Effects of initial position versus prominence in English

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Abstract

This study investigates effects of three prosodic factors—prosodic boundary (Utterance-initial vs. Utterance-medial), lexical stress (primary vs. secondary) and phrasal accent (accented vs. unaccented)—on articulatory and acoustic realizations of word-initial CVs (/nɛ/, /tɛ/) in trisyllabic English words. Articulatory measurements include linguopalatal contact (by electropalatography) for both C and V, and seal duration; acoustic measurements include nasal duration and energy for /n/, VOT, burst energy and spectral center of gravity for /t/, and *F1*, vowel duration and vowel amplitude for /ɛ/. Several specific points emerge. First, domain-initial articulation is differentiated from stress- or accent-induced articulations in many aspects; for the most part, prominence affects vowel measures while initial position affects consonant measures. Nonetheless, the vowel is also effectively louder domain-initially, suggesting that the boundary effect is not strictly local to the initial consonant. Second, the boundary (domain-initial) effect is not seen across-the-board, but is often constrained by stress and accent factors, revealing that domain-initial strengthening is more effective when a relevant phonetic dimension does not undergo a compelling strengthening coming from stress or accent. Third, some accentual effects can be seen on secondary-stressed syllables, suggesting that accentual influences spread beyond the primary-stressed syllable. But this spread is mainly seen with consonantal measures, showing an asymmetric accentual influence between consonantal and vocalic articulations.

1. Introduction

Prosodic structure has been widely recognized as an essential element of speech production, as it conveys a great deal of both structural and discourse information (Selkirk, 1995; Swerts & Geluykens, 1994; Herman, 2000). A large body of phonetic studies in the past two decades has increasingly demonstrated the importance of fine-grained phonetic detail in building up differential prosodic structures of utterances. One of the most conspicuous phonetic hallmarks of prosodic structure is domain-final lengthening (e.g. Klatt, 1975; Wightman et al., 1992; Gussenhoven & Rietveld, 1992, Edwards, Beckman & Fletcher, 1991; Cho, 2002, 2006; Byrd, 2000; Byrd, Krivokapić & Lee, 2006). Another well-known hallmark is articulatory expansion of prominent syllables (de Jong 1995; Beckman, Edwards, & Fletcher, 1992; Fowler, 1995, Erickson, 2002; Mooshammer and Fuchs, 2002; Cho, 2006, *inter alia*).

Yet another recent line of research has focused on domain-initial lengthening and spatial expansion, or strengthening (Fougeron & Keating, 1997; Fougeron, 2001; Cho & Keating, 2001; Keating et al., 2003; Byrd & Saltzman, 2003; Cho, 2002, 2006; Tabain, 2003; Onaka, 2006; Cho & McQueen, 2005; *inter alia*). (Note that here we use the term *domain-initial strengthening* more generally to refer to any phonetic patterning arising in domain-initial position, including spatial and temporal expansion of articulation due to prosodic boundaries. On the other hand, domain-initial *articulatory* strengthening refers specifically to spatial expansion.) In general, studies of domain-initial strengthening have not considered interactions of domain-initial position with other prosodic factors such as lexical stress and accentuation. In Fougeron & Keating (1997), lexical stress and phrasal accent were not considered as experimental factors. They noted that the final syllables of their test words "generally" bore the lexical stress, though not always, while the presence or absence of pitch accents on initial syllables was not noted. In Cho (2002, 2005, 2006), where the relation of initial strengthening to pitch accent was examined, lexical stress was not varied; likewise Pierrehumbert & Talkin (1992) examined effects of position and accent on the glottal articulation associated with /h, ʔ/, but with no lexical stress effect taken into consideration; and Lavoie (2001) compared effects of word-initial position and lexical stress in English and Spanish, but not position in larger domains, or phrasal prominence. That is, each previous study has looked at some piece of prosodic structure, but not the whole at once.

In the present study, we therefore extend these earlier results by examining each of these three prosodic factors (domain-initial position, lexical stress and phrasal accent) concurrently, as well as interactions between these factors, in order to develop a more comprehensive account of the prosody-phonetics interface in English. In the present study, initial test consonants occurred in syllables with primary stress or secondary stress; and each test word was accented or unaccented (by virtue of contrastive narrow focus). We could thus test whether and how domain-initial strengthening effects (i.e., boundary effects) are constrained by these stress/accent conditions. Several questions and hypotheses regarding the relation of boundaries to stresses and/or accents can be raised.

First, domain-initial effects could be the same as those due to prominence. Both initial boundaries and prominences can be described as marked by some sort of "local hyperarticulation" (e.g. de Jong, 1995, 2004; Fougeron & Keating, 1997; Harrington et al., 2000). Furthermore, it has long been noted that prominent syllables have greater energy (Fry, 1958; Lehiste, 1970; Beckman, 1986; Kochanski et al., 2005), and recently it has been suggested that domain-initial syllables do as well (Cho, McQueen & Cox, 2007 on English; Kim, 2004a on Korean). Vaissière (1988) specifically referred to both initial and prominent segments as "[+strong]", since the velum positions she observed during such segments were similarly extreme. Fougeron (2001:130) commented that "the nature of the variations found in initial position… is comparable to that observed in accented position". Yet it seems that these two prosodic factors, initial position and prominence, do not have the same effects on all aspects of articulation. For example, Pierrehumbert & Talkin (1992) found that initial position makes an entire CV more consonant-like, while an accent makes just the rime more vowel-like. However, they did not study oral articulations, only source properties. Cho also concluded that the effects are distinct, based on extensive comparison of kinematic measures of initial strengthening vs.

prominence, which showed that lip opening and closing gestures are associated with larger, longer and faster movement when accented, but are not necessarily faster in initial position (Cho, 2006); and that the tongue position extrema associated with vowels in CVs (and their corresponding F1 and F2) reflect articulatory expansion with accent, but not in initial position (Cho, 2005).

Previous studies thus have suggested that accent and position effects are similar in some aspects of articulation, but different in other aspects. It is, however, still an open question how these effects compare on the sorts of articulatory and acoustic measures that have primarily motivated proposals about initial strengthening. In the present study, we therefore compare boundary effects with stress/accent effects, looking at both articulatory and acoustic data, to determine if their effects on a variety of dimensions are the same.

We also consider the related question of the locality of these effects, where again evidence has been mixed. With respect to domain-initial strengthening, it is unclear whether the strengthening is strictly local to the first segment after a boundary, or extends to V in CV. Fougeron & Keating (1997) found no consistent vowel effects and so characterized English domain-initial strengthening as "a localized effect at prosodic domain edges, i.e., a strengthening of initial consonants…" (p.3736); similarly Cho & Keating (2001) for Korean and Onaka et al. (2003) for Japanese. Fougeron (2001) made a stronger claim for French, that domain-initial articulatory strengthening applied locally to only the initial segment of a constituent (e.g. to the first consonant in #CCV, to the vowel in #V). Barnes (2001, 2002) argued that in English the vowel in CV syllables is not subject to domain-initial lengthening because vowel duration is a major cue for stress. However, in contrast, in an EPG study in Italian, Farnetani and Vayra (1996) showed that greater consonantal constriction is accompanied by more vocalic opening in initial position. For English, Cho (2005)'s EMA study demonstrated increased backing of /a/ in both acoustic (F1-F2) and articulatory vowel spaces, and longer lip opening movements, in /#ba/ when in higher prosodic positions (Cho, 2006), and Byrd (2000) found longer tongue movements to V in #CV when in higher prosodic positions (specifically, from preboundary vowel /ə/ to the target /i/ spanning the domain-initial consonant /m/ as in /ə#mi/). Byrd & Saltzman (2003) present model predictions for boundary effects on V in #CV, and Lee, Byrd & Krivokapić (2006) and Byrd et al. (2006) present data supporting these predictions. Therefore in the present study we compare effects on C vs. on V in initial CVs.

Another locality question arises with respect to prominence, since it is unclear whether the effects of an accent are local to the primary stressed syllable. It is well established that when accent falls on a word, prosodic features such as pitch, duration and amplitude are realized mainly on the primary-stressed syllable (e.g. Fry, 1958; Lehiste, 1970; Beckman and Edwards, 1994. The stressed syllable is the head of the word (e.g., Liberman & Prince, 1977; Beckman, 1986; Hayes, 1989; de Jong, Beckman & Edwards, 1993; Beckman & Edwards, 1994), and as such hosts the accent. But if accent is a property of a word or larger constituent, then its effects could well be expected beyond the stressed syllable (see, for example, de Jong 2004 for discussion). Recently, a large body of experimental studies, especially by Turk and colleagues, has investigated the domain of accent in the temporal dimension (for English, Turk & Sawusch, 1997; Cambier-Langeveld & Turk, 1999; Turk & White, 1999; Cambier-Langeveld, 2000; White, 2002; de Jong, 2004; for Dutch, Eefting, 1991; Cambier-Langeveld & Turk, 1999; Cambier-Langeveld, 2000; Cho & McQueen, 2005). What has generally emerged is that accentual lengthening is not limited to the stressed syllable or the foot, but may spread within the Prosodic Word. For instance, Turk & White (1999) showed that accentual lengthening can affect an entire trisyllabic word with initial stress, but does not affect a preceding (unaccented) word. Even when the first syllable is unstressed and a later syllable is stressed, the initial unstressed syllable shows accentual lengthening. These studies, however, have focused on accentual effects on acoustic duration, and the unstressed condition used carried null prominence—the lowest level in the stress hierarchy, with vowels generally reduced. The present study thus extends these earlier findings by examining whether accentuation affects primary- vs. secondary-stressed initial syllables (both without vowel reduction) equally across a variety of articulatory and acoustic dimensions.

Lastly, if boundary and prominence effects turn out to be different in some way, then we can ask whether and how they interact. It is possible that the effects are completely independent; for example, domain-initial strengthening might be directed to marking prosodic boundaries in order to aid listeners with segmentation (Fougeron & Keating, 1997; Fougeron, 2001; Cho & Keating, 2001; Kim, 2004a, b; Cho, 2004; Cho, McQueen & Cox, 2007, *inter alia*), regardless of prominences. In that case, strengthening would be expected regardless of stress or accent conditions (*the across-the-board strengthening hypothesis*). Statistically speaking, we would expect to see either main effects of both position and stress/accent, without any interaction, on a given dimension, or effects on different dimensions.

However, it is also possible that the effects do interact, and there are several ways in which interactions might be seen. First, strengthening might vary with the information structure of the utterance in a given discourse context; it might be more crucial when the initial word is relatively important and therefore accented. For example, if a non-initial word is focused and therefore the initial word is not the informational locus of the utterance, then segmenting and identifying that word is less important to the listener, and speakers may pay less attention to the initial position. Under this *accent-dependent strengthening hypothesis*, we would expect to see an interaction effect between position and accent, with more strengthening when accented. (See also Turk & Shattuck-Hufnagel (2000), who have shown that there is an interaction between accent-induced lengthening and initial lengthening at the word level: accent-induced lengthening is strongest in word-initial position.) Second, strengthening might be tied to lexical stress, in the same way that accent is. Since the primary-stressed syllable is the head of the word, one might predict that domain-initial strengthening is in effect more robust when the initial segments occur in the primary-stressed syllable (the head), vs. in the secondary-stressed syllable (*the stress-driven strengthening hypothesis*). It was because they expected such an effect to be likely that Fougeron & Keating (1997) tested words with final stress. Statistically speaking, we would expect to see an interaction effect, with more strengthening when stressed. Finally, and conversely, strengthening could be limited by, rather than tied to, accent (Cho, 2006) or stress (Cho & McQueen, 2005). In Cho's study, when a syllable was accented, there was no further effect of a prosodic boundary on the lip opening movement, an interaction interpreted as a sort of ceiling effect: there is a limit to how far articulations can expand. Under a *maximum-limited strengthening hypothesis,* initial strengthening would be attenuated under either accent or stress. Statistically speaking, we would expect to see an interaction effect with less strengthening when stressed/accented.

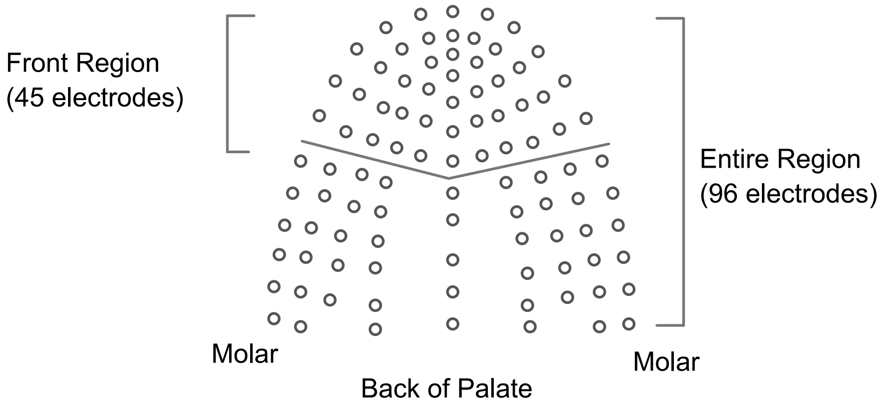
In sum, the present study investigates systematic articulatory variation for English /n,t/ as a function of prosodic factors (domain-initial position, lexical stress and phrasal accent), in order to understand how position and prominence together affect articulation and acoustics.

2. Method

2.1. Electropalatography (EPG)

Linguopalatal contact was studied as an indicator of the degree of contact, and thus of the degree of the oral constriction. Linguopalatal contact was measured by electropalatography using the Kay Elemetrics Palatometer 6300. As shown in Figure 1, a pseudo-palate covers the entire hard palate and the inside surface of the upper molars with 96 electrodes. Contact information was recorded by the Palatometer with a sampling interval of 10 ms, together with the acoustic signal recorded through a head-mounted close-talking microphone at a 12.8 kHz sampling rate.

Figure 1. Placement of 96 electrodes with two analysis regions in Electropalatography.



2.2. Subjects.

Four native speakers of American English (one male and three female), all trained phoneticians at UCLA, participated in this experiment. The three female speakers (who included one of the authors) also participated in Fougeron & Keating (1997), but all speakers except the author were unaware of the specific purposes of the present study.

2.3. Test sentences and Procedure

Test consonants were /n/ and /t/, the same consonants studied by Keating et al. (2003). They appeared in initial position in made-up names *Nebaben* (/nɛbəbɛn/) and *Tebabet* (/tɛbəbɛt/) which were created for the purpose of this study. Each string yielded two names by varying the lexical stress, such that test consonants occurred in either primary- or secondary-stressed syllables (e.g., ˈnɛbəˌbɛn vs. ˌnɛbəˈbɛn). These test words were then placed in different positions in carrier sentences, either Utterance-initial or Utterance-medial (where here, an Utterance (henceforth U) is equivalent to an Intonational Phrase (cf. Beckman & Pierrehumbert, 1986 or Shattuck-Hufnagel & Turk, 1996)). One word in each test sentence (either the test word, or another word) was given a narrow focus accent, so that the test word was either accented, or not. Table 1 shows how all three prosodic factors (Boundary, Stress, Accent) were manipulated across the test sentences. Thus, the experiment has a 2 x 2 x 2 x 2 design (2 consonants x 2 boundary types x 2 stress patterns x 2 accent patterns).

Table 1. Test sentences with target consonants /n, t/.

Boundary	Stress	Accent	Carrier sentences
Utterance/IP-initial	primary	accented	**n̲ɛ́bəbɛ̀n** fed them (**t̲ɛ́bəbɛ̀t**)
		unaccented	n̲ɛ́bəbɛ̀n fed **them** (t̲ɛ́bəbɛ̀t)
	secondary	accented	**n̲ɛ̀bəbɛ́n** fed them (**t̲ɛ̀bəbɛ́t**)
		unaccented	n̲ɛ̀bəbɛ́n fed **them** (t̲ɛ̀bəbɛ́t)
Utterance/IP-medial	primary	accented	One deaf **n̲ɛ́bəbɛ̀n** (**t̲ɛ́bəbɛ̀t**)
		unaccented	**One** deaf n̲ɛ́bəbɛ̀n (t̲ɛ́bəbɛ̀t)
	secondary	accented	One deaf **n̲ɛ̀bəbɛ́n** (**t̲ɛ̀bəbɛ́t**)
		unaccented	**One** deaf n̲ɛ̀bəbɛ́n (t̲ɛ̀bəbɛ́t)

In order to induce the desired variety of accent-placement patterns, speakers were introduced to discourse situations in which the target sentences with the particular accentual pattern (with a narrow focus somewhere in the utterance) could occur. The first speaker recorded in the experiment was not entirely consistent in avoiding unwanted phrase boundaries inside the test sentences, or extra pitch accents. Therefore the other three speakers were specifically asked to produce the entire three-word utterance as one chunk in order to avoid a phrase boundary. (What is called the U-medial boundary here is thus also IP-medial, and roughly equivalent to the Prosodic Word boundary in the prosodic hierarchy (e.g. Hayes, 1989; Selkirk, 1984). They were also asked to accent only one word in the sentence, which also helped ensure the utterance-internal phrasing consistency. These three speakers produced 5 repetitions of each sentence in a block and repeated the whole list three times, giving a total of 15 repetitions of each sentence. Whenever subjects made a mistake or produced an unintended boundary/accentual pattern, they were asked to read the sentence again to fill each block with 5 reliable repetitions. Self-corrections were often made by the subjects. The first speaker produced fewer usable tokens, on average 7.5 repetitions of each sentence.

2.4. Measurements

2.4.1. Linguopalatal contact

For analysis of EPG data, the percent of electrodes contacted in each data frame was computed (see Byrd, Flemming, Mueller, & Tan, 1995 for detailed method). To measure the consonantal linguopalatal contact made during the test consonants, a subset of electrodes was considered consisting of 45 electrodes in the front region of the palate area, as shown in Figure 1. This excluded electrodes contacted only as part of the vowel gesture, and thus measures only the consonant gesture. For linguopalatal contact made during the following vowel, however, all 96 electrodes were considered because, although the primary contact for the vowel was made in the back of the palate, some electrodes in the front region were still contacted.

Peak contact. For each consonant, peak linguopalatal contact was the percent of electrodes contacted in the data frame in which the most extreme contact was made for that segment during the closure. For consonants, larger contact is interpreted as indicating stronger articulation, while the opposite is the case for this vowel.

Release contact. In addition to peak contact, release contact was the percent of electrodes contacted in the data frame within 15 ms before the consonant's acoustic release. (See below for how the acoustic release for /n/ was defined.) Although peak contact may indicate how strongly the consonant is produced during its closure, that measure is usually made in the middle of the closure in silence, especially for the stop consonant /t/. (At least, this is the case in English; in Korean, in contrast, the peak contact comes late in the closure, so that it is perhaps less different from the contact at release (Cho & Keating, 2001).) However, since the release is an important component in both the production and perception of stop consonants, the contact pattern just before the release might reveal additional information about the prosodically-conditioned articulatory variation.

Vowel contact. The amount of linguopalatal contact during the vowel /ɛ/ was also measured, at the point of maximum acoustic amplitude. This is expected to be a point of maximum mouth opening and thus minimal linguopalatal contact.

2.4.2. Seal duration

The time from the first through the last frames during which the oral cavity was completely sealed was measured. Seal duration is therefore a measure of the oral closure duration, which cannot be measured from the acoustic signal for utterance-initial /t/. Thus, unlike acoustic closure duration, seal duration can be compared across consonants and positions, but it is a coarser measure since it is limited to the Palatometer's 10 ms sampling interval.

2.4.3. Acoustic measures

Several measures were made from the acoustic signal.

Nasal duration for /n/. The interval from the onset to the offset of nasal energy (murmur) for /n/ was measured from spectrograms. The offset (the acoustic release) of /n/ generally coincided with the end of continuous lower-amplitude oscillation just before the vowel, as seen in the waveform.

Nasal energy for /n/. The mean nasal energy during /n/ was measured, taking the means over the RMS acoustic energy profile of the entire nasal duration. Cho & Keating (2001) measured the nasal energy minimum, which was measured as the lowest point of the RMS acoustic energy profile. However, they had to exclude this measure for the utterance-initial /n/s after a pause, because in such a case, the minimum was always zero at the onset and the maximum was aligned with the offset associated with the following vowel. The present study had just two boundary levels, U-initial vs. U-medial, of which the former is accompanied by a preceding pause. Thus, it was impossible to base comparisons on the nasal energy minimum. Instead, the mean nasal energy was used to assess the nasal energy difference as a function of Boundary as well as the other two prosodic factors, Stress and Accent, though it is expected to be more reliable for Stress and Accent than for Boundary. The results of this measure will thus be interpreted with this limitation in mind.

It should be noted that nasal duration and nasal energy for /n/ reflect the size of the velopharyngeal opening during the consonant. Building on previous work (e.g., Straka, 1963; Lieberman & Blumstein, 1988; Fujimura, 1990), Fougeron (2001) proposed that an increased articulatory force associated with domain-initial articulation brings about the elevation of the velum (by virtue of relaxation of the contraction of levator palatini muscles). This has been considered as a possible account of the finding that nasal flow tends to be reduced in larger domain-initial positions in French (found in three out of four speakers) (Fougeron, 2001), as well as previous findings on initial velum raising at the word level in English (e.g., Krakow, 1989; cf. Krakow, 1999 for a review) and at the phrase level in Estonian (Gordon, 1996).

Voice Onset Time (VOT) for /t/. VOT for /t/ was measured from the time of the acoustic release burst to the onset of voicing in the following vowel. This measure is primarily related to laryngeal articulation; a longer VOT could result from a larger or longer or later glottal opening. Löfqvist & McGarr (1984) and Cooper (1991) found that glottal opening is larger with stress, and Cooper also found that it is larger in word-initial position. Similarly, Jun, Beckman & Lee (1998) found larger glottal openings in Korean stops in Accentual Phrase-initial positions. VOT likewise follows these patterns; however, a direct correlation between size of glottal opening and VOT has not been documented.

RMS burst energy for /t/. The acoustic burst energy at the stop release was measured from an FFT spectrum giving the RMS value over all frequencies above 500 Hz. The low frequency cut-off was to avoid the potential influence of voicing coming from adjacent vowels. A 256-point (20 ms) window was used to cover the first 10 ms of the release. As discussed in Cho & Keating (2001) and Cho & McQueen (2005), RMS burst energy for /t/ may depend upon articulatory/aerodynamic characteristics of the stop release gesture. For example, degree of intraoral pressure behind the oral constriction may be correlated with it: the higher the oral pressure built up during the stop closure, the higher the RMS burst energy. Conversely, it may also be correlated with degree of linguopalatal contact for /t/, such that the larger contact would induce a longer release duration, which may give rise to reduced peak burst energy (Stevens, Keyser & Kawasaki, 1986). Finally, it may vary at least in part with the speed of the stop release, such that a faster release tongue movement may increase the burst energy.

Center of Gravity (COG) for /t/. The spectral center of gravity (the first spectral moment) is the centroid frequency of a defined range of the spectrum, with each frequency being weighted according to its amplitude. To obtain the centroid frequency, frequencies over all samples were multiplied by the corresponding spectral energies. The sum of these products was then divided by the sum of the spectral energies. The same FFT spectra as used for RMS burst energy measurement were used. COG may be correlated with the size of the cavity in front of the oral constriction, such that a smaller size front cavity may induce a higher centroid frequency (Forrest, Weismer, Milenkovic & Dougall, 1988; Zsiga, 1995; Harrington & Cassidy, 1999; Cho, Jun & Ladefoged, 2002).

Vowel duration. The duration of the vowel /ɛ/ after the test consonant was measured, from the onset of voicing for the vowel to the F2 offset. (F2 offset was used because voicing of the following /b/ sometimes made it hard to determine the exact vowel endpoint in the waveform.) Longer durations could facilitate the attainment of articulatory targets as, for example, predicted by the undershoot hypothesis (Lindblom, 1963; Moon & Lindblom, 1994).

Vowel amplitude. The peak amplitude (dB) during the vowel was measured from the acoustic intensity profile. Vowel amplitude is expected to be inversely correlated with Vowel contact, since a more open vocal tract results in a louder acoustic signal.

Vowel F1. The first formant frequency was measured from the wideband spectrogram at the same point as the Vowel contact and Vowel amplitude measurement. Since *F1* is an acoustic index of vocal tract opening, it is also expected to be (inversely) correlated with Vowel contact.

2.5. Statistical analyses

A series of repeated measures Analyses of Variance (RM ANOVAs) was conducted for statistical evaluation of the influence of the consonant and prosodic factors on these various measures. The within-subject factors considered were Consonant (/n, t/), Boundary (U-initial, U-medial), Stress (primary, secondary), and Accent (accented, unaccented). RM ANOVAs (with each speaker contributing one averaged score per condition) would return significance only if most speakers contributed consistently to any observed variations. However, such statistical analyses would not tell whether non-significance was due to consistent null effects across speakers or whether it was simply because of different speaker behaviors. This would hold especially for articulatory data, due to speaker differences in anatomy. For this reason, in addition to RM ANOVAS, separate univariate ANOVAs were conducted with the factor Speaker added as a random factor in order to determine the speakers' contribution to any observed results. A significant interaction between a within-subject factor and Speaker would imply speaker-by-speaker differences. Therefore, whenever there was such a significant interaction, we note the individual speaker behavior, in comparison with the overall pattern across speakers. In addition, because the present study has only four speakers (a limitation that an instrumental study often imposes), even one speaker's slightly deviant behavior from, or relatively smaller contribution to, the overall pattern is likely to result in a trend effect, even if univariate ANOVAs revealed no interactions with Speaker. Thus, when there was a trend in the main effect at $p<0.08$, remarks on each speaker are also made, based on a series of factorial ANOVAs conducted for each speaker. However, given the problem conducting statistical comparisons within a speaker (Max & Onghena, 1999) the results of ANOVAs for each speaker should be taken only as suggestive.

When there was an interaction between factors, posthoc pairwise comparisons were made. However, with only four speakers, pairwise comparisons could not be made with data averaged over repetitions. Thus, for the posthoc comparisons, a one-way ANOVA for each pair of relevant conditions was conducted with all repetitions included. Inclusion of multiple repetitions, however, can artificially inflate error terms and degrees of freedom, and thus can increase the likelihood of making a Type I or alpha error (Max & Onghena, 1999). To compensate for this, the alpha level for significance was set more conservatively at 1% ($p<0.01$), and any difference at the level of $p<0.05$ was treated as a trend effect. When necessary, effect size was estimated by conducting eta^2 analyses. Eta^2 values are similar to R^2 values in regression analyses, in providing a measure of how much the observed variability can be ascribed to a given factor and, therefore, how large the observed effect might be (Sheskin, 2000:553-556). This is especially useful when two pairwise comparisons both reach significance for a given factor, but the potentially differential effects of the factor are of interest (e.g., when there is a between-factor interaction).

Finally, to investigate the relationship between articulatory and acoustic measures, a series of simple regression analyses were conducted.

3. Results

The present study investigated the effects of the three prosodic factors prosodic boundary, lexical stress, and accent on the production of English /nɛ/ and /tɛ/. The results of these analyses are summarized in Table 2 and described individually in this section, for each measure separately. While Consonant (/n/ vs. /t/) was an independent variable in statistical analyses and is included in Table 2 and some figures, results for that factor will generally not be described, as no hypotheses about consonant differences were being tested.

3.1. Consonantal strengthening

3.1.1. EPG data

Figures 2 and 3 present the results for the EPG measures for /t/ and /n/. Variation in linguopalatal contact as a function of prosodic Boundary strength (U-initial vs. U-medial) showed articulatory strengthening effects. As seen in Figures 2b, 2c vs. 2d, peak contact showed a main effect of Boundary ($F[1,3]=10.05$, $p<0.05$, 61.4% *vs.* 54.0%), but not of Stress ($F[1,3]=3.11$, $p>0.1$) or Accent ($F[1,3]=3.87$, $p>0.1$). Release contact also showed a main effect of Boundary ($F[1,3]=13.98$, $p<0.05$, 44.3% *vs.* 40.8%), but not of Stress ($F[1,3]=3.49$, $p>0.1$) or Accent ($F[1,3]=6.17$, $p>0.08$). Release contact did, however, show a significant interaction between Boundary and Stress ($F[1,3]=12.29$, $p<0.05$), as seen in Figure 3a. This interaction was due to the fact that the boundary difference (U-initial > U-medial) in release contact was significant when consonants were primary-stressed (46.1 % *vs.* 40.8 %, $p<0.005$), but not when they were secondary-stressed (42.7 % *vs.* 40.9 %, $p=0.48$), and also the strengthening pattern Primary > Secondary was seen when consonants were U-initial, but not when they were U-medial. In sum, the Boundary effects on peak and release contacts reflect that U-initial consonants (both /n/ and /t/) are produced with larger linguopalatal contact, as compared to U-medial consonants, in a stress-dependent way for release contact.

Unlike linguopalatal contact, however, seal duration revealed effects of all three prosodic factors. The Boundary factor (Figure 2b) showed a trend effect to U-initial lengthening ($F[1,3]=6.86$, $p<0.08$, 128.6 ms *vs.* 74.1 ms), but all four speakers showed the same pattern. The Stress factor showed a main effect, such that seal duration was longer when consonants were primary-stressed *vs.* secondary-stressed as shown in Figure 2c ($F[1,3]=15.85$, $p<0.05$, 143.9 ms *vs.* 118.0 ms). Finally, the Accent factor (Figure 2d) showed a trend towards a longer seal duration for accented consonants ($F[1,3]=8.170$, $p<0.07$, 107.5 ms *vs.* 94.2 ms), attributable to three out of the four speakers. In sum, seal duration was reliably longer with Stress, but tended to be longer with Boundary and Accent as well.

Table 2. Summary of main effects and between-factor interactions. The first line for each measure indicates the presence or absence of the main effect. The second and the third lines (when provided) explain interactions. * refers p<0.05, and tr. to p<0.08. Ui is Utterance-initial and Um is Utterance-medial.

measures	Consonant (n / t)	Boundary (Ui / Um)	Stress (prim / sec)	Accent (acc / una)
Peak contact (%)	*n.s.*	Ui > Um *	*n.s.*	*n.s.*
	no interactions			
Release contact (%)	/n/ < /t/*	Ui >Um * when prim	*n.s.* prim > sec when Ui	*n.s.*
	Boundary x Stress			
Seal-dur (ms.)	/n/>/t/ $^{tr.}$ (excl. MG)	Ui>Um $^{tr.}$	prim > sec*	*n.s.* acc > una (excl. MG) except Ui/sec
	Speaker x Boundary x Stress x Accent $^{tr.}$			
Nasal-dur (ms.)	*for /n/ only*	*n.s.* Ui<Um (MG) Ui>Um (KT)	prim > sec*	acc > una* when prim
	Speaker x Boundary x Accent*; Speaker x Stress x Accent $^{tr.}$			
Nasal energy (dB)	*for /n/ only*	*n.s.* Ui<Um except when prim/acc	*n.s.* prim > sec* when Ui/acc	acc > unacc* when prim, but more for Ui vs. Um
	Boundary x Stress x Accent*			
VOT (ms.)	*for /t/ only*	Ui > Um* when unaccented	*n.s.*	*n.s.* acc > una when Um
	Boundary x Accent*			
RMS burst energy (dB)	*for /t/ only*	Ui < Um*	*n.s.* prim>sec when acc	acc > una* more for prim vs. sec
	Stress x Accent*			
COG (Hz)	*for /t/ only*	*n.s.* Ui > Um (BB, PK) Ui < Um (MG, KT)	prim > sec*	acc > una (excl. MG)
	Speaker x Boundary*			
V-contact (%)	*n.s.*	*n.s.* Ui<Um when /n/, sec/acc	prim < sec*	*n.s.* acc < una when prim
	Stress x Accent*; Consonant x Boundary x Stress x Accent*			
F1 (Hz)	/n/ > /t/ (excl. PK)	*n.s.* Ui>Um when /n/, sec/acc	prim > sec*	acc > una* when prim.
	Consonant x Boundary x Stress $^{tr.}$; Stress x Accent*; Consonant x Stress*			
V-duration (ms.)	/n/ > /t/	*n.s.*	prim > sec*	*n.s.* acc > una when prim (excl. MG)
	Stress x Accent $^{tr.}$ (MG showed acc>una when both prim and sec.)			
V-amplitude (dB)	*n.s.*	Ui>Um*	prim > sec $^{tr.}$ (excl. MG)	acc > una* when prim
	Boundary x Stress*; Stress x Accent*			
CV contact difference	*n.s.*	Ui>Um* least when prim/acc	prim > sec*	*n.s.* acc > una when prim
	Boundary x Stress x Accent*			

Figure 2. Main effects on peak contact, release contact and seal duration. Error bars refer to standard errors. 'tr.'= p<0.08; '*'= p<0.05.

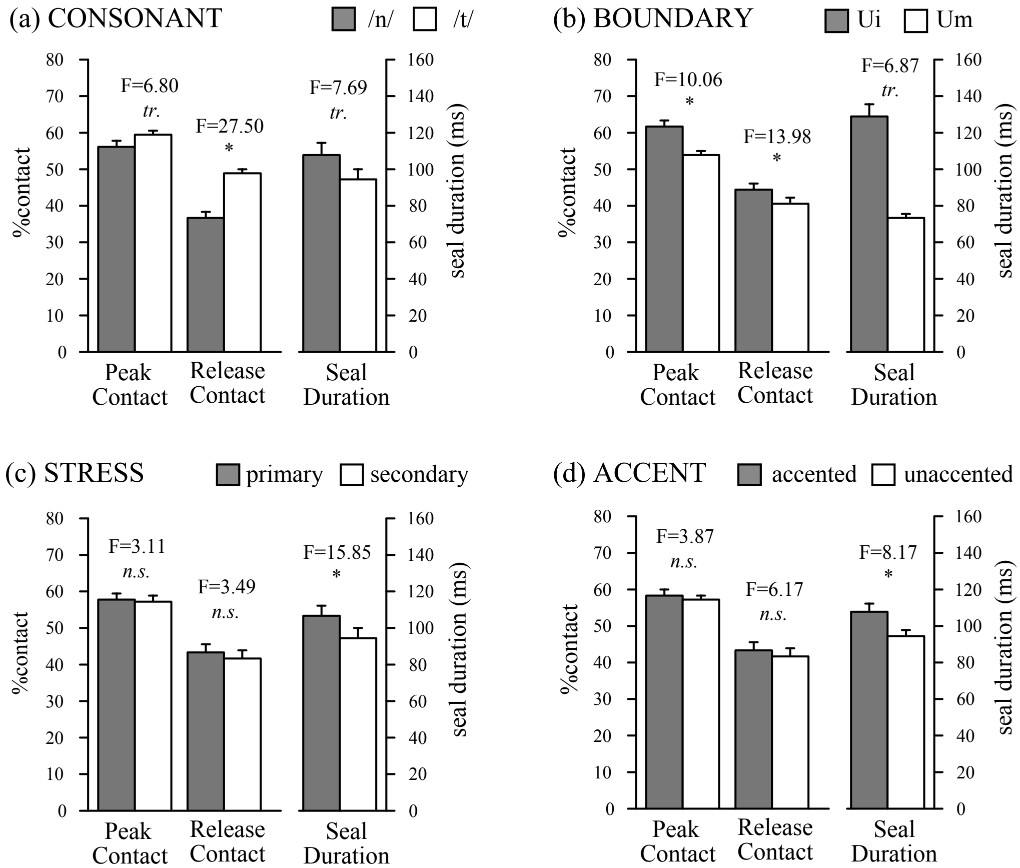
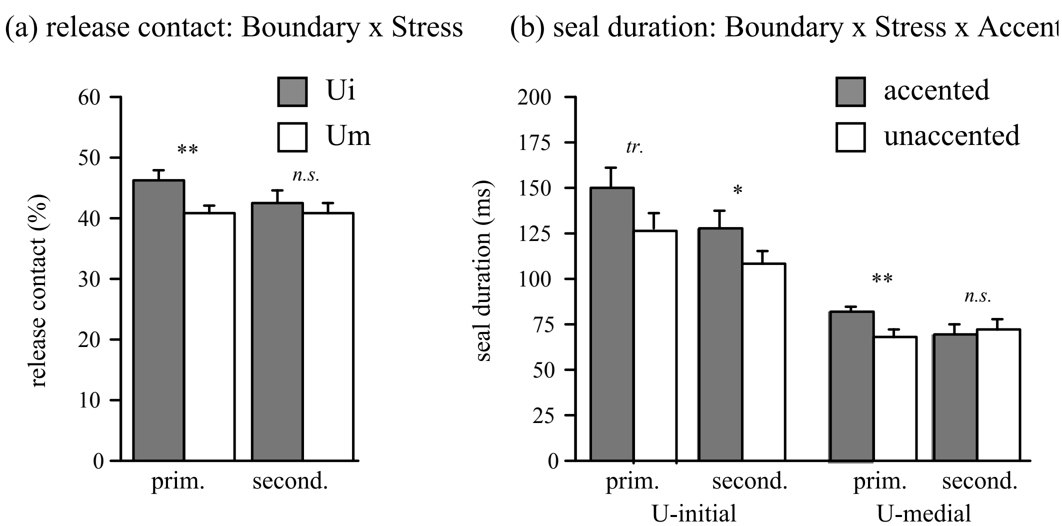


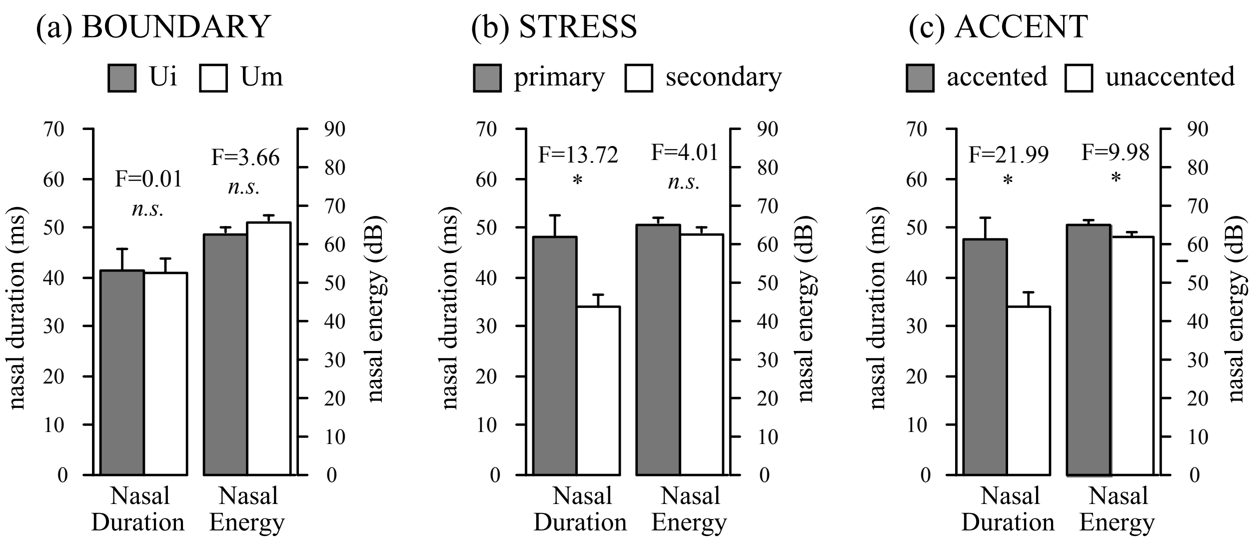
Figure 3. Interactions in release contact and seal duration. Error bars refer to standard errors. 'tr.' = p<0.05; '*'= p<0.01; '' = p<0.001.**



3.1.2. Acoustic data for /n/

Results for measures of /n/ are shown in Figures 4 and 5. Acoustic correlates of the three strong prosodic locations are also seen. Although nasal duration showed no main effect of Boundary (F[1,3]=0.01, p>0.9), both Stress and Accent showed significant main effects (Figure 4): /n/ was produced with a significantly longer nasal duration when primary-stressed *vs.* secondary-stressed (F[1,3]=13.72, p<0.05, 48.7 ms *vs.* 33.8 ms), and when accented *vs.* unaccented (F[1,3]=21.99, p<0.5, 47.7 ms *vs.* 34.4 ms). Univariate ANOVAs with Speaker as a factor found a Speaker x Boundary x Accent interaction (F[3,3]=8.95, p<0.05). This effect reflects that three speakers showed a tendency towards a shortened nasal duration when U-initial vs. U-medial only in the accented condition (and significant only for one speaker, MG), while one speaker (KT) showed an opposite tendency towards a longer nasal duration for U-initial, again only in the accented condition.

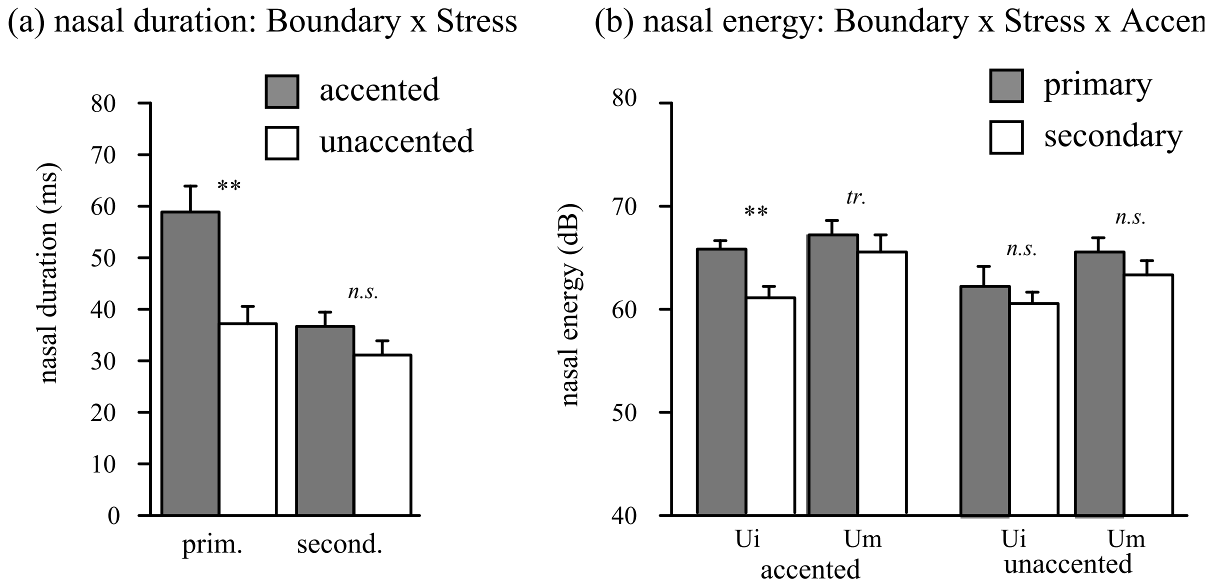
Figure 4. Main effects on nasal duration and nasal energy for /n/. Error bars refer to standard errors. '*'= p<0.05.



With nasal energy, neither Boundary (F[1,3]=3.66, p>0.1) nor Stress (F[1,3]=4.01, p>0.1) showed main effects. The only main effect was of the Accent factor (Figure 4c); /n/ was produced with greater nasal energy when accented *vs.* unaccented (F[1,3]=9.99, p>0.05, 65.1 dB *vs.* 63.1 dB). There was, however, a significant three-way interaction between Boundary, Stress and Accent (F[1,3]=9.937, p<0.05), as seen in Figure 5b, reflecting that an otherwise general trend towards reduced nasal energy for U-initial vs. U-medial is not seen in the primary-stressed/accented conditions.

In sum, /n/ is generally longer with stress and with accent, and has greater energy with accent, but the effects of Boundary vary complexly with these other factors.

Figure 5. Interactions in nasal duration and nasal energy for /n/. Error bars refer to standard errors. 'tr.'= p<0.05, '*' = p<0.01, '' = p<0.001.**



3.1.3. Acoustic data for /t/

Results for measures of /t/ are shown in Figures 6 and 7. VOT for /t/ showed a main effect of Boundary (Figure 6a), with longer VOTs when U-initial ($F[1,3]=373.05$, $p<0.001$, 40.3 *vs.* 37.3 ms). Neither Stress or Accent produced a main effect ($F[1,3]=0.164$, $p>0.3$, and $F[1,3]=0.097$, $p>0.7$, respectively). There was, however, a significant two-way interaction between Boundary and Accent ($F[1,3]=11.243$, $p=0.044$). As shown in Figure 7a, the interaction was caused primarily by the fact that the prosodic position effect was reliable when /t/ was unaccented ($p<0.0001$), but not when accented ($p>0.3$). In sum, VOT of /t/ varied with Boundary, but also sensitive to Accent.

Another measure for /t/ was RMS burst energy, which also showed a main effect of Boundary (middle panel of Figure 6a), with lower energy for U-initial vs. U-medial ($F[1,3]=12.41$, $p<0.05$, 14.5 dB *vs.* 16.6 dB). Cho & Keating (2001) found that in Korean, burst energy was sometimes, but not consistently, lower in higher prosodic positions; the result here is more consistent. Contrary to this Boundary effect, both Stress and Accent to some extent induced *greater* RMS burst energy: a main effect of Accent ($F[1,3]=17.25$, $p<0.05$, 16.8 dB *vs.* 14.3 dB) indicated an accent-induced increase of RMS burst energy regardless of the stress conditions, while a Stress x Accent interaction ($F[1,3]=15.13$, $p=0.03$) reflected that there was a significant stress effect only when /t/ was accented ($p<0.0001$), as can be seen in Figure 6b. Furthermore, eta-statistics suggested that the Stress x Accent interaction was also in part due to a more robust accent effect when /t/ was primary-stressed (mean diff. 3.5 dB, $p<0.001$, $eta^2 = 0.35$) *vs.* secondary-stressed (mean diff. 1.3 dB, $p<0.001$, $eta^2=0.09$). In sum, RMS burst energy of /t/ was lower in initial position, but higher when both stressed and accented.

Finally, spectral center of gravity (COG) at the release showed no main effect of Boundary in RM ANOVA ($F[1,3]=0.82$, $p>0.7$), but a speaker-dependent Boundary effect in Univariate ANOVAs. In univariate analyses, two speakers (BB, PK) showed higher COG for U-initial (both at $p<0.0001$), but the reverse was true for the other two speakers (MG $p<0.0005$, KT $p<0.02$).

There was a main effect of Stress on COG (with no interaction with Speaker), such that /t/ has a higher COG when primary-stressed *vs.* secondary-stressed, as shown in Figure 6b ($F[1,3]=11.445$, $p<0.05$, 3344 Hz *vs.* 3203 Hz). Finally, there was a trend effect of Accent on COG ($F[1,3]=7.083$, $p<0.08$, 3396 Hz. *vs.* 3151 Hz). In sum, release burst COG of /t/ was higher with stress and to some extent with accent, but showed a speaker-dependent effect of Boundary.

Figure 6. Main effects on VOT, RMS burst energy, spectral center of gravity (COG) for /t/. Error bars refer to standard errors. 'tr.'= p<0.08; '*'= p<0.05.

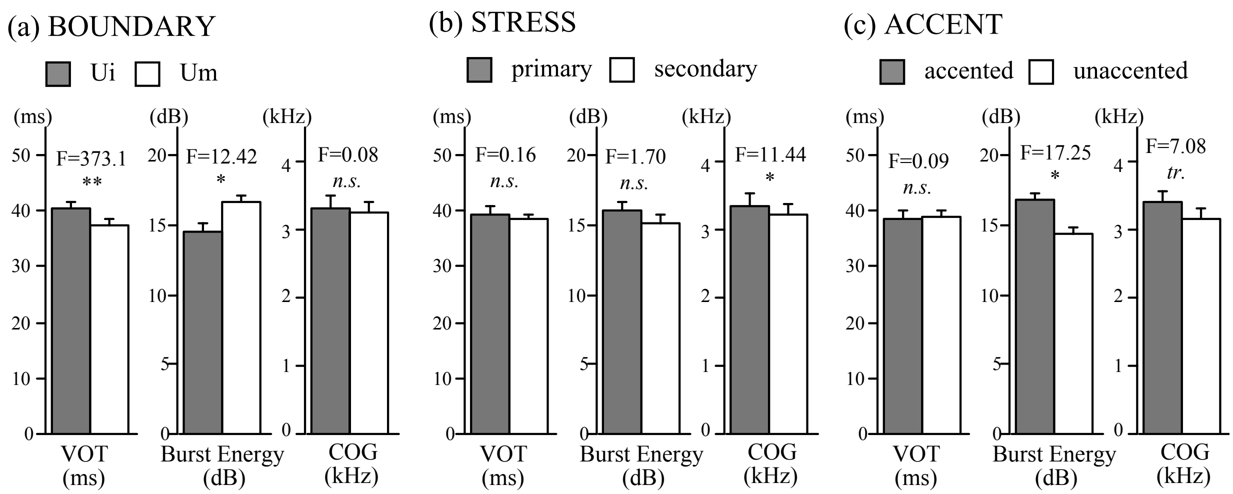
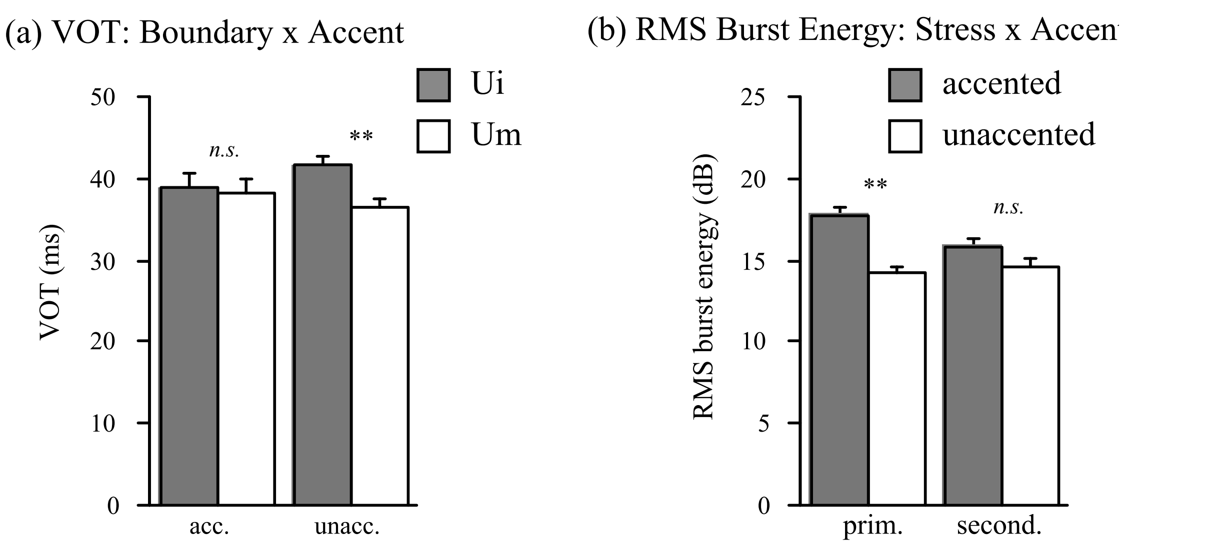


Figure 7. Interactions in VOT and RMS burst energy. Error bars refer to standard errors. '' = p<0.001.**



3.2. Vocalic strengthening

3.2.1. Articulatory measure: Vowel contact

Results for EPG measures of vowels are shown in Figures 8 and 9. Vowel contact showed no main effect of Boundary (Figure 8b), and only a four-way interaction which is too complex to be relevant here. However, there was a main effect of Stress (F[1,3]=27.2, p<0.05, 21.1% *vs.* 23.6%), shown in Figure 8c, such that the amount of linguopalatal contact was smaller (thus indicating larger vocalic opening) in the primary-stressed condition than in the secondary-stressed condition, regardless of other conditions. The Accent factor (Figure 8d) did not show a main effect but there was a robust Accent x Stress interaction reflecting an accentual effect when the vowel occurred in the primary-stressed syllable (Figure 9a) (p<0.0001). In sum, vowel contact was less when both stressed and accented.

Figure 8. Main effects on V-contact, F1, V-duration and V-amplitude. Error bars refer to standard errors. ‘tr.’= p<0.08; ‘*’= p<0.05.

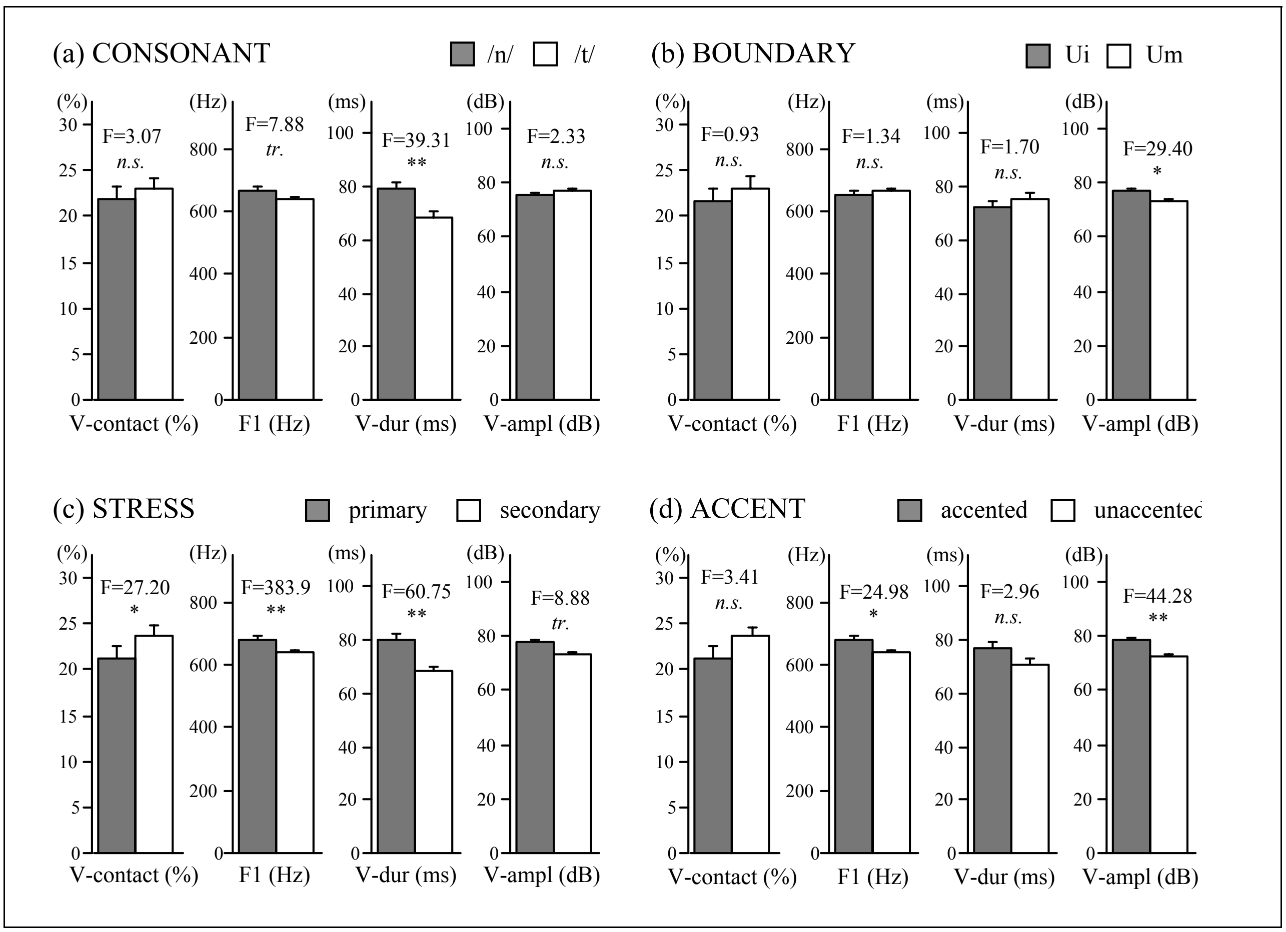
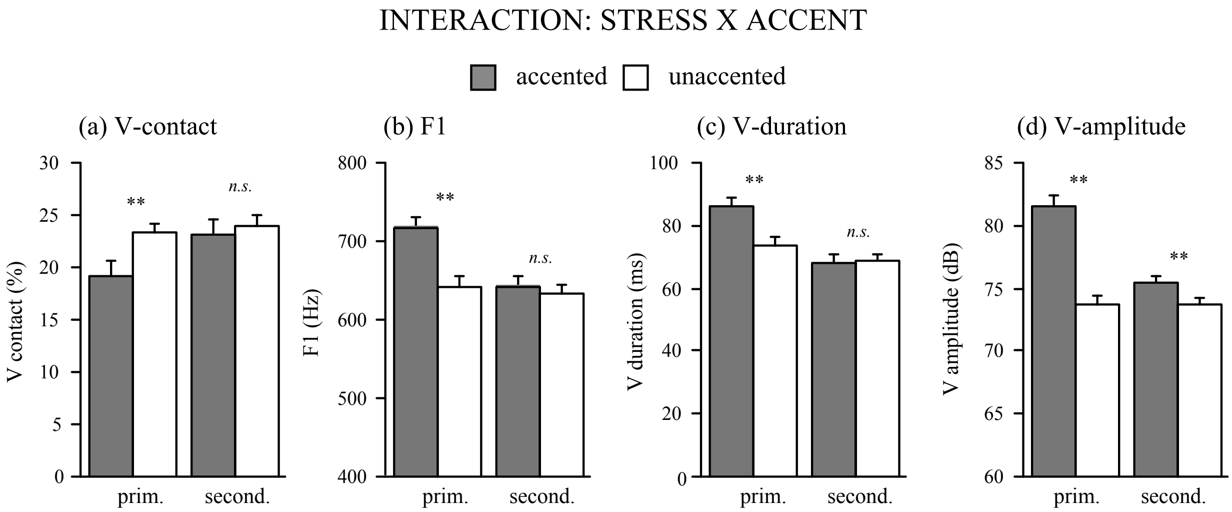


Figure 9. Stress x Accent interactions in V-contact, F1, V-duration and V-amplitude. Error bars refer to standard errors. '' = p<0.001.**



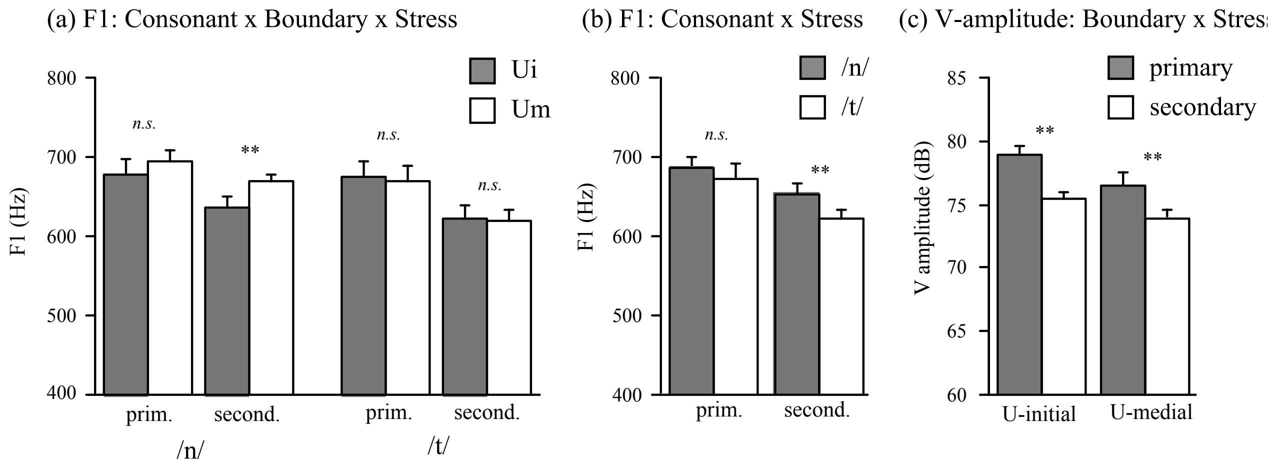
3.2.2. Acoustic measures: F1, Vowel duration, Vowel amplitude

Results for acoustic measures of vowels are shown in Figures 8, 9 and 10. *F1* showed a similar pattern as Vowel contact, with no Boundary effect on *F1* (F[1,3]=1.34, p>0.1), as seen in Figure 8b, and a complex three-way interaction shown in Figure 10a. This Consonant x Boundary x Stress interaction (F[1,3]=9.18, p<0.06) reflected that there was only one case in which Boundary had a significant influence on *F1*—i.e., for /n/ in the secondary-stressed condition (p<0.0001). On the other hand, as seen in Figure 8c and 8d, *F1* was higher when the vowel was primary-stressed vs. secondary-stressed (main effect of Stress (F[1,3]=389.95, p<0.0001)); and when accented vs. unaccented (main effect of Accent (F[1,3]=24.98, p<0.05)), again in line with patterns found in Vowel contact. There was again, as seen in Figure 9b, a significant Stress x Accent interaction (F[1,3]=109.53, p<0.005) due to the accent effect (Accented > Unaccented) being limited to the primary-stressed syllable (p<0.0001), with no difference in the secondary-stressed syllable (p>0.1). In sum, vowel F1 was greatest when both accented and stressed.

Vowel duration also showed no Boundary effect (Figure 8b). As shown in Figures 8c, 8d and 9c, it was, however, greater in the primary-stressed condition (main effect of Stress (F[1,3]=60.75, p<0.005, 79.8 *vs.* 68.4)), and in the accented condition only when the vowel was primary-stressed (no main effect but a Stress x Accent interaction (F[1,3]=7.03, p=0.077)). In sum, vowel duration was greatest when both accented and stressed.

Vowel amplitude, in line with other vocalic measures, showed a main effect of Accent (F[13]=44.28, p<0.01, 78.4 dB *vs.* 73.7 dB) and a trend effect of Stress (F[1,3]=8.877, p<0.06, 77.6 dB *vs.* 74.5 dB), as well as a Stress x Accent interaction as shown in Figure 9d. This was due to the more robust accent effect in primary-stressed syllables (mean diff. 8.1 dB, p<0.0001, eta^2=0.541) than in secondary-stressed syllables (mean diff. 1.8 dB, p<0.0001, eta^2=0.074). However, as opposed to other vocalic measures (including Vowel contact), Vowel amplitude also showed a significant boundary effect (F[1,3]=29.40, p<0.05, 77.1 dB *vs.* 75.1 dB), such that it was higher for U-initial than for U-medial, irrespective of other conditions, as seen in Figure 10c. In addition, a Stress x Boundary interaction (F[1,3]=10.738, p<0.05) was due to the stress effect being stronger for U-initial (mean diff. 4.1 dB, $p<0.0001$, $eta^2=0.181$) *vs.* U-medial (mean diff. 2.8 dB, $p<0.0001$, $eta^2=0.101$). In sum, vowel amplitude was greater in initial position, especially when stressed.

Figure 10. Interactions in F1 and V-amplitude. Error bars refer to standard errors. '' = p<0.001.**



3.3. Correlations between measures

3.3.1. Correlations between measures for /n/

A series of simple regression analyses between peak contact and other measures (seal duration, nasal duration, nasal energy) were conducted for each speaker. Results for /n/ showed that the systematic variation in linguopalatal contact is best accounted for by seal duration, at least for three speakers (excl. KT). As given in Table 3, for three speakers, the longer the seal duration for /n/, the larger the linguopalatal contact, with R^2 ranging from 0.19 to 0.70 (in all cases, $p<0.0001$). As for the relationship between peak contact and other measures, however, no robust correlations were found. Nasal duration was not significantly correlated with peak contact (with $R^2<0.01$ in all cases, $p>0.05$). Nasal energy showed a very weak correlation with peak contact only for two speakers (KT, MG; $R^2=0.045$ and 0.048, respectively, $p<0.01$), and even more complicatedly, the two speakers showed opposite patterns (positive for KT, negative for MG).

Turning to release contact as the dependent variable, as given in Table 3, it showed generally weaker correlations with seal duration as compared to peak contact. In only two cases was R^2 >.10: for BB, seal duration correlated with release contact ($R^2=0.274$), while for MG, nasal duration correlated with release contact ($R^2=0.115$).

Table 3. R2 values from simple regression analyses for /n/. Peak contact and release contact were the dependent variables, and seal duration, nasal energy and nasal duration were predictors. Cells with the highest R2 for each speaker are gray-colored. (* refers to p<0.05, ** to p<0.01, '–' to a negative correlation.)

Constant	Speaker	seal duration	nasal duration	nasal energy
/n/ peak contact (%)	BB	R^2=0.704**	R^2=0.055	–R^2=0.000.
	KT	R^2=0.008	R^2=0.001	R^2=0.045*
	MG	R^2=0.480**	–R^2=0.004	–R^2=0.048*
	PK	R^2=0.188**	R^2=0.008	–R^2=0.008
/n/ release contact (%)	BB	R^2=0.274**	R^2=0.067*	R^2=0.015
	KT	R^2=0.015	R^2=0.002	R^2=0.001
	MG	R^2=0.061**	R^2=0.115**	R^2=0.008
	PK	R^2=0.036*	R^2=0.000	–R^2=0.025

3.3.2. Correlations between measures for /t/.

As was the case for /n/, peak contact was best accounted for by seal duration. As given in Table 4, all four speakers (including KT who showed no contact vs. seal duration relationship for /n/) revealed a reliable pattern: the longer the seal duration, the larger the peak contact (with R^2 ranging from 0.194 to 0.695, in all cases $p<0.0001$). With respect to the relationship between peak contact and other acoustic measures, only weak, often insignificant, correlations were found. For example, with respect to VOT, no speaker showed any significant correlation with peak contact, showing independence between supralaryngeal and laryngeal articulations. For RMS burst energy, only two speakers (MG, PK) showed a weak but significant negative correlation with peak contact (R^2=0.042, $p<0.5$ for MG; R^2=0.091, $p<0.01$ for PK). This negative correlation suggests that if anything, for these two speakers, larger peak contact is associated with smaller RMS burst energy. Finally, with respect to COG, only two speakers (BB, PK) showed a significant correlation with peak contact—the larger the peak contact, the higher the COG. This pattern was more robust for BB (R^2=0.236, $p<0.0001$) than for PK (R^2=0.097, $p<0.0001$).

As for release contact, seal duration was again a better predictor than any other measures, although the correlation was generally weaker than was the case for peak contact, and one speaker (PK) did not show any significant correlation between measures at all, as given in Table 4. For both VOT and RMS burst energy, no correlation with release contact was found in any of the speakers. For COG, however, two speakers (BB, KT) showed its significant correlation with release contact: the larger the release contact, the higher the COG (R^2=0.127 and 0.095 for BB and KT, respectively). Thus, considering both peak contact (shown by BB, PK) and release contact (shown by BB, KT), three speakers showed a positive correlation between COG and linguopalatal contact.

Table 4. R2 values from simple regression analyses for /t/. Peak contact and release contact were the dependent variables, and seal duration, VOT, Burst Energy, and COG were predictors. Cells with the highest R2 for each speaker are gray-colored. (* refers to p<0.05, ** to p<0.01, '–' to a negative correlation.)

Constant	Speaker	Seal dur	VOT	Burst Energy	COG
/t/ peak contact (%)	BB	R^2=0.695**	–R^2=0.001	R^2=0.012	R^2=0.236**
	KT	R^2=0.445**	R^2=0.019	R^2=0.033	R^2=0.025
	MG	R^2=0.194**	R^2=0.020	–R^2=0.042*	–R^2=0.015
	PK	R^2=0.296**	R^2=0.012	–R^2=0.091**	R^2=0.097**
/t/ release contact (%)	BB	R^2=0.475**	–R^2=0.014	R^2=0.040	R^2=0.127**
	KT	R^2=0.090**	R^2=0.021	R^2=0.004	R^2=0.095**
	MG	R^2=0.134**	R^2=0.002	–R^2=0.001	–R^2=0.012
	PK	R^2=0.025	R^2=0.023	–R^2=0.006	R^2=0.002

3.3.3. Correlations between measures for /ɛ/

Table 5 shows vowel contact as the dependent variable and vowel acoustic measures as the independent variables, separately for each consonant context and each speaker. Vowel contact showed a significant inverse relationship with each of the three acoustic measures, *F1*, Vowel duration, and Vowel amplitude except in one case (PK, Vowel duration). Correlations were negative, such that as Vowel contact becomes smaller (thus suggesting more vocalic opening), each of the acoustic measures increased in its value, that is, the smaller the Vowel contact, the more the vowel is lowered in the acoustic vowel space, the longer the vowel duration, and the larger the amplitude of the vowel. As indicated by gray-colored cells in Table 5, it was Vowel amplitude that was most highly correlated with Vowel contact in the /n/ context, with R^2 ranging from 0.26 to 0.49, while in the /t/ context Vowel amplitude was not necessarily the most highly reliable predictor of variation in Vowel contact. As shown in gray-colored cells in the table, for two speakers (KT, PK) Vowel amplitude and F1 accounted for very similar amounts of variance in Vowel contact; while for the other two (BB, MG) F1 was the better predictor.

Table 5. R2 values from simple and multiple regression analyses. The dependent variable is V-contact and predictors are F1, V-duration and V-amplitude. The values in the parentheses indicate standardized coefficient (Beta) values from the multiple regression analyses. Cells with the highest R2 for each speaker are gray-colored. (* refers to p<0.05, ** to p<0.01, '–' to a negative correlation.)

Constant	Speaker	F1	V-duration	V-amplitude
V-contact /n/	BB	$-R^2$=0.21**	$-R^2$=0.19**	$-R^2$=0.49**
	KT	$-R^2$=0.18**	$-R^2$=0.27**	$-R^2$=0.40**
	MG	$-R^2$=0.23**	$-R^2$=0.25**	$-R^2$=0.26**
	PK	$-R^2$=0.04*	$-R^2$=0.05*	$-R^2$=0.36**
V-contact /t/	BB	$-R^2$=0.31**	$-R^2$=0.13**	$-R^2$=0.16**
	KT	$-R^2$=0.60**	$-R^2$=0.52**	$-R^2$=0.62**
	MG	$-R^2$=0.18**	$-R^2$=0.15**	$-R^2$=0.11**
	PK	$-R^2$=0.39**	$-R^2$=0.01	$-R^2$=0.41**

4. Discussion

In the previous section we reported how the production of the consonants and vowels in English /nɛ/ and /tɛ/ is conditioned by the three prosodic factors prosodic boundary, lexical stress, and accent. In this section, we will discuss the results, summarized in Table 2, according to the research questions and predictions outlined at the beginning of the paper.

4.1. Strengthening

4.1.1. Basic domain-initial consonant strengthening effect

The research questions of this study concern the interaction of domain-initial strengthening with other factors. Therefore, it is a necessary requisite that overall domain-initial strengthening be found in this corpus; minimally, that U-initial stops have more linguopalatal contact than U-medial stops, in line with the previous report on /n/ in English reiterant speech (Fougeron &

Keating, 1997). An overall pattern of domain-initial strengthening will be seen in main effects of the Boundary factor on one or more dependent measures. Such effects are indeed seen with consonant peak contact and consonant release contact. Consonant seal duration showed only a trend to initial lengthening, but VOT and burst energy for /t/ also varied with Boundary. Acoustic duration and energy of /n/, and Center of Gravity of /t/, did not.

4.1.2. Are positional and prominence strengthening the same? (Or, are there distinct markings of edges and heads?)

These effects of Boundary can then be compared with the effects of Accent and Stress in order to see if the two kinds of strengthening are the same. For this, we compare the main effects of Boundary listed above, to any main effects of Stress and of Accent. Are the same measures affected by all these variables, and if so, in the same directions?

The two consonant contact measures (peak contact and release contact) and VOT depend on Boundary but are not affected by Stress or Accent. Conversely, the two /n/ acoustic measures (duration and energy) and /t/ COG show no overall effect of Boundary but do depend on Stress and/or Accent. These six measures thus suggest that positional and prominence strengthening are independent, and that articulatory strengthening in linguopalatal contact best characterizes articulatory patterning as a function of boundary strength, but not of stress and accent. Furthermore, /t/ burst energy shows main effects of Boundary and Accent, but in opposite directions: less energy for U-initial /t/, but more energy for accented /t/. With opposing effects like this, these kinds of strengthening must be independent. That is, we see two kinds of independence – above, position and prominence are independent because they affect *different* measures, and here, they are independent because they affect the *same* measure but in directly contradictory ways.

In contrast, if a statistical trend is considered, then Consonant seal duration does show effects of all three factors in the same direction (longer seal when U-initial, primary stressed, and/or accented) – for this measure, the case can be made that position and prominence pattern similarly, even if not always reliably. An initial lengthening effect is in line with previous findings in other languages (in French, Fougeron, 2001; in Korean, Cho & Keating, 2001; in Taiwanese, Keating et al., 2003; in Dutch, Cho & McQueen, 2005) as well as in English (Keating et al., 2003). A joint effect of position and prominence is in line with the 'prosodic lengthening' effect found in Dutch (Cho & McQueen, 2005) in which the same three prosodic factors induced acoustic lengthening for the Dutch consonants /t, d, s, z/. The results suggest that lengthening of consonants is the common feature that arises in prosodically strong locations, regardless of whether consonants are in domain-initial position, primary-stressed, or accented. However, this case for similarity is weakened because only the Stress effect is statistically significant at $p<.05$.

However, these interpretations of the presence/absence of statistical main effects are complicated by the interaction effects. The main effect of Boundary on Consonant release contact arises from a Boundary x Stress interaction: initial consonants have more contact at release only when primary-stressed (and primary-stressed consonants have more contact only when initial). This suggests a similar effect of position and prominence. In contrast, the main effect of Boundary on /t/ VOT arises from a Boundary x Accent interaction, with initial /t/s having longer VOT only when unaccented (and accented /t/s having longer VOT only when medial). This suggests a contrary effect of position and prominence. Likewise, the lack of a main effect of Boundary on /n/ energy arises from opposing effects of position and prominence: while

/n/ has more energy in accented syllables (especially so when initial and primary-stressed) and in primary stressed syllables (especially so when initial and accented), initial /n/ has *less* energy than medial /n/ except when stressed and accented.

In sum, the various measures do not pattern alike with respect to position and prominence.

The measures on which position and prominence have opposite effects are especially intriguing. These include the two energy measures: /t/ burst energy, with main effects showing less energy for U-initial /t/, but more energy for accented /t/, and /n/ energy, with an interaction showing initial /n/s having less energy when not stressed and accented. Earlier we reviewed the hypothesis that increased articulatory force underlies both domain-initial strengthening, and prominence (e.g. Fougeron, 2001). On that view, the same reduction pattern in nasal and t-burst energy seen in initial position should surface with accented or stressed consonants; but this is not what we found. An alternative view is that position and prominence enhance different properties of nasals. In stressed or accented syllables, the feature [nasal] is enhanced, i.e. greater nasal energy. This is in line with the local hyperarticulation proposed by de Jong (1995), which posits maximization of (paradigmatic) phonemic, and hence lexical, distinctions. In contrast, in initial position, the reduction in nasal energy makes the nasals more consonant-like, such that (syntagmatic) CV or sonority contrast between the nasal and the following vowel is enhanced. (See also Hsu & Jun 1998, Fougeron 1999 for reviews of how effects on V in CV would enhance sonority contrasts between C and V) The position and prominence asymmetry found with /t/'s burst energy, however, seems to be more complicated. The increase in burst energy for /t/ in the stressed and accented conditions can be viewed as a local hyperarticulation effect, as a louder burst may heighten the consonantal identity. But the reduction in burst energy for initial /t/ is not compatible with CV enhancement; unlike a reduction in nasal energy, it does not make the stop less vowel-like.

In understanding the effect of prosodic strengthening on /t/ burst energy, it is worth considering results of a small-scale EMG study conducted by Ladefoged (Ladefoged, 1967; Ladefoged & Loeb, 2002)—i.e., stressed syllables are likely to be produced by additional activity of internal intercostals which increases respiratory power. (Note that here the stressed syllables included syllables that received accent in the sentence.) With a higher subglottal pressure, intraoral pressure during the voiceless stop closure will also be higher, which could account for the greater RMS burst energy observed for stressed/accented syllables in the present study. However, on this account, U-initial /t/ is also expected to have more burst energy, since Ladefoged also observed a similar increased muscular activity of internal intercostals, though weaker in amplitude, for the utterance-initial position. Possibly, the overall low level of oral pressure in U-initial position (since it must start at 0), even given extra respiratory effort, is the more important factor in determining burst energy. An alternative account, however, lies in variation in the speed of CV opening movements. McClean & Tasko (2002) showed that speeds of articulatory movements of the jaw, the lips, and the tongue (as measured by peak velocity) are significantly correlated with vocal intensity. Cho (2006) reported that the lip opening movement in CV in English is faster when CVs are accented, while no such effect was found for initial CVs. If a similar faster tongue opening movement obtains for accented and stresssed /t/, then greater burst energy could be expected (Stevens, Keyser & Kawasaki, 1986; Cho & Keating, 2001), and conversely if the opening movement is no faster in initial position, then burst energy should be the same across Boundary conditions.

4.2. Interactions

4.2.1. Is domain-initial strengthening dependent on accent?

If there is more initial strengthening in accented syllables, then we expect to see a Boundary x Accent interaction in that direction. In contrast, if there is a ceiling effect on strengthening of initial/accented syllables, then we expect to see a Boundary x Accent interaction in the opposite direction, that is, less initial strengthening in accented syllables, up to some limit. There is in fact one Boundary x Accent two-way interaction, on VOT of /t/. This goes in the direction of a ceiling effect: domain-initial increase in VOT was not found in the accented condition (but was observed in the unaccented condition).[1]

There is also one three-way interaction which includes both Boundary and Accent, the Boundary x Stress x Accent effect on /n/ energy. This also goes in the direction of a ceiling effect: nasal energy was *not* lower for U-initial when /n/ was primary-stressed and accented.

4.2.2. Is domain-initial strengthening dependent on stress?

If there is more strengthening of initial syllables when they are stressed, then we expect to see a Boundary x Stress interaction in that direction. In contrast, if there is a ceiling effect on stressed syllables, then we expect to see a Boundary x Stress interaction in the opposite direction, that is, less initial strengthening in stressed syllables, up to some limit.

There are in fact two Boundary x Stress two-way interactions, on Consonant release contact and on Vowel amplitude. The effect on Consonant release contact goes in the direction of strengthening when stressed (*stress-driven strengthening*): the domain-initial strengthening effect was anchored with the head of the word. We do not know why only this one measure patterns like this. In contrast, the effect on Vowel amplitude shows strengthening in both the primary and secondary stressed conditions, and the interaction reflects only a significant difference in the size of the Stress effect depending on position. So this strengthening is not stress-dependent.

There is one three-way interaction including Boundary x Stress, namely the Boundary x Stress x Accent effect on /n/ energy discussed above: initial /n/ has less energy than medial /n/ except when stressed and accented in line with a ceiling effect.

Finally, both the Vowel contact and the *F1* measures showed four-way interactions between all factors (including Consonant), such that the boundary effect on these vocalic measures was

[1] At this point, it is also worth noting that although Pierrehumbert & Talkin (1992) showed that VOT for English /t/ was lengthened phrase-initially, other studies have reported inconsistency in domain-initial VOT lengthening in English (Lisker & Abramson, 1967; Choi, 2003). For example, only two out of six speakers in Choi's (2003) study showed significantly longer VOTs Utterance-initially than Utterance-medially. Such inconsistent findings in previous studies may be due to the fact that the presence or absence of accentuation on the word was not fully factored in.

However, unlike our results, Cole, Kim, Choi, & Hasegawa-Johnson (2007) reported that in radio news speech, VOT was significantly longer when stops were accented vs. unaccented, even though the data were pooled across boundary conditions (IP-initial vs. IP-medial). However, in their study, the accented condition included only stressed syllables, whereas the unaccented condition included both stressed and unstressed syllables, which might have induced more extreme accent-induced differences.

The finding of the present study about domain-initial lengthening of VOT being limited to unaccented syllables has also implications for studies that showed boundary-induced VOT lengthening in other languages, such as Korean (Cho & Keating, 2001), Taiwanese (Hayashi, et al., 1999; Keating, et al, 2003) and Onaka (2003, 2006). These languages have different prosodic/metrical systems from English. A question that follows is then whether domain-initial VOT lengthening in these languages will be constrained by accent in much the same way as in English. More work needs to be done on these languages to address this question.

reliable only when the syllable occurred in the weakest prosodic condition—i.e., when secondary-stressed and unaccented. This is again a ceiling effect.

In sum, there is some tendency for initial strengthening to show ceiling effects in interaction with the Stress and/or Accent factors.

4.3. Locality effects

4.3.1. Is domain-initial strengthening limited to C in CV?

If strengthening is limited to C in CV, then we expect to see main effects of Boundary on one or more consonant measures, but no effect of Boundary on any vowel measures. We have already seen that there were Boundary effects on consonants (e.g., peak contact, release contact, seal duration, nasal energy, VOT, RMS burst energy). And most of the effects on the vowel – on Vowel contact, F1, and Vowel duration – only mark prominence from the stress/accent system and thus carry little information about domain-initial positions. Together, then, these consonant and vowel results support the locality hypothesis. This result is in line with earlier studies of vowel contact (Fougeron & Keating, 1997; Fougeron, 2001 for French), with a magnetometer study of C-to-V lip opening displacement (Cho, 2006); and with phonological arguments for language-specific locality (Barnes, 2002) – initial strengthening affects only C, not V, in CV.

Nonetheless, there was also a Boundary effect on one vowel measure: Vowel amplitude was greater in U-initial position. Thus strengthening is not entirely local to the initial C. This result is also in line with previous findings in the literature showing some evidence for domain-initial strengthening effects on the following vowel: magnetometer studies of vowel tongue positions and lip opening movement durations (Cho, 2005, 2006) and vowel-to-vowel tongue movements (Byrd, 2000; Cho, 2002).

Now, one might wonder why increased Vowel amplitude for the domain-initial vowel did not come with increased vocalic opening or increased Vowel duration. At first glance, this may look puzzling because amplitude typically goes hand in hand with duration (e.g., Lehiste, 1970; Beckman, 1986) and with vocalic opening (and *F1*) (e.g., Harrington et al., 2000). One possible explanation comes from the likely increases in respiratory power in the utterance-initial position, discussed earlier (Ladefoged, 1967; Ladefoged & Loeb, 2002). Heightened subglottal pressure by the time of the vowel (well after the consonant closure, when subglottal pressure has risen well above zero) could account for larger Vowel amplitude for U-initial as well as for stressed/accented syllables. Another possible explanation, not mutually exclusive, would involve voice source differences in initial position. Epstein (2002) found that phonation quality was tenser early in a sentence, and on prominent syllables, and this tenser quality could result in greater amplitude.

In sum, results of both previous studies and the present study show mixed evidence about the locality of initial strengthening in English. Domain-initial strengthening is not altogther absent on V in CV, but is likely to be attenuated. This supports the idea that the locality hypothesis is better characterized in terms of *gradation* rather than as an all-or-none constraint: the effect seems to wane gradually away as the articulations get farther away from the left edge of the domain into the following vowel, and perhaps beyond it. (See Byrd & Saltzman, 2003; Lee et al., 2006; Byrd et al., 2006; Cho & McQueen, 2005; Cho, 2005, for relevant discussions.)

4.3.2. What is the domain of accentuation?

If the domain of accentuation in an accented word is local to the primary stressed syllable, we expect to see an interaction of Accent x Stress. If there is no such interaction effect, that is if

Accent has an independent main effect, then the domain of accentuation is seen to include the secondary as well as the primary stressed syllables, rather than being limited to the primary stressed syllables. (Here we do not consider any effects on the reduced /ə/ in the middle syllables of the test words, since no measurements were made of these; only the primary and secondary stresses are considered.)

Accent on a word affects several measures: it has significant main effects on /n/ acoustic duration and energy, on /t/ burst energy, and on vowel F1 and amplitude; and there are trends for Consonant seal duration and /t/ burst COG. Of these, /n/ acoustic duration, Consonant seal duration, and /t/ burst COG do not have significant Accent x Stress interaction effects. These main effects without interactions, all on consonant measures, indicate that consonants in secondary-stressed syllables vary with accent just like consonants in primary-stressed syllables. That is, accent is not completely local to the primary stressed syllable. In contrast, all four vowel measures (contact, F1, acoustic duration, amplitude) showed Stress x Accent interactions, with accent effects either limited to (V contact, F1, duration) or merely greater in (V amplitude) primary stressed syllables. That is, with respect to most effects on vowels, Accent is indeed limited to the primary stressed syllable; but the vowel amplitude effect of Accent is apparently not completely local to the stressed syllable, though it is greatest there.

Two other measures, /n/ energy and /t/ burst energy, entered into other complex interaction effects. For RMS burst energy of /t/, a two-way Accent x Stress interaction reflected that while both primary- and secondary-stressed syllables manifested an accentual effect, the effect of accent was more robust in the primary-stressed syllable (as suggested by eta-statistics). For /n/ energy, a three-way Boundary x Stress x Accent interaction reflected that while accented syllables generally had more nasal energy than unaccented syllables, this effect was greatest when the syllables were both initial and primary-stressed. Again, both of these cases show that the Accent effect is not completely local to the stressed syllable, though it is greatest there.

In sum, three vowel measures (V contact, F1, duration) varied with Accent in a completely local way, limited to the primary stressed syllable of the accented word. Three consonant measures (/n/ acoustic duration, Consonant seal duration, and /t/ burst COG) varied with Accent without regard to Stress, so that Accent was manifest across the word. Finally, three measures (V amplitude, /n/ energy and /t/ burst energy) fell in between these 2 patterns: they varied with Accent across the word, but to a greater extent in primary-stressed syllables. Overall, the vowel measures show locality, while the consonant measures vary across the word. The measures do not pattern uniformly according to whether they are temporal vs. spectral measures, but it can be seen that of the consonant measures, the temporal measures show a simpler across-the-word pattern, while the spectral measures tend to show the more complex across-the-word-but-stress-sensitive pattern.

4.4. Relations of other measures to contact measures

The various acoustic measures were tested for correlations with the linguopalatal contact measures to determine if any of the acoustic variation is linearly related to the articulatory variation. In Cho & Keating (2001) we had found such relations between contact and duration measures in Korean, including VOT; and a modest negative correlation between contact and RMS burst energy.

In general, in the present study of English the acoustic measures were not strongly related to contact. Linguopalatal contact (either peak or release contact) had a very weak relationship with /t/ RMS burst energy (with R^2 ranging from 0.012 to 0.094 for peak contact and 0.004 to 0.04 for release contact). VOT for /t/ was not significantly correlated with linguopalatal contact (either peak contact or release contact, $R^2<0.03$ in all cases). In the case of VOT, longer VOT in initial position (as well as in accented syllables) can be interpreted as reflecting strengthening of the laryngeal glottal opening gesture. One speaker (MG) showed a significant (but very weak) negative relationship between linguopalatal contact and nasal energy ($R^2=0.048$). These non-correlations suggest that strengthening in lingual articulation is independent from strengthening of either laryngeal or velic articulations.

However, regression analyses revealed that linguopalatal contact is positively correlated with COG for three speakers. One speaker (BB) showed a significant positive correlation for both peak and release contacts ($R^2=0.24$ and 0.13, respectively); one speaker (PK) showed a similar significant positive correlation for just peak contact ($R^2=0.097$); and one speaker (KT) for release contact ($R^2=0.095$). The positive relation between contact and COG reflects that a larger amount of linguopalatal contact is likely to make the front cavity smaller, and the smaller the front cavity, the higher the COG. Although the predictability varies from speaker to speaker (with R^2 ranging from 0.095 to 0.24), these results suggest that COG is a comparatively reliable acoustic correlate of prosodically-driven variation in linguopalatal contact, and that COG could be used to assess consonantal articulatory strengthening to some extent. Nonetheless, in our data COG did not vary significantly with Boundary.

All the acoustic measures for the vowel /ɛ/ showed quite a strong (negative) correlation with Vowel contact, suggesting that the articulatory strengthening pattern found in Vowel contact (mainly for stress and accent effects) has clear acoustic consequences. The close relationship between Vowel contact and *F1* also increases the reliability of Vowel contact as a measure of vocalic opening or sonority, since *F1* generally patterns with other sonority measures such as jaw and tongue lowering (e.g., Harrington et al., 2000; Erickson, 2002; Cho, 2005). Furthermore, the correlation between Vowel contact and Vowel duration manifests a duration-dependent aspect of strengthening which is in line with the undershoot hypothesis (Lindblom, 1963; Moon & Lindblom, 1994).

5. Conclusions

In the present study, we have investigated effects of three prosodic factors: prosodic boundary (U-initial vs. U-medial), lexical stress (primary vs. secondary), and phrasal accent (accented vs. unaccented) on the articulation of /nɛ/ and /tɛ/ in English. Prosodic influences on articulation were tested by examining articulatory and acoustic measures for the word-initial consonant and the following vowel. The consonantal measures were linguopalatal contact (peak and release contacts), seal duration, nasal duration and nasal energy for /n/, VOT, RMS burst energy and spectral center of gravity at the release for /t/; and the vocalic measures were linguopalatal contact during the vowel, F1, vowel duration and vowel amplitude. Our results lead to a number of conclusions.

First, we asked whether, for C and V in CV, the effect of domain-initial position is the same as that of prominence due to stress or accent. Boundary effects were differentiated from prominence effects along several dimensions. In general boundaries resulted in consonant strengthening while prominence resulted in vowel strengthening. Some of the consonantal measures show more directly that the boundary effect is distinct from the stress or accent effects, in that these effects were in opposite directions. For example, nasal energy and duration tended to be reduced when /n/ was domain-initial, but the reverse was true when /n/ was in stressed or accented syllables. Another example is VOT: VOT tended to be longer domain-initially (though reliably so only in the unstressed syllable), but it did not vary at all with stress.

Second, we asked whether domain-initial strengthening affects only the consonant adjacent to the boundary, or the entire CV; that is, how local is domain-initial strengthening. Boundary effects were seen primarily in consonantal measures, with the vowel in the initial CV showing only an increased amplitude. That is, while domain-initial strengthening mostly affects the initial consonant, and while most effects on the vowel are due to prominence, domain-initial strengthening does affect the vowel to some extent. Taken together with some previous findings which also showed domain-initial strengthening effects on the following vowel, this result supports a loosening of strict locality, in favor of a gradient effect of prosodic boundaries.

Third, we asked whether domain-initial strengthening is constrained in any way by prominence due to stress or accent. Our results showed that it is. Although two measures (peak linguopalatal contact, and RMS burst energy for /t/) showed an across-the-board boundary effect (that is, irrespective of stress or accent), in many cases the effect of domain-initial strengthening is greater when there is no concomitant effect of stress or accent. That is, there seem to be ceiling effects on the total strengthening of any one segment from all sources, so that an initial segment which is also prominent will show less effect of position.

Fourth, we asked whether the effects of phrasal accent are limited to the primary-stressed syllable, or are seen more widely through the accented word; that is, how local accent is. There was a strong tendency towards more robust accentual effects on the primary-stressed syllable as compared to the secondary-stressed syllable. However, several consonantal measures, and one vowel measure, V amplitude, revealed accentual effects on the secondary-stressed initial syllables. Accentual influences can spread from a primary-stressed third syllable to a secondary-stressed initial syllable, crossing the left edge of the accented syllable, which is also the left edge of a foot; but this leftward spreading is observed primarily with consonantal measures. These results have implications for theories of the domain of accentual effects: the domain of accentual lengthening (as reflected in the seal duration measure) appears to be the same as the domain for non-temporal effects (as reflected in VOT and COG).

Finally, there was only a weak relation of contact to other measures, showing that several separate aspects of articulation participate independently in articulatory strengthening.

The results therefore showed that different aspects of prosodic structure (boundary versus prominence) are phonetically realized differently on some dimensions and similarly on others, but clearly in a distinct way when all the effects are considered together, suggesting differential phonetic encoding of the boundary and prominence information in speech production.

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