Articulation and acoustics of /i/ in pre-boundary position in French

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Abstract

This study presents acoustic and electro-magnetic articulometry (EMA) data for the vowel /i/ in pre-boundary position in French. The boundaries examined are the Utterance, the Intonational phrase, the Accentual phrase, the Word and the Syllable. Our results show that although durational effects of prosodic boundary are still very strong, the effects on supralaryngeal articulation and on spectral characteristics are not as clear as those for the vowel /a/ reported in our previous work (Tabain, 2003a, 2003b). For instance, no effects are observed on the jaw or on F1 or F2. However, differing effects observed on tongue body articulation for male and female speakers together with the same effect on F3 for all speakers suggest that speakers aim for an acoustic/auditory target rather than an articulatory target when producing /i/ at stronger boundaries. These articulatory and acoustic results are argued to reflect featural enhancement of /i/ in French at stronger boundaries, since French has a particularly crowded vowel space in the high front region.

1. Introduction

The study of articulatory prosody – that is, of the effects of the strength of the prosodic boundary on individual speech segments, as well as stress and intonation effects - has been an important topic of research in recent years. Prosodic structure has proved to be a major source of variation in the articulation of individual speech sounds, as shown in a variety of articulatory studies using electro-palatography (EPG) or electro-magnetic articulography (EMA) (Fougeron & Keating 1997; Byrd & Saltzman 1998; Byrd 2000; Fougeron 2001; Cho & Keating 2001; Tabain 2003b; Cho 2002; Keating, Cho, Fougeron & Hsu, 2003; Cho, in press). These studies have shown that consonants and, although less well studied, vowels, are hyperarticulated, or strengthened, at stronger prosodic boundaries, such as the Utterance or Intonational phrase. For example, post-boundary /n/ has greater linguo-palatal contact at stronger prosodic boundaries than at weaker prosodic boundaries (Fougeron & Keating 1997), and pre-boundary /a/ has lower tongue and jaw positions at stronger prosodic boundaries than at weaker prosodic boundaries (Tabain 2003b). Certain authors have argued that it is more correct to refer to this process as strengthening rather than hyperarticulation: for instance, Fougeron (2001) found that /n/ becomes less nasal (i.e. the velum position becomes higher) at stronger prosodic boundaries than at weaker boundaries. If hyperarticulation were the more appropriate description, she argued, /n/ would become more nasal rather than less nasal at stronger boundaries. Fougeron argued that a principle of maximum contrast applies, whereby the consonant /n/ becomes more consonant-like (i.e. less nasal) in order to be maximally differentiated from the adjacent vowel.

However, it appears that not all speech sounds are equally affected by the strength of the prosodic boundary. Fougeron (2001) has shown that (post-boundary) /s/, a segment which is typically highly resistant to coarticulation (Keating 1990; Recasens 1999), is also much less variable across prosodic contexts than are other consonants (at least in terms of linguo-palatal contact).

In this study we examine the behaviour of /i/ in pre-boundary position at different prosodic boundaries in French. Just as /s/ shows greater coarticulatory resistance than other consonants (Keating 1990), /i/ shows greater coarticulatory resistance than other vowels, such as /a/, due to its intrinsically higher tongue body position (Recasens 1999). Indeed, in a study of vowel-to-vowel coarticulation across prosodic boundaries in English, Cho (in press) has shown that, although both /i/ and /a/ showed less coarticulation across stronger boundaries, /i/ was less affected by the nature of the boundary than was /a/. Fougeron (2001) examined /i/ in post-boundary position in French using EPG, and found that /s/ and /i/ behaved similarly in that there were fewer significant differences according to prosodic structure, compared to segments such as /n/. However, as shown by Fitzpatrick & Ni Chasaide (2002), EPG is not as reliable as EMA for describing the articulation of vowels, including high vowels such as /i/. Our purpose is therefore to examine the kinematic aspects of /i/ articulation using EMA in order to provide a fuller picture of its articulation across prosodic boundaries. The relative stability of /i/ across multiple repetitions and different contexts provides a good test of the independence of supralaryngeal effects from durational effects. This question has been of some concern in studies such as those by Fougeron (2001) and Fougeron & Keating (1997), since strengthening of the target segment seemed to increase with increased duration as part of the strategy to mark prosodic boundaries.

Before discussing our hypotheses for /i/ based on results in the articulatory literature, it is worth outlining the articulatory results from our previous work on pre-boundary /a/ in a little more detail, since in the present study we use the same speakers, and similar stimuli and techniques, as were used in the Tabain (2003a; 2003b) studies, which dealt with acoustic and articulatory results respectively. Briefly, in addition to a lower tongue body and jaw position for /a/ at stronger prosodic boundaries, there was a tendency for tongue body (TB) peak velocity of the opening movement gesture from a /t/ into the vowel /a/ in /ta #/ to *increase* at stronger prosodic boundaries (and decrease at weaker boundaries), whereas for the closing movement into the following consonant /a # C/, TB peak velocity tended to *decrease* at stronger prosodic boundaries (and increase at weaker boundaries). We hypothesized that this pattern of velocities was related to syllable structure, whereby the CV sequences are planned, and the VC sequences are produced in the time remaining between successive CV sequences (cf. Kozhevnikov & Chistovich 1965).

Another interesting result from our previous study concerned the data for only one of the three speakers: for this speaker (GR), data for the jaw at the Utterance boundary tended to pattern with the Word and Accentual phrase data, i.e. the /a/ was centralized rather than being hyperarticulated at the Utterance boundary. This result was reflected in the acoustic data as a lower F1 at the Utterance boundary. We interpreted this result as articulatory declination, whereby supralaryngeal articulations at the end of the Utterance become progressively more "lax" (Vayra & Fowler 1992). Such a strategy is contradictory to the predictions made by previous studies in the articulatory prosody framework, in that articulatory prosody predicts greater hyperarticulation or strengthening at the end of the Utterance (see Cho 2002). However, most studies in the articulatory prosody framework, such as Fougeron (2001) and Fougeron & Keating (1997) focus on post-boundary rather than pre-boundary effects, so that the predictions for pre-boundary effects are less clear. We were therefore interested to see whether there was any evidence for articulatory declination in speaker GR's /i/ data (or any other speaker's data), either for the jaw or for the tongue. We hypothesize that this would entail centralization of the /i/ at the Utterance boundary, since vowel declination is manifested as a smaller vowel space overall (Johnson & Martin 2001).

Our main hypotheses for prosodic boundary effects on /i/ are based on studies of prosodic stress/accent. Given that both stress and phrase-final position are marked by greater durations, our assumption is that articulations at stronger prosodic boundaries will resemble articulations in stressed position, and that articulations at weaker prosodic boundaries will resemble articulations in unstressed position. Following Erickson (2002), who showed that jaw position was lower and tongue position higher and/or more forward in stressed as opposed to unstressed syllables in English, we expect that tongue position will be higher/more forward, and jaw position lower, at stronger prosodic boundaries. The higher/more forward tongue position reflects a more hyperarticulated front vowel, and the lower jaw position is believed to indicate a more sonorous vowel. Erickson's results confirm previous results, also for English, presented by Harrington, Fletcher & Beckman (2000), who also found apparently contradictory strategies of the tongue and jaw in stressed vs. unstressed articulations of /i/. Based on previous studies of /a/, which had showed lower tongue and jaw positions in stressed as opposed to unstressed syllables, Harrington et al. had set out to test the competing hypotheses of increased sonority vs. increased peripherality of vowels in stressed syllables. They argued that the higher and fronter tongue position for /i/ gave support for the increased peripherality hypothesis, while the lower jaw position gave support for the increased sonority hypothesis. Harrington et al. also reported - but did not present - greater RMS energy in the /i/ vowel for stressed position in support of the increased sonority hypothesis. Hence, we anticipate that /i/ becomes more peripheral and more sonorous at stronger prosodic boundaries in French as well as English. It is nevertheless possible that exceptions to this will occur for the Utterance boundary, based on results for speaker GR in our previous studies. If this were to occur, we would expect evidence of centralization of the /i/ at the Utterance boundary, since articulatory declination is believed to involve centralization of the vowel space.

Interestingly, the results mentioned above for /i/ were confirmed also by Cho (2002), again for English. In a large-scale study comparing accent-induced vs. boundary-induced effects on /a/ and /i/, Cho (2002) found that /i/ had a more front (though not higher) tongue position, greater lip opening, and a greater jaw opening in pitch-accented position. However, according to prosodic boundary, Cho found that there was *less* jaw opening at stronger prosodic boundaries, at the same time as there was more lip opening and a lower (though not fronter) tongue position. Cho suggested that in both cases (accent-induced and boundary-induced effects), a principle of sonority expansion at stronger prosodic positions was involved (presumably the greater lip opening overrides the higher jaw position at stronger prosodic boundaries). Since Cho's study conflates accent-induced with boundary-induced prosodic effects, the focus of our study on boundary-induced effects in French (a language without lexical stress) may provide a clearer picture of the behaviour of /i/ at stronger prosodic boundaries.

In addition to a basic kinematic description of /i/, we will examine the acoustic effects of the prosodic boundary on /i/. Relatively few studies have looked at the acoustic effects of prosodic boundary in spectral terms. Even papers within the framework of articulatory prosody, which is concerned with supralaryngeal articulations which presumably have spectral consequences, are mostly concerned with durational rather than spectral effects of prosodic boundary (e.g. Cho & Keating 2001; Fougeron 2001). Effects of prosodic boundary on acoustic duration are well-known, and comparatively well-described. For studies of word and syllable duration effects, the reader is referred to various papers by Turk and colleagues (e.g. Turk & White 1999; Turk & Shattuck-Hufnagel 2000), and references cited therein, as well as early work by Lehiste (e.g. 1972, 1974). For studies of duration at larger prosodic boundaries, the reader is referred to Fletcher (1991) for French and Wightman, Shattuck-Hufnagel, Ostendorf, & Price (1992) for English. In terms of articulatory prosody, duration effects can be summarized as "greater duration at stronger prosodic boundaries, in particular at the ends of large phrases; and lesser duration at weaker prosodic boundaries". This is a very strong effect across studies.

To our knowledge, Tabain (2003a) was the first purely acoustic study of articulatory prosody effects – it considered both duration and spectral effects. Examining pre-boundary /a/ in French, we found higher F1 and lower F2 for /a/ at stronger boundaries than at weaker boundaries, in addition to the standard durational effects outlined above. We also found that the F2 formant transitions for the sequence /a # C/, where C was one of /b d g/, were affected by the strength of the prosodic boundary: the intrinsic coarticulatory resistance of the stop affected the variability in F2 at the midpoint of the vowel and at the boundary (Fowler & Brancazio 2000), according to the strength of the boundary. More precisely, F2-consonant was "fixed" for the alveolar /d/ as F2-vowel moved towards this "locus" at weaker prosodic boundaries; while for the velar /g/, both F2-vowel and F2-consonant were displaced in the direction of the velar "locus" at weaker prosodic boundaries. These results are in line with the view that /d/ is highly resistant to coarticulation with adjacent vowels (Recasens 1999), whereas both /d/ and in particular /g/ induce raising of an adjacent /a/ (in this case, the raising effect is observed as prosodic boundary becomes weaker). We also found some effects on formant velocity going into /g/, with greater F2 velocity at weaker prosodic boundaries; however, these effects were not strong as measured by the eta^2 statistic (outlined below). By contrast, effects were somewhat stronger for rate-of-change (RoC) in spectral tilt going from the /a/ into a following fricative /f s ʃ/, with an increased RoC at weaker boundaries.

In summary, our results for /a # C/ suggested that in addition to prosodic effects on formant targets, effects on velocity of the spectral change were also to be found. In the present study we are interested in seeing whether these acoustic results will be replicated for /i/.

It is not clear, however, just what the acoustic correlates of the articulatory enhancement strategies described above for /i/ would be. If we follow the textbook description in Johnson (1997: 93-97), we would expect to see the following effects of a higher and more fronted tongue position for /i/: F1 (the Helmholtz resonance of the /i/ constriction) to become lower as the vowel becomes higher (i.e. as the area of the constriction reduces); F2, the half-wavelength resonance of the back cavity, to become lower as the constriction becomes more forward; and F3, the quarter-wavelength resonance of the front cavity, to become higher as the constriction becomes more forward. However, the textbook description given by Ladefoged (1982: 175-177) would suggest that as the front vowel becomes higher, and at the same time more forward, F2 becomes higher, as does F3 (F1 still becomes lower). These contradictory predictions regarding F2 are based on F2 being associated with the frontness/backness of the tongue position. An alternative view is given by Beckman, Jung, Lee, de Jong, Krishnamurthy, Ahalt, Cohen & Collins (1995), who suggested that F2 for /i/ is in fact more closely related to the degree of constriction, rather than the position, with a lower tongue position for /i/ resulting in a lower F2. [i]

We should note that work by various researchers focusing on enhancement of spectral cues and dispersion-focalization theory (e.g. Schwartz, Boë, Vallée & Abry 1997; Ménard, Schwartz, Boë, Kandel & Vallée 2002) suggests that having F3 and F4 close together is the ideal (i.e. prototypical) situation for /i/, and having F2 and F3 close together is the ideal situation for the front rounded vowel /y/. This view would suggest that it is important for F3 to be higher in order to achieve a more prototypical /i/, especially in French, where /i/ contrasts with /y/. Although Ménard et al. showed that F2-F1 (the difference between F2 and F1) was the most reliable acoustic correlate for the perception of frontness-backness, our preliminary investigations showed that there were minimal effects on F1 and F2 for /i/ in the present study. We will therefore present results for F3-F2 (the difference between F3 and F2) as well as F1, in order to present a more complete picture of the formant results. Given the above discussion, we tentatively assume that F1 is indicative of vowel height for /i/, and that F3-F2 represents the difference between the length of the cavity in front of the constriction and the length of the cavity behind the constriction.[ii]

In sum, if effects of the prosodic hierarchy can be observed for /i/, we expect the tongue position to become higher and more forward at stronger prosodic boundaries, while the jaw becomes lower in order to increase sonority, as accent-induced hyperarticulation predicts. We expect duration to increase at stronger prosodic boundaries, while velocity increases at weaker prosodic boundaries, as reported for /a/ in Tabain (2003b).

2. Method

2.1 *Speakers and recordings*

Three native speakers of metropolitan French (two male [CV, GR] and one female [AV]) were recorded in a sound-treated room at ICP, Grenoble. Recordings took place approximately one year after recordings for the Tabain (2003a, 2003b) studies. Articulatory (EMA) and acoustic data were recorded simultaneously and time-synchronized. The EMA data were recorded at 200Hz using a 5-channel Carstens system. Transducers were placed on: the Tongue Tip; the Tongue Body; the vermilion border of the Upper Lip; and the Jaw (placed on the gums beneath the lower teeth). A reference transducer was also placed on the gums above the upper teeth. The two tongue sensors were attached with Ketac bond, and the other sensors were attached with Cyano. The Tongue Tip sensor was placed approximately 1 to 1.5 cm from the tip of the tongue, and the Tongue Body sensor was placed approximately 4 to 4.5 cm from the tip of the tongue. The acoustic data were recorded directly onto DAT at a sampling rate of 44.1 kHz, and transferred onto PC. Data were subsequently down-sampled to 20 kHz.

2.2 *Stimuli*

Stimuli consisted of 5 sentences, based on Fougeron (2001) each containing a prosodic boundary of interest between the 4th and 5th syllables (5th and 6th syllables in the case of sentence 5). For the purposes of this study, the following prosodic hierarchy is assumed:

Utterance > Intonational phrase > Accentual phrase > Word > Syllable.

The strongest/highest prosodic boundary is the Utterance, and the weakest/lowest prosodic boundary is the Syllable.[iii] The Accentual phrase is the basis of prosodic structure in French, and features an H* accent on the final full syllable of the phrase. The Intonational phrase is marked by a major continuation rise or fall and by significant final lengthening.

The test sentences were (with the type of prosodic boundary listed in brackets):

1. Paul aime Pap<u>i</u>. **B**iba les protège en secret.
   (Utterance)
   "Paul loves Grandpa. Biba looks after them in secret"
2. Le pauv' Pap<u>i</u>, **B**iba et Paul arriveront demain.
   (Intonational phrase)
   "Poor Grandpa, Biba and Paul are coming tomorrow"

3. Tonton, Papi, **B**iba et Paul arriveront demain.
(Accentual phrase)
"Uncle, Grandpa, Biba and Paul are coming tomorrow"

4. Paul et Papi **B**iba arriveront demain.
(Word)
"Paul and Grandpa Biba are coming tomorrow"

5. Tonton et Papi**b**i arriveront demain.
(Syllable)
“Uncle and Papibi are coming tomorrow”

The vowel under study is the /i/ at the end of "Papi" (underlined above). The consonant in bold was varied to be one of /b d g f s ʃ/. There was thus a total of 30 different sentence stimuli (5 prosodic contexts * 6 consonants). Two of the speakers (AV and GR) produced 10 repetitions of the corpus, giving a total of approximately 300 utterances. Speaker CV produced 9 repetitions, giving a total of approximately 270 utterances. The sentences were read in blocks of 5 as presented above. Speakers were encouraged to produce the Utterance boundary with a pause, and the Intonational phrase boundary without a pause.[iv] Speakers were encouraged to produce the Intonational phrase with a major continuation contour, and the Accentual phrase with a minor continuation contour (i.e. as a list). The recordings took place under the guidance of a technician and were supervised by the second author, both of whom are native speakers of French. The nature of the prosodic boundaries was verified auditorily by the first author, who is a trained phonetician and non-native speaker of French.

2.3 *Labelling and analysis environment*

Both acoustic and articulatory data were labelled by the first author using EMU (Cassidy & Harrington 2001) and the R statistical package (Ihaka & Gentleman 1996). All analyses of the data were carried out using the EMU database speech analysis system (Harrington, Cassidy, Fletcher & McVeigh 1993), interfaced with the R statistical package.

2.3.1 *Acoustic analysis*

Acoustic data were segmented and labelled according to standard acoustic criteria (cf. Harrington & Cassidy 1999, chapter 4). The noise following the release of the /p/ in /pi/ was labelled separately and included as part of the /i/ duration (the noise portion was included in order to match the approach used in Tabain, 2003a; in that study, the release of the /t/ in /ta #/ was included as part of the /a/ vowel duration in order to facilitate comparison with the articulatory duration of /a/ as measured by EMA, where the start of the /a/ was taken as the release of Tongue Tip closure for /t/).

Formants were automatically tracked in EMU using LPC (step size = 5 ms), and hand-corrected. Formant values for the vowel /i/ were extracted at the temporal midpoint of the vowel. Results are presented for F3-F2 together with F1.

The transitions into the following stop consonant were also examined. However, contrary to our previous results for /a/, we were unable to interpret the formant transition data for /i/ according to prosodic boundary due to variability within each condition (i.e. each consonant type at each prosodic boundary). The formant transition data are therefore not presented below.

Peak velocity of the F1-F2 transition from the /i/ into the following consonant was defined as the maximum value of the Euclidean distances between successive F1 and F2 samples[v] (as mentioned above, sample rate is 200 Hz), measured from 0.25 of total vowel duration to 1.0 of total vowel duration. Peak velocity, measured in Hz ms^{-1}, was only analyzed for vowels followed by a stop. We expected transition velocity of /i # C/ to be greater at the weaker prosodic boundaries in line with results for /a # C/ presented in Tabain (2003a).

RMS energy was also automatically tracked across the (entire) vowel using EMU (step size = 5 ms), and the maximum RMS energy value extracted. This analysis was carried out in order to see if overall sonority increased at stronger prosodic boundaries, which may reflect a lower Jaw position at stronger boundaries. Although there was indeed a slight trend for RMS energy to increase at stronger boundaries (with the exception of the Utterance boundary, which was followed by a pause), these results were not strong, and will not be presented below.

In order to describe the velocity of the movement from the vowel into a fricative, the Rate-of-Change (RoC) in spectral tilt was analyzed as described in Tabain (2003a). However, the results for this analysis were not as strong for /i/ as they were for /a/. It may be that this particular analysis technique is less well-suited to /i # C/ sequences than to /a # C/ sequences due to different characteristics of the spectrum for these two vowels; or it may be that /i/ does not show as strong effects as does /a/. There was nevertheless a slight trend for RoC in spectral tilt to increase at weaker prosodic boundaries, but since these results were not strong, we have decided not to present them here due to space considerations.

2.3.2 *Articulatory analysis*

The following signal processing was carried out prior to kinematic labelling: (1) x- and y-data were smoothed using the Lowess filter (a regression-based filter) in the R statistical package, with the filter span set to 1/3 the length of the analysis window; (2) mean values for the reference transducer were subtracted from values for the 4 movement transducers; and (3) the resulting data were rotated according to the measured occlusal plane of the speaker. The kinematic signal was examined from a point before the acoustic release of the second /p/ in "Papi" to a point after the acoustic offset of the consonant under investigation. Articulatory data were labelled automatically and hand-corrected (details below). Velocity was calculated as the first differential of the smoothed displacement signal, and this first differential was smoothed using the default smoothing function in the R statistical package. This smoothing function uses a median filter in which the middle value of 3 successive samples is set as the median value of those 3 samples, with this process being repeated until convergence.

The following points were located based on zero crossings in the velocity trace:

(1) TB /i/ target in both the y-plane and the x-plane (the highest point in the y-plane and the most forward point in the x-plane)
(2) Jaw /i/ target in both the y-plane and the x-plane (the lowest point in the y-plane and the most back point in the x-plane) – c.f. results presented in Erickson (2002)
(3) TB y-target for the /a/ in "Papi" (the lowest point in the y-plane)

As already mentioned, any errors in the automatic labelling were hand-corrected. Note also that the x- and y-targets may not coincide in time.

The following derived measures were used for the TB data only, since a preliminary examination of the Jaw results showed much less consistency across speakers and prosodic contexts than did the TB data. The derived measures are used to describe the TB closing movement from the /a/ into the /i/:

(1) Magnitude: the y-target for /a/ subtracted from the y-target for /i/
(2) Duration: the time of the /a/ y-target subtracted from the time of the /i/ y-target
(3) Velocity: maximum velocity in the y-plane during the above interval

The timing of peak velocity was also examined; however, we were unable to interpret these data according to prosodic boundary, and these results are therefore not reported here.

2.3.3 *Statistical analysis*

The results presented below are tested in the first instance using a two-way ANOVA with prosodic boundary and following consonant as factors. Unless otherwise noted, results are significant at 0.05. The prosodic boundary results will be presented in tables, and the consonant boundary results will be presented as part of the text, where appropriate.

Bonferroni-adjusted posthoc tests of Least Significant Difference (LSD) were also carried out for both factors. For the factor prosodic boundary, the results of which will be presented in tables, only results for adjacent pairs along the prosodic hierarchy will be reported (i.e. Utterance vs. Intonational phrase; Intonational phrase vs. Accentual phrase; Accentual phrase vs. Word; and Word vs. Syllable). It is therefore possible that the main two-way ANOVA shows a significant effect for prosodic boundary, but that the posthoc tests presented do not show any significance (for instance, in such a situation, there may be a significant difference between Utterance and Word which we do not report).

Due to the large number of tokens in our database, the possibility of Type I errors is increased. For this reason, we also present results from an eta^2 analysis. The eta^2 analysis is a test of effect size; unlike significance tests, measures of effect size are independent of sample size and therefore facilitate meta-analyses. The eta^2 analysis returns a value between zero and one, which indicates the proportion (or percentage, when multiplied by 100) of variability accounted for by the independent variable (in this case, prosodic boundary). For our purposes, we consider a value of less than 0.100 (or less than 10%) as a weak effect; a value of between 0.100 and 0.200 (between 10% and 20%) as a medium effect; a value between 0.200 and 0.300 (between 20% and 30%) as a strong effect; and a value greater than 0.300 (30%) as a very strong effect.

3. Results

3.1 *Acoustic results*

Table I presents descriptive statistics according to prosodic boundary for acoustic vowel duration and for peak velocity of formant movement for /i # C/ in the F1 vs. F2 plane. Figure 1 presents formant plots for the vowel with F1 on the y-axis and F3-F2 (the difference between F3 and F2) on the x-axis. Table II presents statistical significance tests according to prosodic boundary for all of these acoustic measures (vowel duration; F1 vowel; F3-F2 vowel; peak velocity of the F1 vs. F2 formant transition).

FIGURE 1

TABLE I

TABLE II

It can be seen that the effect of the prosodic hierarchy on vowel duration is significant. Effects of consonant context were significant for all three speakers [AV: (F [5, 270] = 4.01; p < 0.01); CV: (F [5, 249] = 4.56; p < 0.01); GR: (F [5, 280] = 7.78; p < 0.001)], as was the interaction for speakers CV and GR [CV: (F [5, 249] = 1.93, p < 0.05); GR: (F [5, 280] = 2.64, p < 0.05)]. However, LSD posthoc analyses of consonant effect showed no consistent patterns across speakers.

As regards prosodic boundary, it is not always the case that the vowel duration effect occurs in the expected direction. For example, if one assumes a gradual final lengthening as the prosodic boundary becomes higher in the hierarchy, duration at the Word boundary should be greater than at the Syllable boundary, yet this is not the case for any of the speakers (in fact, the opposite is true for speakers AV and CV). Likewise, duration at the Utterance boundary should be greater than at the Intonational boundary, yet this is not the case for speaker GR. In Tabain (2003a), vowel duration for /a/ conformed strictly to the prosodic structure which was assumed, but this is evidently not the case for /i/. Note, however, that Tabain (2003a, 2003b) did not present results for the Syllable boundary, due to an error in methodology

The vowel formant plots in Figure 1 show that the effects of prosodic boundary are far weaker on /i/ than they are on /a/ (as presented in Tabain 2003a). For instance, the range in F1 values for /a/ is about 300 Hz for speakers AV and CV, and about 200 Hz for speaker GR, whereas for /i/, the range is about 250 Hz for speaker AV and about 150 Hz for speakers CV and GR.

The /i/ results are stronger, however, for F3-F2 than for F1. Both speakers CV and GR separate their F3-F2 data into two groups: {U, I, A} and {W, S}. Speaker AV makes an additional distinction between {U, I} and {A}. An examination of the F3 and F2 data separately showed that the change in difference was mostly due to an increase in F3, rather than a decrease in F2. Following Johnson (1997), these results would suggest that, assuming a constant larynx position, the TB remains stable for /i/ across different prosodic boundaries, while the front cavity becomes shorter, perhaps through lip-spreading.

The analysis according to following consonant showed significant effects on F3-F2 for all three speakers: [AV: ($F [5, 270] = 4.08$; $p < 0.01$); CV: ($F [5, 249] = 6.54$; $p < 0.001$); GR: ($F [5, 280] = 2.95$; $p < 0.05$)], and a significant interaction effect for speakers AV and CV [AV: ($F [5, 270] = 1.74$, $p < 0.05$); CV: ($F [5, 249] = 2.41$, $p < 0.01$)]. For all three speakers, F3-F2 was smaller in the environment of /ʃ/, suggesting that the high F2 value associated with this consonant pulls the F2 vowel target value closer to F3.

The F1 data, by contrast, show fewer significant effects and some inconsistencies: for instance, both speakers CV and GR have a significantly lower F1 at the Syllable boundary than at any other boundary, but this goes against our hypotheses of lower F1 at stronger boundaries. However, this result should be added to the list of unexpected results for the Syllable boundary, which will be discussed briefly in the final section of this paper. In addition, speaker AV has a higher F1 at the Utterance boundary than at the Intonational phrase boundary. In fact, the only significant result in the expected direction is speaker AV's Word vs. Syllable boundary data. Speaker AV is also the only speaker to show a significant effect of following consonant [AV: ($F [5, 270] = 10.44$; $p < 0.001$)], with the labials /b, f/ inducing a significantly lower F1 in the vowel than the other consonants. There was, however, no interaction between consonant and prosodic boundary.

Given the above results, we conclude that the effects of prosodic boundary on /i/ vowel formants are not extensive. Indeed, as mentioned in the Method section, an examination of formant transitions into the 3 different stop consonants (not presented here) also showed no consistent effects of prosodic structure. These results are clearly different to results for /a/, for which there were strong and consistent effects of the prosodic hierarchy on vowel formants and formant transitions.

We turn now to the more “dynamic” measure, peak formant velocity, which is presented in Tables I and II with the other acoustic data. Data for the Utterance boundary are not presented for the formant velocity data, since the Utterance boundary is defined by a pause, resulting in the near absence of formant transitions.

It can be seen that speaker AV shows no significant effects of the prosodic hierarchy on peak formant velocity. Speakers CV and GR, by contrast, show significant effects of prosodic hierarchy on formant peak velocity, with a clear separation between Accentual and Word boundary data (with greater velocities at the Word boundary than at the Accentual boundary). There were no significant effects of stop consonant context on peak formant velocity.

Table III presents eta² values for all of the acoustic data presented above. It can be seen that by far the most consistent effect is on vowel duration, for which prosodic boundary accounts for approximately 80% of the variability in the data. The strong duration effect is most likely a reflection of the significant phrase-final lengthening of the vowel at stronger boundaries. Prosodic boundary has a weak effect on F1 for the vowel, accounting for around 10% of the variation in F1 data. By contrast, F3-F2 has a very strong effect for speaker AV (42%), and a medium effect for speakers CV and GR (18% and 15% respectively). The effect of prosodic boundary on formant peak velocity is weak for speakers AV and CV (less than 10%), but strong to very strong for speaker GR (34%).

TABLE III

3.2. *Articulatory results*

3.2.1 Tongue Body

Figure 2 shows plots of TB trajectories for the vowel /i/ at the end of /papi #/, and Table IV presents descriptive statistics for the Duration, Magnitude and Peak Velocity of the closing movement from the /a/ to the /i/ in this word. x- and y-plane data are presented on the same plot in Figure 2. The x- and y-targets are not explicitly marked on these plots, since the trajectories represent averages of movements. However, the average x- and y-targets can be inferred from these plots.

For the 3 derived measures in Table IV, results are presented only for the y-plane. Table V presents statistical significance results for the x- and y-targets in the TB trajectories, as well as for the three derived measures.

FIGURE 2

TABLE IV

TABLE V

It can be seen that, with the exception of speaker AV's y-target data, there is a significant effect on all measures for all speakers. Given our hypothesis that /i/ should be higher and more front at stronger prosodic boundaries, the following observations can be made:

(1) speaker AV has a strong effect of the prosodic hierarchy on the x-dimension (front-back), but not in the expected direction - i.e. speaker

AV's stronger boundaries are more back and the weaker boundaries more front. There is no effect on the y-dimension for this speaker's data.

(2) disregarding the Utterance boundary data, speakers CV and GR group their data into two sets for the y-dimension: data for {I, A} are higher than data for {W, S}. This is in line with the predictions. However, for speaker CV the Utterance boundary data are higher than the {I, A} data, whereas for speaker GR the Utterance boundary data pattern between the {I, A} and {W, S} data.

(3) there is an ordering for the x-dimension within the classes {I, A} and {W, S} for speakers CV and GR. Syllable is more forward than Word for both speakers, and Accentual is more forward than Intonational for both speakers (although this is not significant for speaker GR). Utterance is highest and furthest forward for speaker CV (in line with predictions); and Utterance is furthest back (and intermediate in height between {I, A} and {W, S}) for speaker GR.

The patterning for speaker GR's Utterance data in the x- and y-dimensions is the expected realization of articulatory declination for /i/ at the level of the Utterance for this speaker, i.e. it entails centralization.

The two-way ANOVA showed many significant effects of following consonant on TB targets: **y-targets** [AV: (F [5, 270] = 8.00; $p < 0.001$); CV: (F [5, 249] = 37.42; $p < 0.001$); GR: (F [5, 280] = 19.12; $p < 0.001$)], with a significant interaction effect for speakers CV and GR [CV: (F [5, 249] = 2.61, $p < 0.001$); GR: (F [5, 280] = 3.54, $p < 0.001$)]; **x-targets** [AV: (F [5, 270] = 11.77; $p < 0.001$); CV: (F [5, 249] = 60.33; $p < 0.001$); GR: (F [5, 280] = 6.06; $p < 0.001$)], with a significant interaction effect for all 3 speakers [AV: (F [5, 270] = 1.91, $p < 0.05$); CV: (F [5, 249] = 6.50, $p < 0.001$); GR: (F [5, 280] = 2.25, $p < 0.001$)]. LSD posthoc analyses showed that for speaker AV, fricatives (especially the sibilants) induced a higher TB y-position, and that labials induced a more forward TB x-position. Speakers CV and GR both had higher TB positions before /g/ (for speaker GR, /f/ also induced a higher TB position), while the sibilants induced a more back TB position for these speakers (this was significant for both /s/ and /ʃ/ for speaker CV but significant only for /ʃ/ for speaker GR).

Turning now to the derived measures (Magnitude, Duration and Peak Velocity) presented in Table IV (with statistical tests in Table V), we again see that there are significant effects of prosodic hierarchy on the closing movement from /a/ into /i/. If we ignore speaker CV’s Accentual boundary data for the moment, we can say that there is a pattern of greater Magnitude of movement and greater Duration of movement at stronger prosodic boundaries. There is also a tendency for Velocity to increase at weaker prosodic boundaries.

However, there are inconsistencies in the data which make such generalizations somewhat weak. Still ignoring speaker CV's Accentual boundary data, we can see that for this speaker, Syllable has significantly greater magnitude of movement than does Word, and for speaker AV, Syllable has significantly lesser peak velocity than does Word. Interestingly, the Utterance boundary data for speaker GR again seem to pattern between the {I, A} and {W, S} data for velocity (where Utterance has significantly greater velocity than Intonational). Although this patterning of the Utterance boundary derived measures for speaker GR is similar to the patterning of the more centralized Utterance-boundary /i/ observed in Figure 2 for this speaker, just why a more centralized /i/, indicative of articulatory declination, should result in greater velocity of movement is not clear (especially given that the Utterance boundary data for duration and magnitude seem to pattern with the stronger boundaries, i.e. Intonational and Accentual).[vi]

The unusual results for speaker CV's Accentual boundary Magnitude and Duration data may be due to measurement error. It was observed during labelling that location of the TB /a/ minimum for this prosodic context was particularly difficult for speaker CV. We suspected that the (nasalised) mid-low back vowel /ɔ̃/ at the end of the preceding word, "tonton", merged with the /a/ in "papi", resulting in one long TB "trough", even throughout the closure for /p/. This measurement problem would explain the Duration data for this speaker being so extreme, but not the Magnitude data. However, given the trajectories observed in Figure 2 for this speaker (where the Accentual boundary data are further forward than the Intonational data), and the fact that the Velocity data for this speaker are in line with those of the other two speakers, we have chosen not to exclude speaker CV’s Accentual data altogether.

In sum, despite some inconsistencies, there appear to be effects of prosodic structure on the TB data. Table VI gives eta^2 results for the various TB measures discussed here. It can be seen that prosodic boundary has a medium effect on x- and y-targets for speakers CV and GR, and a strong effect on x-target for speaker AV (with a weak effect on y-target for this speaker). The effects on magnitude are strong for speakers AV and GR and very strong for speaker CV. Effects on duration are very strong for all 3 speakers, and strong to very strong on velocity.

TABLE VI

3.2.2 Jaw

Figure 3 presents Jaw trajectory data parallel to the TB trajectory data in Figure 2. Table VII presents the statistical significance results for the x- and y-targets. Since the x- and y-data for Jaw movement are correlated (due to jaw movement consisting of rotation in an x-y plane), the alpha level has been adjusted to 0.025 instead of 0.05 as was used for the TB data (0.05 / 2 correlated variables = 0.025).

FIGURE 3

TABLE VII

It can be seen that results for the Jaw are not as clear as those for the Tongue Body. Although there is a significant main effect for all but speaker GR's x-target data, posthoc results rarely achieve significance. For speaker AV the Utterance boundary data are significantly lower and more back, in accordance with our predictions. However, for speaker GR, the Utterance boundary data are higher than the Intonational boundary data, which are in turn higher than the Accentual boundary data. This is counter to our predictions (it might be noted that the remainder of speaker AV’s data, although not showing statistical significance, follow a similar pattern to speaker GR’s). Although statistical tests suggest that speaker CV groups the y-target data into two groups, Figure 3 shows that there is no pattern to this speaker's Jaw data which accords with our view of prosodic structure – although not visible on the plot, there was a good deal of variability in speaker CV's Jaw data.

The effect of the following consonant on Jaw position was significant for all 3 speakers: **y-targets** [AV: (F [5, 270] = 5.50; p < 0.001); CV: (F [5, 249] = 66.07; p < 0.001); GR: (F [5, 280] = 3.12; p < 0.01)], with a significant interaction effect only for speaker CV [CV: (F [5, 249] = 5.87, p < 0.001)]; **x-targets** [AV: (F [5, 270] = 15.82; p < 0.001); CV: (F [5, 249] = 33.43; p < 0.001); GR: (F [5, 280] = 9.23; p < 0.001)], with no interaction effect for any of the speakers. LSD posthoc analyses showed that the Jaw was higher for the coronals (higher for the sibilants for speaker AV; highest for /ʃ/ then /s/ and /d/ for speaker CV; and highest for /d/ for speaker GR). These results for effects of consonant context on Jaw as well as

TB articulation are in line with results presented in Keating, Lindblom, Lubker & Kreiman (1994).

Table VIII, which presents the eta^2 results for the Jaw data, confirms these observations: with the exception of speaker GR's y-target and perhaps speaker AV's x-target data (for which the effect is medium), the effect of prosodic boundary on Jaw targets is weak.

TABLE VIII

4. Discussion

4.1. */i/ vs. /a/*

It is clear that the effects of the prosodic hierarchy on V#C sequences containing the vowel /i/ are not as strong as the effects on sequences containing the vowel /a/, at least in spatial or spectral terms. This confirms our hypothesis that /i/ shows less variability overall compared to /a/, and that such variability constraints are not limited to coarticulatory effects on the vowel. As an indication of the difference in spectral effects between /i/ and /a/, we might note that for /i/, the median eta^2 value for F3-F2 and F1 was 0.134 (n = 6; range = 0.050 to 0.419), while for /a/, the median eta^2 value for F2 and F1 was 0.4335 (n = 6; range = 0.126 to 0.680) for the same 3 speakers (Tabain 2003a). This means that prosodic boundary accounted for about 13% of the variability in the formant data for /i/, and about 43% of the variability for /a/. However, as regards temporal effects, in both the present study and in Tabain (2003a), prosodic boundary accounted for around 80% of the variability in acoustic vowel duration. These strong durational effects are most likely due to the strong effects of phrase-final lengthening.

We may speculate that these general variability effects on /i/ as opposed to /a/ are a reflection of the fact that in producing an /i/, the tongue reaches a saturation point whereby any further muscular activity which may be present is not reflected in the acoustic output. According to Perkell (1996), such saturation effects should be reflected in greater variability in constriction location, but not in constriction degree. This is perhaps true for speaker AV’s TB data (where there was less variability in the vertical dimension), but not for speaker CV and GR’s (see Figure 2). Perkell argues that the lesser variability in constriction degree results from the fact that the tongue body is stiffened in production of a vowel: as increased muscle activity pushes the tongue against the palate, the lateral edges of the tongue brace against the sides of the palate. As a result, cross-sectional area of the constriction (effectively, the area of the palatal vault) does not increase beyond a certain point, and formant values remain relatively stable. (Compare, by contrast, the case where the tongue body is not stiffened, and the cross-sectional area becomes smaller as the tongue is pushed against the palate – in this case formant values continue to change, and eventually a stop closure is produced). If one considers Perkell's hypothesis in acoustic terms, one could predict that these saturation effects would result in little variability in F1. This was found to be true in the present study, although as already mentioned, we did observe significant effects on TB y-data for speakers CV and GR.

Another result which requires discussion is the tendency for peak velocity of the closing movement from /a/ to /i/ to increase at weaker prosodic boundaries. It will be remembered from the discussion in the introduction that peak velocity from /a/ into the following consonant /a # C/ tended to show the same pattern of increasing velocity at weaker prosodic boundaries, whereas the opposite pattern was observed from /t/ into the following /a/ for /ta #/. Various researchers have found that opening movements tend to be slower than closing movements (e.g. Gracco 1994), and at first glance it may appear that this tendency is exaggerated by the strength of the prosodic boundary. However, any difference in articulatory targets according to prosodic boundary must also be taken into account when comparing opening and closing movements; therefore, more careful analyses are needed in order to compare the peak velocities of the opening and closing movements at different prosodic boundaries. It should also be noted that although we did not examine /i # C/ articulatory velocity in the present study due to measurement difficulties, our acoustic velocity data for /i # C/ were similar to the articulatory and acoustic velocity data presented for /a # C/ in Tabain (2003b) – i.e. greater velocity at weaker prosodic boundaries.

Given that the effects of prosodic hierarchy on /i/ are not as strong as those on /a/, we may tentatively conclude that duration is the main cue to prosodic structure, as evidenced by the much clearer patterns for the duration data than for the other types of data. The fact that the vowel under study was in pre-boundary position suggests that these duration effects are mainly a reflection of phrase-final lengthening (Fletcher 1991). We might note that Fougeron (2001) also stated her belief that duration was the main cue to prosodic boundary – although in that case, the segments under study were post-boundary. Like Cho (2002, in press) and Fougeron (2001), we find evidence that segments which are resistant to variability and coarticulation, such as /i/ and /s/, are also more resistant to effects of prosodic structure. However, in the present study, more effects were observed in the EMA data than in the acoustic data. It appears that the duration-induced effects on /i/ articulation are not necessarily being translated into the acoustic domain, an observation which may have important consequences for models of speech production and perception.

4.2. *Some thoughts on the Syllable boundary data*

We have observed a consistent pattern of the Syllable data ranking “higher” on the prosodic hierarchy than the Word data. This result is particularly interesting given that Fougeron (2001) observed the same effect for post-boundary /s/, whereby Syllable data patterned with Intonational and Accentual data in terms of EPG contacts (she did not examine the Syllable boundary for /i/). However, this was not observed for other consonants. We wonder whether the intrinsic coarticulatory resistance of /s/ and /i/ in some way interacts with the special status of the syllable in French – for example, the lack of lexical stress in French may mean that every syllable boundary is treated as the potential beginning of a word. We are at a loss, however, to explain the often lower ranking in terms of the prosodic hierarchy of the Word boundary than the Syllable boundary, since our explanation would predict that the two would be treated equally along the prosodic hierarchy. Another possible explanation, given that stimuli in the current data are based on Fougeron's (2001) study, lies in the fact that the /i/ under study is in the penultimate syllable of the noun phrase "Tonton et Papibi" for the Syllable condition, whereas it is in the antepenultimate syllable of the noun phrase "Paul et Papi Biba" in the Word condition. As mentioned in the Method section, the accentual phrase in French is characterized by an H* accent on the phrase final syllable; these noun phrases, then, contain H* accents on their final syllable, in which case the /i/ in the Syllable condition may be influenced by the prosodically stronger final syllable to which it is adjacent. The effect is all the more likely if we consider that the /i/ under study is followed by /b/, which may be considered the onset of the phrase-final syllable in the Syllable condition.

4.3 *Acoustic goals for /i/ in French*

Perhaps the most interesting result in the present study is the significantly greater difference between F3-F2 at stronger boundaries for all 3 speakers, despite apparently contradictory articulatory strategies employed by the female and male speakers to achieve this acoustic result. For speaker AV (the female speaker), the articulatory data showed the TB moving backwards as prosodic boundary became stronger. For speakers CV and GR (the male speakers), the TB x-data were quite complicated and interacted with the TB y-data, although overall there was a tendency for the TB to raise and front at stronger boundaries.

For speaker GR there is the additional consideration that both the x- and y-plane TB data suggested articulatory declination at the Utterance boundary, with centralization of /i/ in this context. However, this is not reflected in the acoustic data for either F1 or F3-F2. (We may also note that in the case of /i/, it is the TB which shows evidence of articulatory declination for speaker GR, whereas in the case of /a/ it was the jaw; and in the present case there are no acoustic effects, whereas for /a/ there was a strong effect on F1). These results are not conclusive as regards declination, and the possibility remains that speaker GR simply marks the Utterance boundary differently to the other speakers and in a way that is not consistent with the prosodic hierarchy. This possibility is given some support by the fact that the syllable position in the sentence for both this study and the previous studies (Tabain 2003a, 2003b) was held constant precisely in order to control for declination.

We suggest that it is not a coincidence that it is the female speaker who shows an articulatory strategy contradictory to the predictions outlined in the introductory section above, i.e. a more back TB movement at stronger boundaries. It is possible that this speaker has a shorter pharyngeal cavity than do the male speakers, leading to a more forward crossover point for F3 and F2.[vii] It may be that this crossover point is so far forward for this speaker, that her /i/ articulation is posterior to the crossover point, rather than anterior as we had assumed in the introduction; this would then result in an F3 affiliation with the back cavity rather than the front cavity. In order to increase her F3, therefore, this speaker would have to move her tongue backwards rather than forwards if she is to enhance the characteristic feature of /i/ as described by the dispersion-focalization theory. Such an interpretation of our articulatory and acoustic results supports the view that speakers aim at an acoustic, rather than articulatory goal, in their articulation of segments at stronger boundaries.

Our results contradict results presented by Cho (2002) on the behaviour of /i/ at different prosodic boundaries. Although both studies examined /i/ in pre-boundary position, Cho's study looked at English, and was designed to compare accent-induced effects with boundary-induced effects, including their interaction (whereas only boundary-induced effects were the focus of the present study). In addition, the statistical treatment was not the same in the two studies, and nor was the treatment of the TB (Cho subtracted the Jaw from the TB data, whereas we did not). With these caveats in mind, we would suggest that our French data do not lend any support to the hypothesis that stronger prosodic boundaries are associated with sonority expansion. Perhaps contrary to our hypothesis, we observed almost no effects of prosodic boundary on the jaw. By contrast, two of our speakers (CV and GR) showed evidence of a higher TB position at stronger boundaries (keeping in mind the exception of speaker GR's Utterance boundary data), whereas Cho's speakers showed evidence of a lower tongue position at stronger boundaries, which according to Cho reflects greater sonority. This higher TB position for speakers CV and GR interacted with a tendency to front the tongue at stronger prosodic boundaries.

These results are clearly different from those for the vowel /a/ reported previously (Tabain 2003b), where there were very clear and consistent effects of the prosodic hierarchy for both the jaw and TB data. We might note that results presented by Cho (2002) for pre-boundary /a/ broadly support our previous results. However, both Cho (2002) and Tabain (2003b) found slightly weaker results for the jaw than for the tongue, reinforcing a view expressed in both studies that the jaw is less sensitive to change at prosodic boundaries than is the tongue.

Another possible explanation for the lesser effect on the jaw in the present study is that lip-spreading in the articulation of /i/ constrains the jaw to such an extent that lowering becomes difficult. Such an effect would be particularly true for French, where /i/ must contrast with the other high front vowel /y/, which is rounded.

The nature of the /i/ in French as opposed to English may also explain why 2 of our 3 speakers showed a higher tongue position at stronger boundaries, whereas the opposite was true for Cho's (2002) English speakers. The /i/ in French is a very peripheral vowel in auditory terms, without the noticeable on-glide such as is found for /i/ in Australian English (the variety of English used in Harrington et al.'s [2000] study). Keeping in mind the opposing strategy adopted by the female speaker in our study, it is likely that French /i/ must be higher and more forward in order to maximally distinguish it from /y/, which may in turn become a little more back in order to emphasize the lowering effect on F3 of lip-rounding. In addition to contrasting a full set of front rounded vs. front unrounded vowels, French also contrasts 4 levels of vowel height, unlike English which only contrasts 3 levels (we disregard vowel duration, which contributes to the "tense-lax" distinction in English). This may explain why the tongue becomes higher in French and not in English, given Manuel's (1990) results showing that the nature of the vowel inventory in a language (i.e. the number of contrasts on the front-back and high-low dimensions) affects the amount of vowel-to-vowel coarticulation in that language. If our interpretation of ours and Cho's results is correct, it would suggest that effects of the prosodic hierarchy are also dependent on the phonemic structure of the individual language.

5. Conclusion

Our results confirm the hypothesis that /i/ shows fewer effects of prosodic hierarchy than does /a/. However, our results suggest that in articulating /i/ at stronger boundaries, French speakers aim to enhance the acoustic feature of a high F3 for this vowel, regardless of whether this entails a greater fronting, raising or backing of the tongue body. We suggest that this particular strategy of acoustic enhancement is crucial in French due to this language's phonemic contrast between /i/ and the high front rounded vowel /y/. Such a view suggests either that at stronger prosodic boundaries, listeners are provided with enhanced cues as to the phonemic identity of the segment being articulated; or that the enhanced phoneme provides an extra cue to a stronger prosodic boundary.

[i] We would like to thank an anonymous reviewer for pointing out these competing predictions for F3 and F2.

[ii] We do not present results for F4-F3 since we were not confident of our F4 measurements. This is also why we chose not to present the F2' measure outlined in Ménard et al. (2002).

[iii] For a basic description of the prosodic structure of French as it relates to the present study, the reader is referred to Tabain (2003a: 518, or 2003b: 2835-2836). For a more detailed description, the reader is referred to Fougeron & Jun (1998), di Cristo (1998) and Jun & Fougeron (2000), and references cited therein.

[iv] A small number of Intonational phrase boundary utterances were produced with a pause. These utterances were checked to verify that they patterned with the other Intonational phrase boundary data.

[v] Note that this approach contrasts with the approach used in Tabain (2003a), where peak velocity for F1 and for F2 were calculated separately. The present approach was found to be more appropriate for /i/, where the movement in F1 is minimal compared to the movement for /a/.

[vi] We do not report results for consonant context from the two-way ANOVA for the three derived measures, since the movement from /a/ to /i/ is further removed in time from the consonant than are the x- and y-targets for /i/.

[vii] We would like to thank Pierre Badin for suggesting this possibility to us.

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		Vowel Duration (ms)			F1-F2 Peak Velocity (Hz ms^{-1})		
Speaker	**Boundary**	**Mean**	**S.D.**	**N**	**Mean**	**S.D.**	**N**
AV	**U**	210	27.4	60	-	-	-
	I	179	34.3	60	42	17.5	30
	A	139	20.5	60	46	16.2	30
	W	93	18.4	60	48	13.1	30
	S	120	20.8	60	53	20.1	30
CV	**U**	184	24.8	56	-	-	-
	I	176	15.6	56	43	14.6	28
	A	164	17.4	55	43	16.6	26
	W	90	8.6	56	55	20.3	27
	S	101	8.6	56	49	13.1	29
GR	**U**	221	20.5	62	-	-	-
	I	234	45.6	62	35	9.8	30
	A	192	27.7	62	34	13.4	30
	W	102	16.5	62	58	18.6	30
	S	101	15.3	62	51	16.1	30

Table I: Descriptive statistics for Acoustic Vowel Duration of /i/ and for Peak Velocity of the F1-F2 transition /i # C/ for 3 speakers of metropolitan French. Data are presented according to prosodic boundary; the peak velocity data were not measured for the Utterance boundary due to the presence of a pause following the vowel. Data are collapsed across consonants; the duration data contain all consonant contexts, and the peak velocity data contain only the stop consonant contexts.

	AV		**CV**		**GR**	
	d.f. = 4,270		d.f. = 4,249		d.f. = 4,280	
Vowel Duration	$F = 217.92$ $p < 0.001$	U > I > A > W < S	$F = 470.28$ $p < 0.001$	U > I > A > W < S	$F = 412.40$ $p < 0.001$	U < I > A > W = S
F1 Vowel	$F = 4.64$ $p < 0.01$	U > I = A = W < S	$F = 8.91$ $p < 0.001$	U = I = A = W > S	$F = 5.06$ $p < 0.001$	U = I = A = W > S
F3-F2 Vowel	$F = 58.75$ $p < 0.001$	U = I > A > W = S	$F = 18.50$ $p < 0.001$	U = I = A > W = S	$F = 14.81$ $p < 0.001$	U = I = A > W = S
	d.f.=3,108		d.f.=3,98		d.f.=3,108	
Peak Velocity	$F = 2.07$ n.s.	-	$F = 3.41$ $p < 0.05$	I = A < W = S	$F = 20.32$ $p < 0.001$	I = A < W = S

Table II: Significance results for the effect of prosodic boundary on acoustic vowel and consonant duration, F1, F3-F2 and peak velocity for the 3 speakers of this study. Unless otherwise noted, for this and subsequent significance tables, alpha for the main effect has been set at 0.05. F-ratio and p-values are presented in the first column, and posthoc pairwise comparisons based on a Least Significant Difference are presented for adjacent pairs in the prosodic hierarchy in the second column (with alpha adjusted according to the Bonferroni method). The direction of the difference is marked by either '<' or '>', or '=' in the case where the result is not significant. For this and all subsequent tables: “U” = Utterance; “I” = Intonational phrase; “A” = Accentual phrase; “W” = Word; and “S” = Syllable. Speaker AV is female and speakers CV and GR are male. Note that “U” is not included in the peak velocity data since the vowel is followed by a pause in this prosodic context.

	AV	CV	GR
Vowel Duration	.737	.859	.817
F1 Vowel	.050	.117	.058
F3-F2 Vowel	.419	.180	.151
Peak Velocity *	.052	.087	.340

Table III: Eta^2 results for the acoustic data. Note that Utterance boundary data were excluded for the measure marked with an asterisk (*) due the presence of a pause following the vowel in this prosodic context.

		Duration (ms)		Magnitude (cm x 10^{-3})		Peak Velocity (cm sec^{-1})		
Speaker	**Boundary**	**Mean**	**S.D.**	**Mean**	**S.D.**	**Mean**	**S.D.**	**N**
AV	**U**	308	30.0	908	109.2	6.0	0.74	60
	I	270	51.6	884	168.8	5.8	0.81	60
	A	254	51.3	822	125.0	6.1	0.78	60
	W	175	33.3	762	128.1	7.3	1.14	60
	S	188	39.1	726	129.2	6.5	1.00	60
CV	**U**	311	44.6	1433	277.2	8.5	1.25	56
	I	308	42.6	1350	197.5	9.4	1.29	56
	A	377	57.2	2026	346.6	9.9	1.28	56
	W	192	26.9	1083	210.1	11.1	2.04	56
	S	208	30.0	1192	198.3	11.4	1.71	56
GR	**U**	319	62.3	1290	140.3	9.4	1.56	62
	I	338	53.8	1303	94.1	7.5	0.82	62
	A	316	30.0	1313	117.0	7.5	1.12	62
	W	224	27.8	1272	161.1	10.5	1.24	62
	S	217	38.7	1108	191.2	10.0	1.24	62

Table IV: Descriptive statistics for Duration, Magnitude and Peak Velocity measures for the Closing Movement from the /a/ to the /i/ in /api #/. Data are for the y-plane only.

	AV		CV		GR	
	d.f.=4,270		d.f.=4,249		d.f.=4,280	
/i/ y-target	F = 2.28 n.s.	-	F = 35.73 p < 0. 001	U > I = A > W = S	F = 26.37 p < 0. 001	U < I = A > W = S
/i/ x-target	F = 39.92 p < 0.001	U = I > A > W = S	F = 36.55 p < 0.001	U < I > A < W > S	F = 9.59 p < 0.001	U > I = A < W > S
Magnitude	F = 23.74 p < 0.001	U = I > A > W = S	F = 149.53 p < 0. 001	U = I < A > W < S	F = 26.93 p < 0. 001	U = I = A = W > S
Duration	F = 140.94 p < 0.001	U > I = A > W = S	F = 214.17 p < 0. 001	U = I < A > W = S	F = 108.64 p < 0. 001	U = I > A > W = S
Velocity	F = 26.16 p < 0.001	U = I = A < W > S	F = 34.35 p < 0. 001	U < I = A < W = S	F = 81.57 p < 0. 001	U > I = A < W = S

Table V: Significance results for the effect of prosodic boundary on Tongue Body closing movement from /a/ to /i/ in /api #/.

	AV	CV	GR
/i/ y-target	.027	.219	.193
/i/ x-target	.303	.176	.098
Magnitude	.215	.630	.219
Duration	.592	.737	.574
Velocity	.247	.331	.516

Table VI: Results from an eta^2 analysis of variance for the measures used to describe Tongue Body closing movement from /a/ to /i/ in /api #/.

	AV		CV		GR	
	d.f.=4,270		d.f.=4,249		d.f.=4,305	
/i/ y-target	F = 5.86 p < 0.001	U < I = A = W = S	F = 4.85 p < 0.01	U = I = A < W = S	F = 12.78 p < 0.001	U > I > A = W = S
/i/ x-target	F = 11.16 p < 0.001	U > I = A = W = S	F = 3.64 p < 0.01	U = I = A = W = S	F = 2.48 n.s.	-

Table VII: Significance results for the effect of prosodic boundary on Jaw closing movement from /a/ to /i/ in /api #/. Note that alpha has been set to 0.025 in order to take into account the correlation between Jaw movement in the x- and y-planes.

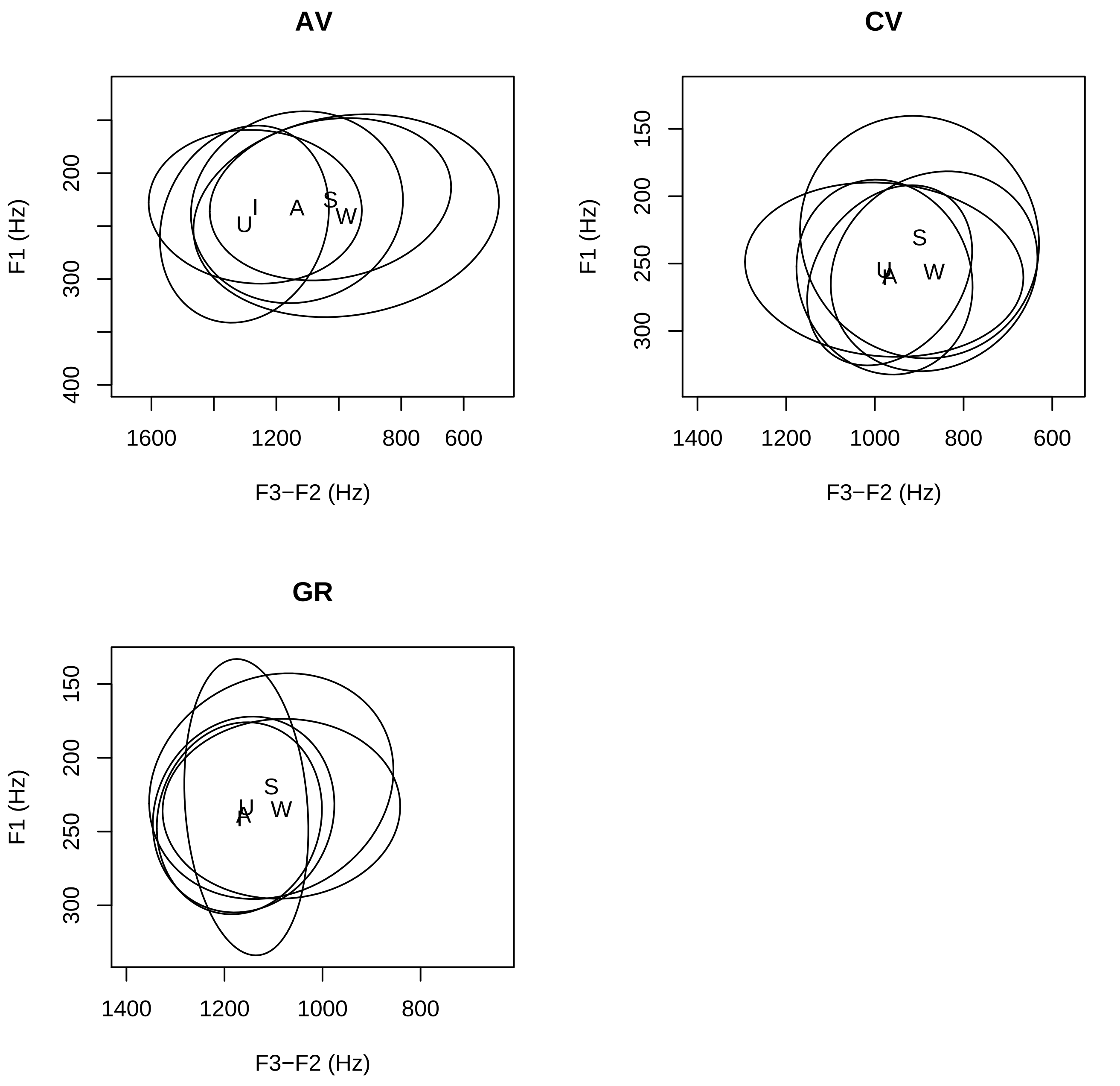
	AV	**CV**	**GR**
/i/ y-target	.071	.026	.139
/i/ x-target	.108	.032	.027

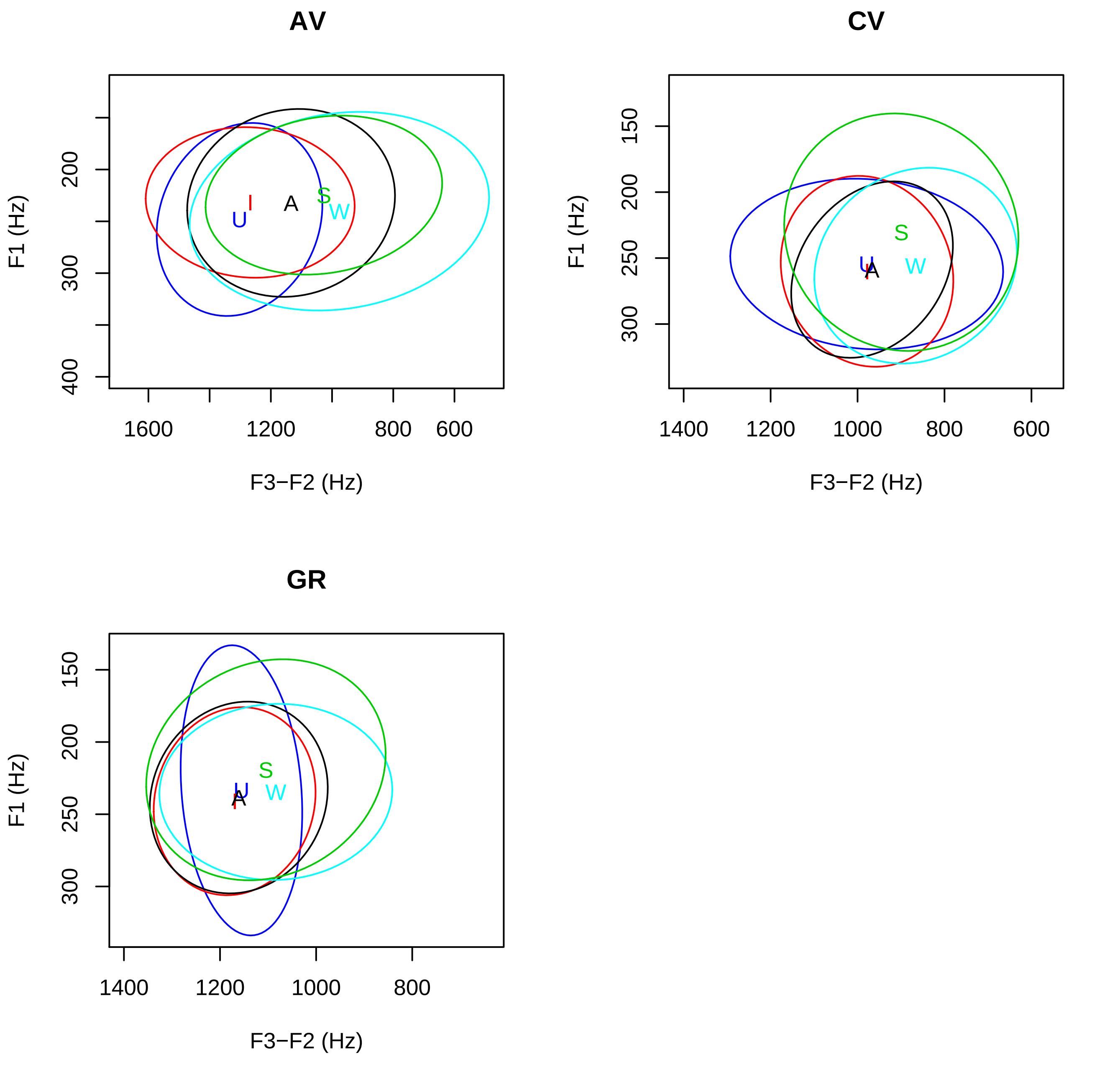
Table VIII: Results from an eta^2 analysis of variance for the x- and y-targets of the Jaw closing movement from /a/ to /i/ in /api #/.

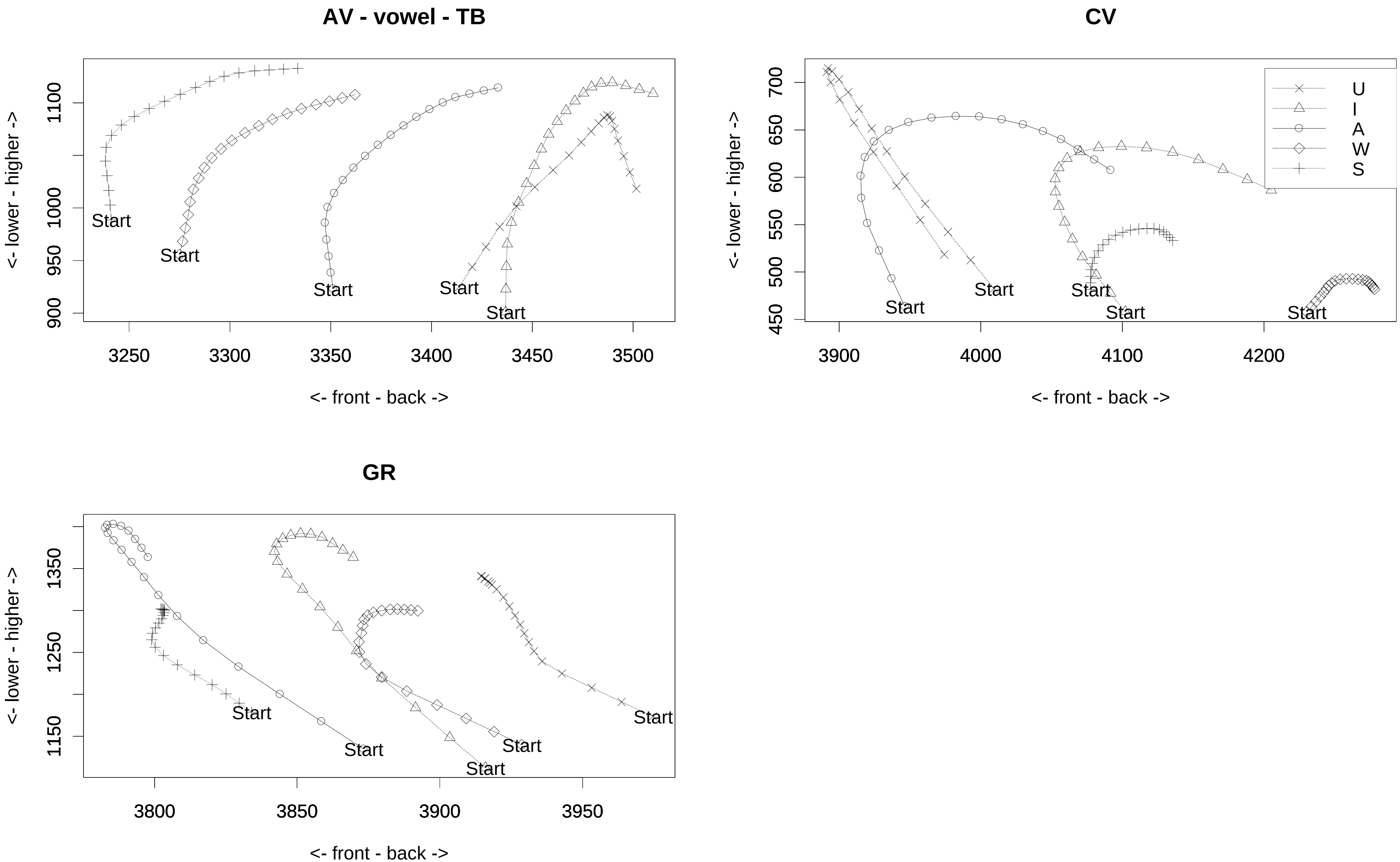
Figure 1: Ellipse plots of F1 vs. F3-F2 data for /i/. Data are sampled at the acoustic midpoint of the vowel. Only the mean values for each prosodic context are shown, with ellipses representing 2.45 standard deviations from the mean. In this and in subsequent figures, "U" = Utterance, "I" = Intonational phrase, "A" = Accentual phrase, "W" = Word, and "S" = Syllable.

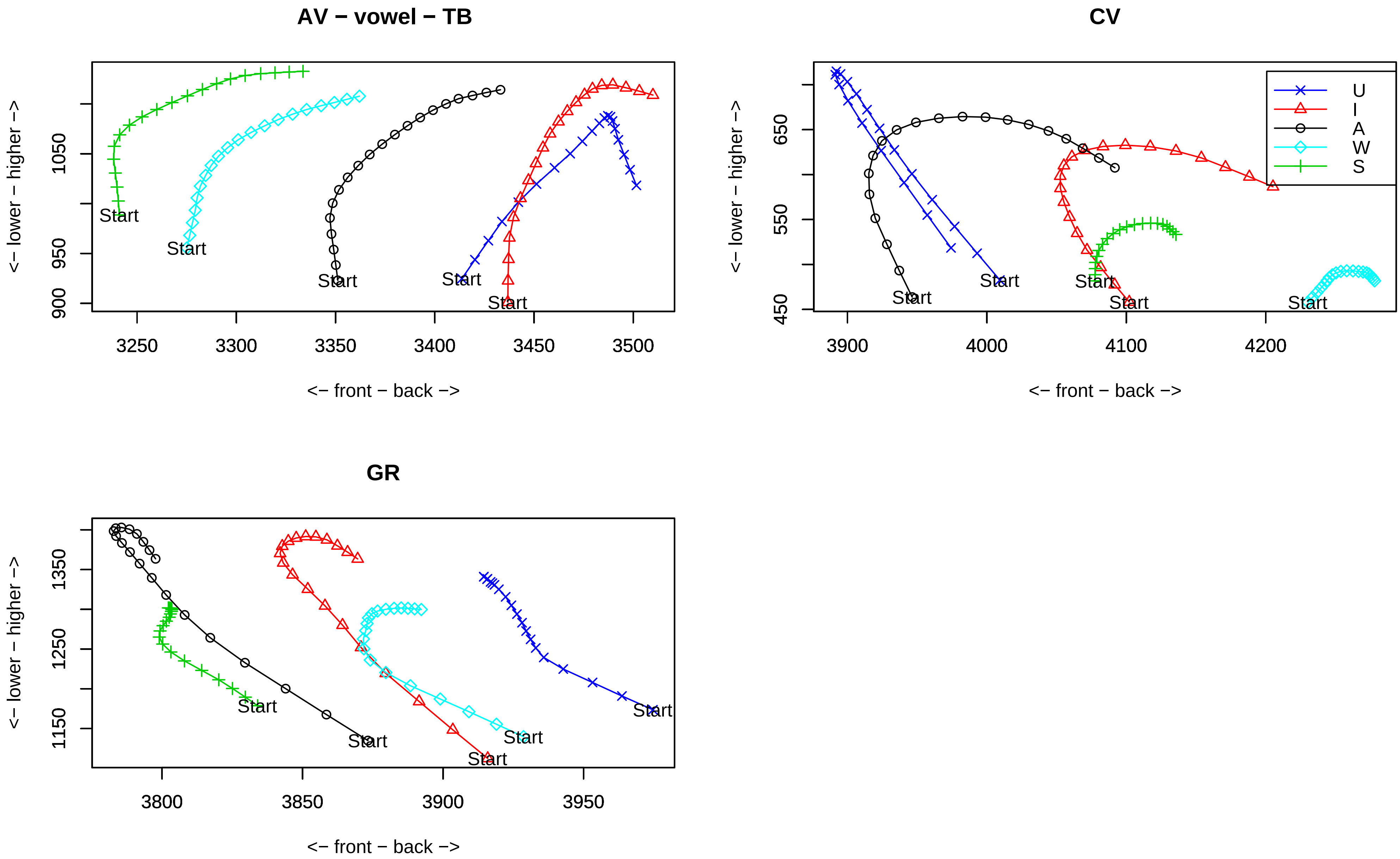
Figure 2: Plots of Tongue Body trajectories for the vowel /i/ at the end of the word "Papi". Data are presented separately for each speaker. Data are time-normalized and averaged across each prosodic context. The beginning of each trajectory, marked "Start", was taken at the acoustic release of the /p/ in /api #/, and the end of each trajectory was taken at the acoustic endpoint of the vowel. Each averaged, time-normalized trajectory is plotted with 20 points equidistant in time. Note that /i/ at the Utterance boundary is followed by a pause, whereas at the other boundaries it is followed by one of 6 different consonants. Units on both the x- and y-axes are cm x 10^{-3} from the reference transducer.

Figure 3: Plots of Jaw trajectories for the vowel /i/ at the end of the word "Papi". Details as for Figure 2. Units on both the x- and y-axes are cm x 10^{-3} from the reference transducer.


AV
F1 (Hz)
200
300
400
1600
1200
800
600
F3−F2 (Hz)
U
I
A
S
W
CV
150
200
250
300
1400
1200
1000
800
600
GR


AV
CV
GR
F1 (Hz)
F3−F2 (Hz)
U
I
A
S
W
200
300
400
1600
1200
800
600
150
250
1400
1000


AV - vowel - TB
CV
GR
<- lower - higher ->
<- front - back ->
900 950 1000 1100
3250 3300 3350 3400 3450 3500
450 500 550 600 650 700
3900 4000 4100 4200
1150 1250 1350
3800 3850 3900 3950
Start
U
I
A
W
S



AV − vowel − TB
CV
GR
<− lower − higher −>
<− front − back −>
Start
U
I
A
W
S
900
950
1050
3250
3300
3350
3400
3450
3500
450
550
650
3900
4000
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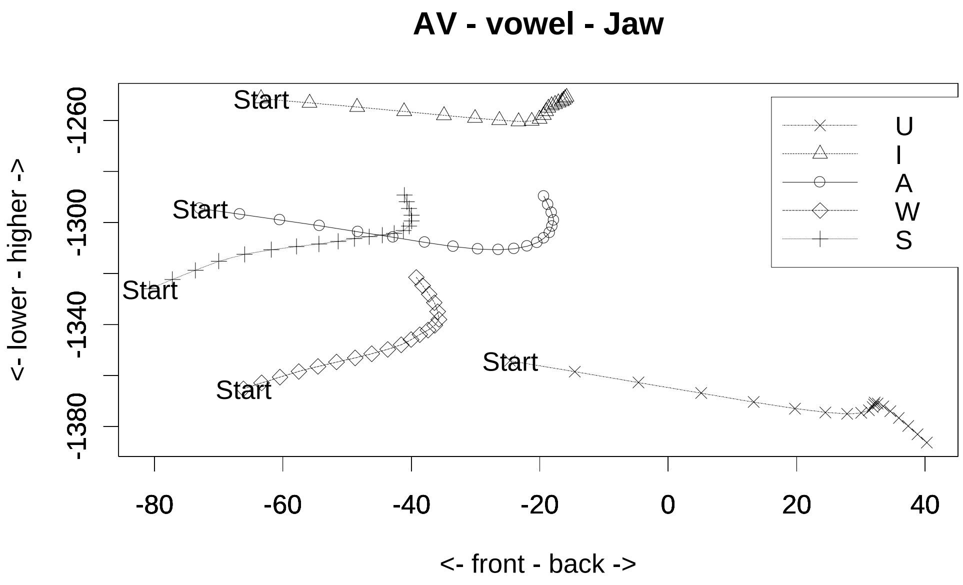
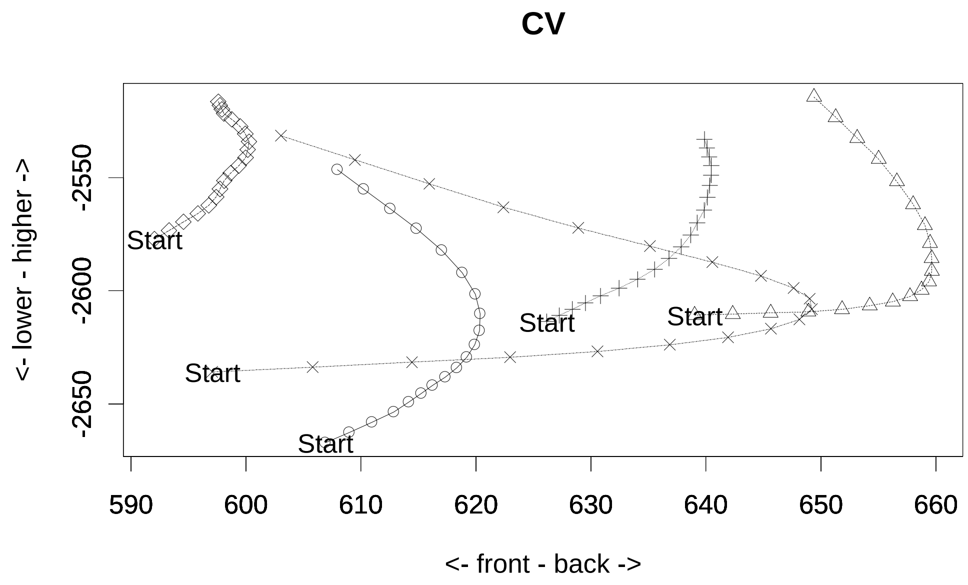
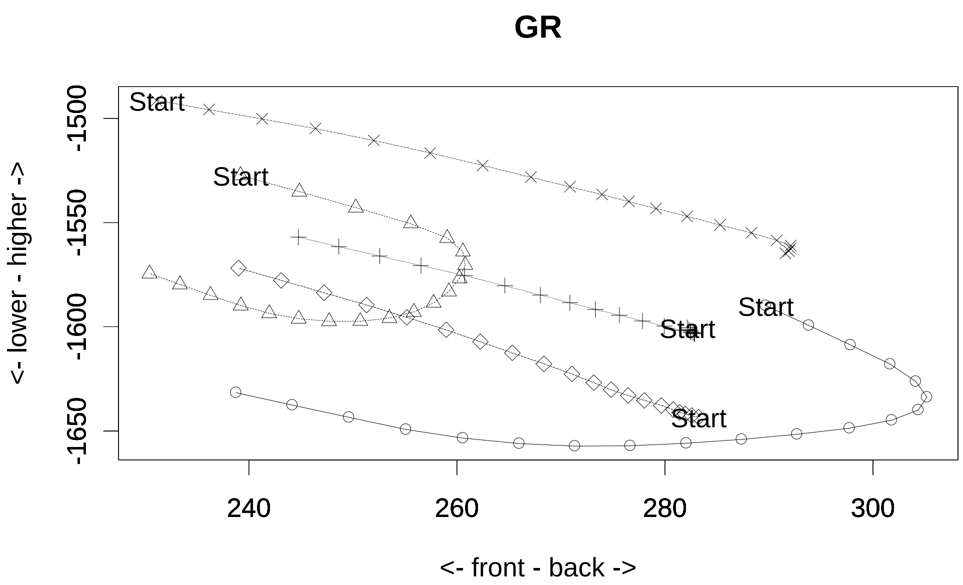
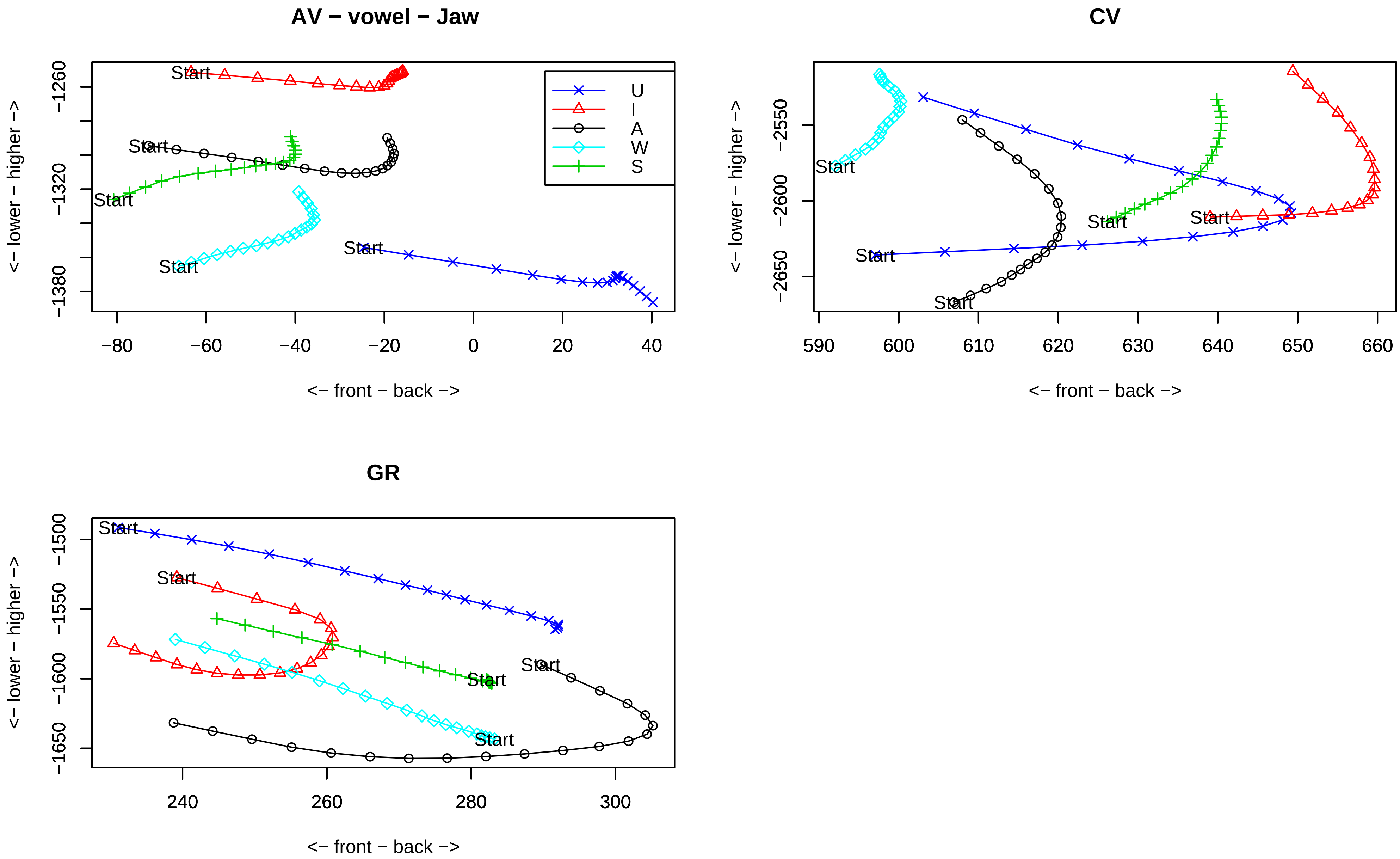
3800
3850
3900
3950


AV - vowel - Jaw
<- lower - higher ->
<- front - back ->
-1260
-1300
-1340
-1380
-80
-60
-40
-20
0
20
40
Start
U
I
A
W
S


CV
<- lower - higher ->
<- front - back ->
-2550
-2600
-2650
590
600
610
620
630
640
650
660
Start


GR
<- lower - higher ->
<- front - back ->
-1500
-1550
-1600
-1650
240
260
280
300
Start



AV − vowel − Jaw
CV
GR
U
I
A
W
S
Start
<− lower − higher −>
<− front − back −>
−1260
−1320
−1380
−80
−60
−40
−20
0
20
40
−2550
−2600
−2650
590
600
610
620
630
640
650
660
−1500
−1550
−1600
−1650
240
260
280
300