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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. The consonantal measures were linguopalatal Peak contact and Release contacts (by electropalatography), 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 Vowel contact, Vowel F1, Vowel duration and Vowel amplitude. Several specific points emerge. Firstly, domain-initial articulation is differentiated from stress- or accent-induced articulations along several measures. Secondly, the vowel is effectively louder domain-initially, suggesting that the boundary effect is not strictly local to the initial consonant. Thirdly, some accentual effects can be seen in secondary-stressed syllables, suggesting that accentual influences spread beyond the primary-stressed syllable. Finally, unlike domain-initial effects, prominence effects are not cumulative. Thus we conclude that, at least for the kind of word-initial syllables tested here, different aspects of prosodic structure (domain boundary vs. prominence) are differentially encoded.

1. Introduction

Prosodic structure has been widely recognized as an essential element of speech production, as it conveys a great deal of structural and discourse information (Herman, 2000; Selkirk, 1995; Swerts & Geluykens, 1994). A large body of phonetic studies in the past two decades has increasingly demonstrated the importance of fine-grained phonetic detail in demarcating differential prosodic structures of utterances. One of the most conspicuous phonetic hallmarks of prosodic structure is domain-final lengthening (e.g. Byrd, 2000; Byrd, Krivokapić, & Lee, 2006; Cho, 2002, 2006; Edwards, Beckman, & Fletcher, 1991; Gussenhoven & Rietveld, 1992; Klatt, 1975; Wightman, Shattuck-Hufnagel, Ostendorf, & Price, 1992). Another well-known hallmark is articulatory expansion of prominent (i.e. accented and/or stressed) syllables (Beckman, Edwards, & Fletcher, 1992; Cho, 2006; de Jong, 1995; Erickson, 2002; Fowler, 1995; Mooshammer & Fuchs, 2002, *inter alia*). These two prosodic effects are known to be different; for example, Beckman and Edwards (1994) showed that domain-final position is generally accompanied by articulatory lengthening of the jaw movement whereas prominence is marked by both lengthening and increased articulatory magnitude.

Yet another recent line of research has focused on domain-initial lengthening and spatial expansion, or strengthening (Bombien, Mooshammer, Hoole, Rathcke, & Kuhnert, 2007; Byrd & Saltzman, 2003; Cho, 2002, 2006; Cho & Keating, 2001; Cho & McQueen, 2005; Fougeron, 2001; Fougeron & Keating, 1997; Keating, Cho, Fougeron, & Hsu, 2003; Tabain, 2003; Onaka, 2006; *inter alia*). In general, studies of domain-initial strengthening have not considered interactions of domain-initial position with other prosodic factors such as lexical stress and phrasal accent. In Fougeron and 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, although 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

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initial strengthening to pitch accent was examined, lexical stress was not varied; likewise Pierrehumbert and 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 of initial position 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, stresses and 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, Fletcher, & Beckman, 2000). Furthermore, it has long been noted that prominent syllables have greater energy (Beckman, 1986; Fry, 1958; Kochanski, Grabe, Coleman, & Rosner, 2005; Lehiste, 1970), and recently it has been suggested that domain-initial syllables do as well (Cho, McQueen, & Cox, 2007 on English; Kim, 2004 on Korean). Vaissière (1988) specifically referred to both initial and prominent segments in English as "[+strong]", since the velum positions she observed during such segments were similarly extreme. Fougeron (2001, p. 130) commented that "the nature of the variations found in initial position […] is comparable to that observed in accented position". These suggestions that initial position and prominence share some kind of strengthening are especially striking given that the languages considered, English, Korean and French, are typologically different in their prosodic structure. Nonetheless 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 and 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 (2005, 2006) 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). A recent EPG study on the German /kl/ cluster (Bombien et al., 2007) has also demonstrated asymmetrical effects of initial strengthening and prominence: domain-initial effects were found primarily on the first consonant /k/, showing both durational and spatial expansions, while the second consonant /l/ was more likely to be influenced by lexical stress, and only in the durational dimension.

Previous studies thus have suggested that accent and position effects are similar in some aspects of articulation, but different in other aspects. 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 two questions about the relation of stress and accent. First, we consider a related question, about the locality of prominence, namely whether the effects of an accent are local to the primary-stressed syllable. It is well established that when accent (nuclear or otherwise) falls on a word, prosodic features (e.g. pitch, duration and amplitude) are realized mainly on the primary-stressed syllable (e.g. Beckman & Edwards, 1994; Bolinger, 1958; Fry, 1958; Hayes, 1995; Lehiste, 1970; Shattuck-Hufnagel, Ostendorf, & Ross, 1994; for a review, see Ladd, 1996). The stressed syllable is the head of the word (e.g. Beckman, 1986; Hayes, 1989; Liberman & Prince, 1977) 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, Cambier-Langeveld, 2000; Cambier-Langeveld & Turk, 1999; de Jong, 2004; Turk & Sawusch, 1997; Turk & White, 1999; White, 2002; for Dutch, Cambier-Langeveld, 2000; Cambier-Langeveld & Turk, 1999; Cho & McQueen, 2005; Eefting, 1991; also Dohen, Loevenbruck, Cathiard, & Schwartz, 2004 for French). Although the effects of accent are seen most strongly on the primary-stressed syllable (e.g. de Jong, 2004), it has generally emerged that accentual lengthening is not limited to the stressed syllable or the foot, but may spread within the Prosodic Word. For instance, Turk and 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 various 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 how accentuation affects primary- vs. non-primary-stressed initial syllables (which we will refer to as secondary-stressed), both of which have full vowels,[1] across a variety of articulatory and acoustic dimensions.

Second, we consider whether stress and accent represent degrees along a single scale of prominence, and are thus manifested in the same set of physical properties. There is overlap in the use of acoustic dimensions for lexical stress and phrasal accent, e.g. F0, duration, intensity/spectral tilt, vowel quality (e.g. Kochanski et al., 2005; Sluijter & van Heuven, 1996). It is therefore possible that different values along a given physical dimension may be signaling different prominence categories. Many studies have provided support for such a hypothesis about higher degrees of prominence. For example, when phrasal stress is more emphatic, the acoustic and/or physiological correlates of prominence are greater (Cooper, Eady, & Mueller, 1985; Gussenhoven & Rietveld, 1988; Herment-Dujardin & Hirst, 2002; Hermes, Becker, Mücke, Baumann, & Grice, 2008; Hirst & Di Cristo, 1998; Strangert, 2003; see also Ladd, 1996, Section 5.3.2). This is a cumulative marking of prominence, in which greater prominence is marked by greater values along physical dimensions. It is thus directly analogous with cumulative domain-final lengthening (Wightman et al., 1992) and cumulative domain-initial strengthening (Keating et al., 2003). The question then is whether lexical stress and phrasal accent can similarly be marked cumulatively along a prominence scale.

Evidence for cumulative marking of prominence in Swedish comes from studies described in Fant, Kruckenberg, and Liljencrants (2000). They propose that phonological categories of prominence can be translated into a single prominence scaling, and that perceivers can differentiate varying degrees of prominence along such a scale. This kind of idea is compatible with traditional views of a metrical hierarchy (for a review, see Hayes (1995, chap. 3)). In Fant et al.'s account, crucially, values along the prominence scale in turn correspond to gradient values of acoustic parameters. Fant et al. then demonstrate correlations between various acoustic measurements and perceivers' prominence ratings.

In this study we therefore test whether articulatory and acoustic measures that have been associated with positional strengthening reveal a cumulative prominence hierarchy. Under the assumption that accent falls on primary-stressed syllable, it is hypothesized that primary-stressed and accented syllables are more prominent than primary-stressed but unaccented syllables, which in turn are more prominent than syllables which are not primary-stressed.

[1] We distinguish primary, secondary, and null stress. In a word with two full vowels, the one without primary stress will be said to have secondary stress. Huss (1978) and Harrington, Beckman, Fletcher, and Palethorpe (1998) demonstrated small production differences between primary and secondary stress (independent of accent), Sugahara (2007) confirmed that the primary vs. secondary stress difference is maintained in the absence of phrase-level accent.

Finally, we also consider a separate locality issue, the locality of boundary and prominence effects. To what extent is domain-initial strengthening strictly local to the first segment after a boundary vs. extending to later segments? Fougeron and Keating (1997) found "some initial strengthening" of V in post-boundary CV (p. 3733), especially that utterance-initial vowels had less contact; but vowel strengthening was consistent and cumulative for only one of the three speakers, and so in the end they characterized English domain-initial strengthening as "a localized effect at prosodic domain edges, i.e., a strengthening of initial consonants…" (p. 3736). Similarly, Byrd et al. (2006) found no consistent effect of a boundary on the displacement of the opening movement from C1 to V1, or of the closing movement from V1 to C2—only one of their four speakers showed larger movements post-boundary. Even less effect on articulation of V in CV was found by Cho and Keating (2001) for Korean and by Onaka, Watson, Palethorpe, and Harrington (2003) for Japanese. The German initial effect on the first consonant /k/ in the /kl/ cluster showed a more strict local effect of initial strengthening (Bombien et al., 2007). Fougeron (2001) made a strong claim based on similar results 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).

In contrast, in an EPG study of Italian, Farnetani and Vayra (1996) showed that greater consonantal constriction is accompanied by more vocalic opening in initial position. And in an EMA study of English, Cho 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, 2005, 2006). It has also been found that spatial effects on opening and closing movements after a boundary persist over at least three consonants (Byrd et al., 2006; Krivokapić, 2007). Thus there is some evidence that the scope of spatial boundary effects is not always local.

Studies of effects of boundaries on *duration* of V in CV have likewise yielded ambiguous results. For example, Byrd (2000, p. 11) found "negligible" lengthening of V in post-boundary CV. Byrd et al. (2006) found that while the opening movement from C1 to V1 was longer after a boundary for 2 of 4 speakers, the closing movement from V1 to C2 was shorter for all 4 speakers. They interpreted this shortening (and shortening of later movements as well) as compensatory rather than boundary-related, but whatever its source, its effect on the acoustic duration of V1 is likely to be one of shortening. Similarly, Krivokapić (2007) found that the only temporal effect of a boundary on C in #VCVCVC was first-C shortening, for one of her three speakers. Barnes (2001, 2002) made the strong claim that in English the vowel in CV syllables is not subject to domain-initial acoustic lengthening because vowel duration is a major cue for stress.

Nonetheless, the idea that boundary effects should be gradient as a function of distance from the boundary is appealing, and not inconsistent with Fougeron and Keating (1997). The π-gesture model of Byrd and Saltzman (2003) predicts such effects. Therefore in the present study we further explore this issue by comparing boundary effects on C vs. on V in initial CVs.

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 Fig. 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.

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 and Keating (1997), but all speakers except the author were unaware of the specific purposes of the present study.

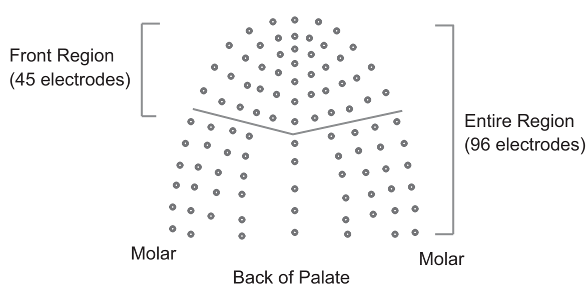

Fig. 1. Placement of 96 electrodes with two analysis regions in electropalatography.

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 names can be related to real names with the same prosody, such as *Caroline* or *Annabelle* with initial primary stress, vs. *Henriette, Marguerite,* or *Desiree* with initial secondary stress, or to other words like *Demerol, imitate* vs. *Halloween, Tennessee*. The vowel /ɛ/ was chosen because it cannot be stressless, and because it generally shows clear EPG contact, but mostly at the back of the pseudo-palate, where it does not overlap with the primary consonant contact.

These test words were then placed in different positions in carrier sentences, either Utterance-initial or Utterance-final, making the word-initial test consonants either Utterance-initial or Utterance-medial (henceforth U-initial and U-medial). One word in each test sentence (either the test word, or another word) was given a narrow focus accent. Only one word per sentence was accented, so the test word was either (nuclear) accented, or not. Table 1 shows how all three prosodic factors (Boundary, (Word) Stress, (Phrasal) Accent) were manipulated across the test sentences. Thus, the experiment has a 2 × 2 × 2 × 2 design (2 consonants × 2 boundary types × 2 stress patterns × 2 accent patterns).

Note that the factors Stress and Accent refer to different constituents: Word vs. Phrase. As described above, in theory a pitch accent on a word is usually attached to the syllable with the primary lexical stress. Thus, we have primary-stressed syllables with and without accents, but in our corpus the secondary-stressed syllables are not expected to bear accents. However, the *words* containing those secondary-stressed syllables occur with and without accents. Thus our accented/secondary-stressed condition means that the accent falls on a different syllable of the

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)

word from the secondary stress. As introduced earlier, however, one of the questions we ask in this paper is whether the accent effect is strictly local to the primary-stressed syllable or may extend to the secondary-stressed initial syllable. Thus, Accent × Stress interactions will be interpreted in terms of this locality question.

On the view that stress and accent are degrees along a prominence scale or hierarchy, we would expect a three-way distinction on a single prominence factor: syllables that are accented (and also primary-stressed) vs. syllables that are primary-stressed but unaccented vs. syllables that are neither primary-stressed nor accented (regardless of whether the word as a whole is accented). In terms of our manipulation of independent factors Accent and Stress, we would expect all primary-stressed syllables to differ from all secondary-stressed syllables (that is, regardless of accent), but accented syllables should differ from unaccented syllables only when primary-stressed. Thus, we can test the hypothesis of a prominence scale at the same time that we test for locality of accent.

In the recording sessions, speakers were first introduced to the test words, with their contrasting stress patterns. The test words were written in regular orthography (*Nebaben* and *Tebabet*) along with phonetic transcriptions (e.g. /nέbəbὲn/ versus /nὲbəbέn/). Speakers were generally able to correctly place the primary stress with no difficulty, on analogy with similar names and other real English words. The test sentences, with their contrasting accent-placement patterns, were then presented to the speakers for comparison and practice before recording.

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. (Since there were no sentence-internal breaks, what is called the U-medial boundary here is thus also IP-medial, and equivalent to the Prosodic Word boundary in the prosodic hierarchy (e.g. Beckman & Pierrehumbert, 1986; Hayes, 1989; Selkirk, 1984; Shattuck-Hufnagel & Turk, 1996)). They were also asked to accent only one word in the sentence, which not only ensured no unwanted accent on the first word when only the last word was to be accented, but also helped ensure 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.

No claim is made here that these utterances were natural in their construction or easy to produce fluently. The phonetics background of the speakers, the partial blocking of the stimuli, and the monitoring and correcting during the session, all helped subjects with the task. Nonetheless, preserving stress differences in unaccented test words was challenging, and subjects' productions sometimes showed some reduction to schwa of intended unaccented secondary-stressed vowels. Some productions showed very weak accenting of unaccented words, but crucially this weak prominence never gave rise to a percept of focus, so that the contrastive accent was always clearly and correctly maintained in intended positions.

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 Fig. 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 vowels.

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. With a Palatometer sampling interval of 10 ms, the 15 ms window ensured the recording of contact in the frame that was immediately before the 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/.[2] 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 /ε/ 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. Measuring linguopalatal contact at

[2]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).

this location not only simplified the measurement procedures, but also allows us to directly relate the articulatory and acoustic vowel measures, as they were all made at the same point. The vowel /ɛ/ is one with no extreme vocal tract constrictions. EPG contact reflects its degree of tongue lowering, which could be greater in prosodically stronger positions. Thus, following Fougeron and Keating (1997), we believe that the interval of minimal EPG contact is of primary interest for comparing the articulation of this vowel in different prosodic positions.

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 U-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. No measures reported here were normalized or calibrated.

Nasal duration for /n/: The interval from the onset to the offset of nasal energy (murmur) for /n/ was measured from the spectrograms and the waveforms combined, such that the offset (the acoustic release) of nasal murmur seen in the spectrogram 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 and 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 U-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, although 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. Fujimura, 1990; Lieberman & Blumstein, 1988; Straka, 1963), 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 (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. Lofqvist and 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, and 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. Alternatively, as Byrd and Saltzman (2003) predict less gestural overlap in initial position, the oral and the glottal (voicing) gestures may overlap less in the strengthening environment, which should result in increased VOT.

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 by Stevens (1998), RMS burst energy for /t/ will depend upon the articulatory/aerodynamic characteristics of the stop release. Stevens shows that the amplitude of a noise source is proportional to the oral airflow, and inversely proportional to the cross-sectional constriction area, at release. Greater linguopalatal contact for the constriction, if it results in a smaller constriction area at release, would lead to more energy in the burst. Conversely, if it results in a slower and longer release gesture, that could mean a later peak in burst energy (Stevens, Keyser, & Kawasaki, 1986), and thus possibly a smaller mean energy for the first 10 ms after release.

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 (Cho, Jun, & Ladefoged, 2002; Forrest, Weismer, Milenkovic, & Dougall, 1988; Harrington & Cassidy, 1999; Zsiga, 1995).

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.) A vowel's duration may be closely related to the attainment of its articulatory target: longer durations could either facilitate the attainment of articulatory targets as, for example, predicted by the undershoot hypothesis (Lindblom, 1963; Moon & Lindblom, 1994) or they could be due to lesser overlap between the vowel and the neighboring consonant as, for example, predicted in Articulatory Phonology (Browman & Goldstein, 1990, 1992).

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

Vowel F1: The first formant frequency was determined from the LPC-based formant-history tracking (with 25 ms frames) in the wideband spectrogram (in combination with visual inspection as supplementary checks) 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 related to 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). Results involving the Consonant factor are not reported here, as no hypotheses about different consonant behavior were being tested and the factor was included in analyses only to increase statistical power. Interested readers are referred to Cho and Keating (2007) for these results.

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 simply to different speaker behaviors. 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' individual contributions 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 of 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, pp. 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).

Correlation analyses, relating acoustic to production measures, were also carried out, but as significant correlations were few and weak they are not reported here, except as noted below. Interested readers are referred to Cho and Keating (2007).

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.

3.1. *Consonantal strengthening*

3.1.1. *EPG data*

Figs. 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 Figs. 2b, c vs. d, Peak contact showed a main effect

Table 2
Summary of main effects and between-factor interactions.

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

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 to $p<0.05$, and *tr.* to $p<0.08$. Ui is Utterance-initial and Um is Utterance-medial.

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 Fig. 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 (Fig. 2b) showed a trend effect to U-initial lengthening ($F[1,3]=6.86$, $p<0.08$, 128.6 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 Fig. 2c ($F[1,3]=15.85$, $p<0.05$, 143.9 vs. 118.0 ms). Finally, the Accent factor (Fig. 2d) showed a trend towards a longer Seal duration for accented consonants ($F[1,3]=8.170$, $p<0.07$, 107.5 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.

3.1.2. Acoustic data for /n/

Results for measures of /n/ are shown in Figs. 4 and 5. Although Nasal duration showed no main effect of Boundary ($F[1,3]=0.01$, $p>0.9$), both Stress and Accent

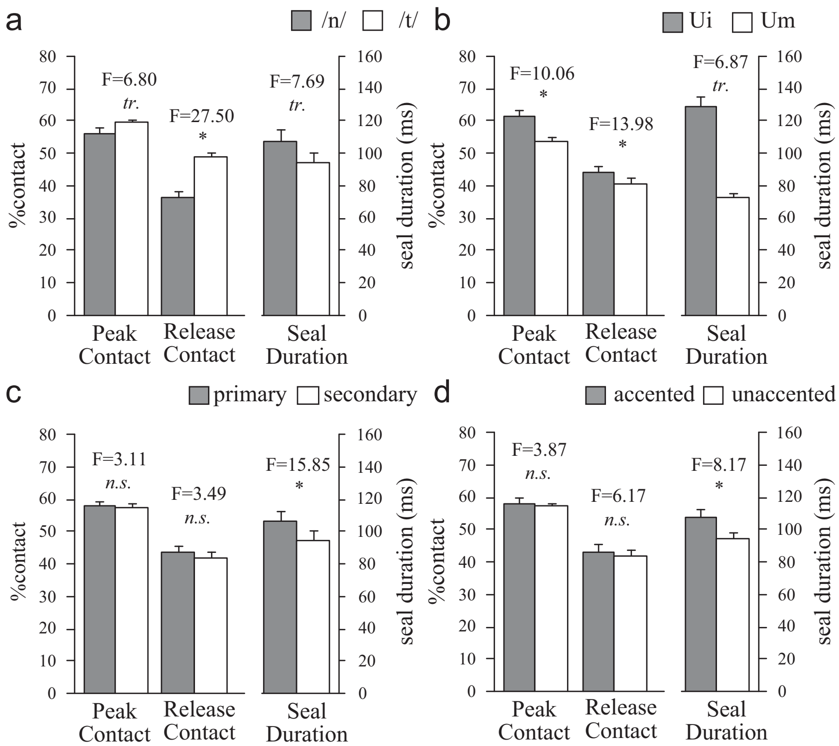

Fig. 2. Main effects on peak contact, release contact and seal duration. Error bars refer to standard errors. '*tr.*' = $p<0.08$; '*' = $p<0.05$. (a) Consonant; (b) Boundary; (c) Stress and (d) Accent.

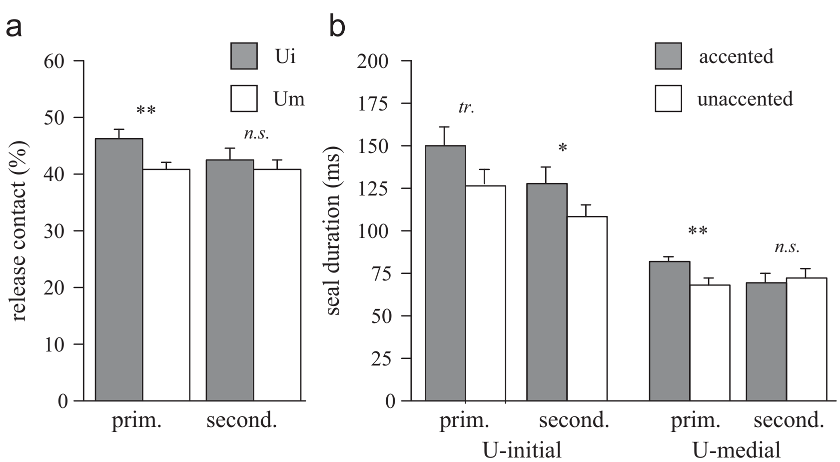

Fig. 3. Interactions in release contact and seal duration. Error bars refer to standard errors. '*tr.*' = $p<0.05$; '*' = $p<0.01$; '**' = $p<0.001$. (a) Release contact: Boundary × Stress and (b) Seal duration: Boundary × Stress × Accent.

showed significant main effects (Fig. 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 vs. 33.8 ms), and when accented vs. unaccented ($F[1,3]=21.99$, $p<0.5$, 47.7 vs. 34.4 ms). Univariate ANOVAs with Speaker as a factor found a Speaker × Boundary × 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. It is also worth pointing out that although RM ANOVA showed no significant Stress × Accent interaction ($F[1,3]=3.54$, $p>0.1$), the accent effect was found to be robust only in the primary-stressed condition: As seen in Fig. 5a, the accent effect was reliable when /n/ was primary-stressed ($p<0.001$, 58.9 vs. 34.7 ms), but it was not when secondary-stressed ($p>0.1$, 36.5 vs. 31.1 ms).

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 (Fig. 4c); /n/ was produced with greater Nasal energy when

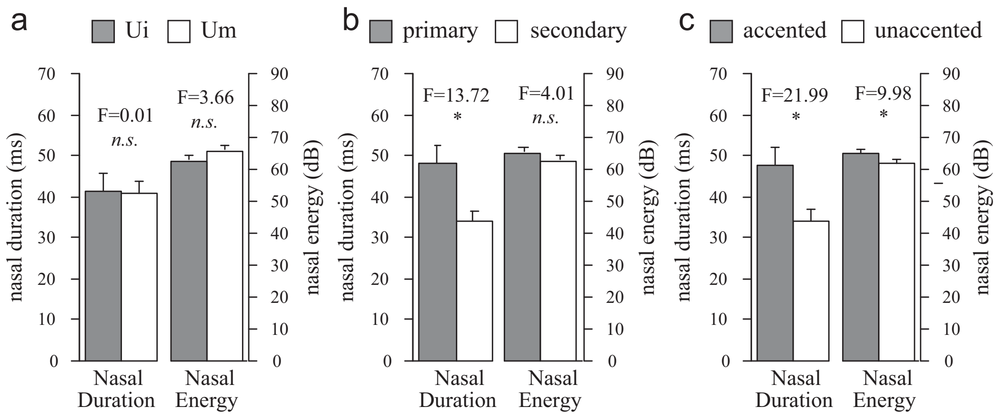

Fig. 4. Main effects on nasal duration and nasal energy for /n/. Error bars refer to standard errors. '*' = $p<0.05$. (a) Boundary; (b) Stress and (c) Accent.

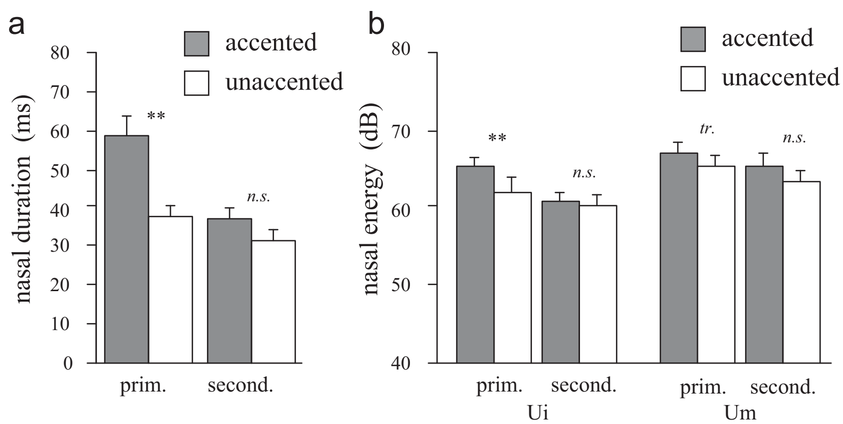

Fig. 5. Interactions in nasal duration and nasal energy for /n/. Error bars refer to standard errors. '*tr.*' = $p<0.05$, '*' = $p<0.01$, '**' = $p<0.001$. (a) Nasal duration: Stress × Accent and (b) Nasal energy: Boundary × Stress × Accent.

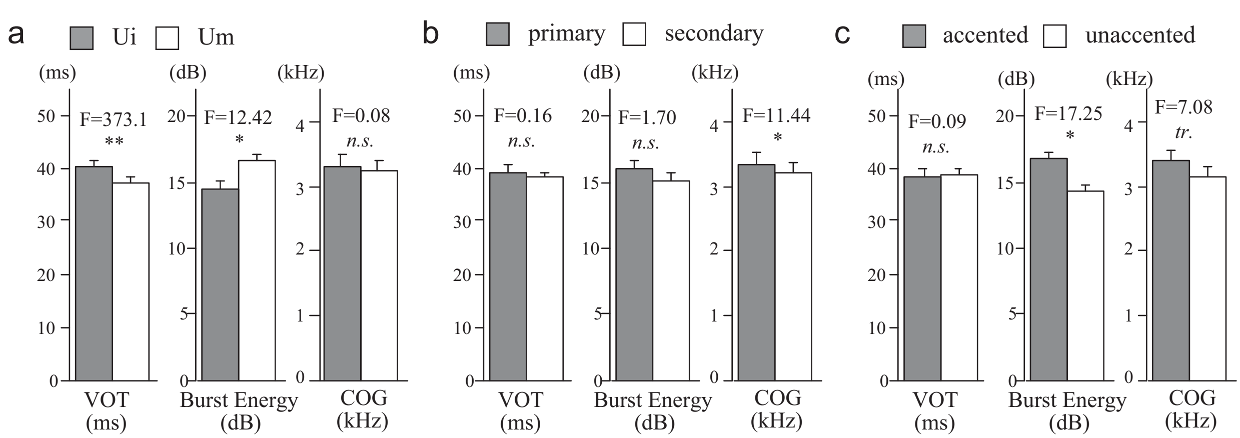

Fig. 6. Main effects on VOT, RMS burst energy, spectral center of gravity (COG) for /t/. Error bars refer to standard errors. '*tr.*' = $p<0.08$; '*' = $p<0.05$. (a) Boundary; (b) Stress and (c) Accent.

accented vs. unaccented ($F[1,3]=9.99$, $p>0.05$, 65.1 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 Fig. 5b, reflecting that the accent-induced greater Nasal energy is most clearly observed in the U-initial/primary-stressed condition ($p<0.001$) and 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.

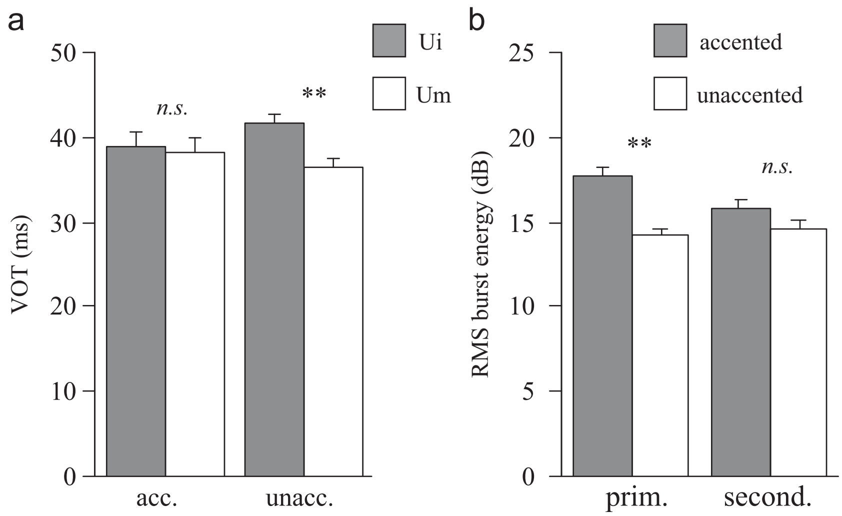

Fig. 7. Interactions in VOT and RMS burst energy. Error bars refer to standard errors. '**' = $p<0.001$. (a) VOT: Boundary × Accent and (b) RMS burst energy: Stress × Accent.

3.1.3. Acoustic data for /t/

Results for measures of /t/ are shown in Figs. 6 and 7. VOT for /t/ showed a main effect of Boundary (Fig. 6a), with longer VOTs when U-initial (F[1,3] = 373.05, $p<0.001$, 40.3 vs. 37.3 ms). Neither Stress nor 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 Fig. 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 ($p>0.3$); and that the accent-induced longer VOT was observed only when /t/ was in the U-medial position ($p<0.05$). In sum, VOT of /t/ varied with Boundary, but also was sensitive to Accent.

Another measure for /t/ was RMS burst energy, which also showed a main effect of Boundary (middle panel of Fig. 6a), with lower energy for U-initial vs. U-medial (F[1,3] = 12.41, $p<0.05$, 14.5 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 vs. 14.3 dB) indicated an accent-induced increase of RMS burst energy regardless of the stress conditions, while a Stress × Accent interaction (F[1,3] = 15.13, $p=0.03$) reflected different sizes of accent effect as can be seen in Fig. 7b. Eta-statistics suggested that the interaction was 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 primary-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 the Univariate analyses, two speakers (BB, PK) showed higher COG for U-initial /t/ (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 Fig. 6b (F[1,3] = 11.445, $p<0.05$, 3344 vs. 3203 Hz). Finally, there was a trend effect of Accent on COG (F[1,3] = 7.083, $p<0.08$, 3396 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.

3.2. Vocalic strengthening

3.2.1. Articulatory measure: vowel contact

Results for the EPG measure of vowels are shown in Figs. 8 and 9. Vowel contact showed no main effect of Boundary (Fig. 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 Fig. 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 (Fig. 8d) did not show a main effect but there was a robust Accent × Stress interaction reflecting an accentual effect when the vowel occurred in the primary-stressed syllable (Fig. 9a) ($p<0.0001$). In sum, Vowel contact was less when both primary-stressed and accented.

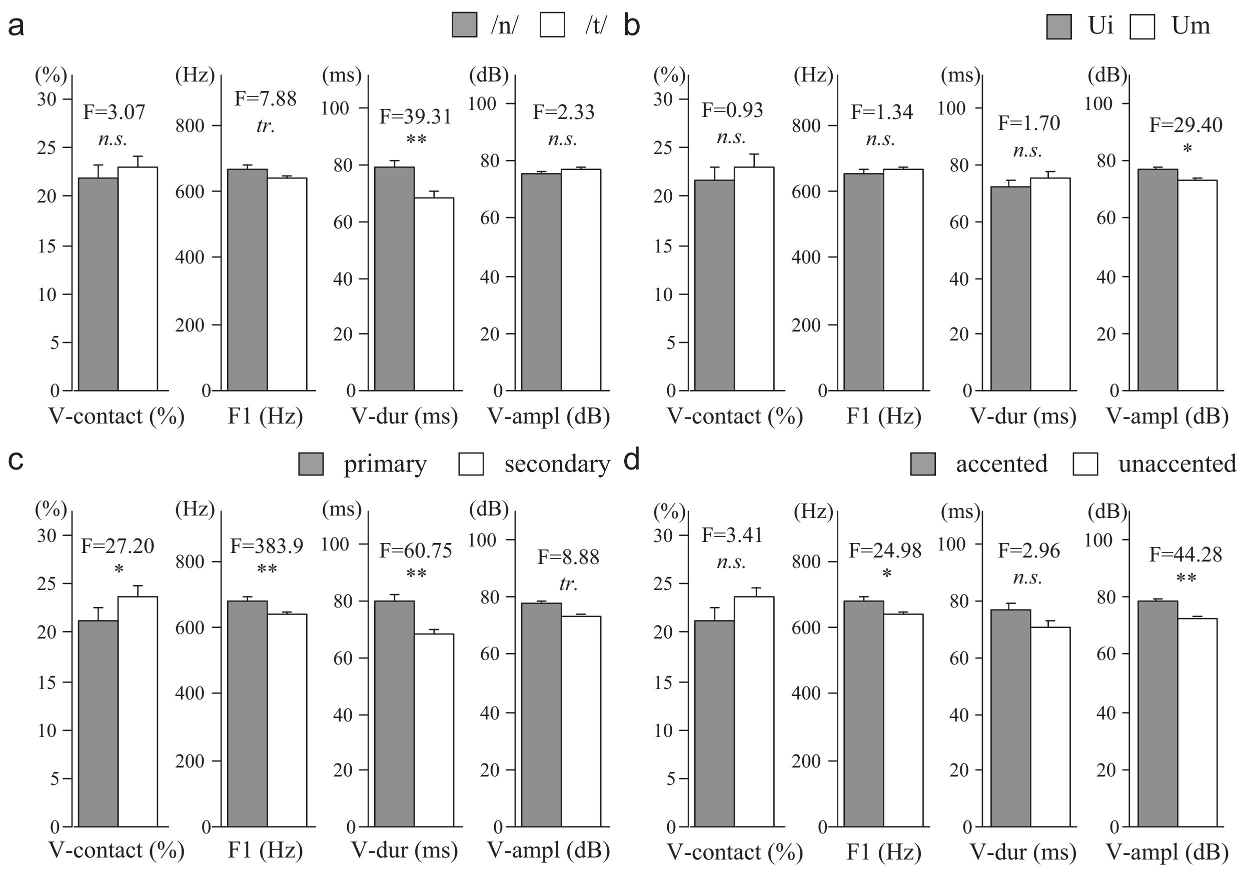

Fig. 8. Main effects on V-contact, F1, V-duration and V-amplitude. Error bars refer to standard errors. '*tr.*' = $p<0.08$; '*' = $p<0.05$. (a) Consonant; (b) Boundary; (c) Stress and (d) Accent.

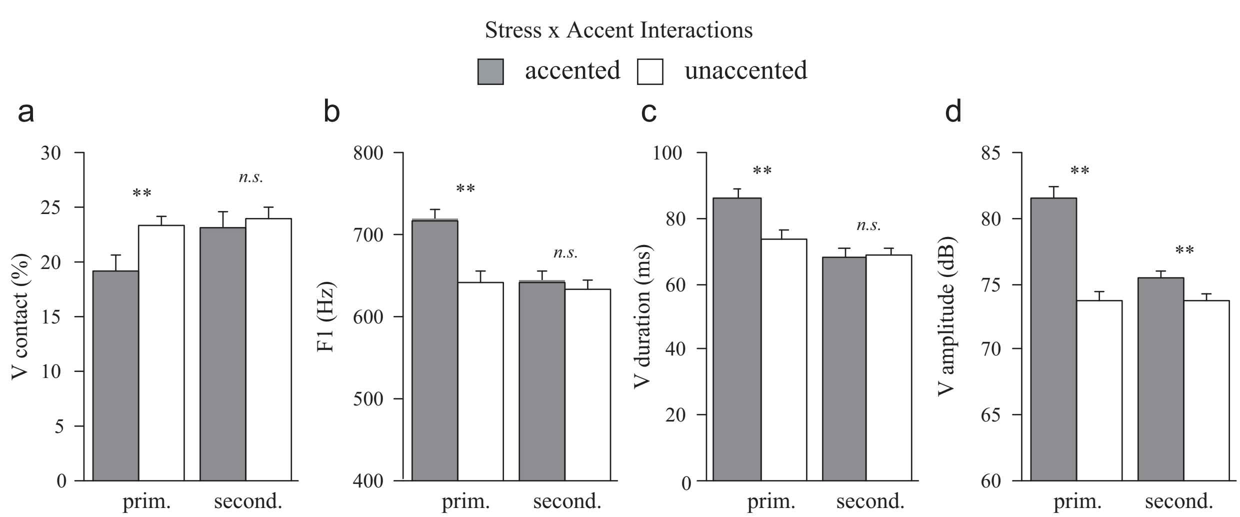

Fig. 9. Stress × Accent interactions in V-contact, F1, V-duration and V-amplitude. Error bars refer to standard errors. '**' = $p<0.001$. (a) V-contact; (b) F1; (c) V-duration and (d) V-amplitude.

3.2.2. *Acoustic measures: F1, vowel duration, vowel amplitude*

Results for acoustic measures of vowels are shown in Figs. 8–10. Vowel 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 Fig. 8b and a complex three-way interaction shown in Fig. 10a. This Consonant × Boundary × Stress interaction ($F[1,3]=9.18$, $p<0.06$) reflected the fact that 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 Fig. 8c and d, F1 was higher when

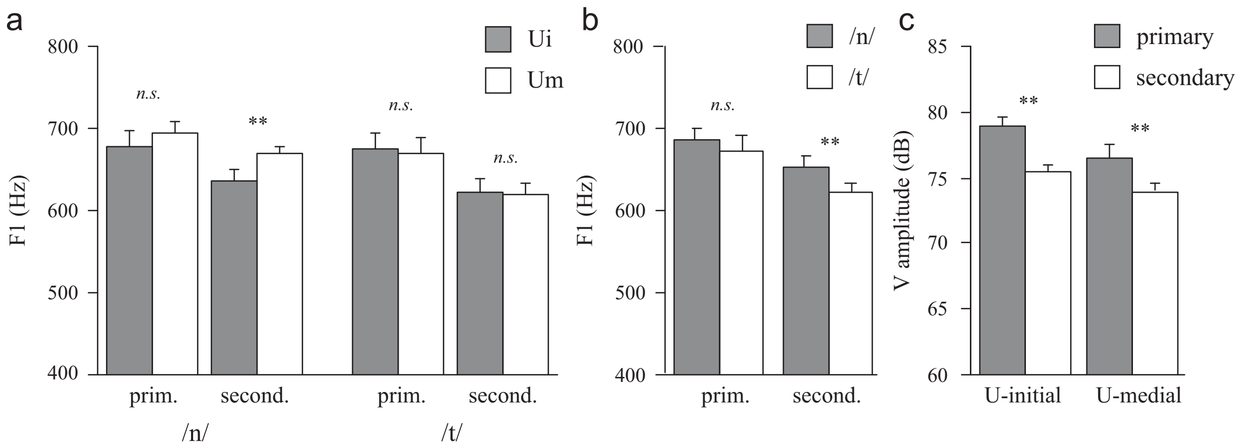

Fig. 10. Interactions in F1 and V-amplitude. Error bars refer to standard errors. '**' = $p<0.001$. (a) F1: Consonant × Boundary × Stress; (b) F1: Consonant × Stress and (c) V-amplitude: Boundary × Stress.

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 Fig. 9b, a significant Stress × 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 primary-stressed.

Vowel duration also showed no Boundary effect (Fig. 8b). As shown in Figs. 8c, d 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 ms)), and in the accented condition only when the vowel was primary-stressed (no main effect but a Stress × Accent interaction ($F[1,3]=7.03$, $p=0.077$)). In sum, Vowel duration was greatest when both accented and primary-stressed.

Vowel amplitude, in line with other vocalic measures, showed a main effect of Accent ($F[1,3]=44.28$, $p<0.01$, 78.4 vs. 73.7 dB) and a trend effect of Stress ($F[1,3]=8.877$, $p<0.06$, 77.6 vs. 74.5 dB), as well as a Stress × Accent interaction as shown in Fig. 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 vs. 75.1 dB), such that it was higher for U-initial than for U-medial, irrespective of other conditions, as seen in Fig. 10c. In addition, a Stress × 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 contrast, the boundary effect did not differ depending on the stress condition (in primary-stressed condition, U-initial vs. U-medial mean diff. 2.47 dB, $p<0.0001$, $eta^2=0.052$; in second-stressed condition; 2.52 dB, $p<0.0001$, $eta^2=0.132$.) In sum, Vowel amplitude was greater in U-initial position, especially when primary-stressed.

All the acoustic measures for the vowel /ε/ showed quite a strong (negative) correlation with Vowel contact, suggesting that Vowel contact is a reliable measure of vocalic opening or sonority, since F1 generally patterns with other sonority measures such as jaw and tongue lowering (e.g. Cho, 2005; Erickson, 2002; Harrington et al., 2000).

4. Discussion

In the previous section we reported how the production of the consonants and vowels in English /nε/ and /tε/ is conditioned by the three prosodic factors prosodic boundary, lexical stress, and phrasal 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 (Fig. 2b). Consonant Seal duration showed only a trend to initial lengthening, but VOT and burst energy for /t/ also varied with Boundary (Fig. 6a). Acoustic duration and Nasal 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?)

The first question explored in this paper is whether the two kinds of strengthening (boundary-induced versus prominence-induced) 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?

Peak consonant contact depends on Boundary, but is not affected by Accent (Figs. 2c and d; 6b and c). Conversely, Nasal duration (Fig. 4) and /t/ COG (Fig. 6) show no overall effect of Boundary, but do depend on Stress and/or Accent. These three measures thus suggest that positional and prominence strengthening are independent, and that articulatory strengthening in linguopalatal contact during consonant closure best characterizes boundary-induced articulatory patternings, but not stress- and accent-induced ones. 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/ (Fig. 6). With opposing effects like this, these kinds of strengthening must be independent. That is, we see two kinds of independence—first, position and prominence are independent because they affect *different* measures, and second, 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 some effect of all three factors in the same direction (longer seal when U-initial, primary-stressed, and/or accented, Fig. 2)—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 Tamil, Byrd, Kaun, Narayanan, & Salzman, 2000; 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 these 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 in our data because only the Stress effect is statistically significant.

Interpretations of patterns for other measures are complicated by interaction effects. While there is a main effect of Boundary on Consonant Release contact, it arises from a Boundary $\times$ Stress interaction (Fig. 3): 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 $\times$ Accent interaction (Fig. 7), with initial /t/s having longer VOT only when unaccented (and accented /t/s having longer VOT only when medial).[3] This suggests a contrary effect of position and prominence. The fact that VOT was longer in U-initial position regardless of prominence, while accent did not give rise to longer VOT in that position, suggests that initial strengthening takes precedence over prominence for VOT. Likewise, the lack of a main effect of Boundary on /n/ Nasal energy arises from opposing effects of position and prominence: while /n/ has more Nasal 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* Nasal energy than medial /n/ except when primary-stressed and accented (Fig. 5b).

In sum, the various measures do not pattern alike with respect to position and prominence. As a corollary of this result, studies that examine only one measure could come to very different conclusions about the relation of domain-initial strengthening effects and prominence effects.

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/ (Fig. 6a), but more energy for accented /t/, especially when primary-stressed (Fig. 6c), and /n/ Nasal energy, with an interaction showing

[3]At this point, it is also worth noting that although Pierrehumbert and Talkin (1992) showed that VOT for English /t/ was lengthened phrase-initially, other studies have reported inconsistency in domain-initial VOT lengthening in English (Choi, 2003; Lisker & Abramson, 1967). For example, only two out of six speakers in Choi’s (2003) study showed significantly longer VOTs U-initially than U-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, and 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 given rise to more extreme accent-induced differences.

The finding of the present study about domain-initial lengthening of VOT being limited to unaccented syllables also has implications for studies that showed boundary-induced VOT lengthening in other languages, such as Korean (Cho & Keating, 2001), Taiwanese (Hayashi, Hsu, & Keating, 1999; Keating et al., 2003) and Japanese (Onaka, 2003, 2006; Onaka et al., 2003). These languages have different prosodic/metrical systems from English. A question that follows then is whether boundary-induced 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.

less energy for initial /n/s when not primary-stressed and accented (Fig. 5b). If a single strengthening mechanism is at work in domain-initial and prominent syllables, then the same reduction pattern in nasal and t-burst energy seen in initial position should surface with accented or primary-stressed consonants; but this is not what we found. An alternative view is then that position and prominence enhance different properties of nasals. In primary-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 Fougeron, 1999; Hsu & Jun, 1998 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, is more complicated. The increased accent-induced burst energy for /t/, especially with primary-stressed syllables, could be viewed as a local hyperarticulation effect, as a louder burst may heighten the consonantal identity. But the reduction in burst energy for U-initial /t/ is not compatible with CV enhancement; unlike a reduction in Nasal energy, it does not make the stop less vowel-like. An alternative account, however, focuses on the fact that, unlike Nasal energy, stop burst energy is a short-term event tied to the consonant release gesture, and thus is sensitive to the speed of CV opening movements. Speed of opening in turn affects release burst energy, as reviewed in the Methods section (Stevens, 1998; Stevens et al., 1986). McClean and Tasko (2002) showed that speed of articulatory movements of the jaw, the lips, and the tongue (as measured by peak velocity) is significantly correlated with vocal intensity. Cho (2006) reported that the lip opening movement in CV in English is faster when (primary-stressed) CV sequences are accented, while no such effect was found for initial CV sequences. If a similar faster *tongue* opening movement obtains for accented and stressed /t/, then greater burst energy could be expected. Conversely, if the opening movement is slower in initial position because of greater linguopalatal contact, burst energy would be reduced. Our results are consistent with this scenario.

4.2. Locality effects

4.2.1. 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, 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, 2001; Fougeron & Keating, 1997 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. This could be so either because consonants are more affected than vowels, or because only the segment closest to the boundary is affected (e.g. Fougeron, 2001); these alternatives cannot be distinguished in our corpus.

Nonetheless, there was also a Boundary effect on one vowel measure: vowel amplitude was greater in U-initial position (Fig. 8b). Thus strengthening is not entirely local to the initial segment. 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. Beckman, 1986; Lehiste, 1970) and with vocalic opening (and F1) (e.g. Harrington et al., 2000). One possible explanation comes from likely increases in respiratory power in U-initial position (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 primary-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 both of previous studies and of the present study show mixed evidence about the locality of initial strengthening in English. Domain-initial strengthening is not altogether 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, as the prosodic boundary gesture model of Byrd and Saltzman predicts. (See Byrd & Saltzman, 2003; Byrd et al., 2006; Cho, 2005; Cho & McQueen, 2005; Lee, Byrd, & Krivokapić, 2006, for relevant discussions.)

4.2.2. 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 × Stress. If there is no such interaction effect, that is if Accent has an independent main effect, then the domain of accentuation must include the secondary as well as the primary-stressed syllables, rather than being limited to the primary-stressed syllables. Recall that in our corpus, all test syllables are word-initial, so we are looking for an effect of accent backwards in the accented word, from a final primary stress (whose properties were not tested) to an initial secondary stress. (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, Consonant Seal duration and /t/ burst COG do not show any sign of Accent × Stress interaction effects. These effects without interactions, on consonant measures, indicate that consonants in word-initial secondary-stressed syllables to some extent vary with accent just like consonants in primary-stressed syllables. That is, accent is not completely local to the primary-stressed syllable but rather can be manifest across the word. In contrast, three vowel measures (contact, F1, acoustic duration) showed Stress × Accent interactions (Fig. 9), with accent effects limited to primary-stressed syllables. That is, with respect to most effects on vowels, Accent is indeed local.

The other measures, Vowel amplitude, /n/ acoustic duration, /n/ energy and /t/ burst energy, fall in between these two patterns: they vary with Accent across the word, but to a greater extent in primary-stressed syllables and only more weakly in the initial secondary-stressed syllables. For both Vowel amplitude and RMS burst energy of /t/, the Accent × Stress interaction reflects that while both primary- and secondary-stressed syllables manifest an accentual effect, the effect of accent is more robust in the primary-stressed syllable (Figs. 7b, 9). For /n/ energy, a three-way Boundary × Stress × Accent interaction reflects that while accented syllables generally have more Nasal energy than unaccented syllables, this effect is greatest when the syllables are both initial and primary-stressed (Fig. 5b). Again, these cases show that the Accent effect is not completely local to the primary-stressed syllable, although it is greatest there. Finally, although /n/ acoustic duration does not show the Accent × Stress interaction which suggests the effect is non-local to the primary-stressed syllable, a significant accent-induced difference is found only in the primary-stressed condition (Fig. 5a), while the secondary-stressed condition show mean values that differ in the same direction, but not significantly. Thus this measure patterns statistically like both the local and the non-local measures.

In sum, Accent does affect an initial, secondary-stressed syllable of an accented word. Overall, the vowel measures tend to show Accent locally on the primary-stressed syllable, whereas consonant measures tend to vary across the word, back onto the initial consonant. It is worth noting that the vowel measures that mark accent locally also are the measures that do not depend on the domain boundary; and two of the energy measures that show stress-sensitive global accent are the measures that show conflicting influences from prominence vs. from domain boundary.

4.3. Prominence

Do any of our consonant or vowel measures show a cumulative marking of prominence on the word initial syllables? If so, we should see accented primary-stressed syllables having the greatest values, unaccented primary-stressed initial syllables lesser values, and all secondary-stressed syllables the lowest values. Such a scale of prominence assumes that marking of accent is local to the primary-stressed syllable. Thus the test for accent locality described above (primary-stressed accented > secondary-stressed accented) is one component of the test for cumulative prominence (primary-stressed accented > primary-stressed unaccented > all secondary-stressed). We already saw above that accent is not always local, and when it is not, then necessarily prominence marking is not cumulative, at least not following any expected hierarchy. Thus consonant Seal duration, /t/ burst energy and Center of Gravity, /n/ acoustic duration and Nasal energy, and Vowel amplitude all counter the expected relation. Most notably, Vowel duration is greater in a secondary-stressed syllable in an accented word, than in a primary-stressed syllable in an unaccented word.

When accent marking *is* local to the primary-stressed syllable, is prominence marking cumulative? Generally not: the only apparent cumulative case is U-initial consonant Seal duration (Fig. 3b). More commonly, there is no three-way distinction, but rather primary-stressed accented syllables have greater values than all other syllables, as described in the previous section for the vowel measures Vowel contact, Vowel F1, and Vowel acoustic duration.

In sum, in our data there is little support for the hypothesis of cumulative marking of prominence, along consonant or vowel dimensions. This is another way, then, in which prominence seems to behave differently from domain-initial strengthening, which previous studies have shown to follow a cumulative pattern.

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 Peak contact 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 Vowel contact, 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. Peak consonant contact was affected by domain-initial position but not prominence. On the other hand, most vowel measures (minimum contact, F1, duration), along with /n/ Nasal duration, were affected by prominence but not by domain-initial position. Two consonant energy measures (/n/ Nasal energy, /t/ burst energy) showed conflicting effects of domain-initial position and prominence. Other measures (consonant Seal duration, /t/ VOT, Vowel amplitude) showed combined effects of domain-initial position and prominence. Thus we conclude that these two kinds of strengthening are distinct, in accord with previous studies.

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 U-initial CV showing only 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 in this limited way. We suggested that this amplitude increase could be due to utterance-level variation in subglottal pressure and/or the voice source. Taken together with some previous findings which also showed domain-initial strengthening effects on the following vowel, this result appears to support a loosening of strict locality, in favor of a weakly gradient effect of prosodic boundaries.

Third, 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 is accent? When the test word was accented, initial syllables with secondary stress sometimes, but not always, showed effects of the accent. Three vowel measures (minimum contact, F1, duration) reflected accent locally, only when primary-stressed. In contrast, some consonant measures (Seal duration, /t/ burst acoustic Center of Gravity) reflected accent on secondary-stressed syllables just as strongly as on primary-stressed syllables. The three energy measures in the study (/n/ Nasal energy, /t/ burst energy, Vowel amplitude), which sample different portions of the CV interval, plus /n/ acoustic duration, all reflected accent on secondary-stressed syllables, but not as strongly as on primary-stressed syllables. In sum, accentual influences can spread from a primary-stressed third syllable to a secondary-stressed initial syllable. When they do so, they cross the left edge of the accented syllable, which is also the left edge of a foot. 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.

Finally, we asked whether prominence marking due to phrasal accent and lexical primary and secondary stress is cumulative like domain-initial strengthening. We found almost no support for this hypothesis. Not only the cases of non-local realization of accent on secondary-stressed syllables, but even the cases of local realization of accent limited to primary-stressed syllables, failed to show the expected three-way distinction among prominence levels: accented primary-stressed > unaccented primary-stressed > secondary-stressed (either accented or unaccented).

In sum, domain-initial position and prominence are realized on different phonetic dimensions, or differently on the same dimension. Domain boundary effects are cumulative while prominence effects are not. Domain boundary effects tend to be local to the boundary-adjacent segment, although with some effect on the following vowel, while accent effects tend to spread beyond the primary-stressed syllable to secondary-stressed syllables. Thus we conclude that, at least for the kind of word-initial syllables tested here, different aspects of prosodic structure (domain boundary vs. prominence) are differentially encoded.

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