Ann. Bull. RILP, No. 10, 81-100 (1976)

LARYNGEAL CONTROL IN FRENCH STOPS: A FIBEROPTIC, ACOUSTIC AND ELECTROMYOGRAPHIC STUDY

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One of the tasks of experimental studies on the adjustment of the larynx is to try to separate features which are universal from those which are language-specific or speaker-specific. In the past few years, several studies have been reported, that analyzed electromyographically, stop consonants (among others) in American English (Hirose and Gay, 1972), in Korean (Hirose et al., 1974), in Danish (Fischer-Jørgensen, and Hirose, 1974a, 1974b), in Hindi (Dixit, 1975; Kagaya and Hirose, 1975), and in Japanese (Sawashima et al., 1975). This last study has also examined interspeaker variability.

Laryngeal adjustment can be broadly viewed as consisting of three main components: abduction, adduction and tension. It is plausible that sound production in various languages may differ through the respective contribution of each of those components to laryngeal adjustment. The present study examines this possibility in the case of French stop consonants.

Experimental Procedures

The present investigation consists of three parts henceforth referred to as Part I, Part II and Part III. Part I was a fiberscopic study done on two subjects (1 and 2). Part II was a fiberscopic study done on Subject 1 only, and Part III was an electromyographic study done also on Subject 1. Part II was run simultaneously with a subset of Part III.

Subject I was a male native speaker of French, in his thirties, originally from Lausanne, Switzerland. Subject 2 was a male native speaker of French, in his twenties, originally from Grenoble, France.

The corpus for Part I consisted of twelve "near minimal" pairs of phrases of the type "un riche chimiste - un riche imitateur", in which there was a contrast nongeminated consonant vs. geminated consonant. By 'gemination" is meant the sequential repetition of a particular segment, at the phonemic level, resulting in a phonetic realization clearly different (although not necessarily a complete duplication) from the realization of the single segment. Although quite frequent and distinctive for /r/ (e.g. "il courait" vs. "il courrait), gemination within a word is much rarer for stops or fricatives and is usually not opposed to the single consonant (e.g. "netteté", /nɛtte/). Consequently, in order to be able to study this opposition, this investigation has considered gemination (of stops or fricatives) at word boundary only. The twelve consonants under consideration were /p/, /t/, /k/, /b/, /d/, /g/, /f/, /s/, /ʃ/, /v/, /z/ and /ʒ/. The utterances were recorded in randomized order; each one was said at least twice by each speaker for a given experimental session; in addition, Subject 1 repeated

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the entire experimental session. The results show a very high consistency from one session to the other.

The corpus for Parts II and III consisted of the fourteen utterances:

1A-1B: terrible

2A-2B: déridé

3A-3B: c'est terrible

4A-4B: c'est déridé

5A-5B: c'est éristique

6A-6B: sept terrines

7A-7B: aide Désiré

said an equal number of times with emphatic stress on the underlined syllable (1B through 7B) and without emphatic stress (1A through 7A). For Part II, the minimum number of repetitions of each utterance was three, while for Part III it was twelve. The utterances were recorded in six groups as follows:

1A and 2A

1B and 2B

4A and 7A

4B and 7B

3A, 5A and 6A

3B, 5B and 6B

They were pronounced in randomized order within each group, and separated from the next one by a pause of a few seconds. Within each group, the same intonation was used.

A standard laryngeal fiberscope (Olympus VF with CLX light source) was used for Parts I and II. It was inserted through the nose of the subject and the glottal view was photographed with a 16-mm cine camera at a rate of 66 frames/second for Part I and 50 frames/second for Part II. Timing marks (one-per-frame) triggered by the camera were recorded on one channel of a stereo audio tape recorder, while the speech signal was recorded on the other channel. Mingograms were then produced, displaying the mike signal, a duplex oscillogram, the speech power envelope and the camera timing marks. Each film frame can be matched with a particular instant of the speech signal with a precision of approximately half the between-frame interval, i.e. 7 ms for Part I, 10 ms for Part II.

The films were projected on the flat screen of a computer terminal, and a joystick-controlled crosshair could be moved to the position of any data point. The data points were stored directly, processed and plotted without further manual intervention, thus minimizing possible errors.

For Part III, conventional hooked-wire bipolar electrodes were used. The posterior cricoarytenoid (PCA) and the interarytenoid (IA) were reached perorally by using an L-shaped hemostat with the carrier needle epoxy-bonded to the shorter arm. The insertions were performed under topical anesthesia (4% Xylocaine) and monitored through indirect laryngoscopy. The lateral cricoarytenoid (LCA), the cricothyroid (CT) and the sternohyoid (SH) were reached percutaneously. Topical anesthesia was administered through a Pan-Jet-70 air jet, at the site of needle insertion. The detailed procedure has been described elsewhere (Hirose, 1971).

The EMG signals were suitably amplified and together with the audio signal, they were recorded on a 7-channel FM tape recorder. They were subsequently computer-processed in the following way:

a) A to D conversion into 6-bit numbers, at a sampling frequency of 4 kHz; the absolute values were obtained, summed and smoothed, using a time window of 10 ms;

b) each processed token was displayed (EMG channels + rectified and smoothed audio) and a time mark entered for alignment with the other tokens of the same type; the alignment point was the onset of the vowel following the stop consonant at the beginning of the underlined syllable (see above);

c) tokens showing artifacts were eliminated

d) all tokens of one type were then averaged with respect to the chosen alignment point.

Measurements and Results, Part 1.

Two measurements of glottal width (Fig. 1) were made for each film frame

1) w, the distance between the vocal processes of the arytenoid cartilages;

2) d, a distance measured on the line connecting the apexes of the corniculate cartilages, and restricted to the portion between the two arytenoid cartilages.

The two points defining w can be selected with a good accuracy, but because of its small size, the distance 2 is subject to a large relative error. The two points defining d, on the other hand, cannot be determined with as much accuracy, but due to the larger size of d, the relative error is comparatively smaller. Observation of both w and d thus provides the best results. Correlation between the two measurements is typically 95% or more.

Two time intervals were also measured:

1) t_c, the time during which the vocal tract is closed supraglottally (in the case of plosives) or constricted (in the case of fricatives); the beginning and end of this interval were determined from the mingograms;

2) t_w, the time during which the glottis is open, as determined from the w and d film measurements.

The precision in measuring t_c was of the order of 2 ms, whereas that for t_w was only of the order of 7 ms.

For both subjects, the (phonologically) voiceless series of consonants (i.e. /p/, /t/, /k/, /f/, /s/, /ʃ/) shows a clear opening-closing gesture of the glottis, whereas the (phonologically) voiced series (i.e. /b/, /d/, /g/, /v/, /z/, /ʒ/) does not show any such gestures. The peak width reached during the abduction gesture does not appear to be a function of its duration, in the case of gemination. If the duration of the consonant is greater than a certain minimum, maximum glottal width is always achieved. This minimum duration is exceeded in all instances of gemination, for both speakers, but only in a few instances of non-geminated consonants. When it is not exceeded, there is a correlation between maximum glottal width and duration of the abduction-adduction gesture. The possibility that the opening and/or closing movements may be faster or slower, due to gemination was envisaged but could not be measured with sufficient accuracy, because of the very low sampling rate (66 Hz).

For voiceless consonants, for both subjects, the glottis starts opening with the beginning of oral closure and finishes at the end of frication (for fricatives), or of aspiration (for plosives). Synchronism or near-synchronism of the two gestures cannot, of course, be ascertained with an accuracy better than that for t_w measurements.

In order to compare the voiceless and the voiced series, the following two ratios were defined and calculated for all relevant cases: 1) r_c, the ratio of geminated versus non-geminated oral closure duration (t_c); 2) r_w, the ratio of geminated versus non-geminated glottal separation duration (t_w); obviously, r_w is undefined for the voiced series.

Subject 1 shows a ratio r_c (oral closure) significantly greater (t-test, $p < 0.001$) for voiced consonants ($r_c = 2.30$), than for voiceless ones ($r_c = 1.52$). Subject 2 shows a similar tendency (1.85 vs. 1.72) but it does not reach statistical significance. This suggests that if increased oral closure duration is used to signal gemination of stop consonants, this increase needs to be greater for the voiced case than for the voiceless one. Perceptual testing would be required to support this possibility.

A comparison of the oral closure ratio r_c and of the glottal aperture ratio r_w for the voiceless series shows that, for both speakers, these two ratios are both greater than 1, for all utterances without exception, but they are not significantly different one from the other. Since the time of release of the oral closure and that of the adduction of the vocal folds coincide (inasmuch as can be ascertained in this experiment), that means that the near-synchronism of the oral gesture (closure + release) and of the laryngeal gesture (abduction + adduction) is independent of gemination. From these data, it also seems to be independent of manner of articulation, if one compares plosives and fricatives, and of place of articulation, if one compares labial, dental and palatal consonants. It thus appears reasonable at this point, to restrict the corpus for Part II and Part III to one manner (stop) and one place (dental) of articulation, and to vary other parameters.

Measurements and Results, Part II

Due to a fiberscope placement different from that in Part I, at least one of the corniculate cartilages was outside the field of view of the fiberscope most of the time. Consequently, d, as defined earlier, could not be measured and was omitted; w was the only measurement made for Part II. In addition, w_m (the width of the glottis in its medial part) was also observed but not measured due to the blur caused by the low camera speed (50 fps) and by the vocal folds' vibration.

Since Part I did not evidence any observable dependence of the glottal gesture on manner or place of articulation, the corpus for Part II was limited to the study of glottal gesture in (and around) dental plosives. Dental place of articulation was chosen, so as to minimize the risks of artifacts (found in bilabials for example) in the EMG data that were recorded simultaneously. The following four dimensions were examined: 1) voiceless vs. voiced;2) stressed vs. unstressed; 3) utterance initial vs. utterance medial; 4) liaison vs. non-geminated vs. geminated.

1) Voiceless vs. voiced

For medial /t/, the glottis opens at the beginning of oral closure and closes at the end of it, whereas for initial /t/, glottal closure consistently precedes the end of the oral closure. This is not surprising since the articulatory constraints for an initial segment are in general less great than for a medial one, due to the absence of a preceding segment.

For both initial and medial /d/ on the other hand, as expected, the glottis closes for the beginning of voicing which of course precedes oral closure. For medial /d/ (as well as for all voiced stops of the data of Part I) voicing is fully sustained through the time of oral closure. It is also worth noting that for initial /d/, whether stressed or unstressed, the medial glottal width $\underline{w}_m$ is clearly different from zero, unlike for medial /d/ where it is always negligible; this may be related to the fact that initial stops are, perceptually, produced with a stronger release than medial ones: initial /d/, through a less tight glottal closure, would allow a greater build-up of oral pressure than a medial /d/, thus producing a stronger release.

Acoustically, the duration of oral closure is always significantly longer for /t/ than for /d/ (t-test, $p < 0.001$).

VOT for /t/ ranges from +15 to +45 ms over all contexts, with a mean of +21 ms and a standard deviation of 5 ms. For /d/ on the other hand, VOT is strongly context-dependent. VOT for initial /d/ (whether stressed or not) ranges from -90 ms to -130 ms with a mean of -107 ms and a standard deviation of 14 ms. For medial /d/ on the other hand, voicing is sustained during the whole oral closure, VOT consequently varies according to the duration of oral closure. since the beginning of oral closure defines the end of the previous vowel and thus the onset of voicing for /d/.

2) Stressed vs. unstressed

As far as glottal gesture is concerned, the contrast stressed-unstressed is quite evident for /t/, but none is observable for /d/.

For all /t/'s, the maximum value of $\underline{w}$ reached during oral closure is greater in the stressed case than in the unstressed case. However, the duration of glottal aperture is also greater in the stressed case than in the unstressed case. In fact, extent and duration of glottal aperture are highly (positively) correlated and it appears that the velocity of the opening and of the closing gesture are roughly independent of stress.

Acoustically, the duration of oral closure is significantly greater in the stressed case than in the unstressed case (t-test, $p < 0.001$), except for the utterance "sept terrines"(with a geminated /t/) where the difference did not reach statistical significance, but tended to be in the same direction as for the other utterances.

VOT for /t/, as mentioned earlier, is relatively independent of context. VOT for initial /d/, also seems independent of stress, but for medial /d/, there is a marked influence of stress; the greater the amount of stress, the earlier the onset of voicing (in both the non-geminated and geminated cases).

3) Utterance initial vs. utterance medial

The main difference in glottal gesture is observed in the case of /t/; for initial /t/, the glottal gesture is initiated from some "neutral" rest or pre-speech position in which the glottis is open; for medial /t/ on the other hand, the glottal gesture is initiated from the position required by the previous segment, the vowel /ɛ/ in our experiment. For /d/, the vocal folds are adducted all through, thus no particular contrast in glottal behaviour can be observed.

Acoustically, no comparison can be performed for oral closure, since its onset is not well defined for initial /t/.

VOT for /t/ is relatively constant, regardless of position in the utterances; for /d/ on the other hand it is not invariable; however, it does not seem to vary systematically with position in the utterance, but rather with stress and gemination.

4) Liaison vs. non-geminated vs. geminated

The results for this threefold contrast are very similar to those for the contrast stressed versus unstressed; for /d/, the folds are adducted and no opening gesture is observable, whether the /d/ is geminated or not (no liaison is possible with /d/); for /t/ on the other hand, the duration and maximum extent of the glottal separation are small for the liaison case ("c'est éristique"), greater for the non-geminated case ("c'est terrible"), and greatest for the geminated case ("sept terrines"). This holds in both the stressed and unstressed case. As noted previously, the velocity of the opening and of the closing gesture does not seem to depend on the type of /t/ (word initial, liaison, or geminated).

Acoustically, the duration of the oral closure is significantly different between the three categories (two in the voiced case). As expected, there is a positive correlation with the duration of glottal separation. The shortest oral closure duration is found for the case of liaison, the longest for gemination. All differences are significant beyond the 0.001 level.

VOT for /t/, as already stated, is insensitive to gemination. VOT for /d/, on the other hand, is consistently affected by gemination: in the unstressed case, mean VOT is -72 ms for the non-geminated case, -163 ms for the geminated case. For the stressed case, the corresponding values are -140 ms and -191 ms.

Although the corpus of Part II was not designed to investigate the consonant /r/, it is worth noting that the glottal gesture during /r/ shows very reliably abduction of the vocal folds, to a lesser extent than in voiceless plosives but comparable to that in stressed voiced fricatives.

To summarize the fiberscopic data, it can be said that:

1) voiceless stops, whether stressed or unstressed, whether initial or medial, whether non-geminated or geminated or liaison elements, are produced with the glottis open during oral closure;

2) under the same conditions, voiced stops are produced with the vocal folds adducted, as measured at the vocal processes, and vibrating; medial glottal width, however, is not always negligible, particularly in utterance

initial position; this suggests that glottal closure for initial voiced consonant is less tight than for medial voiced consonants and for vowels;

3) maximum glottal aperture during the oral closure of non-geminated voiceless stops correlates highly with the duration of glottal aperture (and with the duration of the concommitant oral closure);

4) maximum glottal aperture during the oral closure of geminated stops is not a function of glottal separation duration (or of oral closure duration

5) duration of glottal separation (as well as duration of oral closure) depends highly on factors such as stress, allophonic variant, and position in the utterance;

6) velocity of the glottal opening or closing gesture does not appear to vary significantly as a function of other factors; however, a rigorous check of this last statement will require a considerably higher film frame rate.

Measurements and Results, Part III

The EMG data will be examined along the same four dimensions which are considered in the film data. An additional dimension will be the particular muscle under consideration.

1) Voiceless vs. voiced

Figure 1 represents PCA activity for six different pairs of utterances illustrating the contrast voiceless-voiced (cf. section on experimental procedures). Figure 2 represents the corresponding IA activity. In both figures, the dashed line stands for the voiceless utterance and the full line for the voiced one. For all tokens, the alignment point was chosen at the onset of the vowel following the stop consonant. A look at the graphs of Figure 1 shows that the onset of all utterances is preceded by high PCA activity, presumably for prephonatory inspiration.

For all /t/'s, there is a high PCA activity up to 175 ms prior to oral closure release; for initial /t/'s, this high PCA activity appears as a simple continuation of the high prephonatory PCA activity; for medial /t/'s, it appears as a peak following a period of lesser activity for the first vowel of the utterance. It then starts decreasing in preparation for the voicing of the vowel following /t/, dipping to a minimum at about 75 ms before oral closure release. At or near oral closure release time, PCA activity starts increasing in both types of utterances (/t/ and /d/) in preparation of the postvocalic /r/, during which the vocal folds are abducted, as evidenced by the fiberscopic data. In utterances 7A and 7B, the post vocalic consonant is /z/ (instead of /r/), but EMG activity and vocal fold gesture are both similar to those in the other twelve utterances with an /r/.

For /d/'s, nearly full suppression of PCA activity starts at least 250 ms prior to oral closure release, and PCA activity returns to values similar to those for the corresponding /t/ utterance approximately 50 to 100 ms prior to oral closure release.

For both /t/ and /d/, the IA shows a sort of reciprocal pattern of activity when compared to the PCA. This can be easily observed in Figures 1 and 2: the period where PCA activity is increased preceding /t/ and decreased preceding /d/ (Figure 1) corresponds to IA activity greater for /d/ than for /t/. In the 75-100 ms preceding the line-up point, this pattern is just reversed in preparation for the upcoming vowel.

Figure 3 shows LCA activity for the same six pairs of utterances. It can be seen that in four of the six pairs (namely those produced initially and/or with emphatic stress) there is a peak of LCA activity at the time of release of the stop consonant, in prevision of the adduction of the vocal folds for the vowel following the stop consonant. This increased LCA activity takes place earlier when the prevocalic stop is voiceless, thus pointing at the adductor function of the LCA supplementary to that of the IA. The nature of the LCA's adductor function appears to be secondary to that of the IA as suggested by the fact that for the two pairs of utterances which have no stress and where the stop is not utterance-initial, there is a noticeable voiceless-voiced difference of IA activity but not of LCA activity.

SH activity appears to be antagonistic to that of PCA, as illustrated in Figure 4, for utterance 1A. In particular, the well-marked peak of PCA activity just preceding the production of postvocalic /r/ (cf. supra) corresponds to an equally well-marked suppression of SH activity, synchronous with the less well-marked IA suppression. This SH suppression may be due to the tongue elevation gesture for /r/. Apparant SH activation after voiceless consonants may be similarly due to jaw opening in the vowel gesture after the consonant. It appears precarious at this point to relate SH activity to abduction-adduction gestures.

CT activity seems to vary in a more complex way, and to be a function of voicing, stress and place in the utterance. In the utterance initial case, illustrated in Figure 4, CT activity shows marked changes in the voiced case but only small and smooth ones in the voiceless case; for /d/, CT activity is suppressed up to 80-100 ms prior to stop release, and then increases rapidly to a maximum around the time of stop release; for /t/, CT activity has a maximum at the same time as for /d/, but it never shows suppression before the peak, as it does for /d/. Without further data, an interpretation of this contrast is difficult: it could be due to a pitch difference, or, alternatively, CT suppression for /d/ may assist vocal fold vibration.

2) Stressed vs. unstressed

For all five muscles under study, one can observe very generally that, as expected, muscular activity is markedly increased, not only on the stressed syllable but, in most cases, in the rest of the utterance. Figure 5 shows LCA activity for the seven pairs of utterances 1 through 7. The peak of aciivity corresponding to the adduction of the vocal processes for the vowel /ɛ/ is clearly visible for all fourteen utterances, and in all pairs, it is greater in the stressed utterance than in the unstressed one. It may appear that the timing of the other peaks in a given utterance is different from that of the (un)stressed utterance, but this is due to the different overall durations, always greater in the stressed case. A peak left of the alignment point will thus occur earlier in the stressed utterance, whereas a peak right of the alignment point will occur later in the stressed utterance. CT, PCA, and SH show a contrast stressed-unstressed quite similar to that of LCA.

For one muscle, namely the IA, the difference of activity between the stressed and unstressed cases, although always observed in the direction indicated above, seems to be extremely small as compared with those for the other four muscles. This could be due to the fact that IA is primarily responsible for adduction gesture and not for stress (or vocal pitch) control.

3) Utterance-initial vs. utterance-medial

In general it is much more difficult to observe possible differences in the middle of an utterance than at its beginning, due to the contextual effects: in the "initial" case, the anterior context consists of a pre-speech neutral position, similar for all utterances, whereas in the "medial" case, the anterior context consists of several coarticulated phonetic segments, possibly different from one utterance type to another.

Here again, the adductory activity of LCA can be observed, as evidenced by Figure 6. In all four graphs, the (dotted) curve corresponding to the initial stop whether voiced or not, shows a markedly higher activity leading to stop release. In the medial case, a smaller peak can be observed for the stressed utterances, but not for the unstressed ones. This indicates that, in the medial case, most of the ab/adduction control is performed by IA and PCA (see Figures 7 and 8), whereas in the initial case, additional control is performed by LCA. IA activity (Figure 7) is greater for the vowel following the voiceless stop than for that following the voiced ones (regardless of stress, or of position in the utterance), as noted earlier.

SH and CT activity does not appear to vary reliably in accordance with the position of the syllable in the utterance.

4) Liaison vs. non-geminated vs. geminated

The fiberscopic data have indicated that for the voiced case, this two-way contrast (non-geminated vs. geminated) does not show any difference in glottal gesture. This finding is paralleled by the fact that EMG activity does not seem to vary with this dichotomy (cf. Figure 9). In the voiceless case, however, the three-way contrast is best illustrated by PCA activity, whose peak occurs earliest (with respect to vowel onset time) for the geminated stop, less early for the non-geminated stop, and least early for the liaison stop (cf. Fig. 9). Not surprisingly, this is the same timing order found in the fiberscopic data. The other four muscles show analogous differences reflecting the differences in timing of the three-way contrast.

To summarize the EMG data and the fiberscopic data, it can be said that, for this speaker of French,

1) the voiceless stop consonant is characterized by the abduction of the vocal folds at or near the onset of oral closure; the vocal folds are then adducted simultaneously with the release of oral closure; the abduction-adduction gesture is primarily controlled by the increased activity of the PCA and of the IA, respectively, and by the reciprocal suppression of the IA and of the PCA, respectively;

2) the voiced stop consonant is characterized by the adduction and the vibration of the vocal folds through the period of oral closure and through the following vowel, without any interruption; correspondingly, the suppression of PCA activity and the increased (with respect to the voiceless case) IA activity are initiated well before the onset of the consonant;

3) although the primary control of abduction-adduction is performed by the reciprocal action of the PCA and the IA, complementary action to the IA is exhibited by the LCA, particularly after a voiceless segment and/or in initial position; initial stops, whether voiced or not, exhibit a higher LCA activity than medial ones, thus pointing at a greater contribution of the LCA to the adduction gesture in initial position than in medial position;

4) utterances produced with emphatic stress show increased muscular activity not only on the stressed syllable but in most cases in the rest of the utterance as well; this increased muscular activity is most observable for the LCA, the PCA and the CT, while minimal for the IA; for the SH, it is manifested mostly before the stressed syllable; segment durations are markedly increased, particularly on and in the vicinity of the stressed syllable;

5) the three-way contrast between liaison, non-geminated, and geminated voiceless stop is evidenced primarily by the duration of oral closure, and thus reflected in the timing of the laryngeal gesture (abduction-adduction) and of the corresponding EMG activity; the duration of oral closure is shortest for the liaison stop, intermediate for the non-geminated stop and longest for the geminated one;

6) the two-way contrast between non-geminated and geminated voiced stop is not characterized by any difference in glottal gesture since the vocal folds are maintained in adducted position through the complete VCV sequence; the duration of oral closure, however, is shortest for the non-geminated voiced stop, longest for the geminated one.

Conclusions

At the acoustic level, the two types of stops are clearly distinguished by VOT, as stated before by many phoneticians. The voiceless type is characterized by a VOT which is small but always positive, whereas the voiced type has a VOT which is at least three times as large, and always negative, if one assumes the definition given earlier.

Fiberscopic observation correspondingly reveals two characteristic time courses of glottal width for the consonantal portion of the test utterances. For the voiceless type, in a -VCV- context, the glottis opens as the oral vocal tract closes, then closes at oral release time (or very slightly thereafter), whereas for the voiced type, the vocal folds are adducted and vibrating all through the time of oral closure.

EMG analyses indicate that it is the abduction-adduction gesture which determines the voiceless-voiced contrast by its presence or absence; this gesture is primarily controlled by reciprocal PCA-IA activity, LCA providing supplementary (to IA) adduction control.

CT, primarily a tension controlling muscle, is found to be most active in emphatic stress, as well as in all contexts involving pitch control. Stressed utterances are generally characterized by heightened EMG activity not only before the stressed syllable, but also in the rest of the utterance. The three way contrast liaison vs. non-geminated vs. geminated seems to be manifested essentially by the duration of the consonant involved in the contrast, and, for the voiceless case, by the duration of the corresponding laryngeal opening gesture.

Although the data presented are relatively straight-forward, more extensive experiments including a combined recording of EMG, fiberscopic and subglottal pressure data are needed to provide further information on the relations between muscle activity, glottal configuration and aerodynamic parameters.

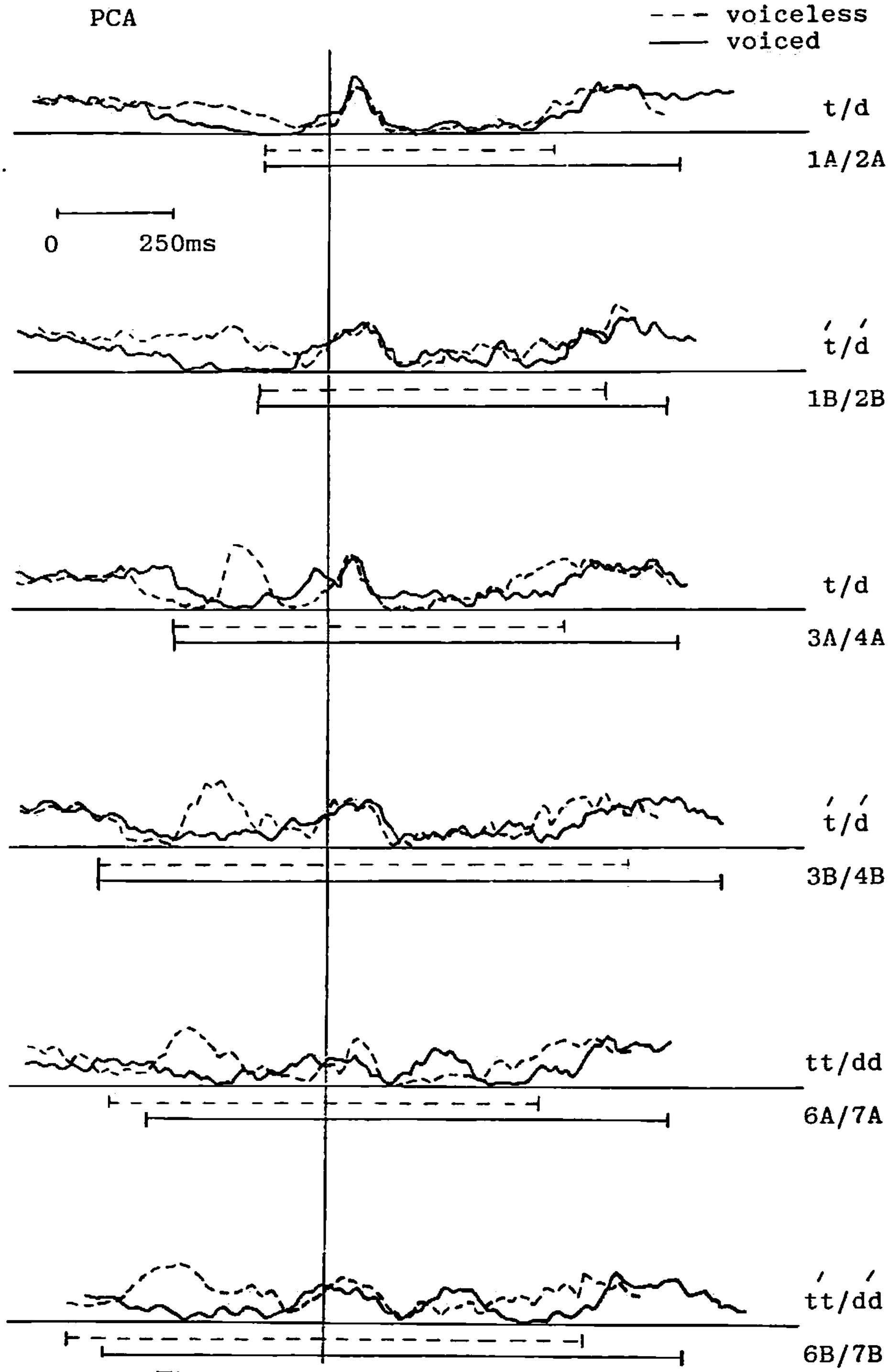

Fig. 1: PCA activity, voiceless vs. voiced.

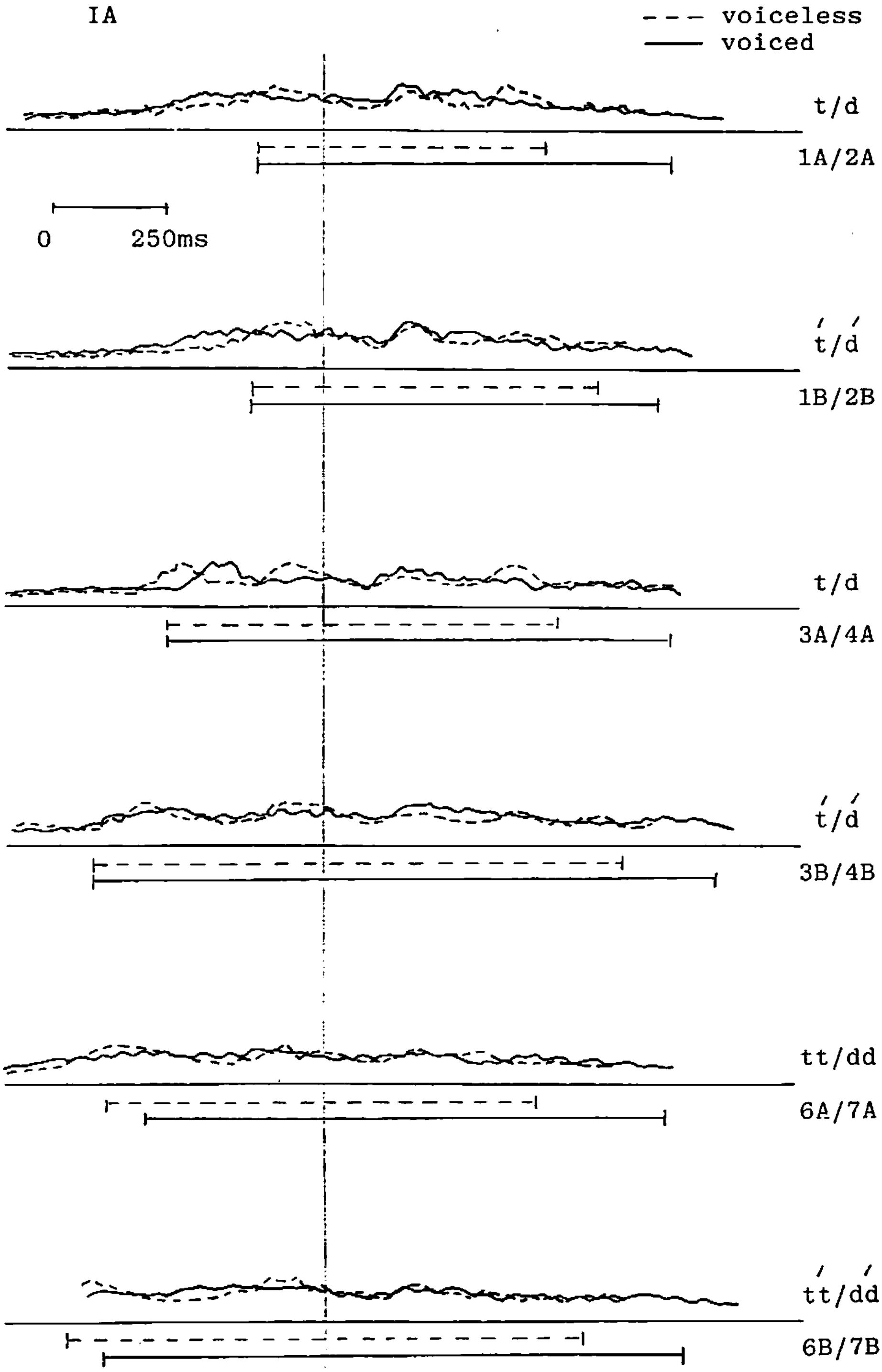

Fig. 2: IA activity, voiceless vs. voiced.

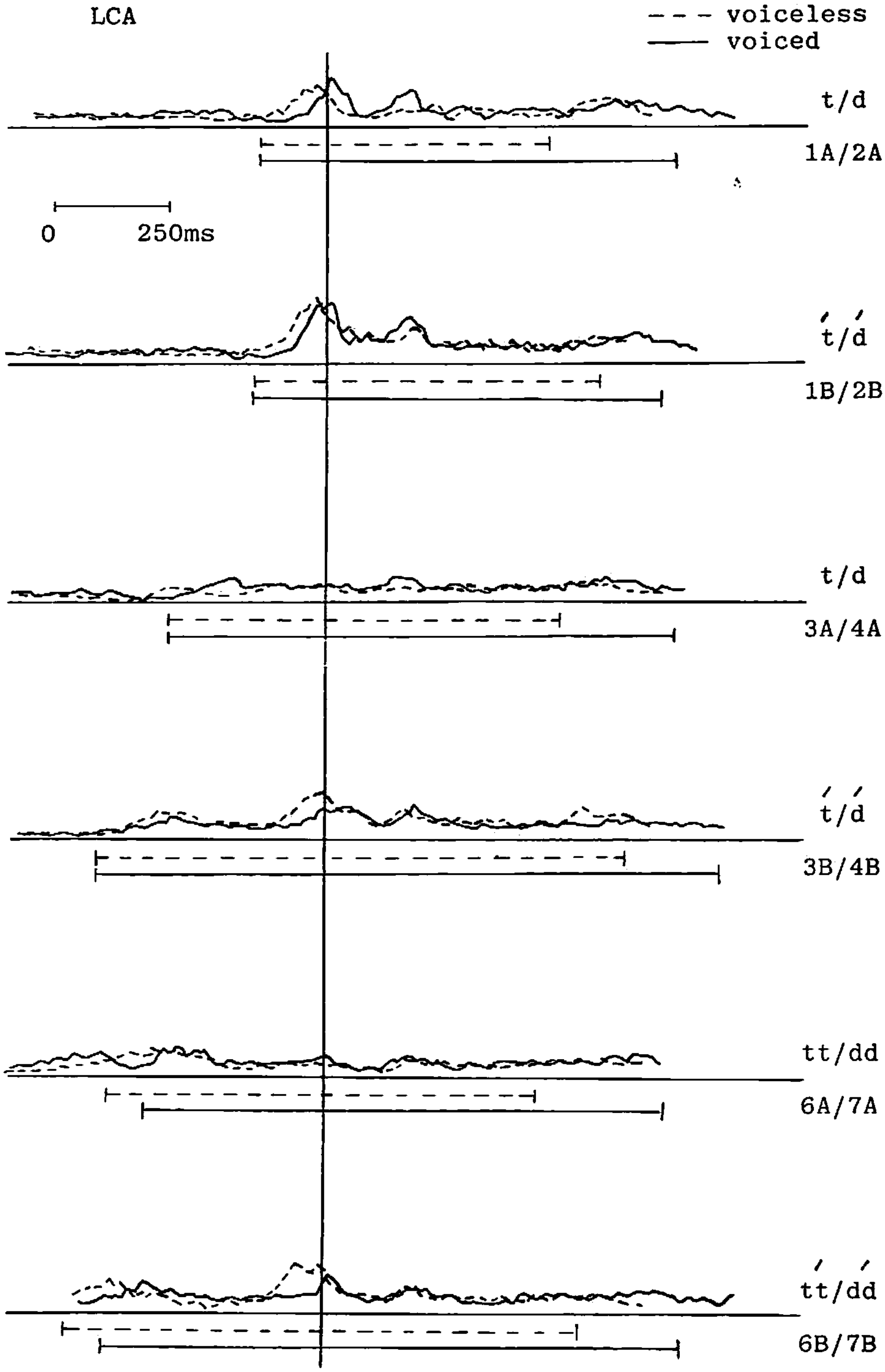

Fig. 3: LCA activity, voiceless vs. voiced.

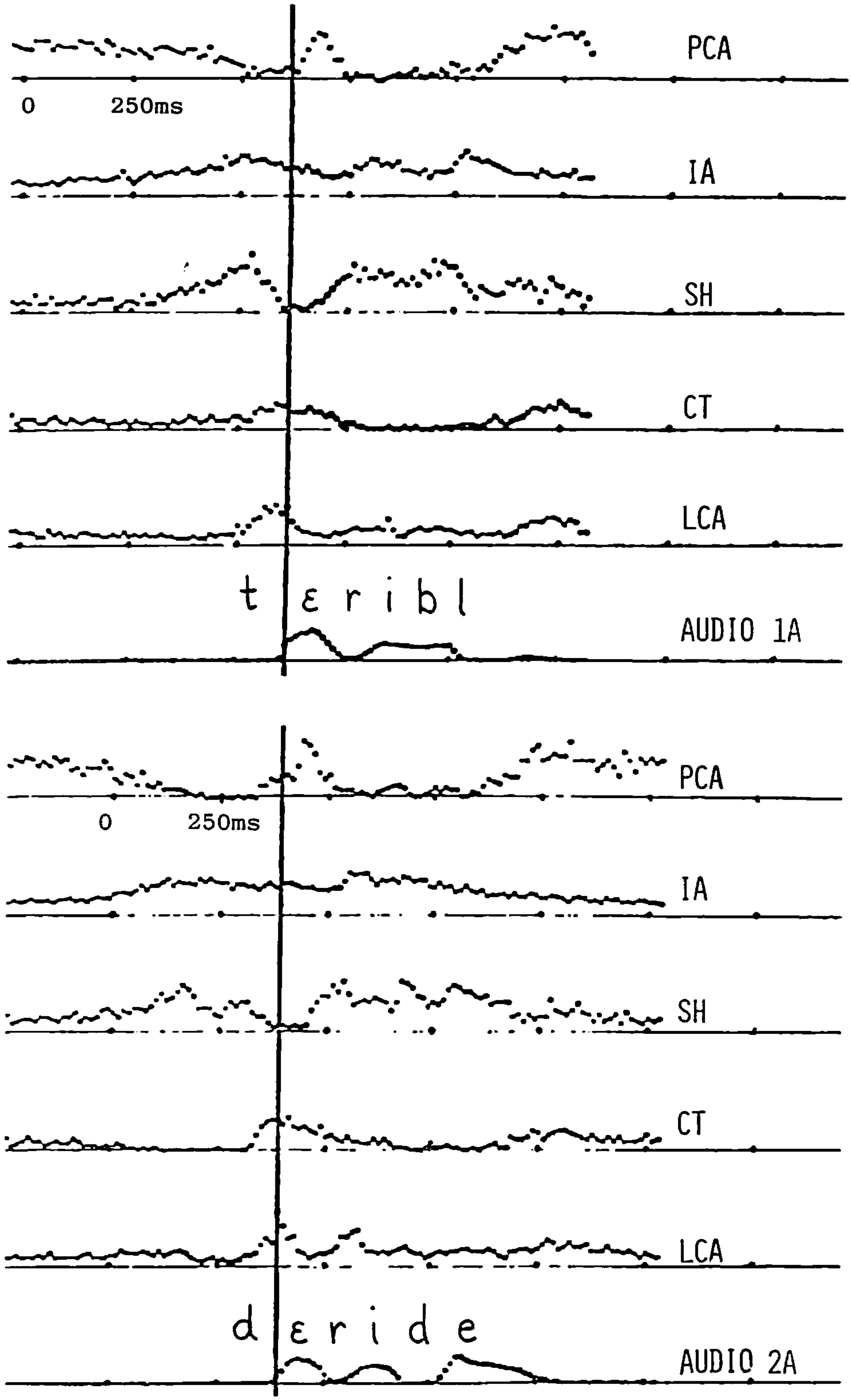

Fig. 4: EMG activity, initial /t/ vs. initial /d/, unstressed.

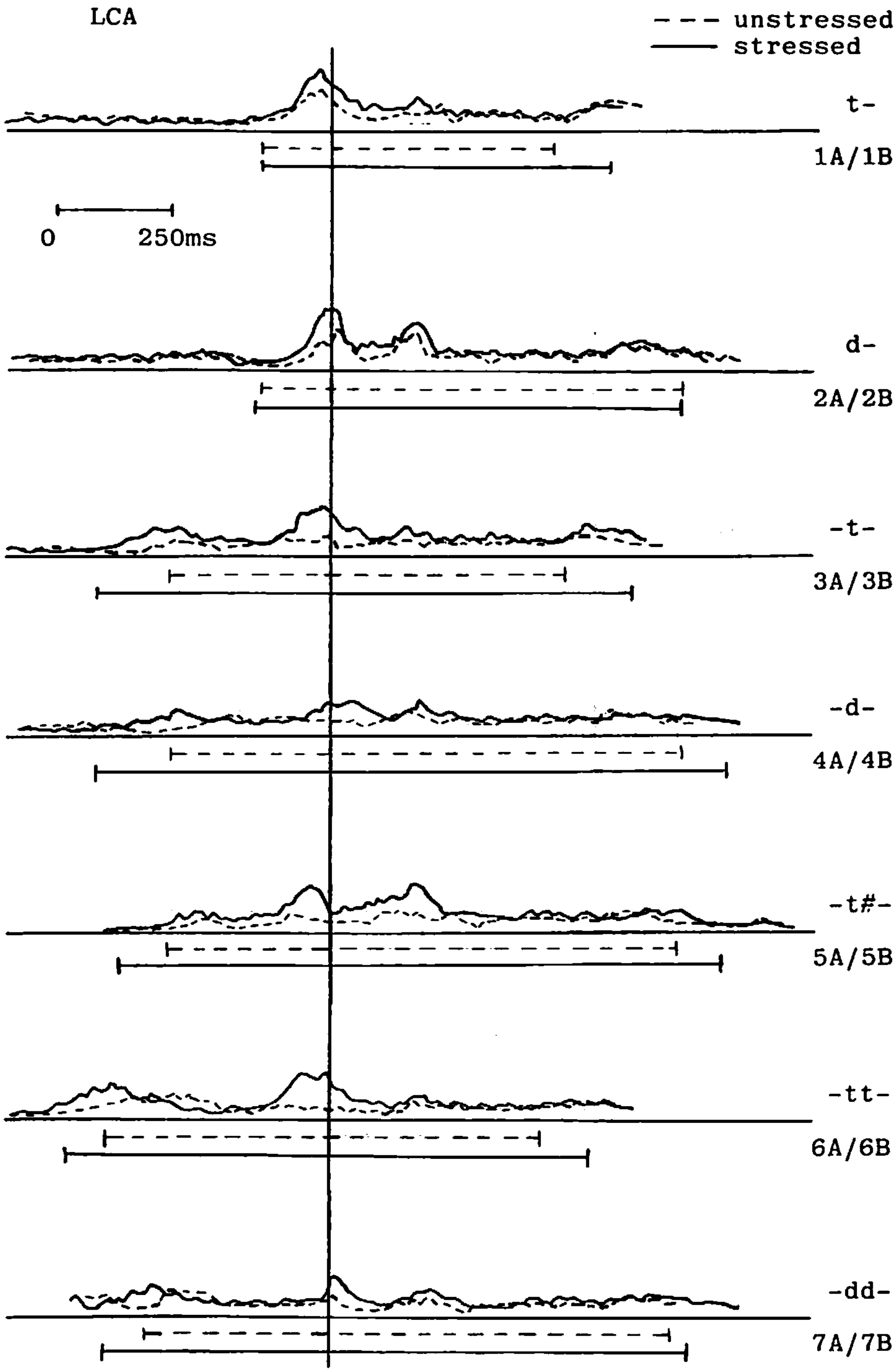

Fig. 5: LCA activity, stressed vs. unstressed.

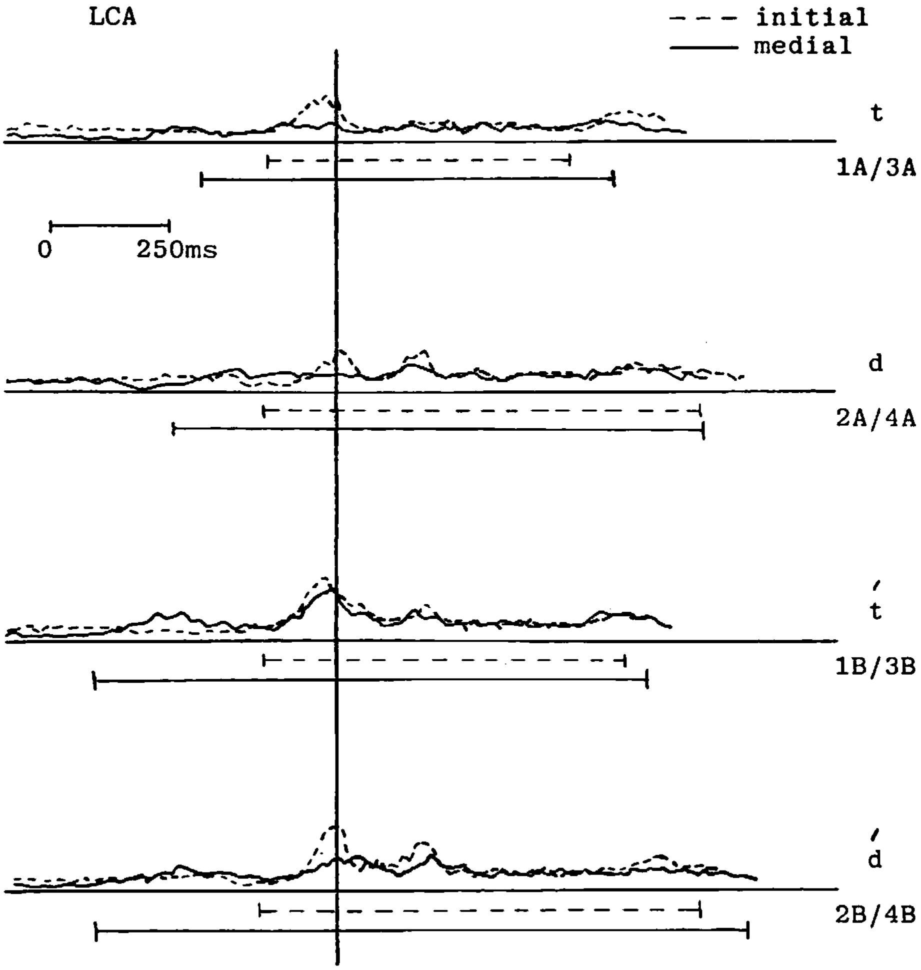

Fig. 6: LCA activity, initial vs. medial.

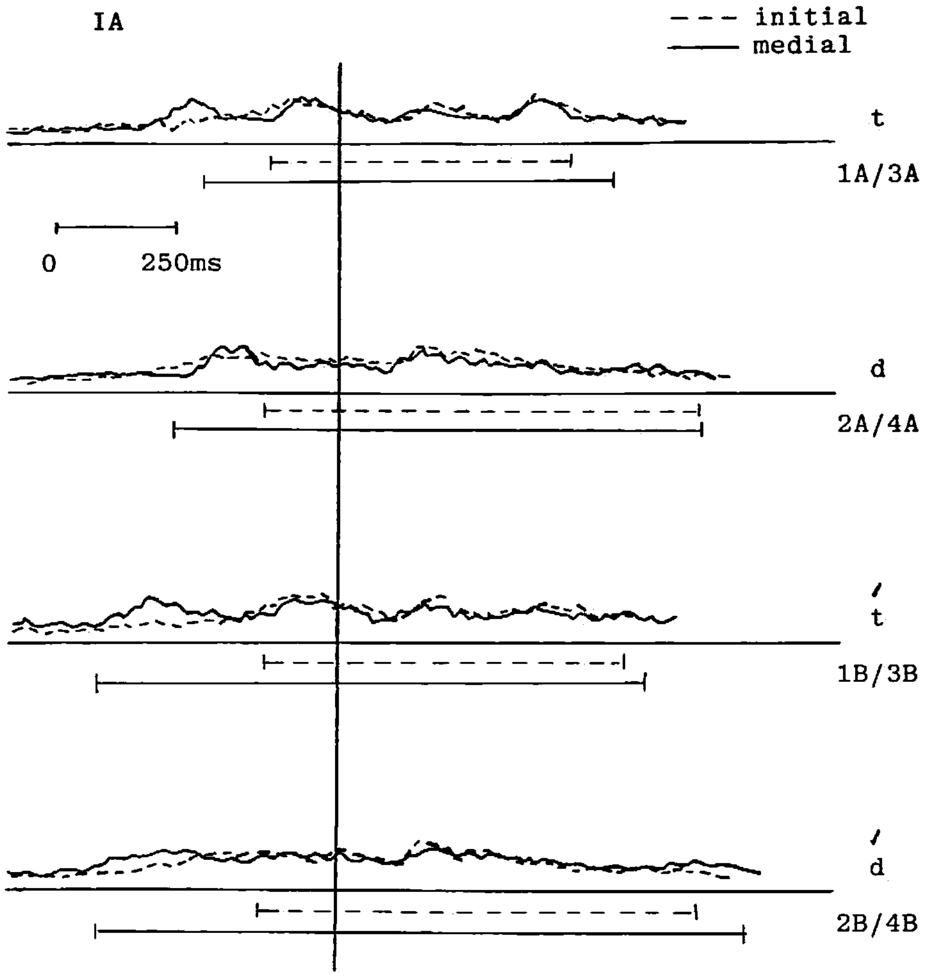

Fig. 7: IA activity, initial vs. medial.

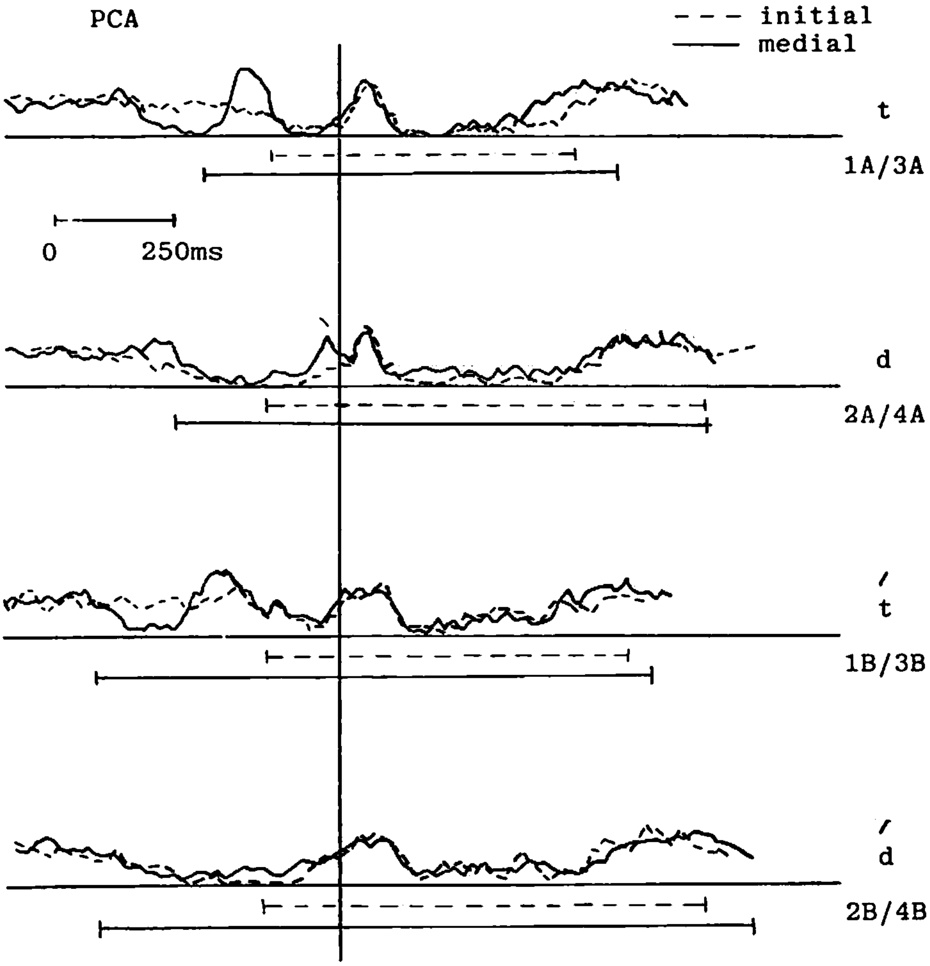

Fig. 8: PCA activity, initial vs. medial.

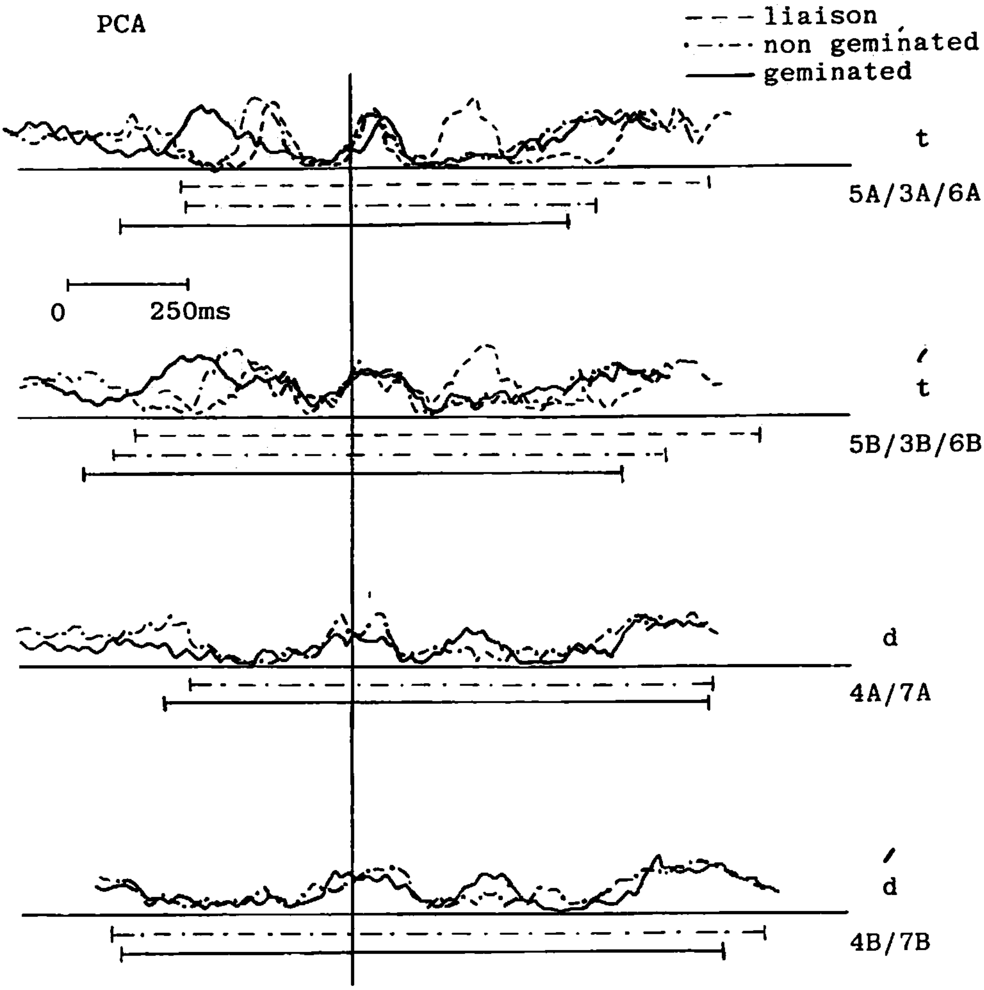

Fig. 9: PCA activity, liaison vs. non-geminated vs. geminated.

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