the single token values did not follow the averaged values.

[4] The only exceptions were /ab/ – LAO for subject D.L. and /bi, ba/ – MEN for subject T.G.

Table II. Averaged and single token (in parentheses) peak EMG values for subject D.L. Values for the moderate speaking rate are in the left column and values for the fast speaking rate are in the right column of each cell

	OOSM	OOSL	OOI	LAO	BUC	DAO	IP
pi	83–127 (60–190)	(25–52)	58–69 (110–40)	27–38 (38–52)	46–126 (354–550)	690–710 (450–975)	(130–550)
pa	56–75 (60–83)	(25–125)	77–77 (50–65)	27–27 (33–60)	76–304 (30–142)	451–564 (605–950)	(150–690)
pu	67–71 (150–170)	(95–195)	70–74 (65–135)	26–37 (20–35)	77–191 (50–350)	504–616 (820–960)	(125–700)
ip	54–82 (75–155)	(65–75)	37–47 (40–50)	22–26 (60–80)	65–156 (85–175)	626–788 (710–920)	(75–650)
ap	53–67 (65–105)	(60–95)	34–41 (35–40)	35–39 (35–40)	112–183 (65–410)	915–1009 (960–980)	(65–620)
up	77–88 (95–115)	(80–125)	95–111 (105–180)	138–149 (145–185)	135–242 (75–85)	837–1167 (850–960)	(130–600)
bi	78–114 (70–180)	(65–90)	59–69 (65–130)	27–68 (30–40)	81–230 (120–180)	671–965 (920–1020)	(75–700)
ba	99–108 (60–155)	(40–80)	63–69 (75–105)	39–61 (50–60)	132–514 (75–650)	730–854 (900–950)	(125–695)
ib	65–85 (40–160)	(40–45)	48–62 (40–60)	191–124 (60–240)	58–114 (60–350)	532–717 (225–950)	(125–650)
ab	64–80 (40–160)	(70–80)	47–54 (40–55)	81–47 (80–70)	103–134 (95–120)	763–938 (740–890)	(130–595)
mi	110–120 (45–190)	(35–95)	66–72 (42–65)	59–67 (55–85)	73–290 (40–560)	698–836 (475–980)	(160–480)
ma	85–113 (95–195)	(65–130)	53–58 (60–95)	37–65 (85–105)	179–560 (65–705)	662–704 (575–1145)	(140–710)
im	63–70 (70–110)	(35–65)	57–54 (45–55)	31–35 (30–35)	63–185 (50–170)	654–630 (550–950)	(130–620)
am	74–76 (55–170)	(80–95)	67–69 (70–80)	30–32 (50–55)	70–108 (190–275)	809–918 (640–950)	(180–390)
wi	68–78 (60–130)	(55–105)	88–69 (75–155)	22–26 (25–200)	124–145 (100–150)	318–367 (75–775)	(105–705)
wa	58–60 (55–60)	(65–150)	33–37 (55–95)	25–34 (25–30)	113–184 (105–200)	213–505 (50–650)	(125–485)

Whereas the speaking rate effects were consistent for both subjects, other effects, both contextual and supra-segmental, were quite variable. For example, examination of the orbicularis oris data for subject D.L. shows that, for the most part, muscle activity levels were

Table III. Averaged and single token (in parentheses) values for subject T.G. Values for the moderate speaking rate are in the left column and values for the fast speaking rate are in the right column of each cell

	OOSM	OOI	QLI	MEN	AD
pi	381–555 (414–451)	82–111 (91–95)	36–37 (43–46)	34–26 (47–51)	(20–22)
pa	323–634 (425–502)	62–101 (91–161)	33–36 (32–43)	37–39 (39–202)	(68–90)
pu	369–588 (409–523)	98–113 (83–113)	29–31 (32–40)	36–26 (42–52)	(24–41)
ip	528–580 (431–540)	90–111 (141–151)	40–49 (29–38)	61–65 (65–70)	(57–112)
ap	542–583 (551–563)	92–115 (111–112)	76–80 (81–108)	64–67 (81–89)	(35–45)
up	346–435 (305–420)	110–186 (91–133)	32–39 (35–40)	19–19 (39–40)	(65–82)
bi	357–532 (305–529)	56–94 (63–97)	25–27 (27–43)	29–22 (44–45)	(10–13)
ba	299–458 (458–478)	55–126 (41–80)	23–26 (24–27)	41–30 (47–47)	(57–101)
bu	317–456 (283–409)	84–106 (72–127)	20–22 (21–24)	36–20 (52–59)	(10–46)
ib	432–508 (403–409)	52–84 (61–66)	26–29 (29–31)	55–57 (42–65)	(32–52)
ab	535–588 (409–431)	61–75 (55–62)	42–54 (39–48)	62–71 (71–77)	(10–38)
ub	307–347 (376–447)	94–188 (94–233)	16–21 (27–35)	23–29 (31–39)	(11–41)
wi	244–440 (245–321)	80–143 (80–105)	15–20 (19–27)	7–8 (7–10)	(10–32)
wa	277–441 (218–300)	88–185 (80–147)	14–32 (13–21)	7–11 (7–10)	(32–41)
wu	277–392 (218–343)	89–149 (91–169)	12–18 (18–27)	10–8 (7–28)	(10–46)

higher for /p b m/ produced before a stressed vowel, than for /p b m/ produced after a stressed vowel. (The other muscles do not show any consistent stress effects.) For subject T.G., on the other hand, stress contrasts for /p b/ in combination with the vowels /i a/, show exactly opposite effects: consistently higher EMG activity (OOS, OOI, QLI) for the post-stressed position; /u/ showed small, probably inconsequential effects the other way (pre-stressed). For both subjects, these effects occurred across changes in speaking rate. Likewise, subject T.G. showed higher OOS, OOI, QLI activity levels for /p/ as opposed to /b/, while no consistent differences were evident for subject D.L. This latter variability has been shown in a number of earlier studies [HARRIS *et al.*, 1965; FROMKIN, 1966; TATHAM and MORTON, 1968].

One other interesting finding is worth mentioning. Although the internal pterygoid location for subject D.L. was not useable for the entire EMG run, it was stable for the motion picture segment. The fact of the single token notwithstanding, the effect of speaking rate on the activity of this muscle was dramatic. Activity levels for all utterances increased from what might be considered resting levels for normal speaking rate to very high peaks for fast speaking rate. This is especially interesting in light of the fact that subject T.G. did not seem to use this muscle at all for speech.

To summarize at this point then, the major effect of an increase in speaking rate on labial consonant production is a generalized increase in the activity levels of the muscles; this in turn indicates an overall increase in articulatory effort for these consonants during faster speech.

Lip movements. Figure 2 shows typical lip movement curves for /p b w/, for subject D.L. For /p b/, these graphs show that the rates of lip opening and closing are faster for the faster speaking rate condition, while lip closure duration remains essentially the same across both rates. This was generally the case for all utterances, although in two instances (both involving /u/), rates of movement were similar for both conditions. However, in no case were the rates of lip movement ever slower for the faster speaking rate condition. The data for subject T.G. were essentially the same, with only one instance (/pu/) showing similar rates.

These differences in lip movements are consistent with the EMG data and show that in order for the gesture to be completed during faster speech, it must be done so faster, and with greater articulatory effort. This increase in effort for the consonant gesture carries over to the adjacent vowel as overshoot in lip opening. This greater amount of lip opening during faster speech occurs primarily for the stressed vowel, regardless of whether it precedes or follows the consonant. Although overshoot was present for some of the unstressed vowels, it was not a particularly strong or consistent feature.

Figure 2 also shows typical lip movement curves for /w/. Here the

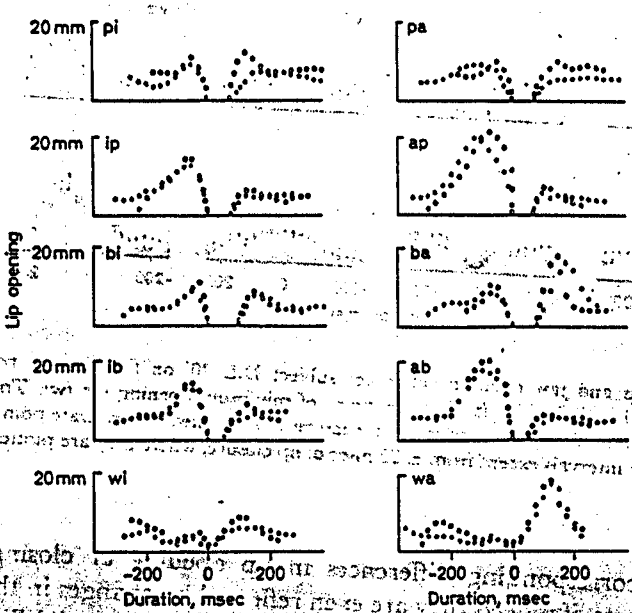

Fig. 2. Vertical lip opening curves for subject D.L. '0' on the abscissa represents the point of lip closing for /p b/ and the point of minimum opening for /w/. The moderate rate is represented by filled circles and the fast rate by unfilled circles. Data points are plotted at 25-msec intervals except from ± 25 msec of lip closure, where they are plotted at 10-msec intervals.

targets for lip opening and closing are essentially the same across changes in speaking rate. This indicates, again, that the effect of an increase in speaking rate is to cause the articulators to move faster and more forcefully toward these targets. Although this finding for the stops is not unexpected, the data for /w/ are somewhat surprising. Whereas stop consonant production involves an occlusal target, one that must be reached in order to produce the sound, /w/ involves only a spatial target, and, theoretically can be undershot. One possible explanation for the lack of /w/ undershoot though, is that /w/ might be characterized by an acoustic steady state, and thus, would require an invariant target position.

As might be predicted from the EMG data, the lip movement curves did not show any consistent stress or contextual effects. Any effects that might have been evident for the averaged EMG data did

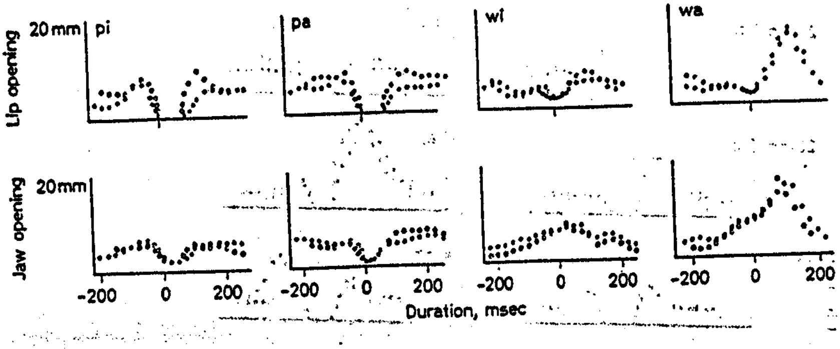

Fig. 3. Vertical lip and jaw opening curves for subject D.L. '0' on the abscissa represents the point of lip closing for /p/ and the point of minimum opening for /w/. The moderate rate is represented by filled circles and the fast rate by unfilled circles. Date points are plotted at 25-msec intervals except from ± 25 msec of lip closure, where they are plotted at 10-msec intervals.

not show any corresponding differences in lip opening or closing. These subtle effects, if indeed they are even reflected by changes in the pattern of lip movements, are probably masked by the variability inherent in single token analyses.

Based upon both the EMG and motion picture data, it would appear that LINDBLOM's [1963] undershoot model cannot be applied to the production of labial consonants. Although changes in timing are present, the primary physiological correlate of increased speaking rate is an increase in effort, and consequently, a faster articulatory movement. As was mentioned before, this is not necessarily an unexpected result for the stops, since these phones require an occlusal rather than a spatial target, and thus, cannot in a strict sense be undershot (except, of course, in terms of decreased closure duration, which also does not occur). The data for /w/, however, are unexpected since /w/ does involve a spatial target.

Jaw movement. Although the EMG levels for the muscles that control jaw opening and closing (anterior belly of the digastric and internal pterygoid) showed some increase for the faster speaking rate condition, the jaw movement data did not show any clear speaking rate effects. There were no consistent differences in either rate or degree of jaw opening or closing, i.e., there were no consistent undershoot effects for the consonant, or overshoot effects for the vowel, as a function of speaking rate. Although these inconsistencies might be due to the variability inherent in single token measurements, or for that matter, the coordinate system itself (movement inferred from superficial measurements), the most likely explanation is that the jaw, unlike the lips, does not need to reach a specific target during the production of a labial consonant, and thus, can be more susceptible to mechanical or inertial factors.

Although the jaw movement curves did not show consistent speaking rate effects, they did show interesting contextual effects. Figure 3 shows lip movement data replotted against jaw movement curves for words containing /p/ and /w/. This figure shows, that for /p/, jaw movement is more or less locked to lip movement, i.e., when one is closing so is the other (this was also the case for /b m/). Lip and jaw coordination for /w/, however, behaved quite differently; jaw movement was much more independent of lip movement, anticipating the following vowel by opening for it during lip closure for /w/. This phenomenon was evident for both subjects, and in each case, the starting point for jaw opening preceded the point of maximum lip constriction by approximately 200 msec.

Discussion

The major finding of this experiment is that for labial consonant production, an increase in speaking rate is accompanied by both an increase in the activity level of the muscles as well as an increase in the speed of movement of the articulators. Both of these effects are consequences of an increase in articulatory effort. Although these results fit easily into a target-based view of speech production, they do not at all fit into a simple physiological model of the supra-segmental structure of speech.

LINDBLOM's [1963] original undershoot hypothesis was proposed to account for changes in both stress and speaking rate; that is, his model predicts that undershoot would occur for both destressed and faster speech. Indeed, this seems to be the case for vowels. Both LINDBLOM [1963] and KENT and NETSELL [1971] found that the effect of increased stress is to cause the articulators, specifically the tongue, to move closer to its intended target. LINDBLOM [1964] also showed the same effect for slower speaking rates, as did KENT and MOLL [1972], whose data also suggest the same trend for lingual consonants as well as for vowels.

The data of this experiment, however, show that the production of labial consonants is not controlled in the same way as vowels and perhaps, lingual consonants. For labial consonants, an increase in speaking rate is not accompanied by undershoot, or any corollary change in lip closure duration; rather, the articulatory movement is reorganized at the motor command level in much the same way it is for increased stress, i.e., in the form of greater articulatory effort. Not only does this suggest the existence of more than one mechanism employed in the control of speaking rate but, moreover, that stress and speaking rate variations are not simply covarying components of the same overall structure. Instead, they appear to be two features which are controlled by two separate mechanisms.

The data of this experiment show instances of both subject-to-subject and individual token variability. The most interesting subject differences had to do with the EMG measures of the stress and voicing contrasts. These differences were more than likely real ones since the muscle activity patterns were consistent for utterance versus subject contrasts. The extent of this type of variability, though, is perhaps best illustrated by the data for the internal pterygoid muscle. For subject D.L., this muscle showed rather large speaking rate effects, while for subject T.G., the internal pterygoid was not even used for speech. These variations would seem to indicate, among other things, that physiological data of this type should be handled on an individual, non-pooled basis.

The other type of variability apparent in our data was that for jaw opening and closing. As was mentioned earlier, these inconsistencies are probably due to the compounding effects of single token analysis and the fact that the jaw is under less severe constraints than the lips during labial consonant production.

The data of this experiment preclude the hypothesis that the suprasegmental feature of speaking rate is controlled *solely* by changes in the timing function of the motor commands. It is apparent that an additional, active mechanism is employed in the production of, at least, the labial consonants. However, the extent to which this mechanism operates and the question of whether it operates by feature or by phoneme, cannot be answered without additional data on the way in which the movements of the peripheral mechanism are coordinated with those of the tongue and jaw.

Résumé

Influence du débit sur la production de consonnes labiales
Etude combinée par électromyographie et cinématographie rapide

On a utilisé concurrement l'électromyographie et la cinématographie rapide pour étudier l'influence du débit sur la production de consonnes labiales.

Deux sujets furent filmés tandis que des signaux électromyographiques étaient dérivés de divers muscles faciaux. Le matériel linguistique utilisé était formé de syllabes contenant les consonnes /p b m w/ combinées aux voyelles /i a u/ soit sous la forme CV, soit sous la forme VC.

On put constater de la sorte qu'une accélération du débit s'accompagne d'une augmentation du niveau d'activité musculaire ainsi que d'une augmentation de la vitesse de déplacement des organes articulatoires. Les enregistrements mirent aussi en évidence une certaine influence sur la manière d'articuler et révélèrent des variations interindividuelles ainsi que des variations pour un même individu. Ces observations sont discutées à la lumière de modèles théoriques de la production linguistique.

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