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Interarticulator programming: Effects of closure duration on lip and tongue coordination in Japanese

Anders Löfqvist[a)]
Haskins Laboratories, New Haven, Connecticut 06511 and Department of Logopedics, Phoniatrics & Audiology Clinical Sciences, Lund, Lund University, Lund, Sweden

Abstract

This paper examines the coordination of lip and tongue movements in sequences of vowel-bilabial consonant-vowel where the duration of the oral closure for the consonant is varied for linguistic purposes. Native speakers of Japanese served as subjects. The linguistic material consisted of Japanese word pairs that only differed in the duration of the labial consonant, which was either long or short. Recordings were made of lip and tongue movements using a magnetometer system. Results show a robust difference in closure duration between the long and short consonants. The tongue movement from the first to the second vowel had a longer duration in the long than in the short consonants, and its average speed was slower in the long consonant. The size of the tongue movement path between the vowels did not consistently differ between the long and short consonants. The tongue movement almost always started before the oral closure for the consonant, while the onset of the lip movement towards oral closure mostly started before that of the tongue movement. The offset of the tongue movement occurred after the release of the closure, but there was no clear pattern for the long and short consonants.

I. INTRODUCTION

This paper examines the coordination of lip and tongue movements in sequences of vowel-bilabial consonant-vowel, where the duration of the oral closure for the consonant is varied for linguistic purposes, using speakers of Japanese. An earlier study of American English (Löfqvist and Gracco, 1999) showed that the onset of the tongue movement from the first to the second vowel in such a VCV sequence almost always started before the oral closure for the consonant. In addition, more than 50% of the tongue movement trajectory between the vowels occurred during the oral closure. There was also a weak positive correlation between the magnitude of the tongue movement for the vowels and the interval between tongue movement onset and the onset of the lip closing movement. That is, the tongue started to move earlier than the lips as the tongue trajectory increased.

In Japanese, the ratio of closure duration for long and short consonants is about 2:1 (Beckman, 1982; Han, 1994; Hirata and Whiton, 2005). There is an extensive body of acoustic studies of the Japanese sound system with particular emphasis on the role of the mora for speech timing (e.g., Warner and Arai, 2001). The long consonants in Japanese are sometimes referred to as “geminates,” and such a consonant contributes one mora; it is also traditionally assumed that a mora boundary occurs in the long consonant. This paper does not address the general issue of mora timing, however. Its primary focus is on speech motor control, capitalizing on the length distinction in Japanese sound structure to study the coordination of lip and tongue

a)lofquist@haskins.yale.edu

movements under two conditions of consonant length. It is thus beyond the scope of this study to review the many different views of the mora in Japanese. The reader is referred to Vance (1987) and Warner and Arai (2001).

If the duration of the oral closure for the consonant is increased, a speaker can in principle use two strategies for the coordination of the tongue and lip movements, as illustrated in the bottom panel of Fig. 1; the top panel in Fig. 1 shows tongue, jaw, and lip movements between the two vowels in the word /kami/ with a short labial consonant. One strategy would make the same tongue movement trajectory for a long and a short consonant. Such a strategy could have one or two versions, or a combination of them. The onset of the tongue movement might be shifted later relative to the oral closure, so that the tongue movement reached its position for the second vowel at the same point in time for the long and short consonant, pattern 1a in the lower panel of Fig. 1. Alternatively, the onset of the tongue movement could have the same temporal relationship to the consonant closure, pattern 1b in the lower panel of Fig. 1. In this second case, the interval between the offset of the tongue movement and the release of the oral closure for the labial consonant would thus increase for the long consonant. Pattern 1c in the lower panel of Fig. 1 shows a tongue movement trajectory that is shifted both relative to the onset and offset of the labial consonant. A second strategy would be to modify the tongue movement during the long consonant, so that the relative timing between the tongue movement for the vowels and the lip movements for the oral closure of the consonant would be more or less the same for the long and short consonants, pattern 2 in the lower panel of Fig. 1. This would imply making a slower tongue movement trajectory for the long than for the short consonant. The timing between the tongue and lip movements would thus be similar in the two conditions of consonant length. Experimental evidence for the second strategy has been provided by (Smith, 1992,1995). Using the x-ray microbeam system (Nadler *et al.*, 1987), she showed that Japanese speakers tended to increase articulatory intervals from the medial consonant to the second vowel in long compared to short consonants.

The present study extends the findings of Smith, using the measurement procedures developed by Löfqvist and Gracco (1999). For example, to analyze temporal patterns of tongue movements, Smith made separate measurements in the vertical and horizontal tongue movements, and also used “target intervals” based on a criterion of minimum movement. In this study, a single measure of tongue movement speed, taking into account both the vertical and horizontal movement components, is used for determining onset and offset of tongue movements. In addition, measurements are made of the duration and magnitude of the tongue movement trajectory, the average speed of the tongue movement between the two vowels, and the coordination of lip and tongue movements. The question addressed is whether these measures differ between words with long and short consonants. The hypothesis, based on the work of Smith, is that the tongue movement in the words with a long consonant will be slower and of longer duration than in a word with a short consonant, implying that speakers maintain a similar overall phasing between lip and tongue movements in long and short consonants.

II. METHOD

A. Subjects

Five native speakers of Japanese, three male and two female, served as subjects. They reported no speech, language, or hearing problems. They were naive as to the purpose of the study. Before participating in the recording, they read and signed a consent form. (The experimental protocol was approved by the IRB at the Yale University School of Medicine.)

B. Linguistic material

The linguistic material consisted of Japanese words with a sequence of vowel-labial nasal-vowel. These words formed minimal pairs, where the only difference between the pairs was the duration of the labial consonant. The words were designed to require a substantial amount of tongue movement from the first to the second vowel. The following words were used: /kami, kammi/, /kamee, kammee/, /kema, kemma/, /semu, semmu/. The productions of the last word pair turned out to have a very small amount of tongue movement, so they were not analyzed. In addition, to examine tongue movements in symmetrical vowel contexts, the following words were also recorded for three of the subjects: /kama, kamma/, /ʃimi, /ʃimmi/. The linguistic material was organized into randomized lists and presented to the subjects in Japanese writing, with the words occurring in a short frame sentence. Fifty repetitions of each word were recorded.

C. Movement recording

The movements of the lips, the tongue, and jaw were recorded using a three-transmitter magnetometer system (Perkell *et al.*, 1992); when proper care is taken during the calibration, the spatial resolution of the system is on the order of 0.5 mm. Receivers were placed on the vermilion border of the upper and lower lip, on three positions of the tongue, referred to as tip, blade, and body, and on the lower incisors at the gum line. Two additional receivers placed on the nose and the upper incisors were used for the correction of head movements. The lip and jaw receivers were attached using Isodent, a dental adhesive, while the tongue receivers were attached using Ketac-Bond, another dental adhesive. Care was taken during each receiver placement to ensure that it was positioned at the midline, with its long axis perpendicular to the sagittal plane. Two receivers attached to a plate were used to record the occlusal plane by having the subject bite on the plate during the recording. All data were subsequently corrected for head movements and rotated to bring the occlusal plane into coincidence with the *x* axis. This rotation was performed to obtain a uniform coordinate system for all subjects (cf. Westbury, 1994).

The articulatory movement signals (induced voltages from the receiver coils) were sampled at 500 Hz after lowpass filtering at 200 Hz. The resolution for all signals was 12 bits. After voltage-to-distance conversion, the movement signals were low-pass filtered using a 25-point triangular window with a 3-dB cutoff at 14 Hz; this was done forwards and backwards to maintain phase. A measure of lip aperture was obtained by calculating the vertical difference between the upper and lower lip receivers. To obtain instantaneous velocity of the lip aperture and tongue receivers, the first derivative of the position signals was calculated using a 3-point central difference algorithm. For the lip aperture signal, its acceleration was also calculated from its velocity. For each tongue receiver, its speed $v=\sqrt{(\dot{x}\,2+\dot{y}\,2)}$ was also calculated. The velocity signals were smoothed using the same triangular window. All the signal processing was done using the Haskins Analysis Display and Experiment System (HA-DES)(Rubin and Löfqvist, 1996). The acoustic signal was pre-emphasized, low-pass filtered at 4.5 kHz, and sampled at 10 kHz.

The onset and release of the oral closure for the nasal consonant were identified in waveform and spectrogram displays of the acoustic signal. They were both identified by a change in the amplitude and the spectral properties.

To define the onset of the closing movement of the lips for the nasal consonant, an algorithmically obtained minimum in the lip aperture acceleration signal just before oral closure was used, following Löfqvist and Gracco (1999); see Fig. 2(a). In the words with asymmetrical vowel contexts, tongue movement onsets and offsets were defined algorithmically in the tongue body speed signal as minima during, or close to, the first and second vowels; see Fig. 2(b). We should note that, at these points in time, the horizontal and vertical velocity of the tongue is usually not zero. The duration of the tongue body movement was measured between its onset and offset. The magnitude of the tongue movement trajectory from the first to the second vowel was obtained by summing the Euclidean distances between successive samples of the tongue body vertical and horizontal receiver positions from movement onset to movement offset. The average speed of the tongue body was obtained by adding the speed of all the individual samples between movement onset and offset and then dividing by the number of samples in the interval. The vertical and horizontal positions of the tongue body receiver at movement onset and offset were measured to examine if any observed changes in movement magnitude were due to changes in onset position, offset position, or both. Three temporal measurements were made. The first one consisted of the interval between tongue movement onset and oral closure; it provides information about the tongue movement relative to consonant closure. The second one was the interval between tongue movement onset and lip closing movement onset; it examines the coordination between tongue and lip movements. The third one was the interval between tongue movement offset and oral release; it is useful for examining the tongue movement relative to consonant release. The kinematic signals are expressed in a maxilla-based coordinate system. Thus, the tongue body movement includes the contribution of the jaw, which is appropriate when we are interested in the tongue as the end effector.

In the words with symmetrical vowel contexts, no temporal landmarks could be defined in the tongue movement signals. For these words, the movement path of the tongue, and the jaw were measured during the acoustically defined oral closure for the nasal consonant, and also the tongue body and jaw positions at consonant onset and offset. The jaw was included, since it might contribute to the labial closure, and hence to tongue movements, in particular in the words with the open vowel /a/.

To assess differences between the long and short consonants for each subject, *T*-tests were used. Given the large number of comparisons, a conservative α-level of 0.001 was adopted. Since the variances usually differed between the long and short consonants, as shown by Levene's test, the statistical tests assumed unequal variances, so the degrees of freedom were adjusted (e.g., Winer *et al.*, 1991, p. 67).

III. RESULTS

A. Consonant duration

The duration of the oral closure for the long and short nasal consonants is summarized in Fig. 3. For all speakers, there is a clear and robust difference between the long and short consonants, with the long ones having about twice the duration of the short ones. The statistical analysis showed all the differences to be significant (for /kami, kammi/ t=−20.28, −24.39, −24.83, −18.28, and −17.86, for speakers YK, YM, KN, SO, and TT, respectively; for /kamee, kammee/ t=−19.88, −29.19, −40.79, −38.19, and −23.01, and for /kema, kemma/ t=−19.72, −28.78, −38.73, −26.32, and −15.67, with p<0.001 in all cases).

B. Tongue movements

The first analysis focused on the kinematic properties of the tongue movement from the first to the second vowel.

1. Tongue body movement duration—Figure 4 shows the duration of the tongue body movement from the first to the second vowel. For most subjects and words, the duration is longer in the long than in the short consonant. The two exceptions were for the productions of /kema, kemma/ by speakers SO and TT, where the duration of the movement trajectory was

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longer for the short consonant, but the difference was not significant in either case (t=1.27, and 3.23 for SO and TT, ns). For all the other cases, the difference was significant (for /kami, kammi/ t=−11.2, −8.19, −4.2, −12.17, −13.63; for speakers YK, YM, KN, SO, and TT, respectively; for /kamee, kammee/ t=−13.48, −7.55, −10.34, −17.58, −14.55; and for /kema, kemma/ t=−9.97, −4.64, −4.97, for speakers YK, YM, and KN, with p<0.001 in all cases).

2. Average speed of tongue body—Figure 5 shows the average speed of the tongue body movement from the first to the second vowel. Overall, the average speed is slower for the long than the short consonant. With the exception of /kami, kammi/ of speaker YM (t=3.2, ns) the difference was statistically significant (for /kami, kammi/ t=6.39 14.91. 7.0, 8.64, for speakers YK, KN, SO, and TT, respectively; for /kamee, kammee/ t=9.55, 6.63, 22.12, 10.61, 13.42; and for /kema, kemma/ t=−6.73, 17.56, 12.52, 11.91, 3.84, for speakers YK, YM, KN, SO, and TT, respectively, with p<0.001 in all cases).

3. Magnitude of tongue movement path—Figure 6 shows the path of the tongue body movement from the first to the second vowel. Here, the results differ both within and across speakers. Speaker YK always produced the long consonant with longer movement path, but the difference was only statistically significant for /kami, kammi/ (t=−5.17, p<0.001) and /kema, kemma/ (t=−4.3, p<0.001) but not for /kamee, kammee/ (t=−1.98, ns). Speaker YM made significant differences between all the word pairs, but in /kami, kammi/ (t=−7.26, p<0.001) and /kamee, kammee/ (t=−5.86, p<0.001) the path was longer for the long consonant, whereas the opposite pattern was found for /kema, kemma/ (t=4.49, p<0.001). Speaker KN consistently produced the short consonant with a longer tongue movement path, but the difference was only significant in two cases (t=9.38 and 11.6 for /kami, kammi/ and /kamee, kammee/, respectively, with p<0.001 in both cases, but not for /kema, kemma/ t=1.97, ns). Also for speaker SO, the results varied between words. For /kami, kammi/ and /kamee, kammee/ the path was longer for the long than for the short consonant (t=−8.53, and-5.29, with p<0.001 in both cases). However, the opposite was found for /kema, kemma/ (t=14.03, p<0.001). Finally, speaker TT only showed a significantly longer path for the short consonant in /kema, kemma/ (t=5.08, p<0.001), while no difference was found for the other two words (t=−3.34, and 2.83, ns, for /kami, kammi/ and /kamee, kammee/, respectively).

The path of the tongue body movement was not influenced by consonant length in a systematic manner across speakers. Whenever an influence was found, it could be due to a difference in onset position, offset position, or both, but there was no consistent pattern across subjects.

In summary, the results for the tongue movement from the first to the second vowel show that it generally had a longer duration for the long than the short consonant. Its average speed was always lower for the long than for the short consonant. The path of the tongue movement showed no consistent influence of consonant length.

C. Interarticulator programming

The next analysis examined the timing between the lip and tongue movements for the labial consonant and the two vowels. Three different measurements were made.

1. Onset of tongue body movement relative to onset of oral closure—Figure 7 summarizes the duration of the interval between tongue movement onset and oral closure for the consonant. Of note here is that, with the exception of only one case, /kammee/ for subject KN, the tongue movement onset always occurs before the closure. Overall there is no clear pattern for the long and short consonants. For /kami, kammi/, only subjects KN and YM showed a reliable difference (KN, t=11.1, p<0.001, and YM, t=12.9, p<0.001), but they were not in the same direction. The corresponding t values for the other subjects were 1.45, 0.36, and 0.83

for YK, SO, and TT, respectively, all ns. Also for the pair /kamee, kammee/, the results were inconsistent. Subjects YM, KN, and SO had significant differences (t=11.30, −10.41, and 3.39, with p<0.001 in all cases), but only speakers YM and SO showed this interval to be longer for the long than for the short interval. Speaker KN produced the long consonant with a tongue movement that started after the closure. The other two speakers, YK and TT, showed no difference (t=2.75, and −2.37, ns). In contrast, four of the speakers produced the long consonant in /kema, kemma/ with an earlier start of the tongue movement for the short consonant (t= −4.45, −9.74, −17.87, and −17.59 for YM, KN, SO, and TT, respectively, with p<0.001 in all cases). Speaker YK showed the opposite pattern(t=5.26, p<0.001).

2. Onset of tongue body movement relative to onset of lip movement for closure—The results for this interval are shown in Fig. 8. The overall results suggest that the lips lead, but there is no clear difference between the long and short consonants. For /kami, kammi/, speakers YK, YM, and KN showed a significant difference between the long and short consonants (t=−2.61, 3.57, and −11.51, for YK, YM, and KN, respectively, with p<0.001). However, the difference went in opposite directions for YK and KN, compared to YM. For the remaining two speakers, SO and TT, there was no difference (t=0.92 and −1.93, ns). For /kame, kammee/, only speakers YK and KN had a reliable difference in this interval between the long and short consonants (t=−5.59, and 14.36, p<0.001) and here the lips led with a longer time for the long than for the short consonants. For the other speakers, YM, SO, and TT, no difference was found (t=−0.67, −1.54, and −2.04, ns). Four of the subjects, YM, KN, SO, and TT showed a longer lead of the lip movement in /kemma/ than in /kema/ (t=−7.65, 9.78, −19.6, and −16.64, for YM, KN, SO, and TT, respectively, with p<0.001 in all cases). Note that, for the short consonant /kema/, these four subjects started the tongue movement before the lip movement. Subject YK showed a different pattern with the tongue movement leading the lip movement, with a significant longer tongue movement lead for the long consonant (t=3.49, p<0.001).

3. Offset of tongue body movement relative to oral release—As shown in Fig. 7, the onset of the tongue movement from the first to the second vowel almost always started before the oral closure for the consonants. Its offset tended to occur after the oral release; see Fig. 9. The pattern was, however, quite variable as shown by the standard deviations. Only speakers YK and YM showed a significant difference between the long and short consonants in /kami, kammi/, with the tongue movement offset occurring later for the short consonant (t=3.19 and 4.06, p<0.001). The remaining three subjects had no difference (t=0.06, 2.39, and 1.13, for speakers KN, SO, and TT, respectively). A similar pattern with a later offset for the short than for the long consonants in /kame, kammee/ was found for speakers YK, SO, and TT, but the difference was only significant for SO and TT (t=5.03, and 4.35, p<0.001), and not for YK (t=2.54, ns). The remaining two speakers, YM and KN, showed no difference (t=0.09, and −1.28, ns). Finally, for the pair /kema, kemma/, only subjects YK and SO showed a reliably later offset in the short than in the long consonant (t=5.3, and 3.59, p<0.001). The other subjects showed no difference (t=0.88, 1.89, and −0.6, ns, for YM, KN, and TT, respectively).

4. Symmetrical vowel contexts—Two word pairs with symmetrical vowel contexts, / kama, kamma/, /ʃimi, /ʃimmi/, were examined in three of the subjects. The results for tongue body and jaw path lengths during the acoustically defined oral closure are shown in Fig. 10. For the open vowels in /kama, kamma/, the movement path during the oral closure is longer for the long than for the short consonant for both the tongue body and the jaw (tongue body: t=−12.88, −5.94, and −11.73, for subjects YK, SO, and TT, with p<0.001; jaw t=−16.8, −22.78, and −11.58, p<0.001). For the high vowels in /ʃimi, /ʃimmi/, the path of the tongue body movement is longer during the short than during the long consonant (t=6.51, 6.51, and 8.17, p<0.001). In contrast, the path of the jaw during the oral closure is longer for the long than for the short consonant, but the difference was only statistically significant for subjects YK and TT (t=−4.37, and −6.83, p<0.001), but not for subject SO (t=−2.55, ns). The movement of the jaw is made to assist in making the labial closure, which is reflected in the longer movement path of the jaw for the open vowel context /a/ than for the high vowel context /i/. As shown in the lower panels of Fig. 11, the jaw positions at the onset and offset of the nasal consonant do not differ very much in either vowel context. Nor is there any clear pattern within and across subjects for the long and short consonants.

Although the tongue is not rigidly coupled to the jaw, some of its movement is related to that of the jaw. This was particularly the case during the oral closure in the open vowel context, where the tongue body positions at closure and release were almost identical for subject YK, while the offset position tended to be lower for subjects SO and TT (Fig. 11, upper left panel). In the high vowel context, however, the tongue movement appeared to be more related to coarticulatory influences, since the tongue body had moved forward and upward during the oral closure; the movement magnitude ranged from 0.5 to 1.0 cm in both the horizontal and vertical dimensions (Fig. 11, upper right panel). This movement was most likely made to position to the tongue for the upcoming /t/ in the carrier phrase.

IV. DISCUSSION

This study examined the influence of consonant duration on the coordination of lip and tongue movements in VCV sequences with a labial nasal consonant. It was hypothesized that a speaker could use one of two possible strategies of interarticulator programming if the duration of the consonant was increased. In one of them, the tongue movement trajectory would be similar for the long and short consonants; thus, the timing between the lip and tongue movements would change. In the second one, the tongue movement would be modified for the long consonant, resulting in a similar coordination of lip and tongue movements for both the long and short consonants. The present results clearly support the second strategy.

They thus show that speakers of Japanese modify their tongue movements when they produce a sequence of a vowel-bilabial consonant-vowel with a long and a short consonant. In particular, the duration of the tongue movement is increased, while its average speed is reduced in the long consonant. However, the path of the tongue movement did not vary consistently with vowel duration. The onset of the tongue movement started before the oral closure for both the long and short consonants. Similarly, the offset of the tongue movement occurred after the release of the consonant. Thus, the coordination of the tongue movement relative to the onset and release of the oral closure was similar for the long and short consonants. Importantly, all five speakers showed the same modification of tongue movement speed and duration for the long consonant. These findings are similar to the ones reported by (Smith, 1992, 1995). They thus suggest that the Japanese speakers tend to maintain a similar, but not identical, coordination between the tongue and lip movements across consonant length.

Although all subjects changed the tongue movement between the two vowels, they did not change it in such a way that its duration in the long consonant was about twice the duration of the movement for the short consonant; see Fig. 4. Thus, the duration of the tongue movement did not correlate closely with the duration of the oral closure. The onset and offset of the tongue movement were defined as minima in the speed signal, but as suggested by the large variability in some of the temporal intervals in Figs. 7-9, these points need not be under tight temporal or spatial control. Tongue positions for vowels do not have point targets, but rather regions, that are influenced by phonetic context and speaking rate (e.g., Gay, 1974;Guenther, 1995).

As shown in Fig. 5, all subjects reduced the speed of the tongue body movement between the two vowels in the long consonant, thus maintaining a similar interarticulator timing for the two consonant durations. However, no subject completely stopped the movement of the tongue. This finding could follow from a general principle of motor control, based on a cost minimization, often expressed as a minimum jerk criterion (Flash and Hogan, 1985;Flash, 1987) or as a smoothness constraint (Uno *et al.*, 1989). Thus, speakers avoid excessive accelerations and decelerations of the tongue by keeping it moving.

The present results are generally in agreement with those of Löfqvist and Gracco (1999). As in their study, the onset of the tongue movement very rarely starts after the oral closure. They also found that the tongue started to move earlier than the lips as the tongue trajectory increased (their Fig. 7). A similar analysis of the coordination of tongue and lip movement onsets and tongue movement magnitude in the present results showed the same overall trend for all the speakers, although the correlations were generally less than 0.5. Interestingly, an inspection of Figs. 6 and 8 shows that there is sometimes a relationship between the path of the tongue movement and the interval between tongue movement onset and lip movement onset for the individual speakers. For example, for /kema, kemma/, speakers YM, KN, SO, and TT all had a longer path for the short than for the long consonant. These subjects also had the tongue movement leading the lip movement in producing the short consonant. In addition, speaker YK had a longer movement path for the long consonant, and also an earlier tongue movement onset for the long consonant. Similarly, speaker KN consistently produced a longer path in for the short than for the long consonant (Fig. 6) and also had a shorter interval between tongue and lip movement onsets for the short consonant.

The present results thus show that speakers of American English and Japanese have similar coordination between lip and tongue movements in VCV sequences, and that this is true for both the long and short consonants in Japanese. At the same time, American English and Japanese are described to have stress- and mora timing, respectively, but the interarticulator programming of lip and tongue movements appears to be very similar for the two languages.

This raises the issue of whether the prosodic structure of a language will influence patterns of interarticulator timing. The results presented by Smith (1992,1995) suggest that this may he the case, since speakers of Japanese and Italian, which also has a length contrast, may have different patterns of coordination in VCV sequences when the consonant length differs. Japanese is described as having mora timing, Italian is said to have syllable timing, but how, and if, such a difference will influence speech timing is debatable (e.g., Dauer, 1983;Bertran, 1999). Vatikiotis-Bateson and Kelso (1993) examined lower lip movements in English, French, and Japanese, using reiterant speech. Analyzing movement duration, amplitude, and peak velocity, they found that movement dynamics were qualitatively similar in the three languages but also that there were quantitative differences. Among these were speaking rate, the quantitative relationship between movement amplitude and peak velocity, and movement variability. Since the results presented by Smith for the Italian speakers were not as robust as for the Japanese speakers, it is of interest to further pursue this issue by applying the methodology used in the present study to languages such as Italian and Finnish.

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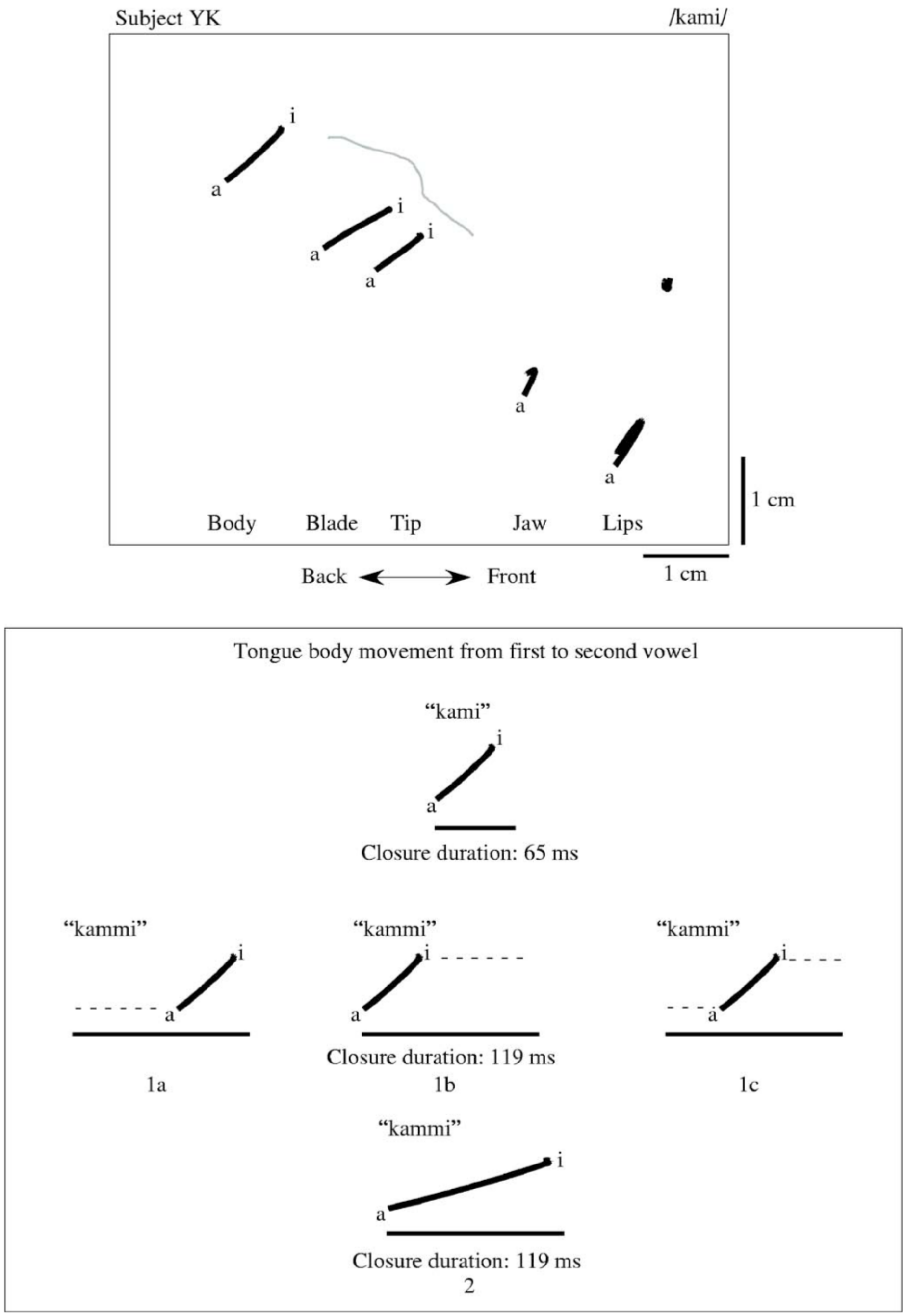

FIG. 1.

The top panel shows tongue, jaw, and lip movements between the two vowels in the word /kami/ with a short labial consonant; the gray line is an outline of the hard palate. The bottom panel shows the actual tongue body movement between the two vowels in the word with a short labial consonant and potential tongue movement trajectories in a word with a long consonant. See the text for further explanation.

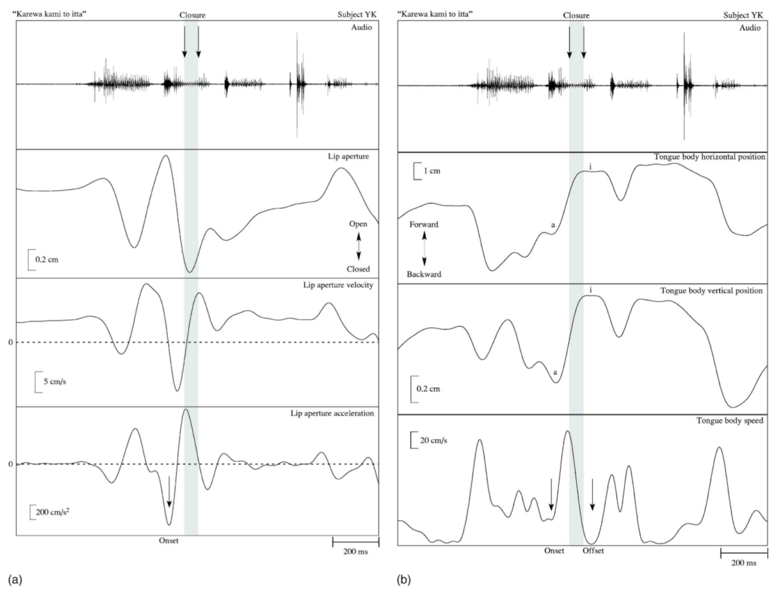

FIG. 2.

(a) Audio and lip aperture signals for the word /kami/, showing the point in the acceleration signal used for defining the onset of the lip closing movement. (b) Audio and tongue body signals for the word /kami/, showing the points used in the speed signal for defining the onset and offset of the tongue movement between the two vowels. The baseline in the bottom panel with the speed signal represents zero speed.

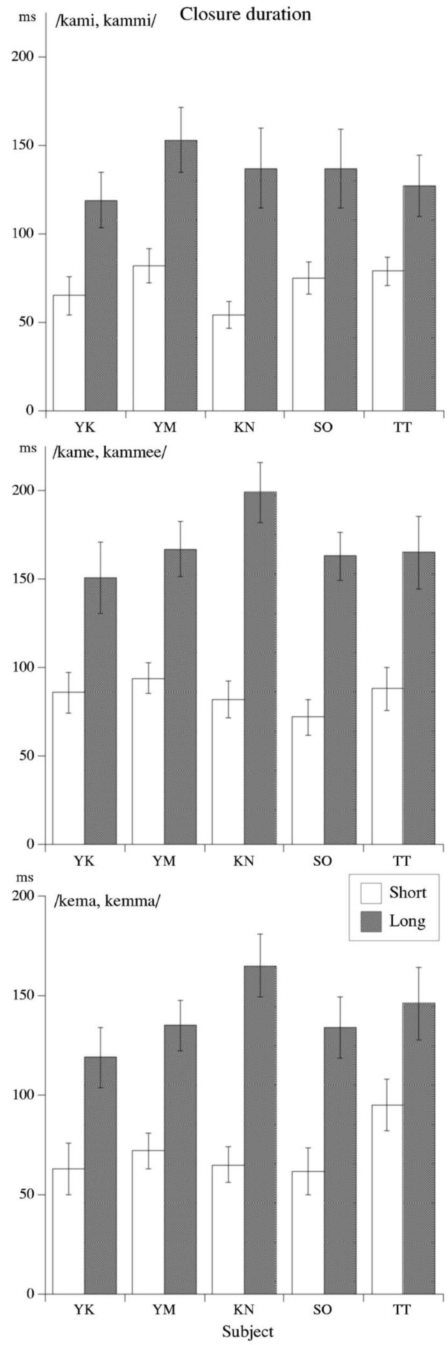

FIG. 3.
Closure duration of the bilabial nasal consonant (mean and standard deviation).

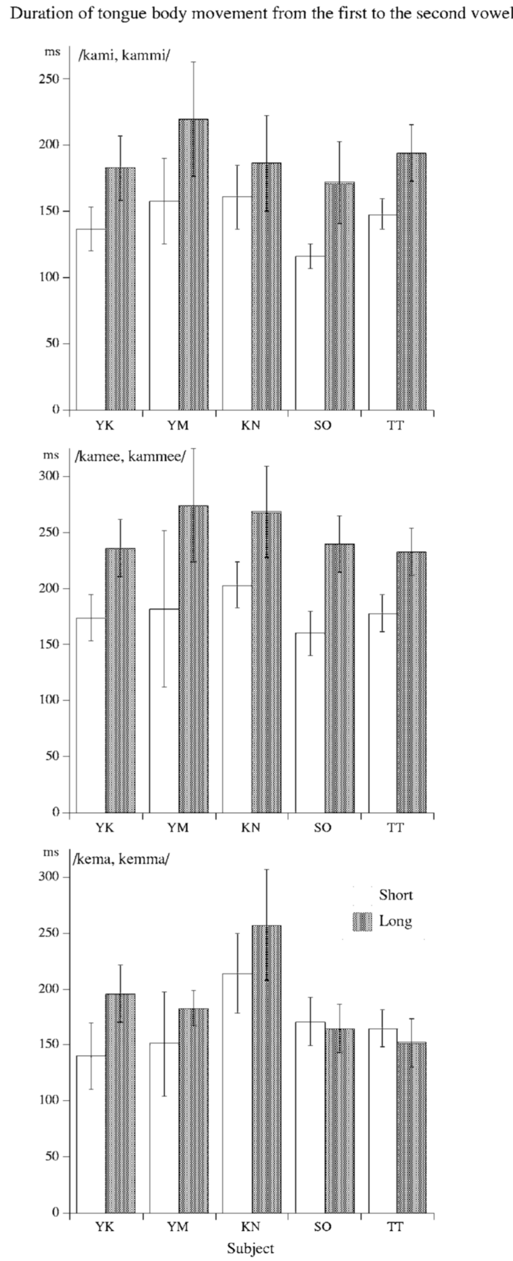

FIG. 4.

Duration of the tongue body movement from the first to the second vowel (mean and standard deviation).

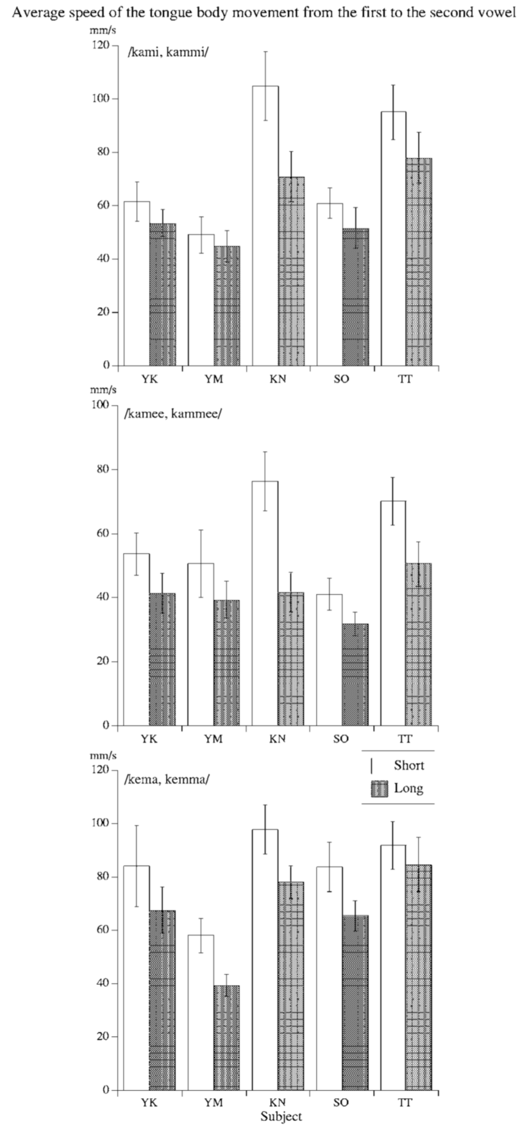

FIG. 5.
Average speed of the tongue body movement from the first to the second vowel (mean and standard deviation).

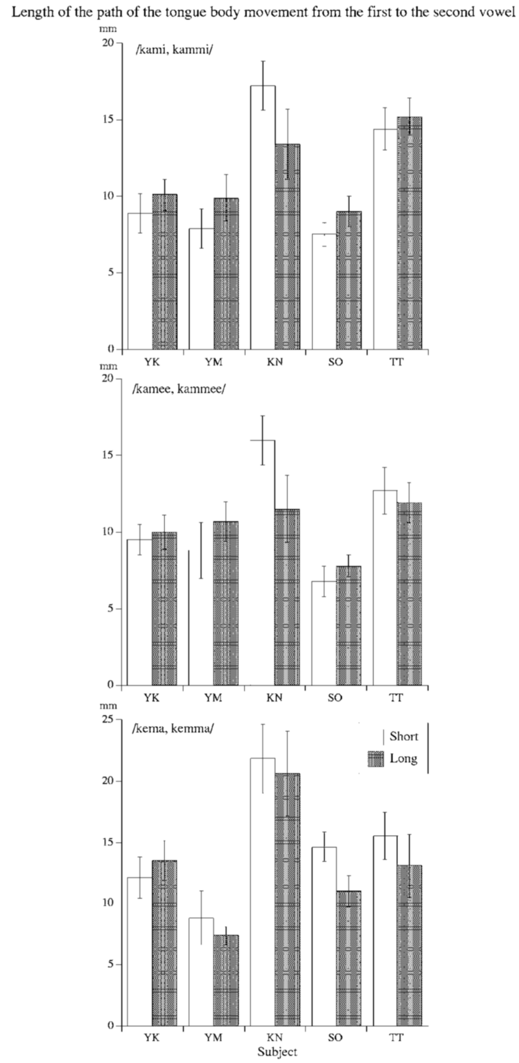

FIG. 6.
Path of the tongue body movement from the first to the second vowel (mean and standard deviation).

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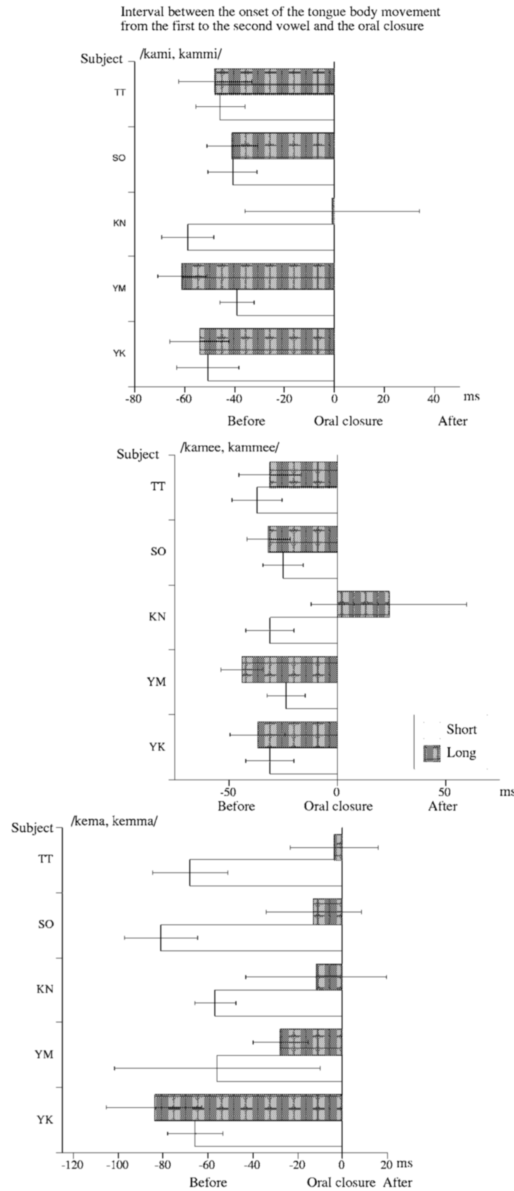

FIG. 7.

Interval between the onset of the tongue body movement from the first to the second vowel and the oral closure (mean and standard deviation).

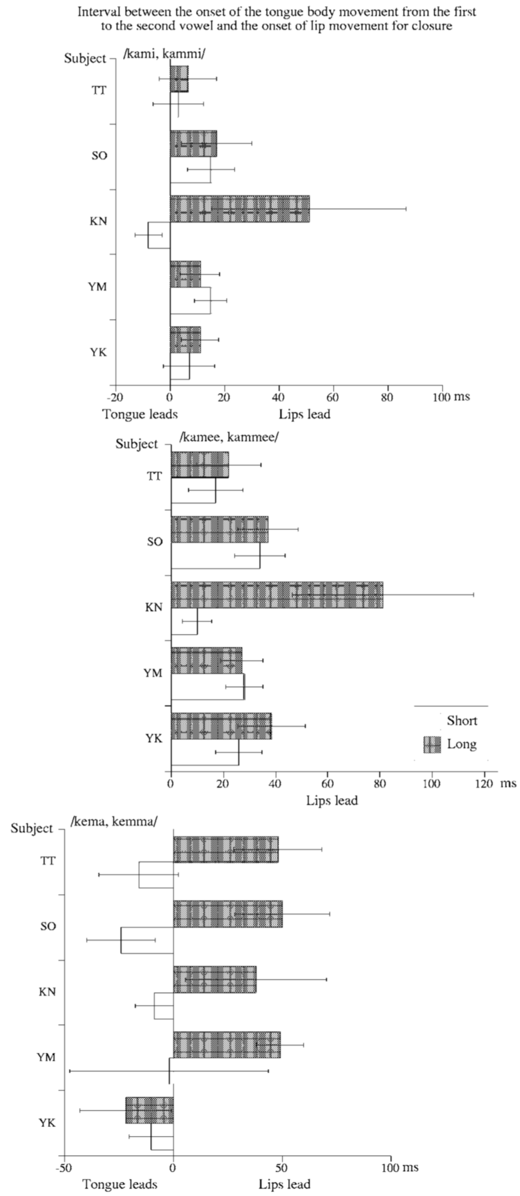

FIG. 8.
Interval between the onset of the tongue body movement from the first to the second vowel and the onset of the lip movement towards closure (mean and standard deviation).

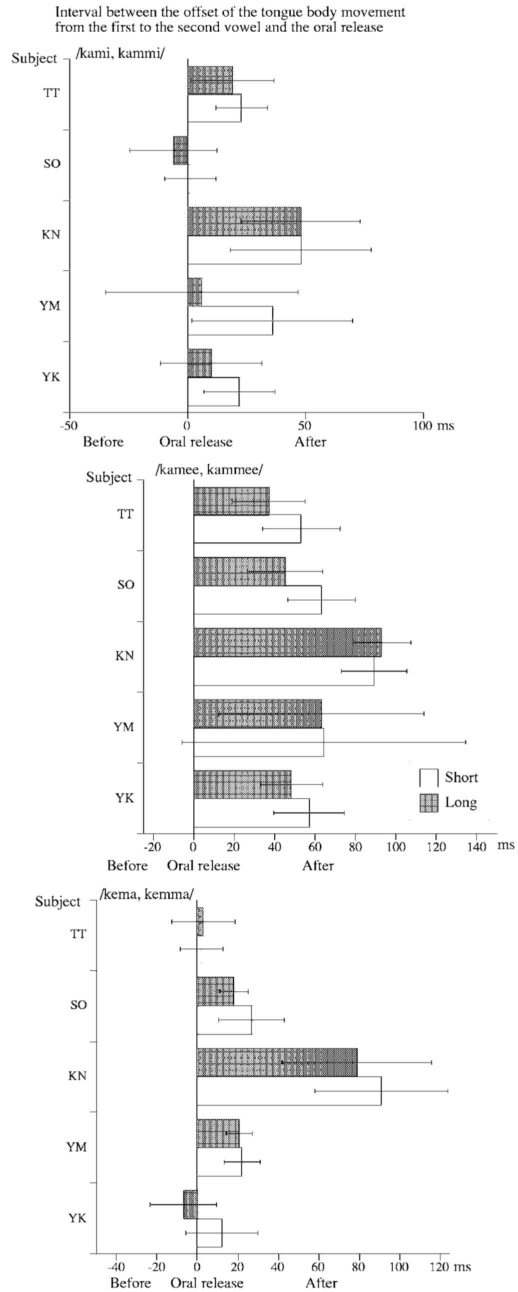

FIG. 9.

Interval between the offset of the tongue body movement from the first to the second vowel and the oral release (mean and standard deviation).

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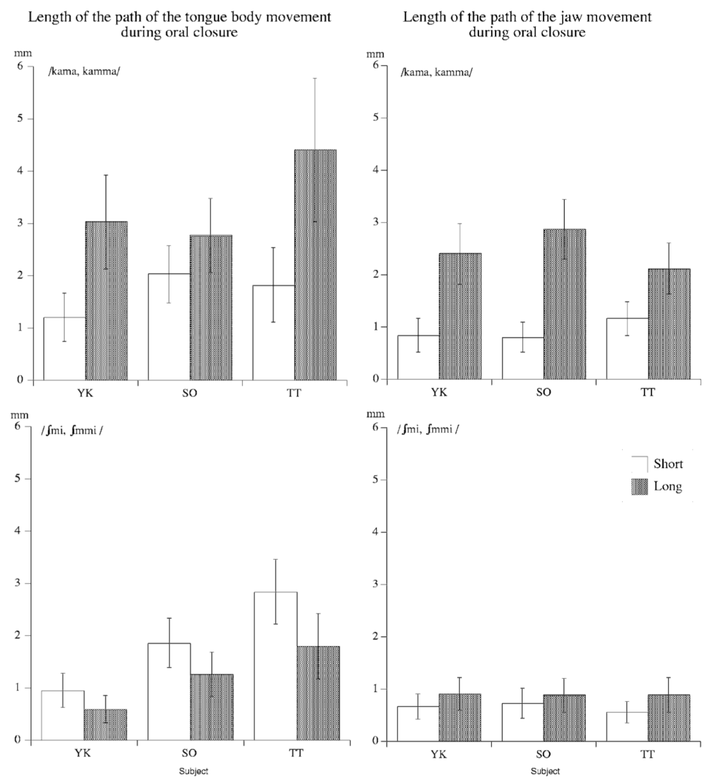

FIG. 10.

Paths of the tongue body and jaw movements during the oral closure (mean and standard deviation).

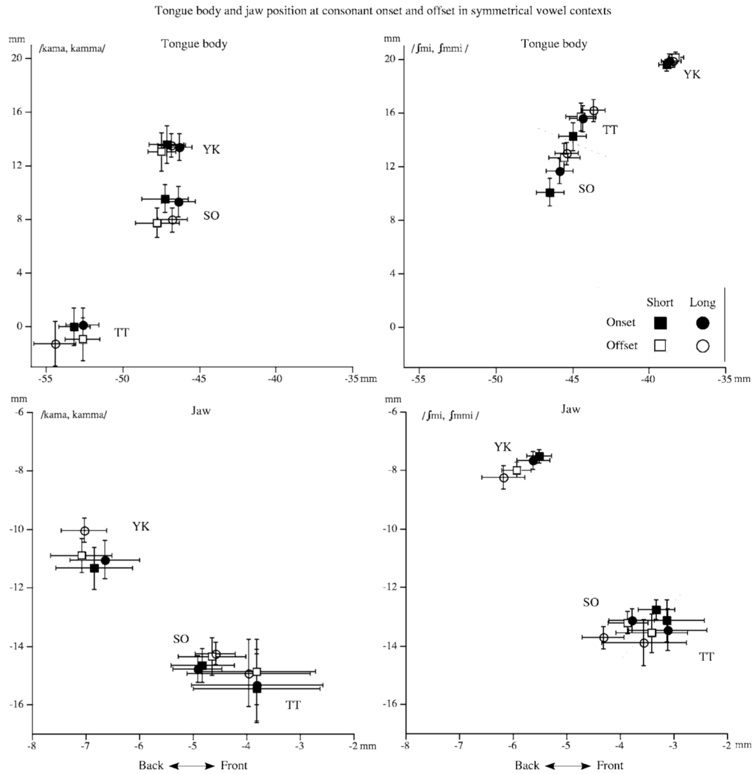

FIG. 11.

Tongue body and jaw positions at onset and offset of the nasal consonant in symmetrical vowel contexts (mean and standard deviation). For clarity of presentation, the horizontal and vertical scales are different. The dashed lines in the two right panels separate the data points for subjects SO andTT.