Word-level asymmetries in consonant articulation

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A variety of studies have shown articulatory asymmetries between consonants which are initial vs. final in their syllable and/or word; however, the asymmetry is not always found and its nature is not clear. In this paper we investigate some factors that might seem to make the asymmetry less than universal, using dynamic electropalatography. First, we considered a range of consonants, to see whether only some classes of consonants show the asymmetry, and found it for the non-sibilant non-continuants /t/ /d/ /k/ /n/ and /l/, but not for sibilant fricatives, though all consonants showed an asymmetry in acoustic duration. Second, we considered how the word-level asymmetry interacts with phrase-level effects on articulation, and found that it can be countered by an independent effect of final position in utterance. Third, a pilot study considered whether a word-level asymmetry can be distinguished from a syllable-level asymmetry, but no systematic or consistent differences were found.

1. Introduction

There has long been interest in whether and how syllable and word edges are marked phonetically, or, put conversely, how the position of a segment in its syllable or word affects its phonetic realization. For example, Pike [1947:162] noted:

> In many languages certain grammatical units - such as words - have as one of their characteristics the induction of sub-phonemic modification of some of the sounds.

Pike went on to make a distinction between ‘modifiable’ and other sounds. For ‘modifiable sounds’, the grammatical boundary ‘becomes phonologically recognizable,’ that is, can be heard. For other sounds, ‘the boundary is not phonetically perceptible.’ Pike is surely correct that some sounds make boundaries easier to hear, and the focus of most research has been on such sounds.

Regardless of whether such effects are perceptible, however, subtle boundary effects can be detected using acoustic and articulatory techniques of the phonetics laboratory.

Troubetzkoy [1949:Part II] also discussed the ‘delimitative function’ in language: marking of morpheme, word, and sentence boundaries by ‘boundary signals’. He considered these to be optional, though widespread (‘it is possible to get along without them’). Languages range from those that rarely mark boundaries to those that mark them thoroughly; French is given as an example of the one extreme, and Tamil of the other. Troubetzkoy laid out several kinds of boundary signals. One division is between ‘positive’ and ‘negative’ signals: the presence of a sound or sound sequence may mark the presence, or the absence, of a boundary. Another, orthogonal, division is between phonemic vs. nonphonemic (allophonic) signals, e.g. whether a boundary is signaled by a distinctive feature; we can consider the nonphonemic signals to include any nondistinctive phonetic property. Yet another is between ‘individual’ and ‘group’ signals. The former arise from the presence of individual phonemes or allophones. Thus if a sound appears only adjacent to some boundary, it is thereby an individual, positive signal to the presence of that boundary. In contrast, (positive) ‘group’ signals are seen when certain phoneme or allophone sequences can only occur across an intervening boundary, so that the combination itself serves as a boundary marker. For example, English sequences /θs, ðz, sθ, zð, tʃt, tʃs, ʃs, sʃ, dz/ ‘and very many others’ are said to (positively) signal morpheme boundaries, while the German sequence /dl/ is a negative signal for word boundaries (that is, it only occurs word-medially). Troubetzkoy noted, however, that in languages with many loan words, such as English, phonemic boundary markings are statistically weakened and therefore less reliable. One might hypothesize that in a language with reliable phonemic boundary signals, marking by means of nonphonemic signals would be less important, while in a language with less reliable boundary signals, phonetic marking would be more favored.

Most subsequent research has been concerned with positive individual nonphonemic signals, i.e. allophones that occur adjacent to some boundary. For example, Lehiste [1960, 1961, 1964] conducted a classic set of experiments on allophonic cues to syllable, morpheme, and word boundaries. (‘Internal open juncture’ refers to a boundary inside an utterance.) She recorded spoken minimal pairs differing in juncture and analyzed them acoustically. Her studies showed that boundaries can be detected from ‘marginal allophones’ and/or ‘the overall intensity and duration pattern’ [1960:42]. Initial allophones are longer than medials or finals; marginal allophones involve such phonetic properties as aspiration, flapping, or formant differences. However, the studies did not yield acoustic differences between different types of boundaries; morpheme boundaries were phonetically marked only if they were also ‘lexical word’ boundaries.

Several studies have followed up on Lehiste's results on the acoustic duration of segments at a boundary [e.g. Klatt, 1975, Nakatani and Dukes 1977, Quené 1992, Berkovits 1993, Dumay et al. 1999]. A general interest in such studies is the potential or observed cue value of duration for word segmentation. For example, Quené [1992] showed that in Dutch, not only is a word-initial consonant longer than a word-final consonant, but also that lengthening of the initial consonant can serve as perceptual cue to Dutch word boundaries. The presence of phonetic cues to word boundaries is an important issue for word recognition and for phonotactic learning, because to the extent that listeners have such signal-based cues, they do not need to rely only on statistics of phonological patterns and knowledge of the lexicon.

In addition to acoustic duration, there are several other ways in which production of segments has been shown to vary according to the location of a word boundary. Many studies have compared the articulation of segments in word-initial vs. word-final position. These studies have spanned several articulators and several experimental techniques. They include: Rousselot [1901], Fromkin [1965], McGlone & Proffit [1967], McGlone et al. [1967], Fujimura and Sawashima [1971]; Kohler and Hardcastle [1974], Benguerel [1977], Fujimura [1977], Hardcastle and Barry [1985], Vaissière [1988], Macchi [1988], Krakow [1989, 1993], Byrd [1994, 1996], Browman and Goldstein [1995] (see also Krakow [1999] for a review of syllable-position effects). Fougeron [1999a:26] summarizes the articulatory literature as showing that :

> In initial position, the glottal opening gesture for consonants is longer and greater. Vowels are glottalized or preceded by a glottal stop. Labial muscular activity in initial consonants and vowels is greater. The velum is higher in initial oral and nasal consonants. The tongue is higher and linguopalatal pressure greater in consonants. The few spectral data available about vowels suggest that the tongue has a more peripheral position word-initially in some languages.

Of the studies cited above, only Macchi [1988] provides a clear counterexample to these generalizations: in an analysis of X-ray microbeam recordings of short sentences and nonsense phrases with /p/ in different positions, she found no effect of position-in-word on lower lip movement, and effects on jaw height in opposite directions for her two speakers, though initial /p/ was longer than final /p/.

Kohler [1992] puts such articulatory weakenings in a listener-oriented perspective when he suggests that speakers put their effort into segments that are already highly perceptible to listeners; final consonants are less important to listeners, and therefore to speakers.

Regardless of where they arise, these phonetic patterns play a role in synchronic phonological constraints and alternations across languages, as reviewed by e.g. Bell and Hooper [1973], Ohala and Kawasaki [1984], Fougeron [1998,1999a] and Lavoie [2000]. Syllable-initial and word-initial consonants tend not to undergo assimilations and lenitions seen in other positions.

Fougeron [1999a:41-43] reviews the similar implications of articulatory strengthenings and weakenings for historical sound change. Scholars such as Martinet [1955] have observed that segments in strong positions, such as the beginning of the word, are more often preserved, while segments in weak positions, such as the middle of the word, are more often reduced or lost. Word-final position is weak if it is phrase-internal, but it is strong when pre-pausal. Martinet [1955], Hock [1991,1992], and Vennemann [1993] discuss how the result of such changes is that the initial and stressed consonants, in strong positions, are more likely obstruents, while consonants elsewhere, in weak positions, are more likely sonorants. Such a pattern maximizes the distinction between vowels and consonants in strong positions but minimizes them in weak ones. Historical changes of "initial strengthening" as well as "medial weakening" bring about this ideal word-shape. Although historical scholars emphasize the phonological pattern symmetry of initial strengthening vs. medial weakening (e.g. Hock [1991: 162-3]), the *phonetic* asymmetry between initial and other positions is another aspect of this word-shaping.

Thus, phonetic differences between word-initial and other consonants are of interest to psycholinguistics, machine recognition of words, synchronic phonology, and diachronic phonology.

Although a word-level asymmetry thus seems fairly well established, the research to date raises several fundamental questions. One is the extent to which the *word* is really the relevant domain. In a CVC word, the first C is initial in both a syllable and a word, and the second C is final in both a syllable and a word. While some studies of CVCs describe the object of study as effects of position-in-word, and others as effects of position-in-syllable, in fact these effects are usually confounded. Moreover, as Gow et al. [1996] point out in their review, other effects are often confounded in studies of position-in-word: most notably, effects of lexical stress and phrasal position. Few studies explicitly compare position-in-word with position-in-syllable, at the same time controlling other variables. Krakow [1989], in a study of lip and velum movements in /m/, constructed materials which did compare these positions. Her results showed no difference between syllable-initial vs. word-initial /m/, but she did find differences between syllable-final and word-final /m/: the labial and the velic movements were longer in duration and greater in displacement word-finally. However, the prosody of the test items was not always tightly controlled. Fougeron and Keating [1997] compared articulation of word-initial with syllable-initial /n/s, and found that two of three speakers had reliably more linguopalatal contact in word-initial position, but they did not look at coda consonants. Lavoie [2000] also found an effect of word-initial position on linguopalatal contact for English consonants, but that effect was weaker than the one she found for lexical stress.

Another question is the robustness of the effect across prosodic positions. Berkovits [1993] found that in Hebrew, phrase final lengthening resulted in a word final consonant that was longer than a word initial one. If the same is true for English, then initial lengthening might be found only in some prosodic positions, and only there would a word-level asymmetry be seen.

Finally, as Pike suggested, some consonants seem more prone to exhibit boundary effects than others. Macchi's and Krakow's results described above suggest that effects are weak with labial consonant articulations. Browman and Goldstein [1995], in an Xray microbeam study of the peaks of consonant gestures (lip aperture, tongue tip height, tongue dorsum height) showed that boundary effects are much larger for /t/ than for /p/ or /k/; Byrd et al. [1996], in an EMA study of Tamil, found more significant effects of boundary on /n/ than /m/. A consonant that seems relatively unaffected by position is /s/. McGlone et al. [1967], measuring lingual pressure behind the incisors, found a difference in palatal pressure for /t d n l/ but not /s/, and Byrd [1994, 1996], in an EPG study of linguopalatal contact, found a durational but not a spatial effect on /s/. However, no study has examined a large enough set of consonants to compare across manner and place.

Thus, although a word-level asymmetry in articulation is in one sense well-documented, at the same time the asymmetry is not always found and its nature is not clear. In this paper we investigate some factors that might seem to make the asymmetry less than universal. First, we consider a range of consonants, to see whether only some classes of consonants show the asymmetry. Second, we consider how the word-level asymmetry interacts with phrase-level effects on articulation. Third, we briefly consider whether a word-level asymmetry can be distinguished from a syllable-level asymmetry.

2. General Method Across Experiments

The three experiments were carried out in separate sessions. Additional studies on other topics, not reported here, were also included in these sessions. Except for the speech materials, which are described separately for each experiment below, the methods are essentially the same over the three sessions.

2.1. Electropalatography

The articulatory measure used in these studies is linguopalatal contact, that is, contact between the tongue and the palate, obtained by electropalatography (EPG). EPG data was collected with the Kay Palatometer, which uses custom-fitted pseudo-palates with 96 contact electrodes covering the entire hard palate and the inside surfaces of the molars. Contact information from these electrodes is sampled every 10 ms. The speech signal is recorded simultaneously into a computer file at a 12.8 kHz sampling rate.

2.2. Subjects

A total of six subjects served in these experiments, with five in the first, four in the second, and two in the third. All were linguists; one was the first author, the others were UCLA faculty, students or former students. All but two had participated in previous EPG studies [Byrd, 1994 and/or Fougeron and Keating, 1997], but all except the author were naive about the specific goals of the experiments.

2.3. Procedure

Test utterances were digitized directly to disk in Kay Elemetrics's CSL format. Subjects wore both their pseudo-palates and a head-mounted close-talking microphone. They were cued by the experimenter to read each test item one or more times from a printed list, and then paused while the experimenter saved the file to disk. Test items were repeated a total of 9-10 times; specific experiment details are given below.

Control items with labial consonants (instead of test consonants) were recorded in each experiment. These items revealed the contact patterns of the context vowels.

2.4. Data processing and analysis

The main measure used was peak (maximum) consonantal linguopalatal contact. Consonantal contact is defined with reference to those electrodes not contacted during the control (labial consonant) items. Thus the first step of analysis was to identify those electrodes contacted during the control labial consonants -- these are taken to be characteristic of the vowel's contact pattern. Those electrodes were then excluded from analysis of the consonants' contact patterns. The remaining electrodes may be considered to form a non-vowel region. Because different experiments used different test vowels, the non-vowel region had to be defined separately for each experiment.

The percentage of electrodes contacted in this region, over time, was computed for each file. The maximum contact during the test consonant(s) was then identified. Where other measures were made, they are described below, for the particular experiment.

Statistical comparisons are largely based on Repeated Measures Analysis of Variance (RM ANOVA), with subject as the experimental unit. In general, trials were included as a separate factor (Repetition) in the analyses simply for convenience and are not discussed; the result in such cases is the same as if the repetitions were averaged beforehand. Analysis of experiments with few subjects can be problematic, since with subject (rather than the trial, as is often seen in the literature) as the experimental unit, an analysis may have little power to detect significant differences. We will indicate when this was a problem. Post-hoc comparisons, which cannot be automatically performed with repeated measures designs, were typically made by subsequent individual 1-factor RM ANOVAs.

3. Experiment I: Consonant Differences

3.1. Methods

The first experiment compares a variety of obstruent consonants (tʃ, dʒ, t, ʃ, ʒ, s, z, d, and k) in word-initial vs. word-final position in CVC test words. These are all the obstruent consonants of English (except /g/) for which linguopalatal contact can be registered for the consonantal constriction by our Kay pseudo-palates. The other English obstruents, which are labiodental or interdental, cannot be studied in detail using EPG. The speech materials are shown in Table 1. Each CVC test word contains only one test C (either initial or final); the other C is always /b/. For the coronal test consonants, shown in Table 1A, the vowel in the test word is always /ʌ/ (a vowel which for our speakers of American English seems to involve little if any linguopalatal contact). Thus, for example, the test word for word-initial /t/ was *tub*, while the test word for word-final /t/ was *but*. As can be seen in Table 1, most of the resulting test words are real words, but a few are nonsense words. For the test consonant /k/, shown in Table 1B, a front vowel context was needed to produce a fronted velar with linguopalatal contact on the EPG pseudo-palate. Therefore for these test items the vowel in the test word was /ɪ/. Thus the test words for /k/ are *kib* and *bic*. Unfortunately, there is no way to guarantee that all of the contact for a /k/ will take place on the pseudopalate. In our experiment, all subjects show a stop seal on the palate for all the tokens of /k/; however, only some tokens have all of this seal contact visible (i.e. in front of the backmost row of electrodes). Therefore, the results for velar consonants cannot be interpreted with as much certainty.

The test words were put in a carrier sentence 'A CVC CVC ***again***.', with nuclear accent on *again* and near-equal stress, but no pitch accents, on the two CVC words. The two CVC words in a given utterance were the same, but only one of them was the test word in that utterance. For C in word-initial position, the second CVC was the test word (e.g. *tub tub*, while for C in word-final position, the first CVC was the test word (e.g. *but but*). This was done so that all the test utterances could be produced with the same prosody, while the segmental context remained as controlled as possible. In addition, following Byrd [1994], the CVC CVC design puts word-final Cs in an earlier position in the test utterance (CVC CVC) than the word-initial Cs (CVC CVC). Thus if there are any global, utterance-level trends in articulation [e.g. Krakow et al., 1994], these work against, not for, the hypothesis being tested. That is, if final C is reduced relative to initial C, it will not be because the final C came later in the utterance.

Table 1. Speech materials for Experiment I. Materials for coronal and velar test consonants are shown separately. In the 'carrier frame' column, CVC is a placeholder for the test words, and boldface indicates phrasal stress (nuclear accent).

Expt.	Test C	Test words	Carrier frame
1A	t	bʌt tʌb	
	d	bʌd dʌb	
	s	bʌs sʌb	
	z	bʌz zʌb	'A CVC CVC **again**.'
	ʃ	bʌʃ ʃʌb	(same CVC, equal stresses)
	ʒ	bʌʒ ʒʌb	
	tʃ	bʌtʃ tʃʌb	
	dʒ	bʌdʒ dʒʌb	
1B	k	kɪb bɪk	same as above

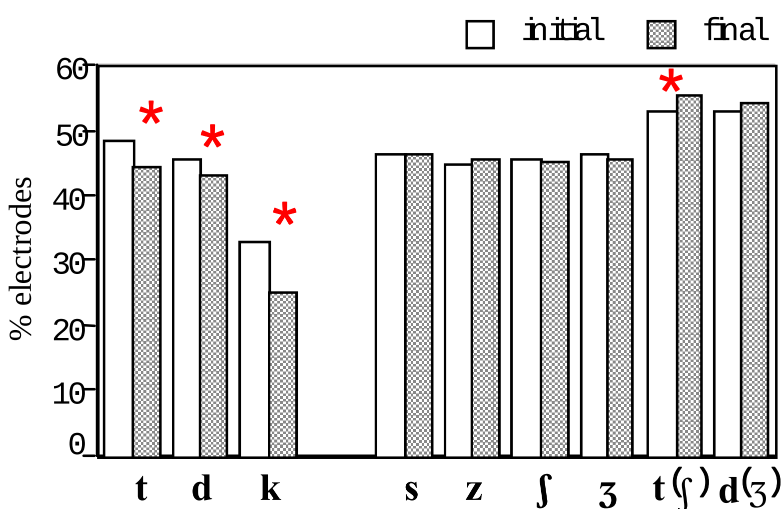
The test utterances were generally ordered so that all repetitions of an item were together, the initials for one consonant followed by the finals for that same consonant, and the consonants in the order listed above. However, one subject produced a different order, in which tokens were in blocks of three repetitions of each item at a time. In sum, there were a total of 810 consonant tokens (9 consonants x 2 positions x 9 repetitions x 5 speakers).

3.2. Results

3.2.1. Peak contact

Figure 1 shows the average (across speakers and repetitions) of the peak contact for each of the nine consonants in word-initial vs. word-final position. Note that for affricates, the peak contact was always found during the stop portion of the segment.

Fig. 1. Peak EPG contact: word-initial vs. word-final stops vs. sibilants in Experiment I. Data are pooled across subjects. Asterisks indicate significant differences within consonants.



These data were tested for a main effect of Position and an interaction of Position with Consonant. The eight coronal consonants were first tested in a 3-way RM ANOVA, with factors Consonant(8), Position(2), and Repetition(9). There was no overall effect of Position [$F<1$]. However, the interaction of Position with Consonant was reliable [$F(7,28) = 4.24$, $p = .0027$]. This means that there is some effect of position with some consonants. To assess which consonants show such an effect, two kinds of further tests were done. The first was a set of RM ANOVAs on the individual consonant data. Their power was low, and none of them showed a significant effect of Position on contact. However, three consonants showed a nearly significant trend ($p < .08$): /t/, /d/, and /tʃ/, with the first two consonants having more contact in initial position, and the latter the reverse pattern. To complement this analysis, a set of corresponding factorial ANOVAs (with each subject's repetitions as experimental unit, as is often seen in the literature) was performed. These in principle overestimate significance of differences, but they gave the same pattern of results as the RM analyses: /t/ /d/ and /tʃ/ showed highly significant effects of Position, but no other consonants did. Thus we can take these two analyses to converge on a single result: that /t/ and /d/ have more contact in initial position than final, that /tʃ/ has more contact in final position than initial, and that /s/ /z/ /ʃ/ /ʒ/ /dʒ/ have equal contact in the two positions.

Data for the velar stop /k/, analyzed separately in a RM ANOVA with factors Position(2) and Repetition(9), show a significant effect of position in word on contact, with initial /k/ having more contact than final /k/ [$F(1,4) = 8.997$, $p = .04$]. As noted above, not all the velar contact is captured in the EPG data. It seems that the contact for the initial stops is more likely to be entirely on the pseudopalate. Thus it is possible that the initial /k/ shows more contact because it is articulated more forward on the palate (and thus more of its contact is captured by the pseudopalate). (A more fronted articulation would in turn suggest more coarticulation with the following front vowel.)

When individual speaker data are examined qualitatively there are some differences across subjects: not all subjects show all of the effects summarized above (which hold for the subject group as a whole). For example, only 2 subjects seem to show more contact for initial /t/ than for final /t/; only 3 subjects do so for /d/, and 4 for /tʃ/. Four subjects show a difference in contact for /dʒ/ according to its position, but they are evenly split as to the direction of that difference.

3.2.2. Segmental context

A follow-up analysis of these contact data addressed the following concern. Recall that the consonants are in CVC_f C_iVC sequences. This controls for (indeed, works against) any effect of sequential declination; but it does put the test consonants into different segmental contexts. The final-C is preceded by a vowel, while the initial-C is preceded by a labial consonant. It is conceivable that a preceding vowel, with its open vocal tract, could pull open the consonant that follows it, more than a preceding labial consonant would. If that were so, then our asymmetry would not be due to position-in-word, but to the preceding segmental context. The corpus allows a check of this: the 'non-test' word in each sentence provides a copy of the test consonant, but in the converse context. Thus in *a tub tub* ***again*** the first /t/ is an onset after a vowel, and this /t/ can be compared to our two test /t/s. Such a comparison was carried out for the four consonants which showed an effect of Position on contact, in a 2-way RM ANOVA with factors

Consonant(4) and Context(3). For this analysis there were several missing datapoints, due to data files that began after the 'non-test' word; therefore repetitions were averaged rather than being included as a factor.

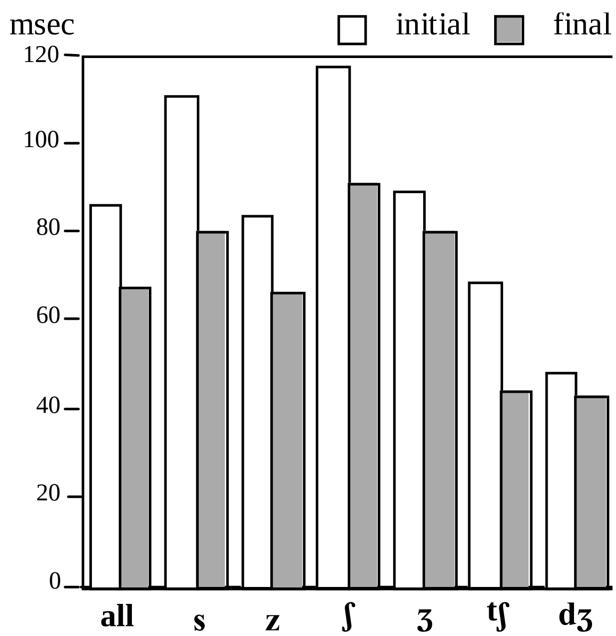
Both main effects – Consonant [$F(3,12) = 10.989$, $p = .0009$] and Context [$F(2,8) = 14.821$, $p = .002$] – were significant, as was their interaction [$F(6,24) = 9.26$, $p < .0001$]. Overall, the non-test initial consonants had the most contact and the word-final consonants the least, but this was not consistent across consonants. Though RM ANOVAs for each consonant gave a significant effect of Context for each of them, that doesn't answer the question of interest, namely whether segments after a vowel generally have less contact – that is, whether the non-test initials have less contact than the test initials, and the same contact as the finals. To this end, paired t-tests were performed on each pairwise comparison, within consonants; the results of these do not support this proposed interpretation. Testing whether the non-test initials have less contact than the test initials: contrary to this hypothesis, either the non-test initials have *more* contact (/t/, /d/, /tS/), or no difference in contact (/k/). Testing whether the non-test initials have the same contact as the finals: this is so for /tS/, but the initials have more contact for /d/, /t/, /k/. In other words, the results are consistent with all initials having more, not less, contact. These results suggest that our initial vs. final effect is generally due to position in word, not segmental context. (Why three onset consonants have more contact than our test onset consonants is a separate question, but given the clear negative results in Fougeron & Keating [1997], we doubt that it is due to declination. More likely, the first syllable tended to have a slightly greater stress than the second, or the two words were grouped together into a small phrase.)

3.2.3. Further analysis of fricatives

Because these analyses of peak contact during the consonant revealed no general effects of position-in-word on the four fricative consonants, two further analyses of these were performed. The first was of the acoustic duration, which was taken to include the interval of noise plus any silent gap next to the vowel (as is often seen after sibilants). For this analysis, the fricative components of the two affricates were also included (making a total of six consonants: /s z ʃ ʒ tʃ dʒ/. The results are shown in Figure 2. A 3-way RM ANOVA with factors Consonant(6), Position(2), and Repetition(9), showed a significant main effect of Position [$F(1,4) = 13.77$, $p = .0206$]; thus initial fricatives are longer than finals. The data for all five speakers, when examined individually, conform to this pattern. However, the particular comparison of interest is the interaction between Consonant and Position, and this was also significant [$F(5,20) = 6.142$, $p = .0013$]. Posthoc analysis consisting of a paired t-test for each consonant shows that while the mean initial duration is always higher than the mean final duration, this difference is significant beyond a corrected alpha level of .008 for only /s/ and /tʃ/, and at the less conservative .05 level also for /z/ and /ʃ/. The durational difference is not at all significant for /ʒ/ and /dʒ/ because for those consonants the individual speakers differ.

Because position does affect fricative duration, a finer analysis of the EPG record was performed for the four fricatives /s z ʃ ʒ/: the size of the fricative air channel was measured, following Fougeron [1998,1999b]. The data frame with peak consonant contact was displayed for each token, and the fricative air channel was identified in that display. Length of the fricative channel and its width at its narrowest point were measured in #electrodes. Testing the effect of

Fig. 2. Word-initial vs. word-initial sibilant duration. Data are pooled across subjects. The first pair of bars shows the average effect for the six sibilants combined.



position on the width of the fricative channel for each consonant, a RM ANOVA with factors Consonant(4), Position(2), and Repetition(9) showed neither a main effect of Position nor an interaction of Position with Consonant, though neither test had sufficient power to reveal a small effect if there was one. Results were the same for tests of channel length and area.

4. Experiment II: Phrasal Position

4.1. Methods

Experiment II was a large experiment in which three experimental variables are of interest here. The speech materials are shown in Table 2. First, four different test consonants were used, all non-continuants: /t d n l/. Second, each test consonant occurs word-initially and word-finally, with each test word containing two test consonants (the initial and final consonants in the word). Third, each test word occurs either first or last in its sentence, which is a prosodic Intonational Phrase (IP). Thus the word-initial consonants occur IP-initially or IP-internally, and the word-final consonants occur IP-internally or IP-finally. However, because these sentences are set off by pauses, they are also Utterances (IPs with break index 5). In what follows, these will be called simply ‘utterances’. In sum, there are three experimental factors of interest: Consonant (4), Position of C in word (2), and Position of word in utterance (2). Since each test word contains 2 test consonants (word-initial and word-final), there are twice as many test consonants as test sentences (16 test consonants in 8 test sentences).

Table 2. Speech materials for Experiment II. In the ‘test words’ column, an acute accent indicates primary stress, a grave accent indicates secondary stress, and underlining indicates the test consonants. In the ‘carrier frame’ column, ‘word’ is a placeholder for the test words, and boldface indicates phrasal stress (nuclear accent).

Test C	**Test words**		**Carrier frame**
t	tɛ́bəbɛ̀t,	tɛ̀bəbɛ́t	
d	dɛ́bəbɛd,	dɛ̀bəbɛ́d	**Word** fed them. / One deaf **word.**
n	nɛ́bəbɛ̀n,	nɛ̀bəbɛ́n	Word fed **them**. / **One** deaf word**.**
l	lɛ́bəbɛ̀l,	lɛ̀bəbɛ́l	

The experiment manipulated other factors, not part of the present report, in addition to the identity and position of the test consonant. These factors are the location of the lexical stress of the test word (each test consonant occurs in a syllable with primary lexical stress, or secondary lexical stress), and the location of the phrasal stress, or accent, of the test sentence (each test word occurs accented or unaccented). The effects of these factors will be reported elsewhere [Keating, Cho, and Wright in preparation], and here the data are always collapsed across them. These extra factors mean that each of our test sentences comes in four variants, so that instead of 8 test sentences there are 32 (and thus 64 test consonants).

Pilot work showed that the vowel /ɛ/ (unlike the vowel /ʌ/ used in the first experiment) has relatively similar contact patterns under different degrees of stress and accent, and therefore the test words contain that vowel.

Subjects were asked to accent only one word in a sentence. If they do that sucessfully, then the entire sentence must be produced as a single Intermediate Phrase, as well as a single Intonational Phrase/utterance. For example, in the test sentence ***Tebabet** fed them*, only the boldfaced testword **tebabet** was to be accented, with the following two words therefore post-nuclear and within the same Intermediate Phrase. However, post-hoc transcription of the test utterances, as actually produced by the subjects, showed that sometimes the prosody was different from requested. Most notably, one subject made a small phrasal break (an Intermediate Phrase, with a L- boundary tone and break index 3) after about half the test words in the ***Testword** fed them* utterances. As a result, about half of her word-final test consonants are also Intermediate Phrase-final. Thus for this one subject the positional category "word-final" means "final in a domain smaller than the Intonational Phrase/Utterance", with which it is being compared.

The four subjects produced 10 repetitions of each sentence. The test items were generally ordered so that all repetitions of a sentence were together, with the sentences having a test word in sentence-initial position followed by the sentence-final versions for that same word. However, one subject produced them in blocks of two repetitions of each item at a time. Four subjects (all of whom also participated in Expt. I) recorded the test materials. With 10 repetitions of 32 test sentences by four subjects, there are 1280 test utterances yielding 2560 test consonants.

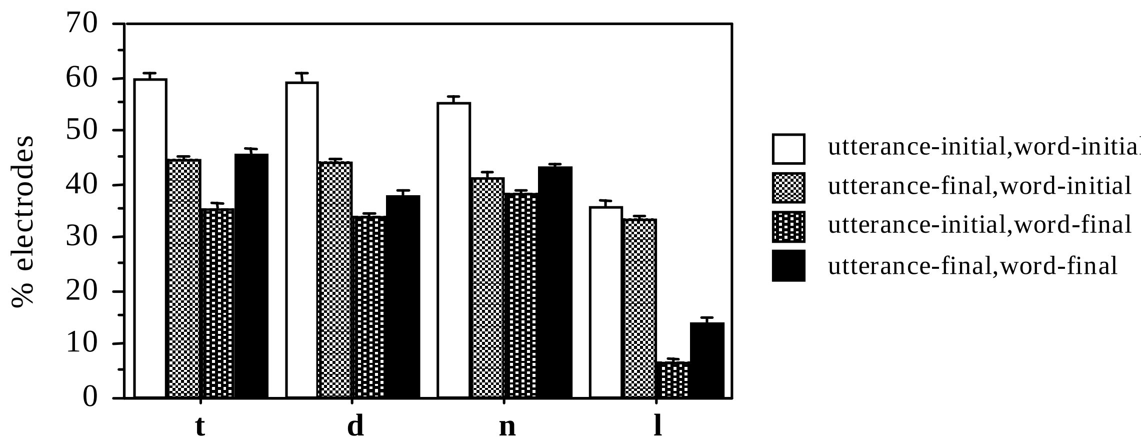
Peak linguopalatal contact was measured for each test consonant as described for the previous experiment.

4.2. Results

Statistical comparisons were performed by RM ANOVA with factors of interest Consonant, Position-in-word, and Position-in-utterance. Other experimental factors were collapsed into a single ad-hoc factor which will not be reported here, and datapoints were averaged across the 10 repetitions of each item. A main effect was found for Position-in-word [$F(1,3) = 53.852$, $p = .0052$], with word-initial consonants having more contact than word-final ones, but not for Position-in-utterance [$F < 1$], though the power of the latter test was low.

However, the effect of Position-in-word by itself is not the best indicator of a word-level asymmetry, because it confounds the different positions in the utterance of the word-initial and word-final consonants. The interaction of Position-in-word and Position-in-utterance is shown in Figure 3 and was also statistically significant [$F(1,3) = 48.997$, $p = .006$]. When a word-initial consonant is also utterance-initial, then it is in absolute utterance-initial position; but when a word-final consonant is ‘utterance-initial’, it is merely at the end of the first word in the utterance; conversely, when a word-final consonant is also utterance-final, then it is in absolute utterance-final position; but when a word-initial consonant is ‘utterance-final’, it is merely at the beginning of the last word in the utterance. This confounding turns out to be important because consonants in absolute utterance-initial position have the most linguopalatal contact. Averaged across consonants and speakers, the most contact is seen for consonants which are utterance-initial and word-initial; the next-most contact is seen for consonants which are word-initial but utterance-medial; the next for consonants which are utterance-final and word-final; and the least contact is seen for consonants which are word-final but utterance-medial. It can be seen in Figure 3 that all four consonants show this pattern; so do the individual subjects. In what follows, we consider which differences seen are statistically reliable.

Fig. 3. Peak EPG contact in Experiment II: /t d n l/ showing interaction of position-in-word and position-in-utterance. Data are pooled across subjects, repetitions, and other prosodic variables.



In Expt. I all consonants were utterance-medial. Such a comparison can be made in the present experiment as well, if the word-initial consonants are taken from the utterance-final words and the word-final consonants are taken from the utterance-initial words (the second and third bars for each consonant in Figure 3). On average, this difference in contact is about 12 percentage points. A RM ANOVA comparing just these two position conditions across the consonants shows significant effects of both Position [$F(1,3) = 51.8$, $p = .0055$] and Position x Consonant [$F(3,9) = 29.02$, $p < .0001$]. The latter effect appears to be due especially to the very large positional difference for /l/, and to a lesser extent to the smaller positional difference for /n/, as compared to /t/ and /d/.

Another comparison picks out the utterance-edge consonants: word-initial&utterance-initial vs. word-final&utterance-final (the first and last bars for each consonant in Figure 3). Because the utterances were set off by pauses, the contact for the utterance-initial and utterance-final consonants is likely influenced by the pausing. In this comparison the word-level asymmetry is still clearly seen; on average it is larger, the difference in contact being about 17 percentage points. A RM ANOVA comparing just these two position conditions across the consonants shows a significant effect of Position [$F(1,3) = 13.332$, $p = .0355$] , but not Position x Consonant [$p < .07$], that is, all the consonants show a similar effect of more contact in initial position. This asymmetry holds qualitatively for all four subjects individually, but the size of the effect is variable, and for two subjects this effect is in fact smaller than the one described just above.

The comparison which makes the word-level asymmetry greatest is the one in which the word-initial consonant is also utterance-initial (and therefore postpausal), while the word-final consonant is utterance-medial (i.e. in the utterance-initial word) (the first and third bars for each consonant in Figure 3). On average that difference in contact is 24 percentage points. A RM ANOVA comparing just these two position conditions across the consonants shows significant effects of both Position [$F(1,3) = 55.62$, $p = .005$] and Position x Consonant [$F(3,9) = 3.95$, $p = .0475$]. As with the first comparison in which the interaction was significant, it seems that the effet is larger for /l/ and smaller for /n/.

In contrast, the asymmetry is much weaker when we compare the utterance-final consonants to the word-initial, but utterance-medial, consonants (the fourth and second bars for each consonant in Figure 3). Utterance-final consonants, also adjacent to a pause, generally have somewhat more contact than other word-final consonants (i.e the fourth bars are higher than the third bars). This extra boost minimizes the advantage of the word-initial consonants – the fourth bars are similar to the second bars. Across all the consonants, this difference is about 6 percentage points. A RM ANOVA comparing just these two position conditions across the consonants shows significant effects of both Position [$F(1,3) = 26.001$, $p = .0146$] and Position x Consonant [$F(3,9) = 39.279$, $p < .0001$]. Clearly the consonants pattern somewhat differently in this comparison: /l/ maintains a large asymmetry, /d/ a smaller one, and /t/ and /n/ none, or even a reversed effect.

Thus the word-level comparisons, however they are done, generally replicate (for /t/ and /d/) the results of Expt. I, and extend them to additional non-strident noncontinuants (/n/ and /l/). However, phrasal position also plays a role, either enhancing or minimizing the word-level asymmetry.

The data in Figure 3 also allow us to answer another question about the word-level asymmetry, at least for these English speakers and these consonants. How does the magnitude of the word-level asymmetry compare with the magnitude of (utterance-level) initial strengthening? The magnitude of the word-level asymmetry is seen by comparing word-initial with word-final (both utterance-medial); the magnitude of initial strengthening above the word is seen by comparing word-initial with utterance-initial consonants. We have already seen that the first difference is, on average, about 12 percentage points. The second is on average also 12 percentage points. Viewed as ratios, the effects are also very similar in size [1:1.4 vs 1:1.3). That is, whatever boost a consonant gets from being at the beginning of a word, is about equal to what it gets from being at the beginning of an utterance. Note however that /l/ shows little more contact in utterance-initial position; for this consonant the effect of position-in-word is much more striking than the effect of position-in-utterance.

5. Pilot Experiment III: Word vs. Syllable

5.1. Methods

The goal of this pilot experiment was to compare the coronal consonant /t/ in word-medial vs. word-edge positions. A set of minimal pairs was constructed in which one member of the pair contains a word-initial or word-final /t/, while the other member of the pair contains a matching syllable-initial or syllable-final /t/. These are shown in Table 3. The following are some design considerations for the corpus, beyond the usual considerations for all EPG experiments: first, the syllabic positions of the word-medial /t/ must be unambiguous; second, all other prosody (especially, the lexical stress and the phrase-level accenting) on the test syllables must be matched for the pairs of test items, third, the test syllables in the matched pairs should occur in similar linear locations.

Two subjects (the author, plus one who had not participated in any previous studies) were recorded in this experiment. They produced the test items, in a variety of orders, 10 times each. Peak EPG contact over all 96 electrodes was measured for each test consonant. A set of paired t-tests was done for each pair of test items, for each speaker separately, with repetitions as the experimental unit. (Such a test will overestimate significance, which is not inappropriate for a pilot test and makes any failure to find significant differences all the more striking.)

Table 3. Speech materials for the pilot experiment. The test words are underlined. Phrasal prosody is not shown here but was matched across pairs.

word-initial /t/	syllable-initial /t/
This is a prep-tile.	This is a reptile.
Say a tune again.	Say attune again.
Say (a) tapwater.	Say attack dog.
word-final /t/	**syllable-final /t/**
The cat must fear the sunshine.	An atmosphere of sunshine.
He bit Matt.	the bitmap
I saw a fat man.	I saw Batman.
I cut most pears.	Use utmost care.
The bout put James in the hospital.	The output changed in the summer (months).

5.2. Results and Discussion

The two subjects showed quite different results for the various pairs of test items. The first subject made no more contact for word-initial /t/ than for syllable-initial /t/. Two test pairs showed no difference [$p > .1$], while *attack* had more contact than *a tapwater* [$p < .02$]. The second subject did make more contact for word-initial /t/ in two pairs [$p < .01$), but *attune* had more contact than *tune* [$p = .02$]. Thus for none of the three initial-consonant pairs did the two subjects show the same result. The same was true for the five final-consonant pairs. The second subject showed no differences in contact for four of the five pairs, while in *bout put* had more contact than *output* [$p < .008$]. In this pair, the syllable-final items are consistently completely reduced (showed no contact at all), while the word-final items have a bimodal distribution of reduced vs non-reduced contact. Note that although *utmost/cut most* also has /t/ followed by a labial, none of those completely reduced, so the effect is specific to the pair *bout put/output* for this speaker. The first subject, on the other hand, showed a reliable difference in contact for four of the five pairs, but the direction of the difference is variable. The one pair which for this subject shows no difference, *output/bout put*, is exactly the case where the other made a difference. This subject does have one pair of this sort, in which one word is consistently reduced and the other shows a bimodal distribution, but it is for the pair *utmost/cut most* [$p < .004$], and it is the word-final *cut* that is consistently reduced.

Because these two speakers behaved so very differently, we did not pursue this experiment with other speakers. It seems clear that no highly general result about Word vs. Syllable edges is likely to emerge from such a study. For neither of these two speakers do the two domains have any consistent differential effect on consonant contact.

6. Discussion and Conclusions

These experiments show that, as expected, some lingual consonants have more linguopalatal contact in word-initial, compared to word-final, position. However, the experiments have also clarified how this word-level asymmetry effect interacts with other influences on articulation.

First, not all lingual consonants show the effect. Of the set of obstruents tested in Experiment I, only /t/, /d/, and /k/ did; Experiment II added /n/ and /l/ to this set. These consonants share the property of being non-sibilant non-continuants. Most notably, there is no reliable effect of position-in-word on the peak EPG contact of sibilant fricative articulations. This result accords with and extends results of previous studies. Furthermore, for the sibilant affricate /tʃ/, the effect of position is in the opposite direction: finals have more contact. Nonetheless, fricatives, like the other consonants, are overall acoustically longer in initial position.

Second, it was seen in Experiment II that the word-level asymmetry can be countered by an independent effect of position in phrase. When a word-final consonant is also final in an utterance, that consonant has more contact than otherwise, and for /t/ and /n/ this increase equalizes the word-initial and word-final contact. This increase in contact in utterance-final position accords with Vaissière [1988], who observed that for velum articulation, final position in a large phrase is a strong position.

One point to be made from this result is that whether or not the word-level asymmetry will be found in a study of CVCs would seem likely to depend in part on the carrier phrase used. Thus, the asymmetry will be seen if no carrier phrase is used, because that puts the test consonants at the edges of the utterance; similarly if carrier phrases like 'Say (word) again' or '(Word) is it' are used the asymmetry will be seen, because they put the word-final consonant in utterance-medial position; but if a carrier phrase like 'Say (word)' is used, the asymmetry would probably not be seen, because only the final consonant is at the edge of the utterance.

Another point to be made from this result is that the word-level asymmetry must be independent of the phrasal effect. Thus we saw that the consonant /l/ shows the word-level asymmetry quite strongly, but little phrase-initial effect. Furthermore, for those consonants that do show both effects, the experiments allow us to compare the size of the word-level asymmetry with the size of domain-initial strengthening above the word. Comparison of word-initial consonants with utterance-initial vs. word-final shows that the word-level asymmetry is about equal in size to the phrasal strengthening effect.

Finally, pilot Experiment III showed no clear effects of position in word vs. position in syllable. Comparisons of initial positions and of final positions for two speakers showed no systematic or consistent differences. This result is somewhat surprising for the comparison of word-initial and syllable-initial consonants, since Fougeron and Keating [1997] did find more contact in word-initial position, but only one test 'word' was used in their study, /nonono/. One of our subjects did show this effect, but only for two of the three word pairs tested. Thus we cannot tease apart the contributions of word and syllable to the word-level asymmetry. This result is somewhat different from that of Krakow [1989], who did find some reduction (both spatial and temporal) in syllable-final, compared to word-final, /m/; but is in accord with her failure to find any systematic differences between word-initial and syllable-initial /m/. It is quite possible that there are stronger effects of lexicalization and lexical frequency that dominate for each pair of words and each speaker, but that are not seen in the nonsense word data.

In sum, the word-level asymmetry in consonant articulation, by which word-initial consonants are stronger in articulation than word-final consonants, is robust for certain consonants, the non-sibilant non-continuants /t/ /d/ /k/ /n/ and /l/, but is reflected in greater acoustic duration for other word-initial consonants. However, the asymmetry can be lost in phrase-final position, where it is countered by phrase-final strengthening of coda consonants.

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References

Bell, A.; Hooper, J. B.: Syllables and segments (North-Holland Publishing Company, Amsterdam 1973).

Benguerel, A.-P.: Velar coarticulation in French: a fiberscopic study. J. Phonet. 5: 145-158 (1977).

Berkovits, R.: Utterance-final lengthening and the duration of final-stop closures. J. Phonet. 21: 479-489 (1993).

Browman, C.; Goldstein, L.: Gestural syllable position effects in American English; in Bell-Berti, Raphael, Producing Speech: A Festschrift for Katherine Safford Harris, pp. 19-34 (American Institute of Physics Press, Woodbury New York 1995).

Byrd, D.: Articulatory timing in English consonant sequences; PhD diss., UCLA (1994). (Distributed as UCLA Working Papers Phonet. 86, 1994).

Byrd, D.: Influences on articulatory timing in consonant sequences. J. Phonet. 24: 209-244 (1996)

Byrd, D.; Kaun, A.; Narayanan, S.; Saltzman, E: Phrasal signatures in articulation; in Broe, Pierrehumbert, Papers in laboratory phonology, V. Acquisition and the Lexicon, pp. 70-87 (Cambridge University Press, Cambridge 2000).

Dumay, N.; Content, A.; Frauenfelder, U.: Acoustic-phonetic cues to word boundary location: evidence from word spotting. Proc. ICPhS99: 281-284 (San Francisco1999)

Fougeron, C.: Variations articulatoires en début de constituants prosodiques de différents niveaux en français; PhD diss., Université Paris III - Sorbonne Nouvelle (1998).

Fougeron, C.: Prosodically conditioned articulatory variation: A review, UCLA Working Papers Phonet. 97: 1-73 (1999a).

Fougeron, C.: Articulatory properties of initial segments in several prosodic constituents in French, UCLA Working Papers Phonet. 97: 74-99 (1999b).

Fougeron, C.; Keating, P.: Articulatory strengthening at edges of prosodic domains. J. Acoust. Soc. Am. 106: 3728-3740 (1997).

Fromkin, V. A.: Some phonetic specifications of linguistic units: an electromyographic investigation; PhD diss., UCLA (1965). (Distributed as UCLA Working Papers in Phonet. 3, 1965).

Fujimura, O.: Recent findings on articulatory processes; in Carré, Descout, Wajskop, Articulatory modeling and phonetics, pp. 115-126 (Groupement des Acousticiens de Langue Française, Grenoble 1977).

Fujimura, O.; Sawashima, M: Consonant sequences and laryngeal control. Annual Bulletin of Research Institute of Logopedics and Phoniatrics, University of Tokyo, 5: 1-13 (1971).

Gow, D. W.; Melvold, J.; Manuel, S: How word onsets drive lexical access and segmentation: evidence from acoustics, phonology and processing. Proc. ICSLP96 (CD-ROM) (Philadelphia 1996)

Hardcastle, W.; Barry, W.: Articulatory and perceptual factors in /l/ vocalization in English. Working Papers Phonet. Lab., University of Reading 5: 31-44 (1985)

Hock, H. H.: Principles of Historical Linguistics, 2nd edition (Mouton de Gruyter, 1991)

Hock, H.H.: Initial strengthening, in Dressler et al., Phonologia 1988 (Cambridge University Press, Cambridge 1992)

Klatt, D. H.: Vowel lengthening is syntactically determined in connected discourse. J. Phonet. 3: 129-140 (1975).

Kohler, K.: Gestural reorganization in connected speech: a functional viewpoint on “articulatory phonology”, Phonetica 49: 205-221 (1992).

Kohler, K.; Hardcastle, W: The instability of final alveolars in English and German: proposal for an instrumental investigation. Speech Comm. Seminar 2: 95-98 (1974).

Krakow, R: The Articulatory Organization of Syllables: A Kinematic Analysis of Labial and Velic Gestures; PhD diss., Yale University (1989).

Krakow, R.: Nonsegmental influences on velum movement patterns: syllables, sentences, stress, and speaking rate; in Huffman, Krakow, Nasals, nasalization and the velum, pp. 87-116 (Academic Press, San Diego 1993).

Krakow, R.: Physiological organization of syllables: a review. J. Phonet. 27: 23-54 (1999).

Krakow, R. A.; Bell-Berti, F.; Wang, Q. E.: Supralaryngeal declination: evidence from the velum; in Bell-Berti, Raphael, Producing speech: A Festschrift for Katherine Safford Harris, pp. 333-353 (Chapter 23). (American Institute of Physics Press, Woodbury New York 1995).

Lavoie, L. M.: Phonological patterns and phonetic manifestations of consonant weakening; PhD diss., Cornell University (2000).

Lehiste, I.: An acoustic-phonetic study of internal open juncture. Supplement to Phonet. 5 (1960).

Lehiste, I.: Acoustic studies of boundary signals. Proc. 4th ICPhS, pp. 178-187. (Helsinki 1961)

Lehiste, I.: Juncture. Proc. 5th ICPhS, pp. 172-200. (Munster Germany, 1964)

Macchi, M.: Labial coarticulation pattern associated with segmental features and syllable structure in English. Phonetica 45: 109-121 (1988).

Martinet, A: Economie des changements phonétiques: traité de phonologie diachronique (Francke SA, Berne 1955)

McGlone, R.; Proffit, W. R.: Lingual pressure associated with speaker consistency and syllable variations. Phonetica 17: 178-183 (1967).

McGlone, R.; Proffit, W. R.; Christiansen, R. L.: Lingual pressure associated with alveolar consonants. J. Speech Hear. Res. 10: 606-615 (1967)

Nakatani, L.H.; Dukes, K.D.: Locus of segmental cues for word juncture. J. Acoust. Soc. Am. 62: 714-719 (1977)

Ohala, J.; Kawasaki, H.: Prosodic phonology and phonetics. Phonology Yearbook 1:113-127 (1984)

Oller, D. K.: The effect of position in utterance on speech segment duration in English. J. Acoust. Soc. Am. 54: 1235-1247 (1973).

Pike, K. L.: Grammatical prerequisites to phonemic analysis. Word 3: 155-172 (1947).

Quené, H.: Durational cues for word segmentation in Dutch. J. Phonet. 20: 331-350 (1992).

Rousselot, P. J.: Principes de phonétique expérimentale (Welter, Paris 1901).

Troubetzkoy, N.S.: Principles of Phonology. (Translated from *Grundzüge der Phonologie*, 3rd edition, 1962, by C. A. M. Baltaxe) (University of California Press, Berkeley and Los Angeles 1971).

Vaissière, J.: Prediction of velum movement from phonological specifications. Phonetica 45: 122-139 (1988).

Vennemann, T.: Language changes as language improvement; Jones, Historical Linguistics: Problems and Perspectives. (Longman, London and New York 1993)