An articulatory and acoustic study of /u/ in preboundary position in French: The interaction of compensatory articulation, neutralization avoidance and featural enhancement

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An articulatory and acoustic study of /u/ in pre-boundary position in French: the interaction of compensatory articulation, neutralization avoidance and featural enhancement

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Abstract

This study presents acoustic and electro-magnetic articulometry (EMA) data for the back rounded vowel /u/ in pre-boundary position in French. Five boundary types are examined: the Utterance, the Intonational phrase, the Accentual phrase, the Word and the Syllable. The three speakers studied produce similar acoustic output, with both F1 and F2 becoming lower before stronger prosodic boundaries. However, the Utterance boundary has a particularly strong effect on F1, which is particularly low before this boundary. To achieve the acoustic output observed, the speakers adopt different articulatory strategies at different prosodic boundaries. The strategies observed before the strongest boundaries are tongue dorsum backing (coupled with either raising or lowering, depending on the speaker); tongue tip retraction; and lip protrusion. Somewhat unexpectedly in light of acoustic considerations, lip constriction is observed to be greater before the weaker prosodic boundaries. This result, considered in conjunction with the tongue data and with the lip protrusion data, leads us to suggest that the French speakers in our study are actively aiming to prevent F2 from becoming too high before the weaker prosodic boundaries. We suggest that a high F2 for /u/ may lead to perceptual confusion with the front rounded vowel /y/, which is also present in the French phoneme inventory. This result echoes our previous results for the front unrounded vowel /i/ (Tabain & Perrier 2005), and suggests that the structure of a language's phoneme inventory has important effects on the articulatory strategies adopted by its speakers.

1. Introduction

In this paper, we study the effects of the prosodic hierarchy on the vowel /u/ in pre-boundary position in French. Over recent years, many studies have shown that the prosodic hierarchy has a profound effect on the articulation and acoustics of individual consonants and vowels, in languages as varied as English, French, Korean and Tamil (for example, Fougeron & Keating 1997; Byrd & Saltzman 1998; Byrd 2000; Cho & Keating 2001; Fougeron 2001; Cho 2002; Keating, Cho, Fougeron & Hsu 2003; Tabain 2003a, 2003b; Tabain & Perrier 2005). To our knowledge, no study has looked at the effects of the prosodic hierarchy on the back rounded vowel /u/.

Broadly speaking, the effects of the prosodic hierarchy on segmental articulation and acoustics are as follows: duration is greater, articulation less reduced, and formant structure more centralized, at stronger prosodic boundaries (e.g. Utterance or Intonational phrase) as opposed to weaker prosodic boundaries (e.g. Word or Syllable). For example, there is greater linguo-palatal contact for /n/ after stronger prosodic boundaries than after weaker prosodic boundaries (Fougeron & Keating 1997), while for /a/ the tongue and jaw positions are lower before stronger prosodic boundaries than before weaker prosodic boundaries (Tabain 2003b; Cho 2005).

This effect of prosodic structure is, however, not identical across segments – for instance, segments which are intrinsically resistant to variability and coarticulation, such as /i/ and /s/, show less effect from prosodic structure than do other segments (Fougeron 2001; Cho 2002, 2004; Tabain & Perrier 2005). Moreover, certain effects appear to be language-specific, in that they are affected by the broader phonemic structure of the language (cf. Manuel 1990).

Tabain & Perrier (2005) studied French speakers' productions of /i/ according to the prosodic hierarchy, and Cho (2002) studied English speakers' productions of /i/ according to the prosodic hierarchy. Both studies looked at /i/ in pre-boundary position using electro-magnetic articulography (EMA), and despite minor differences in methodology, the two studies agreed that /i/ showed weaker effects of the prosodic hierarchy than did /a/. However, while Cho's English speakers showed an overall tendency to lower the tongue in order to increase overall sonority before stronger prosodic boundaries, the French speakers showed an opposing tendency of raising and fronting the tongue before stronger prosodic boundaries (but see the following paragraph for further discussion of the "fronting" issue). It should be noted that Cho's results are in line with studies of stress effects on /i/ in English, such as Erickson (2002) and Harrington, Fletcher & Beckman (2000). In Tabain & Perrier (2005), we interpreted this difference between ours and Cho's results as being due to the presence of the front rounded vowels in the French phoneme inventory. In particular, it is the presence of the high front rounded vowel /y/ that induces the constraints observed in the French production of /i/, a high front unrounded vowel. In both languages /i/ must contrast with the high back rounded vowel /u/, but only in French must /i/ also contrast with /y/. The characteristic of all high vowels is a low F1, and the characteristic of /u/ among the high vowels is a low F2; however, both /i/ and /y/ are characterised by a relatively high F2. It is therefore the case in French that speakers must control F3 as well as F2 for /i/, since a high F3 (near F4) characterises /i/, and a low F3 (near F2) characterises /y/ (Ménard, Schwartz, Boë, Kandel & Vallée 2002). It is noteworthy that for the low vowel /a/, both English (Cho 2002, 2005) and French (Tabain 2003b) show a lower tongue and jaw position before stronger prosodic boundaries, presumably since in the low part of the vowel space the two languages' phoneme inventories are relatively similar.

The argument that speakers aim to control an acoustic goal rather than an articulatory goal is supported by the French /i/ data in the Tabain & Perrier (2005) study. It was stated above that the French speakers showed raising and fronting of the tongue before stronger prosodic boundaries. In fact, this was only true for two of the three speakers studied. For the third speaker, the tongue showed consistent backing, rather than fronting and raising, before stronger prosodic boundaries. It is important to note that this speaker was the only female speaker in the study. We argued that the most likely reason for such a strategy by this speaker (speaker AV, who also appears in the current study) is the relatively shorter pharyngeal cavity found in female speakers when compared to the oral cavity. Although we could not verify whether this was the case for the female speaker in our study, the difference in relative cavity size would certainly explain why all three speakers had the same acoustic results (namely, a higher F3 before stronger prosodic boundaries) but differed in the articulatory strategies used to achieve these results. It is normally assumed that F3 is associated with the front (oral) cavity for /i/ in male speakers, and F2 with the back (pharyngeal) cavity (cf. Johnson 1997: 93-97). However, if the pharyngeal cavity is relatively shorter for the female speaker (cf. Johnson 1997: 109, figure 5.11), F3 would then become affiliated with this cavity, rather than with the oral cavity as would be the case for the male speakers. Hence, in order to increase F3, the French female speaker must move the tongue backwards, rather than forwards. As a result, although the articulatory strategy goes against traditional phonetic descriptions of this vowel (presumably based on adult male speech), the acoustic characteristic of a very bright spectral timbre, characterized by a strong and broad prominence in the F3/F2 region, is maintained.

It is this final result which has motivated the present study of /u/. In this paper, we explore /u/ through the prosodic hierarchy. It is our hope that the important aspects of /u/ production will be highlighted by its behaviour in the prosodic hierarchy. The present study is a continuation of our previous work on /a/ (Tabain 2003a, 2003b) and on /i/ (Tabain & Perrier 2005) in pre-boundary position in French.

1.1 *Acoustics of /u/ and previous studies of /u/*

/u/ is one of the three "point" vowels, together with /a/ and /i/. Yet, it has received comparatively less attention than its unrounded counterparts. /u/ is characterized by a high tongue position towards the rear part of the oral cavity, in contrast to /i/ which has a more front (high) tongue position, and to /a/ which has a low tongue position. /u/ also involves significant rounding of the lips, in contrast to both /i/ and /a/.

The gestures involved in the production of /u/ are therefore quite different from those required for the other point vowels which we have studied within a prosodic framework. In acoustical terms, the raising of the tongue in the velar region of the oral cavity can be considered to form one constriction, and the rounding of the lips can be considered to form another constriction. The constriction formed by the tongue together with the volume of the pharyngeal cavity can be considered to form the first Helmholtz resonance of the system (F1), and the constriction formed by the lips together with the volume of the oral cavity can be considered to form the second Helmholtz resonance (F2). F3 can be considered to be the half-wavelength resonance of the back cavity (Savariaux, Perrier & Orliaguet 1995).

A given Helmholtz resonance can be lowered by decreasing the (cross-sectional) area of the constriction, or by increasing the (cross-sectional) area of the cavity. It can also be lowered by lengthening either the constriction, or the cavity, or both. Inversely, a given Helmholtz resonance can be raised by increasing the area of the constriction, or by decreasing the area of the cavity. It can also be raised by shortening either the constriction, or the cavity, or both. In the case of [u], these constrictions are formed by the back of the tongue and by the lips.

It is important to note that given this model of [u], any change in the tongue constriction will affect not just F1, but also F2, since the tongue also forms the endpoint of the F2 resonator.

As mentioned above, prototypical /u/ is characterized by a low F1 and a low F2 (Savariaux et al. 1995; Schwartz, Boë, Vallée & Abry 1997). Hence, we would expect to find low F1 and low F2 before stronger prosodic boundaries, such as the Utterance. By contrast, we would expect to find relatively higher F1 and/or higher F2 before weaker prosodic boundaries, such as the Word or Syllable. If this is true, the question remains: how do speakers achieve these acoustic effects?

Several studies have looked at /u/ from a motor equivalence perspective (e.g. Perkell, Matthies, Svirsky & Jordan 1993; Savariaux et al. 1995; de Jong 1997; Savariaux, Perrier, Orliaguet & Schwartz 1999). Perkell et al. (1993) had a different point of departure to that proposed here: they assumed that both tongue raising and lip-rounding affected F2, with tighter constrictions leading to a lower F2 (assuming a Helmholtz model), and they do not appear to consider

F1. In their EMA study of American English, Perkell and colleagues aimed to demonstrate that variability in F2 is reduced via "complementary covariation" of the tongue and lips: that is, that there is a trading relation, or inverse correlation, between lip-rounding and tongue-raising. However, Perkell et al. found only weak support for their hypothesis, with three of their four subjects showing weak negative correlations between lip-rounding and tongue-raising, while the fourth subject showed positive correlations (i.e. as lip-rounding became greater, tongue-raising also became greater). It is quite possible that a careful consideration of F1 may have elucidated Perkell et al.'s results, since the location and degree of the tongue constriction may affect F1 as well as F2.

de Jong (1997) is in some ways a follow-up study of Perkell et al. (1993), in that de Jong too assumes that lip-rounding and tongue-raising (in his terms, "lip protrusion" and "dorsovelar constriction") have an effect on F2, and hence that there may be compensation between the labial and dorsal gestures. Like Perkell et al., de Jong manipulates stress in order to induce variation in vowel production. His study differs from Perkell et al.'s in some minor respects (e.g., de Jong uses X-ray microbeam instead of EMA, and he examines /o/ as well as /u/ - in American English, [ow] and [ʊ]), but his conclusion is even clearer than Perkell et al.'s: "Results reveal systematic speaker differences in the direction of correlation between measures of labial and dorsal position. These results show that speakers differ as to whether they exhibit coupling between labial and dorsal activity in the lower back vowel timbre" [quotation taken from abstract]. It is a pity that, like Perkell et al., de Jong does not present F1 data, since his results clearly suggest that there is no simple relationship between the lip and tongue gestures for /u/ as regards F2.

Savariaux et al. (1995) used a perturbation study to examine /u/ articulation (a follow-up study, Savariaux et al. 1999, provided a perceptual/rating analysis of the acoustic data from the first study). The authors were concerned with the question of how speakers adapted to the insertion of a 20 mm tube between the lips, and they examined the adaptations via x-ray data and acoustic data. The insertion of the tube between the speakers' lips effected a change in the resonance mode of F2 for /u/, from a Helmholtz resonance to a quarter-wavelength resonance of the front cavity. This change in mode resulted in a significant increase in F2 - in Savariux et al.'s nomogram-idealized situation, from about 850 Hz to about 1500 Hz. The only way for the speaker to decrease the F2 resonance value was by moving the tongue constriction backwards, thereby lengthening the front resonance. However, such a movement has the undesired side-effect of a slight increase in F1. The authors note that one way of lowering F1 without significantly changing F2 and F3 is to decrease the tongue constriction area and/or to increase the constriction length. They found that no speaker compensated fully for the insertion of the lip tube on the first trial (although seven of the eleven speakers did so partially). By the twentieth trial, all speakers had achieved an "optimal compensation strategy". The authors used this result to argue for an acoustic/perceptual representation, rather than an articulatory representation, of the speech signal in the speakers' mental representation of speech. (Story [2004] may be regarded as a follow-up study to Savariaux et al. [1995], in that it presents a model strongly in line with Savariaux et al's real speaker data).

The present study continues in the spirit of Savariaux et al. (1995), in that we assume that speakers are aiming to control both F1 and F2 for /u/. Our methodology, however, is more in line with Perkell et al. (1993) and de Jong

(1997), in that we use prosodic variables to manipulate our data, rather than articulator perturbation. Our prosodic variables, however, are more extensive than those of the previous /u/ studies, in that we examine five levels on the prosodic hierarchy, rather than having just two levels of stress (Perkell et al. 1993) or three levels of stress (de Jong 1997). [1]

2. Method

2.1 *Speakers and recordings*

Three native speakers of metropolitan French (two female [AV, LN] and one male [CV]) were recorded in a sound-treated room at ICP, Grenoble. All three speakers were in their 20s or 30s at the time of recording, and all three were involved in speech research. Recordings took place approximately 2 years after recordings for the Tabain & Perrier (2005) study of /i/; and approximately 3 years after recordings for the Tabain (2003a, 2003b) studies of /a/. Speakers AV and CV had participated in the previous recordings, while speaker LN was new to this series of recordings.

Articulatory (EMA) and acoustic data were recorded simultaneously and time-synchronized. The EMA data were recorded at 500 Hz using a 10-channel Carstens system. Four transducers were placed on the tongue (one on each of the Tongue Back, Tongue Dorsum, Tongue Blade and Tongue Tip); two sensors were placed on the vermilion borders of the lips (one on each of the Upper Lip and Lower Lip); and one sensor for the Jaw was placed on the gums beneath the lower teeth. A reference transducer was placed on the gums above the upper teeth, and another reference transducer was placed on the nose. The tongue sensors were attached with Ketac bond, and the other sensors were attached with cyano-acrylate. The Tongue Tip sensor was placed approximately 1 cm from the tip of the tongue; the Tongue Blade sensor was placed approximately 2 to 2.5 cm from the tip of the tongue; the Tongue Dorsum sensor was placed approximately 3.5 to 4 cm from the tip of the tongue; and the Tongue Back sensor was placed approximately 5 to 5.5 cm from the tip of the tongue. Rotation of the data to the occlusal plane of the speaker, and subtraction of the reference transducers for each speaker, were both carried out using MATLAB.

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. For the purposes of this study, the following prosodic hierarchy is assumed (cf. Nespor & Vogel, 1986):

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

The strongest/highest prosodic boundary is the Utterance, and the weakest/lowest prosodic boundary is the Syllable.[2] 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:

1. Utterance

Paul aime Pap<u>ou</u>. **B**ouba les protège en secret.

Paul loves Papou. Bouba looks after them in secret

2. Intonational

Le pauv' Pap<u>ou</u>, **B**ouba et Paul arriveront demain.

Poor Papou, Bouba and Paul are coming tomorrow

3. Accentual

Tonton, Pap<u>ou</u>, **B**ouba et Paul arriveront demain.

Uncle, Papou, Bouba and Paul are coming tomorrow

4. Word

Paul et Pap<u>ou</u> **B**ouba arriveront demain.

Paul and Papou Bouba are coming tomorrow

5a. Syllable

Tonton et Pap<u>ou</u>**b**ou arriveront demain.

Uncle and Papoubou are coming tomorrow

[Speaker AV]

5b. Syllable

Les belles Pap<u>ou</u>**b**oubas arriveront demain.

The beautiful Papouboubas are coming tomorrow

[Speakers CV & LN]

The vowel under study is the /u/ at the end of "Papou" (underlined above – note that /u/ is "ou" in the written form). 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) with the target vowel always located before the prosodic boundary in the sequence /apu # Cu/ (target vowel underlined).

Note that the Syllable sentence context differs for the 3 speakers, due to planning error. For sentence 5a, the pitch accent of the noun phrase "Tonton et Papoubou" is located on the final "-bou", which is adjacent to the syllable under study, "-pou-". This may lead to the target syllable being affected by the pitch accent in the following syllable. By contrast, in sentence 5b, the pitch accent of the noun phrase "Les belles Papouboubas" is located on the final "-bas", which is two syllables away from the target syllable "-pou-", and hence less likely to be affected by the final pitch accent. Furthermore, the target syllable in sentence 5b is the 4th syllable, as is the case for the first 4 sentence stimuli, whereas for sentence 5a, it is the 5th syllable. It is therefore the case that speaker AV's Syllable context is a little less well controlled than the Syllable context for the other two speakers.

Speakers produced 10 repetitions of the corpus, giving a total of approximately 300 utterances. Note however that speaker AV produced about 330 utterances, due to technical difficulties during the recording which required her to repeat sets of sentences; the repeated sentences which were free of technical problems were included in the analysis. 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.[3] 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*

Both acoustic and articulatory data were labelled by the first author using EMU (Cassidy & Harrington, 2001) and the R statistical package (R Development Core Team, 2003). All analyses of the data were carried out using the EMU speech database 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 /pu/ was labelled separately and included as part of the /u/ duration. It should be noted that /p/ is unaspirated in French, and hence its burst is of short duration.

Formants were automatically tracked in EMU using LPC (step size = 5 ms), and hand-corrected. Formant values for the vowel /u/ were extracted at the temporal midpoint of the vowel. Results are presented only for F1 and F2, since F3 and F4 did not seem to provide useful data for /u/ according to prosodic boundary.[4] However, it may be worth noting that F3 tends to vary between 2000 and 2500 Hz for all three speakers studied here.

2.3.2 *Articulatory analysis*

Prior to kinematic labelling, x- and y-data were smoothed using the Loess filter (a regression-based filter with a second-degree polynomial fit) in the R statistical package, with the filter span set to 1/3 the length of the analysis window.

The kinematic signal was examined from a point before the acoustic release of the second /p/ in "Papou" to a point after the acoustic offset of the vowel /u/. The Tongue Back sensor was chosen as the main tongue sensor for the articulatory analyses of /u/ for speakers CV and LN (i.e. this was the sensor that was examined and labelled, and measurements for all other sensors were taken from the time points identified in this sensor signal); however, for speaker AV, the Tongue Dorsum sensor was chosen as the main tongue sensor, because the Tongue Back sensor for this speaker caused problems during the recording.

An interactive program written in R presented the time-course of the sensor movement in the x-y plane for a given utterance/token, with the point of minimum velocity identified by a special symbol. Note that minimum velocity was calculated in the x-y plane (i.e. as a tangential velocity). The labeller (the first author) accepted the automatically calculated minimum velocity point if she believed it was correct, and hand-corrected the point if she believed it was incorrect. During this process, the labeller was aware of the consonant context of the token, but not of the prosodic context. Only a small number of tokens were affected by the hand-correction procedure, and these were mostly Syllable- and Word-boundary tokens where the movement duration was quite short.

The point of minimum tangential velocity was considered the target for the /u/. As mentioned above, this target was located in the Tongue Back signal for speakers CV and LN, and in the Tongue Dorsum signal for speaker AV. Measurement points for the other tongue sensors, for the lips and for the Jaw, were all taken at this same point in time. That is, all articulatory signals were measured at the minimum tangential velocity for the Tongue Back (CV and LN) or the Tongue Dorsum (AV). It should be noted that with this labelling process, x- and y-targets coincide in time.

Traces of the hard palate were also made during the recordings; however, although these traces are shown on the figures presented below, they were not used in the analysis process (e.g. for calculating distance between a tongue sensor and the palate), since a closer examination showed that the traces were not consistently reliable. The palate traces on the figures below are therefore to be used as a guide only (c.f. Hoole & Nguyen 1999).

Finally, the Euclidean distance between the Upper Lip and Lower Lip was calculated at the point of minimum tangential velocity identified in the tongue signal during the interactive labelling process.

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 independent factors. Unless otherwise noted, results are significant at 0.05.[5]

Bonferroni-adjusted posthoc tests of Least Significant Difference (LSD) were also carried out for both independent factors.

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.

Statistical tests of significance and effect-size were carried out using the SPSS software package.

2.4 *Caveat*

In our presentation of results, we will compare the acoustic data with the articulatory data, and we will interpret our articulatory data in light of the acoustic results. However, as will have been noted above, our acoustic data are sampled at the temporal midpoint of the vowel, and our articulatory data are sampled according to standard kinematic measures. Therefore, the acoustic and articulatory data are not sampled at the same point in time. We wished for our articulatory data to be comparable to standard kinematic studies, yet if we sampled our acoustic data at the kinematically defined time-points, our formant results showed too much variability (presumably because the kinematic targets were often located later than the temporal midpoint of the vowel, and hence formant data at this point was too much affected by the transitions into different consonants). For these reasons, no correlations are presented between the articulatory and acoustic data.

We stress that the purpose of our study is not to provide definitive data on articulatory-acoustic relations for /u/; rather, it is to show how the vowel /u/ changes according to prosodic boundary, while at the same time providing preliminary data and generating hypotheses as to the possible articulatory strategies used to achieve a particular acoustic goal.

3. Results

All statistical results are presented in tables in the Appendix. Table A1 gives the results from the 2-way ANOVA according to prosodic boundary; Table A2 gives the results of the eta^2 analysis for prosodic boundary; Table A3 gives the results from the 2-way ANOVA according to consonant context; and Table A4 gives the results from the 2-way ANOVA for the interaction between prosodic boundary and consonant context.

3.1 *Acoustic results*

Table 1 presents descriptive statistics for acoustic vowel duration for each speaker. In line with previous studies, vowel duration is greater before stronger boundaries (up to about 250 ms for the Utterance boundary data) and shorter before weaker boundaries (often less than 100 ms for the Word and Syllable boundary data, which are rarely differentiated by our speakers). Note that the eta^2 analysis shows that prosodic boundary accounts for about 80% of the variance found in the vowel duration data – this is a very strong result, in line with our previous studies of /a/ and /i/. It should also be noted that not all speakers differentiate all boundaries: for instance, while speaker AV differentiates the Intonational phrase boundary from both the Utterance boundary and the Accentual phrase boundary, speaker CV groups the Intonational phrase boundary data with the Accentual phrase boundary data. Finally, a greater duration for the Syllable boundary data than the Word boundary data can be seen for speaker AV – this is most likely due to the problems with the sentence stimulus for the Syllable boundary for this speaker, as mentioned above in the Method section.

TABLE 1

FIGURE 1

Figure 1 presents formant plots for the /u/ vowel at different prosodic boundaries. It can be seen that all three speakers separate the Utterance boundary data from the rest of the vowel data by lowering F1 (significant for all three speakers). Speaker AV further separates the Intonational and Accentual boundaries from the Word and Syllable boundaries with a lower F1 for the Intonational and Accentual boundaries. Prosodic boundary accounts for 45% of the variance in F1 for speaker AV (very strong effect), but only 9-15% of the variance for the other two speakers (weak-medium effect).

By contrast, the effect of prosodic boundary on the variance in F2 is very strong for all three speakers (eta^2 values ranging from 35% for speaker AV to 58% for speaker CV). Speakers AV and LN group the Utterance and

Intonational boundaries together, whereas speaker CV groups the Intonational and Accentual boundaries together. Speakers AV and CV also group the Word and Syllable boundaries together.

It is worth noting that there is a correlation between F1 and F2 for speakers AV and CV (0.403 for speaker AV, significant at 0.01, with d.f. = 1, 336 for a Pearson 2-tailed test; and 0.319 for speaker CV, also significant at 0.01, with d.f. = 1, 298 for a Pearson 2-tailed test). However, there was no significant correlation between F1 and F2 for speaker LN (Pearson 2-tailed test gives a correlation value of 0.047). These results should be kept in mind when examining the articulatory results below.

3.2 *Articulatory results*

Figure 2 presents the Tongue trajectory data for all four sensors, together with the Upper and Lower Lip trajectory data and the Jaw trajectory data. Data are presented for each speaker separately. It should be noted that on the trajectory figures, data are time-normalized and collapsed across consonant contexts.

Figure 3 presents normal distribution plots of the Euclidean distance data for the Lips.

FIGURE 2

FIGURE 3

It can immediately be seen that all three speakers raise and/or back the tongue for the Utterance boundary condition. For speaker AV, the front three sensors are significantly higher and more back in the Utterance condition (the Tongue

Back sensor just missed significance in the x-dimension, but it can be seen in the figure that this sensor is more back for the Utterance boundary). For speaker LN, all four sensors are significantly higher (but not more back) in the Utterance condition. For speaker CV, the Tongue effects are weaker overall; nevertheless, the Tongue Back sensor is significantly lower and more back in the Utterance condition, and the Tongue Tip is significantly more back. Grossly speaking, we can interpret this strategy as aiming to achieve a greater constriction in the velar (or in the case of CV, perhaps uvular) region, thereby lowering the Helmholtz resonance assumed to be associated with F1. Indeed, the formant results observed above (i.e. lowered F1 associated with the Utterance condition) support such an interpretation.

It should also be noted that the only speaker who shows a lowering and backing of the tongue, rather than a raising and backing, is speaker CV (the male speaker). Looking at CV's formant data, we can see that he is the only speaker to show a significant difference in F2 between the Utterance and Intonational boundaries. Thus, we may speculate that the lowering and backing gesture serves the extra purpose of increasing the area and/or length of the front (oral) cavity, thereby lowering F2 for the Utterance boundary. We will consider the possible strategies for manipulating F2 as part of the following description of results, as we exam the Tongue, Lip and Jaw data for all three speakers for all of the prosodic conditions.

We start with speaker AV, whose data are perhaps easiest to interpret. For this speaker, the eta^2 analysis shows very strong effects on the x-dimension for all four Tongue sensors, with strong effects on the y-dimension for the Blade and Tip sensors. By contrast, prosodic boundary has a weak effect on the Jaw and Lip data for this speaker, with the exception of the Upper Lip x-dimension data which show a very clear effect of greater protrusion before stronger prosodic boundaries; however, it should be noted that the effect on Distance between the lips is weak. It therefore appears that speaker AV maintains a relatively constant constriction at the lips, but increases the length of the front resonating cavity, normally associated with F2, as the prosodic boundary becomes stronger. It is this increased cavity size which presumably results in a lower F2, achieved by protruding the Upper Lip, and by backing the Tongue, in particular the Tip and Blade. We should note that lip protrusion may serve to increase the length of the constriction, rather than the length of the cavity, although the effect on the resonance is still to lower it. Thus, not only are the lips protruded in order to lower F2 at its constriction point, but the Tip/Blade is retracted so as to increase the (cross-sectional) area of the resonating cavity, if not its length. This strategy recalls the strategy adopted by speakers in Savariaux et al.'s (1995) study.

By contrast, F1, broadly speaking, appears to be controlled by speaker AV by an overall retraction of the Tongue, with a higher and more back position before stronger prosodic boundaries for all four sensors except the Back, which has a lower and more back position. It appears that the more retracted tongue position decreases the area of the Tongue constriction, thereby lowering the F1 resonance.

The correlation between F1 and F2 for speaker AV may thus be due to the fact that the Tongue Tip and Blade are involved in both cavity enlargement for F2, and in overall Tongue retraction leading to constriction tightening for F1.

A related pattern is observed for speaker CV. For this speaker, the effect on all four Tongue sensors is weak according to the eta^2 analysis, with the exception of the Tongue Tip x-dimension data, on which prosodic boundary has a medium effect. By contrast, prosodic boundary has a medium-strong effect on the Jaw, and a medium-strong effect on the Upper Lip and Lip Distance (the effect on the Lower Lip is weak). We saw above that the Tongue Back is lower and more back for the Utterance boundary, which can be interpreted as resulting in the lower F1 and F2 for this prosodic condition due to a longer F2 resonating cavity, and a tighter F1 constriction (note however that the overall effect of prosodic condition on the Tongue Back is weak). We can see in the figures that the Jaw position is higher and more back at the Utterance boundary, the Tongue Tip is more back, and the Upper Lip is higher and more retracted at the Utterance boundary than at the Intonational phrase boundary (note that this last point contrasts with speaker AV). This strategy can perhaps be interpreted as an overall enlargement of the front resonating cavity designed to lower F2 (similar to the interpretation of the Tongue data for speaker AV). However, speaker CV's lips are not protruded at the Utterance boundary, presumably because the oral cavity is sufficiently enlarged to lower F2 by the retraction of the Tip/Blade (it will be recalled that this was the only speaker with a significantly lower and more retracted Tongue Back in the Utterance condition). The Jaw is higher and more back at the Utterance boundary than in all other prosodic conditions for this speaker. Although it is not clear what the acoustic effect of the Jaw position may be in this case, it is quite likely that the Jaw aids in manoeuvring the Tongue Back into a lower and more retracted position at the Utterance boundary.

Turning to the Intonational phrase boundary data for speaker CV, it can be seen that the Tongue Back is higher and more fronted, and the Tip is also more fronted, in comparison to the stronger Utterance boundary data. The Jaw is lower and more forward. The Upper and Lower Lip are further forward for the

Intonational boundary compared to the Utterance boundary, although Lip Distance remains constant. It is possible that the fronting of the tongue results in both a wider velar/uvular constriction (thereby raising F1), and a concomitant decrease in the oral cavity size (thereby also raising F2). Presumably the increase in F2 by tongue fronting would be too great and would jeopardize vowel recognition in this prosodic context, since speaker CV also protrudes his lips in going from the Utterance to the Intonational boundary condition. This lip protrusion (which we already noted above is not accompanied by a change in lip constriction area) may serve to lengthen the front resonating cavity, and hence prevent F2 from becoming too high.

There is very little change in moving from the Intonational boundary to the Accentual phrase boundary for speaker CV: the Tongue Tip is a little lower (and though not statistically significant, also a little more retracted), and the Dorsum is more forward. The Jaw is higher than in the Intonational boundary condition, though not as high as in the Utterance boundary condition. Although the Upper Lip is a little lower in the Accentual boundary condition, there is no significant effect on Lip Distance. The net effect of these articulatory changes appears to be negligible, since there is minimal change in F1 and F2 between the Intonational and Accentual phrase boundaries. This suggests that slightly different articulatory strategies may be used at different prosodic boundaries without significantly affecting the acoustics

The Word boundary data for speaker CV show a lower Dorsum and a more forward Tip than the Accentual boundary data. The Jaw is lower and more forward. Importantly, there is a decrease in Lip Distance, apparently achieved by raising the Lower Lip and lowering the Upper Lip. The Upper Lip is also less protruded at the Word boundary than at the Accentual boundary. Since the difference between the Accentual and Word boundaries is primarily in F2, we can infer that the decrease in oral cavity size due to the less protruded lips and/or the more forward Tip is the main cause of the higher F2. The role of the Jaw and the Dorsum are less clear. However, the lower Dorsum may serve to counter-act some of the effect of the less protruded lips and more forward Tip by preventing the oral cavity from becoming too small. The decreased Lip Distance may serve the same purpose, since by decreasing the area of the lip constriction, F2 is prevented from becoming too high.

Finally for speaker CV, we turn to the Syllable boundary data. For this speaker, the Dorsum and Blade are more back and higher than in the Word boundary position (and though not statistically significant, the Tip is also more back). The Jaw is more forward in this condition (in fact, the most forward of all the prosodic conditions except Word for this speaker). Both the Upper and the Lower Lips are less protruded than in the Word condition, and the Upper Lip is lower. However, there is no change in Lip Distance compared to the Word boundary data. Importantly, these articulatory changes once again have minimal effect on the acoustic output. Presumably the slightly more back tongue position is matched by the slightly less protruded lips.

For speaker CV we have thus seen a very complex interplay between tongue and lips to achieve the same acoustic pattern as we observed for speaker AV. However, for speaker CV, the eta^2 analysis suggests an important role for the Jaw, rather than the Tongue (whereas the opposite was true for speaker AV). It is not clear how best to account for this discrepancy. We had suggested that the Jaw was instrumental in helping achieve the especially retracted and lowered tongue position in speaker CV's Utterance boundary data, but for the other prosodic conditions it seemed simply to help bring the tongue forward compared to the Utterance boundary condition.

However, perhaps a more important role for the Jaw can be suggested. It should be noted that the Jaw trajectories for speaker CV vary by about 2 cm x 10^{-1} on the x-dimension, and by about 4 x 10^{-1} on the y-dimension; whereas for speaker AV, the Jaw trajectories vary by about 5 cm x 10^{-2} on the x-dimension, and by about 1 x 10^{-1} on the y-dimension. These differences are unlikely to be due only to gender. In particular, the fact that prosodic boundary accounts for about 25% of the variance in Jaw y-dimension data for speaker CV motivated us to explore the possible role of Jaw Height a little further, using modelled articulatory-to-acoustic data.

To do this, we examined nomograms and transfer functions of /u/ articulations, based on a "natural" /u/ articulation produced by an adult male French speaker as part of a larger set of Magnetic Resonance Imaging (MRI) recordings (for some details on the original MRI data, see Badin, Bailly, Revéret, Baciu, Segebarth & Savariaux 2002; and for details on the midsagittal articulatory-to-acoustic modelling, see Beautemps, Badin & Bailly 2001).[6] The nomograms showed midsagittal contours of the oral cavity as a function of Jaw Height, with a tongue pivot point in the uvular region (i.e. as the tongue body became higher, the tongue root became more forward). The transfer functions showed that a variation in Jaw Height of 4 x 10^{-1} cm can have quite a large acoustic effect: about 25-30 Hz on F1, and about 110-270 Hz on F2 (the exact magnitude of the effect depending on the absolute Jaw Height for the speaker). This modelled result is comparable to the effect of prosodic boundary on F1 and F2 for speaker CV (see Figure 1). Of course, we have not separated the effects of Jaw Height from overall Tongue height (and have also not considered the effects of Jaw Height on overall spectral amplitude), but we hope that this description has shown that it is quite possible for Jaw Height to contribute significantly to the overall spectral timbre of /u/.

We turn finally to speaker LN. The eta^2 analysis suggests that there is a very strong effect of prosodic boundary on the variance of the Dorsum and Blade y-dimension data for this speaker, as well as on Lip Distance. There is a strong effect on the Tongue Back (y-dimension, and almost strong on the x-dimension), as well as on the Tip x-dimension and on Lower Lip y-dimension. All other sensors/dimensions show medium effects. The reader is reminded that this is the speaker for whom no correlation was found between F1 and F2.

We noted above that this speaker shows a very high Tongue position at the Utterance boundary, which, we argued, has the effect of lowering F1. For the weaker Intonational boundary data, the Tongue and Jaw are lowered. The Upper Lip is raised and protruded, but with no apparent effect on Lip Distance. The change in Upper Lip position does not appear to have a significant effect on F2, while the lowered Tongue and Jaw presumably serve to increase F1 as the constriction becomes wider. It should be noted, however, that F2 is slightly lower in the Intonational boundary data than the Utterance boundary data, presumably due to the change in Upper Lip position and perhaps to an increase in cavity size due to the lower Tongue.

For the Accentual boundary data, all four Tongue sensors are significantly more forward than in the Intonational boundary condition, although the Jaw is more back. The Tongue Dorsum and Blade are lower, and the Upper and Lower Lips are less protruded for the Accentual boundary. The Lower Lip is higher in the Accentual boundary condition than in the Intonational boundary condition, and this is accompanied by a decrease in Lip Distance. Since there is a statistically significant increase in F2 for the Accentual phrase boundary, we may assume that the more forward tongue body and the less protruded lips serve to decrease the size of the resonating oral cavity. The increase in F2 is not very large, however, and this is perhaps due to the decreased Lip Distance observed.

Perhaps unexpectedly, for the Word boundary data, all four Tongue sensors are significantly more back (rather than more forward) than in the Accentual boundary condition. The Tongue Back sensor is lower, while the Dorsum and Blade sensors are higher. The Jaw is lower and more forward. It may also be noted on speaker LN's Jaw trajectory that there is minimal movement in the Jaw for the Word and Syllable boundaries, compared to the other prosodic boundaries. The Upper Lip is less protruded and lower, while the Lower Lip is more protruded and higher, with yet another resultant decrease in Lip Distance. It can be seen on the formant plot that F1 is a little bit lower (though not significantly), and F2 a good deal higher, at the Word boundary in comparison to the Accentual boundary. However, the more back Tongue position, as well as the decreased Lip Distance, should in principle serve to lower F2, rather than raise it, due to a narrower constriction at the Lips and increased cavity size. Given the increase in F2, we may tentatively hypothesize that the cavity and constriction area are not as important as the cavity and constriction length. If we examine the Upper and Lower Lip data for speaker LN (Figure 2), we can see that for the Word boundary data, the Upper and Lower Lip have relatively similar x-coordinates, suggesting a reduced constriction length. It may be noted, however, that the Upper and Lower Lip x-coordinate values are also similar for the Utterance boundary condition, suggesting that a decrease in the length of the lip constriction may not provide the entire answer to the increase in F2 at the Word boundary for this speaker.

We may also, again very tentatively, speculate on the length of the front resonating cavity. At around the Tongue Dorsum sensor, it is not very clear where the F2 resonating cavity ends, and the F1 constriction begins. By speculating that the raised Tongue Dorsum for the Word boundary serves to decrease the length of the front resonating cavity, we may have found another source of the increased F2 at the Word boundary for this speaker.

Turning finally to the Syllable boundary data for speaker LN, the only significant difference we see in the Tongue data is in the y-dimension of the Tip sensor, with a higher position for the Syllable boundary than the Word boundary. The Jaw is higher and more back. Both the Upper and Lower lips are lower, and the Lower Lip is less protruded; however, there is no significant difference in Lip Distance. Although there is a slight (non-significant) decrease in F1, there is a significant increase in F2 between the Word and Syllable boundaries. As was the case for the Word boundary data, it is not clear what aspects of the articulation at the Syllable boundary serve to increase F2 for this speaker.

3.3 *Acoustic and articulatory results according to consonant context.*

The results from the 2-way ANOVA according to consonant context are presented in Table A3 in the Appendix. An examination of these results shows that effects are consistent with standard results on the effects of consonant context on the various speech articulators (e.g. Keating, Lindblom, Lubker & Kreiman 1994; Recasens 1999). However, the variety of effects from the different consonants on the different articulators suggests that the varied consonant contexts in the present study may be useful in bringing out more clearly the features of /u/ regardless of consonant context. It is difficult to design a study of /u/ where consonant context does not interfere: if a labial context is chosen, this interferes with lip-rounding, whereas if a lingual consonant context is chosen, this interferes with the tongue gesture in different ways depending on whether the consonant is articulated with the tip, blade or dorsum. The different consonant contexts in our study therefore serve as a useful sort of "noise", through which the properties of /u/ which are consistent across consonant contexts may be seen to emerge. However, we do recognize that our preceding consonant context is always bilabial.

Table A4 in the appendix presents results from the 2-way ANOVA showing the interaction between prosodic boundary and consonant context. It can be seen that 29 of the 54 results presented are not statistically significant. Overall, speaker AV has the fewest significant interactions (5 significant out of 18), and speaker LN has the most significant interactions (12 out of 18). It is worth noting that the interaction is significant for all three speakers for F2, the Tongue Dorsum x-dimension, and the Tongue Blade y-dimension. It is not significant for all three speakers for Acoustic Duration, Tongue Back x-dimension and Upper Lip x-dimension. It is perhaps not a coincidence that the two articulatory measures which show the least interaction between consonant context and prosodic boundary are precisely the ones that are most likely to be recruited in /u/ articulation (i.e. the Upper Lip and the rear-most portion of the tongue), while the acoustic measure which shows the least interaction is the one that is most affected by prosodic boundary (i.e. duration). However, we acknowledge that it is difficult to make firm conclusions based on only three speakers.

4. Discussion

4.1. *Summary*

We have seen that the three French speakers of this study achieve remarkably similar acoustic results for /u/ in different positions of the prosodic hierarchy. Broadly speaking, both F1 and F2 become lower before stronger prosodic boundaries; however, the Utterance boundary has a particularly strong effect on F1, and this marked lowering is achieved by a pronounced raising and/or backing of the tongue in the velar/uvular region. It would appear that the parameter of vowel height is a particularly important one to highlight at this strongest of boundary positions.

For the other prosodic boundaries, there is an inter-play between tongue lowering/fronting and lip protrusion and constriction. A particularly interesting observation was that the speakers at times seemed to use the tip of the tongue to manipulate the F2 cavity. Whilst it is possible that this movement may be a concomitant of the overall tongue movement - and whilst it is also possible that the acoustic effect of the tongue tip movement is relatively minor compared to the effect of the lip movement - it is nevertheless the case that the differences in tongue tip data were significant between prosodic boundaries for all three speakers on different occasions. The possibility that the tongue tip, in addition to the tongue back and the lips, is recruited in the production of the /u/ vowel cannot be discounted.

The present paper also contributes to our understanding of domain-final vowel articulations with regard to temporal and spatial expansion. Although it was once believed that domain-final vowel articulations showed temporal expansion (i.e. longer durations) but not spatial expansion (i.e. articulatory expansion – c.f. Beckman, Edwards & Fletcher 1992), the present study shows that this is not the case, since all speakers showed a more peripheral tongue position at the Utterance boundary (in line with ours and Cho's previous studies on /i/ and /a/). Moreover, this point regarding articulatory expansion is important in an understanding of the phonetics/prosody interface, since it shows that not only domain-initial, but domain-final articulations are subject to articulatory expansion (c.f. Fougeron & Keating 1997).

4.2 *The interaction of compensatory articulation, neutralization avoidance and featural enhancement.*

Perhaps the most surprising finding in the present study is that lip constriction becomes tighter before weaker prosodic boundaries, rather than before stronger prosodic boundaries. We suggested that this strategy was adopted by speakers in order to prevent F2 from becoming too high, since a higher F2 may result in the percept of /y/.

However, it is also possible that reduced lip constriction at the weaker boundaries is due to greater coarticulation with the preceding bilabial stop. Whilst we do not completely discount this possibility, there are two factors which suggest that this explanation is unlikely. Firstly, the current results recall previous results presented by Lubker & Gay (1982) showing that speakers of Swedish, which has front rounded vowels, control the degree of vowel rounding quite precisely when compared with speakers of American English, which does not have front rounded vowels. In addition, our previous results showing that French speakers actively control F3 for /i/ in order to keep it distinct from /y/ suggest that a similar strategy of /y/-avoidance may be at play for French /u/.

Our second reason for discounting the greater /b/ coarticulation hypothesis before weaker prosodic boundaries lies in recent results presented in Tabain (submitted) for Australian English speakers' productions of the high central rounded vowel /ʉ/. This vowel lies somewhere between French /y/ and /u/, and is the only high rounded vowel in Australian English:[7] it has an F2 value of around 1800-2000 Hz, compared to the French vowel which has an F2 of around 600-800 Hz. Since English does not have a high front rounded vowel, it can be argued, English speakers are under no constraint to maintain a low F2 for the high back vowel. Of relevance here is that the articulatory results on Australian English /ʉ/ show that there is no effect of prosodic boundary on Lip Distance whatsoever; that is, there is no greater lip constriction before weaker prosodic boundaries, and also no greater lip constriction before stronger prosodic boundaries. The English speakers do not control Lip Distance according to prosodic boundary, despite showing changes in tongue position according to prosodic boundary. Importantly, the stimuli in the English study were similar to the French stimuli presented here: that is, the target vowel was preceded by a bilabial consonant, and followed by one of the six different obstruent consonants used here. We therefore believe that French speakers do control their lip gesture at weaker prosodic boundaries in order to keep F2 low.

Our French results also recall Savariaux et al.'s (1995) results for French /u/, in that we observe compensatory strategies adopted by our French speakers in order to maintain a lower F2. This adds extra support to Savariaux et al.'s argument that the mental representation of speech sounds is an acoustic/perceptual one, rather than an articulatory one. We also see some differences between speakers in terms of which articulator plays a more important role in achieving the acoustic goal (c.f. de Jong 1997): for instance, speakers AV and LN have clearer effects on the Tongue, while speaker CV has clearer effects on the Jaw. However, all French speakers seem to use the Lips in some crucial way.

An important criticism of our explanation for the Lip Distance results was succinctly provided by an anonymous reviewer: "the /i/ results illustrate a contrast enhancement at greater boundaries, but the results here seem to suggest neutralization avoidance at weaker boundaries". In reply, we point out that in the current study, we examine a speech sound which requires simultaneous control of two different articulatory sub-systems: the lips and the tongue. As discussed in the Introduction section, it is well known that there are trading relations (compensation strategies) in the articulation of rounded vowels, and it is perhaps not surprising that such strategies should be manifested in a special way according to prosodic boundary.

In summary, and in line with Manuel (1990), speakers will manipulate articulation to avoid perceptual confusion in their language. Based on the present study, and on Tabain & Perrier (2005), it is clear that French speakers' articulations of /i/ and /u/ are constrained by the presence of the comparatively rare phoneme /y/ in their vowel inventory. For /u/ in particular, the inter-play between lip rounding and tongue constriction (both degree and location) is especially complex given this constraint. Although we have not been able to provide a full explanation for all of the articulatory strategies observed here, we hope that our results will provoke further study of the less well-understood rounded vowels.

[1] In fact, since French is not a stress language, it is not possible for us to manipulate stress in the same way Perkell et al. and de Jong did. However, both languages have a prosodic structure which can be manipulated as is done here.

[2] 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.

[3] A small number of Utterance boundary tokens were produced without a pause (2 for speaker CV). These utterances were excluded from the statistical analysis.

[4] RMS energy was also examined in this study. However, there appeared to be no consistent pattern across prosodic boundaries; moreover, there appeared to be no clear relationship between RMS energy and lip constriction area. For these reasons, RMS data will not be reported here.

[5] It should be noted that we did not use a Repeated Measures ANOVA, because we believe such an ANOVA is not appropriate for studies of speech articulation, where opposite strategies can be adopted by different speakers for the same acoustic goal. Consequently, our data are not corrected for sphericity violations, and ANOVAs all have high degrees of freedom. The effect size measure eta^2, described next, was carried out in order to compensate for these problems.

[6] We are extremely grateful to Pierre Badin for providing these MRI data and models for us.

[7] Indeed, the (tense) high back rounded vowel /u/ has become centralized to /ʉ/ in several varieties of English. Affected varieties include Australian English (Cox 1996), Californian English (Ladefoged 1999, 2001), New Zealand English (Watson, Harrington & Evans 1998) and Standard Southern British English (Hawkins & Midgley 2005).

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Figure captions.

Figure 1: Ellipses showing F1 and F2 (in Hertz) for the /u/ vowel in each prosodic context for each speaker (colour online). Data are sampled at the acoustic midpoint of the vowel. Only the mean values for each prosodic context are shown, with each ellipse containing 2.45 standard deviations around the mean.

Figure 2: Plots of averaged Tongue trajectories (right), averaged Upper and Lower Lip trajectories (left), and averaged Jaw trajectories (middle) for the vowel /u/ at different prosodic boundaries (colour online). Data are presented separately for each speaker. All four tongue sensors are shown on the Tongue plots, and a palate trace is provided for each speaker. Data are collapsed across consonant contexts and time-normalized for plotting purposes, with each trajectory showing 20 points equi-distant in time. The beginning of each trajectory, marked “S”, is taken at the acoustic release of the /p/ in /apu #/, and the end of each trajectory is taken at the acoustic endpoint of the vowel. Note that /u/ at the Utterance boundary is followed by a pause, whereas at the other boundaries it may be followed by one of 6 different consonants. Units on both the x- and y-axes are in cm from the reference transducer. Note that the scales differ for the Tongue, Lip and Jaw trajectory plots.

Figure 3: Normal distribution plots for Euclidean distance between the Upper and Lower Lips (in cm), according to prosodic boundary, for three speakers of French (colour online). The data are sampled at the time-point identified as the target in the Tongue Back (CV and LN) or Tongue Dorsum (AV) trajectories. Each curve contains all the data points for a given prosodic context and speaker.

Table

		Mean	S.D.	N.
AV	**U**	223	27.6	65
	I	148	29.4	68
	A	112	19.2	69
	W	92	15.7	67
	S	102	18.2	67
CV	**U**	166	24.1	61
	I	144	17.0	61
	A	140	21.0	61
	W	84	13.3	60
	S	82	8.4	60
LN	**U**	210	21.9	60
	I	198	34.5	60
	A	158	25.4	61
	W	98	15.9	61
	S	97	14.7	61

Table 1: Descriptive statistics for acoustic vowel duration (in milliseconds) according to prosodic boundary for 3 speakers of metropolitan French. In this and in following tables: "U" = Utterance; "I" = Intonational phrase; "A" = Accentual phrase; "W" = Word; and "S" = "Syllable".

	AV d.f. = 3, 335	CV d.f. = 3, 297	LN d.f. = 3, 302
Acoustic Duration	110.08	249.14	312.47
F1	14.56	2.10 N.S.	0.99 N.S.
F2	42.16	79.95	78.85
Back X	24.46	1.44 N.S.	23.39
Back Y	4.75	0.931 N.S.	19.55
Dorsum X	33.77	10.81	20.74
Dorsum Y	2.42	6.31	22.54
Blade X	52.85	4.65	20.54
Blade Y	21.98	4.72	50.40
Tip X	38.59	12.29	55.34
Tip Y	19.25	5.20	10.28
Jaw X*	3.03 N.S.	16.07	34.29
Jaw Y*	12.52	15.92	8.92
Upper Lip X	23.05	33.29	28.29
Upper Lip Y	14.14	44.67	31.70
Lower Lip X	10.26	11.69	35.95
Lower Lip Y	3.91	10.55	25.16
Lip Distance	5.57	34.37	51.42

Table A1a: Results from a 2-way ANOVA with prosodic boundary and consonant context as independent factors, with p set at 0.05. The value given in the table is the F-ratio. Only results for the prosodic boundary are reported in this table. All results are significant unless indicated otherwise. Acoustic measures are given in the top part of the table, and articulatory measures in the bottom part of the table (separated by a double line).

*Note that significance levels are halved for the Jaw results, since movement in the x- and y-planes is correlated for this articulator.

	AV	CV	LN
Acoustic Duration	U > I	U > I	U > I
	U > A	U > A	U > A
	U > W	U > W	U > W
	U > S	U > S	U > S
	I > A	I = A	I > A
	I > W	I > W	I > W
	I > S	I > S	I > S
	A > W	A > W	A > W
	A > S	A > S	A > S
	W < S	W = S	W = S
F1	U < I	U < I	U < I
	U < A	U < A	U < A
	U < W	U < W	U < W
	U < S	U < S	U < S
	I = A	I = A	I = A
	I < W	I = W	I = W
	I < S	I = S	I = S
	A < W	A = W	A = W
	A < S	A = S	A = S
	W = S	W = S	W = S
F2	U = I	U < I	U = I
	U < A	U < A	U < A
	U < W	U < W	U < W
	U < S	U < S	U < S
	I < A	I = A	I < A
	I < W	I < W	I < W
	I < S	I < S	I < S
	A < W	A < W	A < W
	A < S	A < S	A < S
	W = S	W = S	W < S
Back X	U = I	U > I	U = I
	U > A	U > A	U > A
	U > W	U > W	U > W
	U > S	U = S	U = S
	I > A	I = A	I > A
	I > W	I = W	I > W
	I > S	I = S	I = S

	A = W A = S W = S	A = W A = S W = S	A < W A < S W = S
Back **Y**	U = I U < A U < W U < S I < A I < W I < S A = W A = S W = S	U < I U < A U = W U < S I = A I = W I = S A = W A = S W = S	U > I U = A U > W U > S I = A I > W I > S A > W A > S W = S
Dorsum **X**	U > I U > A U > W U > S I > A I > W I > S A = W A = S W = S	U = I U > A U > W U = S I > A I > W I = S A = W A < S W < S	U = I U > A U = W U = S I > A I = W I = S A < W A < S W = S
Dorsum **Y**	U > I U > A U > W U > S I = A I = W I = S A = W A = S W = S	U = I U = A U > W U = S I = A I > W I = S A > W A = S W < S	U > I U > A U > W U > S I > A I = W I < S A < W A < S W = S
Blade **X**	U > I U > A U > W U > S I > A	U = I U = A U > W U = S I = A	U = I U > A U = W U = S I > A

	I > W I > S A = W A = S W = S	I > W I = S A = W A = S W < S	I = W I = S A < W A < S W = S
Blade **Y**	U > I U > A U > W U > S I > A I > W I > S A = W A = S W = S	U = I U = A U > W U = S I = A I > W I = S A = W A = S W < S	U > I U > A U > W U > S I > A I > W I > S A < W A < S W = S
Tip **X**	U > I U > A U > W U > S I > A I > W I > S A > W A > S W = S	U > I U = A U > W U > S I = A I > W I = S A > W A > S W = S	U = I U > A U = W U < S I > A I = W I = S A < W A < S W = S
Tip **Y**	U > I U > A U > W U > S I > A I > W I > S A = W A = S W = S	U = I U = A U = W U = S I > A I = W I = S A = W A = S W = S	U > I U > A U > W U > S I = A I = W I < S A = W A < S W < S
Jaw* **X***	U = I U = A U = W	U > I U > A U > W	U = I U < A U = W

	U = S I = A I = W I > S A = W A = S W = S	U > S I > A I = W I > S A > W A > S W = S	U = S I < A I > W I = S A > W A > S W < S
Jaw* **Y***	U = I U = A U = W U = S I > A I > W I > S A = W A = S W = S	U > I U > A U > W U > S I < A I = W I = S A > W A > S W = S	U > I U = A U > W U > S I = A I > W I = S A > W A = S W < S
Upper Lip **X**	U = I U < A U < W U < S I < A I < W I < S A < W A < S W = S	U > I U > A U > W U = S I = A I < W I < S A < W A < S W < S	U > I U = A U = W U = S I < A I < W I < S A < W A < S W = S
Upper Lip **Y**	U = I U = A U > W U = S I = A I > W I = S A > W A = S W < S	U > I < A > W > S U = A U > W U > S I < A I = W I > S A > W A > S W > S	U < I U = A U = W U > S I = A I > W I > S A > W A > S W > S
Lower Lip	U = I	U > I	U = I

X	U = A	U > A	U < A
	U = W	U = W	U = W
	U > S	U = S	U < S
	I = A	I = A	I < A
	I = W	I = W	I = W
	I > S	I < S	I < S
	A = W	A = W	A > W
	A = S	A < S	A = S
	W > S	W < S	W < S
Lower Lip	U = I	U = I	U = I
Y	U = A	U = A	U < A
	U = W	U = W	U < W
	U < S	U = S	U < S
	I = A	I = A	I < A
	I = W	I < W	I < W
	I < S	I < S	I < S
	A = W	A < W	A < W
	A = S	A < S	A = S
	W = S	W = S	W > S
Lip	U = I	U = I	U = I
Distance	U > A	U = A	U = A
	U > W	U > W	U > W
	U = S	U > S	U > S
	I > A	I = A	I = A
	I > W	I > W	I > W
	I = S	I > S	I > S
	A = W	A > W	A > W
	A = S	A > S	A > S
	W = S	W = S	W = S

Table A1b: Results from LSD posthoc tests based on Table A1a ('>' and '<' are greater and less than, respectively; and '=' indicates no significant difference). The significance level is adjusted to 0.005 for the posthoc tests, following the Bonferroni method. Posthoc tests were conducted even where the main test failed to reach significance.

*Note that significance levels are halved for the Jaw results, since movement in the x- and y-planes is correlated for this articulator.

	AV	CV	LN
Acoustic Duration	.814	.789	.807
F1	.454	.093	.151
F2	.349	.578	.414
Back X	.315	.053	.196
Back Y	.090	.045	.222
Dorsum X	.427	.067	.149
Dorsum Y	.056	.030	.439
Blade X	.478	.031	.151
Blade Y	.256	.024	.400
Tip X	.329	.111	.263
Tip Y	.297	.023	.133
Jaw X	.030	.137	.170
Jaw Y	.089	.257	.140
Upper Lip X	.209	.176	.159
Upper Lip Y	.082	.259	.157
Lower Lip X	.043	.066	.128
Lower Lip Y	.025	.050	.258
Lip Distance	.064	.142	.339

Table A2: Results from an eta^2 analysis for the acoustic and articulatory measures presented in Table I. The independent factor is prosodic boundary.

	AV d.f. = 6, 335	CV d.f. = 6, 297	LN d.f. = 6, 302
Acoustic Duration	25.64	1.19 N.S.	12.05
F1	3.44	2.22 N.S.	3.42
F2	10.67	7.38	15.72
Back X	4.28	27.91	14.59
Back Y	9.34	30.38	7.02
Dorsum X	13.85	64.33	12.37
Dorsum Y	50.89	115.14	55.00
Blade X	18.71	53.50	25.31
Blade Y	86.91	152.68	67.18
Tip X	39.52	44.85	31.75
Tip Y	27.09	83.00	100.09
Jaw X*	8.10	63.25	43.06
Jaw Y*	6.63	67.56	3.42
Upper Lip X	13.89	66.70	38.41
Upper Lip Y	36.94	37.36	40.75
Lower Lip X	76.51	66.10	91.05
Lower Lip Y	51.92	60.78	2.65
Lip Distance	18.67	72.53	13.76

Table A3a: Results from a 2-way ANOVA with prosodic boundary and consonant context as independent factors, with p set at 0.05. The value given in the table is the F-ratio. Only results for the <u>consonant context</u> are reported in this table. All results are significant unless indicated otherwise. Acoustic measures are given in the top part of the table, and articulatory measures in the bottom part of the table (separated by a double line).

*Note that significance levels are halved for the Jaw results, since movement in the x- and y-planes is correlated for this articulator.

** Note also that for the purposes of the main ANOVA, the pause following the Utterance boundary was treated as a consonant. However, this pause was not examined in the post-hoc tests.

	AV	**CV**	**LN**
Acoustic Duration	b < d b < f b < s b < S d < f g < d g < f g < s g < S s < f	N.S.	b < g d < g f < g s < g S < g
F1	b < g f < g	N.S.	d < b d < S
F2	b < s b < S f < d f < g f < s f < S	g < d g < s f < b f < d f < s S < s	b < d b < s g < d g < s f < d f < s S < d S < s
Back X	f < b s < b s < d	b < S d < b d < f d < S g < s g < S f < S s < f s < S	d < g d < f s < b s < d s < g s < f s < S S < g
Back Y	b < f b < s g < d g < f g < S S < s	b < S d < b d < f d < s d < S g < f	d < b d < S g < b g < s g < S s < S

		g < S f < S s < S	
Dorsum X	d < b d < f g < b g < f g < S s < b s < f s < S	b < f b < S d < b d < f d < S g < b g < s g < S f < S s < f s < S	d < s d < S s < b s < g s < f s < S S < b
Dorsum Y	d < b d < f d < s d < S g < b g < f g < s g < S s < f s < S	b < S d < b b < f d < g d < f d < s d < S g < b g < f g < S f < S s < f s < S	b < S d < b d < f d < S g < b g < f g < s g < S f < S s < f S < b
Blade X	g < b g < f g < S s < b s < d s < f s < g s < S S < d	b < S d < b d < f d < S g < b g < f g < S f < S s < b s < f s < S	b < S d < S g < S f < S s < b s < d s < g s < f s < S

Blade **Y**	b < f b < S d < b d < f d < S g < b g < d g < f g < S f < S s < b s < f s < S	b < S d < b d < f d < s d < S g < b g < f g < s g < S f < S s < S	b < S d < b d < f d < S g < b g < s g < S f < S s < b s < f s < S
Tip **X**	d < b d < f g < b s < b s < d s < f s < g s < S S < d	d < b d < g d < f d < S g < b g < f g < S s < b s < f s < S S < f	b < S d < S g < S f < S s < b s < d s < g s < f s < S
Tip **Y**	b < f b < S d < f d < S g < b g < d g < f g < s g < S f < S s < f s < S	b < S d < S g < b g < d g < f g < s g < S f < S s < S	b < S d < S g < b g < S f < S s < b s < f s < S
Jaw* **X***	b < f d < f	b < f d < f	b < d b < f

	g < f s < f S < f	g < f s < f S < b S < d S < g S < f S < s	b < s g < d g < f s < d S < b S < d S < g S < f S < s
Jaw* Y*	b < S f < d f < g f < S	b < d b < s b < S d < s d < S g < b g < d g < f g < s g < S f < s f < S	
Upper Lip X	b < f d < f g < f s < f S < f	b < g d < g f < g s < d s < g s < f S < b S < d S < g S < f S < s	b < f b < s d < f g < f s < f S < f S < s
Upper Lip Y	b < f d < f g < b g < f s < b s < d	b < S d < S g < f g < s g < S f < S	b < S d < b d < g d < f d < S g < S

	s < f s < g s < S S < b S < f	s < S	f < S s < b s < g s < f s < S
Lower Lip X	b < f d < f g < f s < f S < f S < s	b < g b < f b < s d < f g < f s < f S < b S < d S < g S < f S < s	b < d b < g b < f b < s d < f g < f s < f S < d S < f S < s
Lower Lip Y	b < f d < f g < f s < f S < f	b < d b < f d < f g < f s < f S < b S < d S < g S < f S < s	g < f
Lip Distance	g < d g < S f < b f < d f < g f < s f < S s < b s < d s < S	b < S d < b d < s d < S g < b g < s g < S f < b f < s f < S s < S	b < S d < g d < S f < g f < S s < g s < S

Table A3b: Results from LSD posthoc tests based on Table A3a. The significance level is adjusted to 0.0033 for the posthoc tests, following the Bonferroni method. Posthoc tests were not conducted when the main test failed to reach significance (marked "N.S."). Note that for the articulatory data, a lower value in the x-dimension denotes a more forward articulation, and in the y-dimension, denotes a lower articulation.

*Note that significance levels are halved for the Jaw results, since movement in the x- and y-planes is correlated for this articulator.

** Note also that for the purposes of the main ANOVA, the pause following the Utterance boundary was treated as a consonant. However, this pause was not examined in the post-hoc tests.

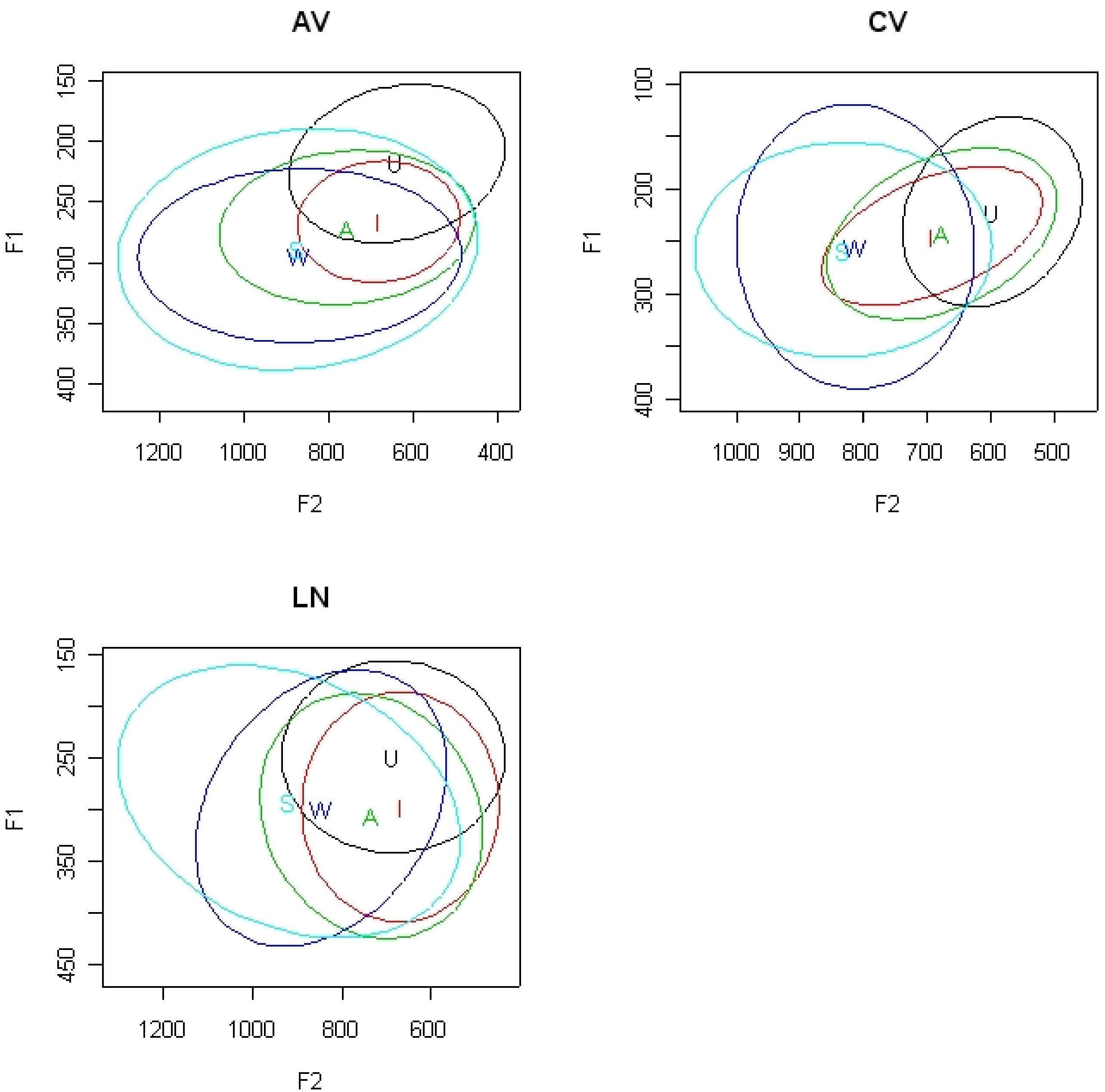
	AV d.f. = 15, 335	CV d.f. = 15, 297	LN d.f. = 15, 302
Acoustic Duration	1.31 N.S.	1.05 N.S.	0.97 N.S.
F1	1.06 N.S.	0.66 N.S.	1.77
F2	2.46	2.71	3.76
Back X	1.05 N.S.	1.53 N.S.	0.97 N.S.
Back Y	0.75 N.S.	0.96 N.S.	1.93
Dorsum X	2.08	2.25	1.83
Dorsum Y	1.49 N.S.	1.75 N.S.	2.44
Blade X	1.60 N.S.	2.80	2.16
Blade Y	3.20	2.10	3.12
Tip X	1.48 N.S.	2.00	2.34
Tip Y	1.07 N.S.	1.13 N.S.	3.44
Jaw X*	0.68 N.S.	1.95	2.08
Jaw Y*	1.57 N.S.	1.66 N.S.	1.94
Upper Lip X	1.26 N.S.	1.47 N.S.	1.28 N.S.
Upper Lip Y	2.45	1.32 N.S.	1.55 N.S.
Lower Lip X	1.07 N.S.	1.04 N.S.	4.27
Lower Lip Y	2.81	1.82	0.93 N.S.
Lip Distance	1.12 N.S.	2.22	0.76 N.S.

Table A4: Results from a 2-way ANOVA with prosodic boundary and consonant context as independent factors, with p set at 0.05. The value given in the table is the F-ratio. Only results for the interaction between consonant context and prosodic boundary are reported in this table. All results are significant unless indicated otherwise. Acoustic measures are given in the top part of the table, and articulatory measures in the bottom part of the table (separated by a double line).

* Note that significance levels are halved for the Jaw results, since movement in the x- and y-planes is correlated for this articulator.

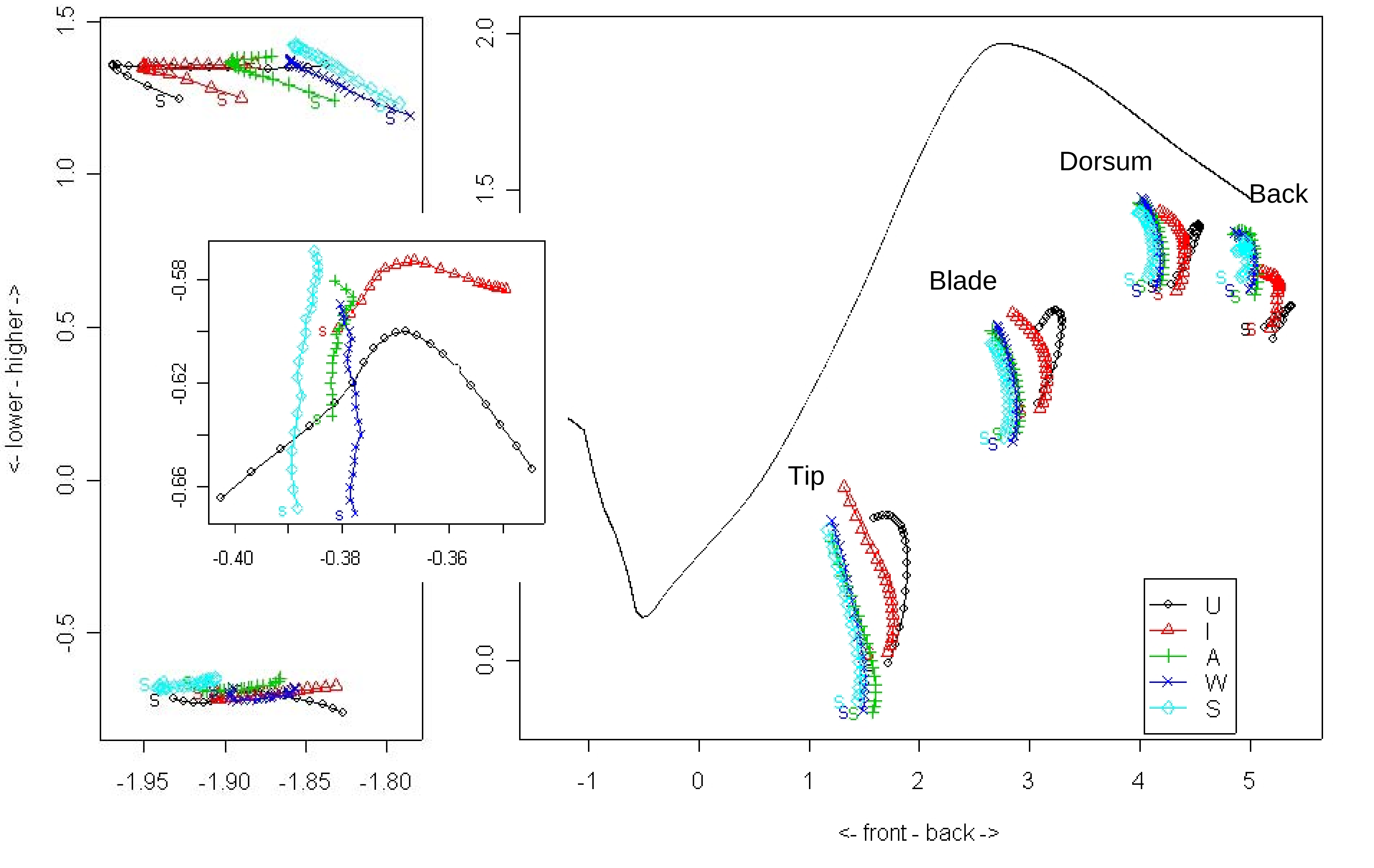
** Note also that for the purposes of the ANOVA, the pause following the Utterance boundary was treated as a consonant.

Figure

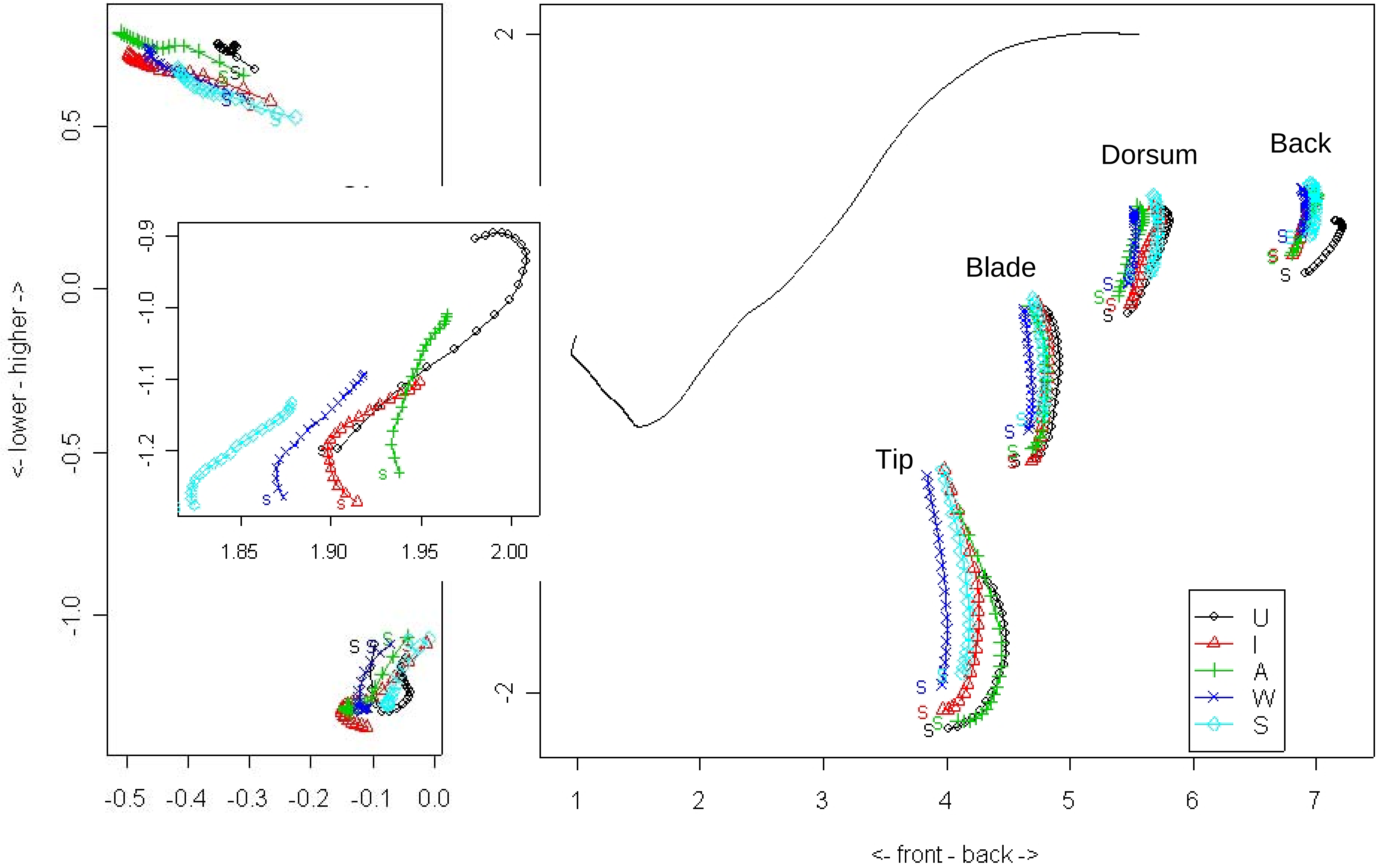


AV
CV
LN
F1
F2
150
200
250
300
350
400
1200
1000
800
600
400
U
A
I
S
W
100
900
700
500
450

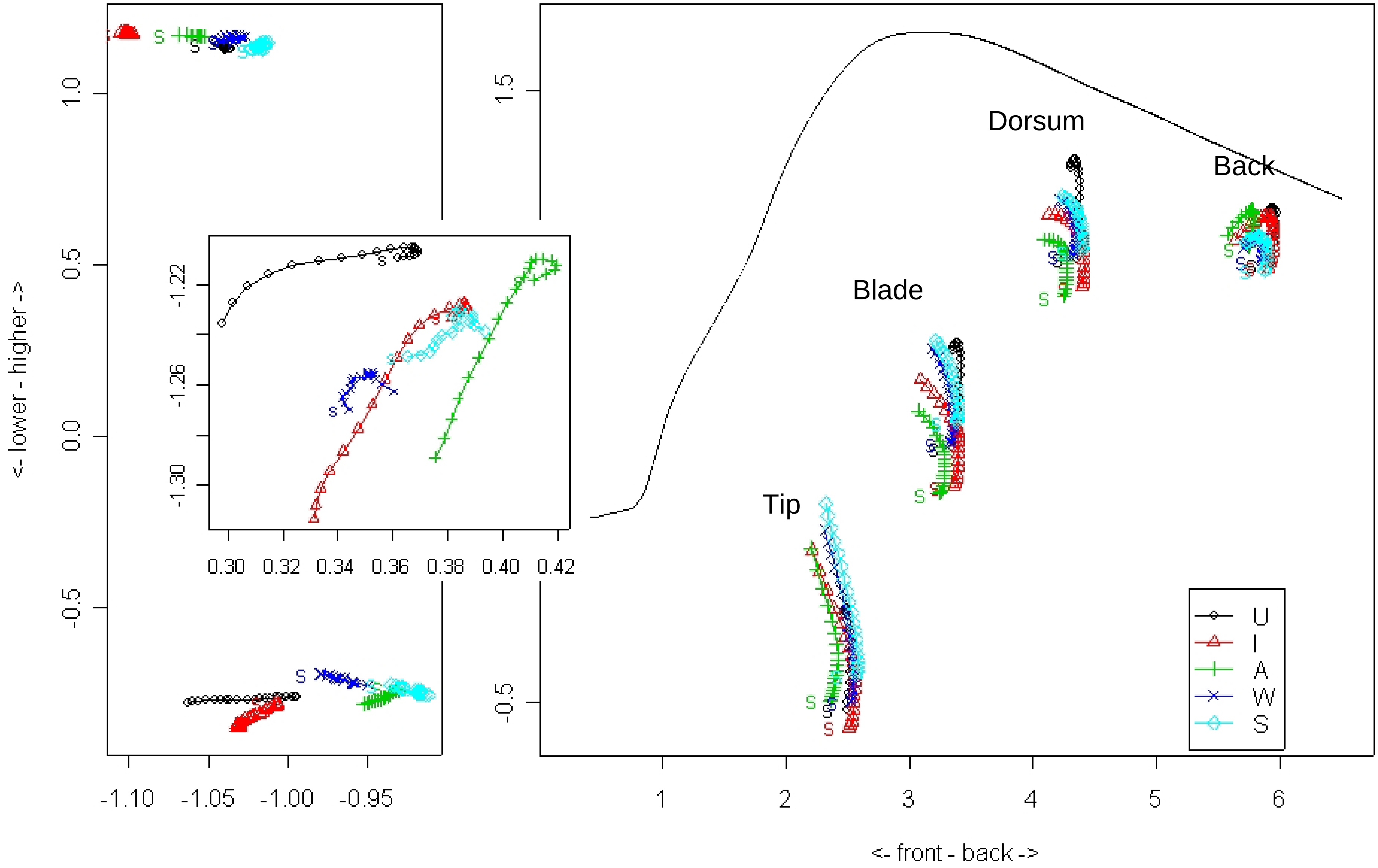
AV - female

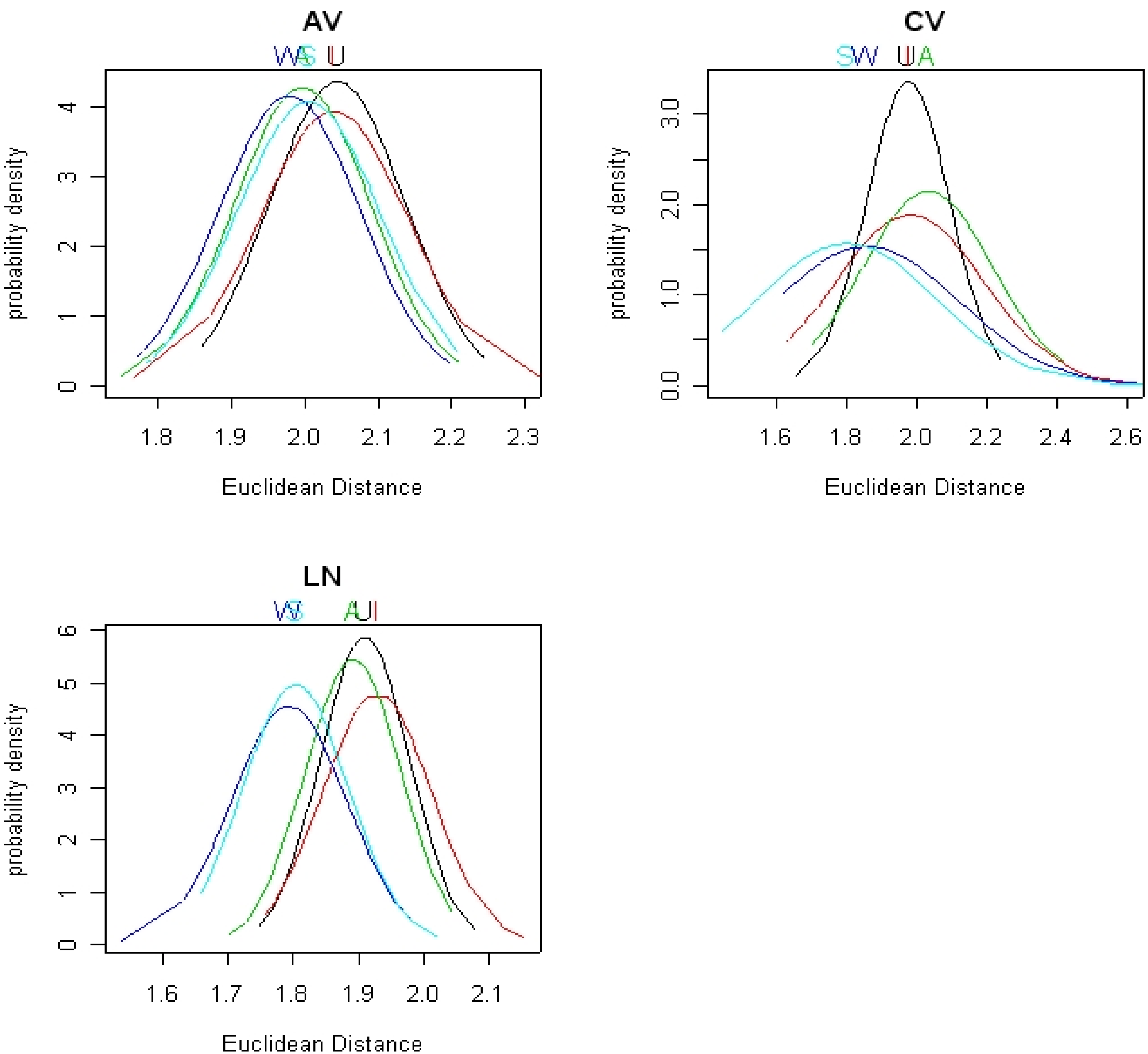


CV - male



LN - female




AV
W A S U I
CV
S W U I A
LN
W S A U I
probability density
Euclidean Distance
0
1
2
3
4
5
6
0.0
1.0
2.0
3.0
1.6
1.7
1.8
1.9
2.0
2.1
2.2
2.3
2.4
2.6