PHONETIC CORRELATES OF STRESS AND THE PROSODIC HIERARCHY IN ESTONIAN

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This paper presents results of several experiments designed to examine some of the phonetic properties associated with stress and the prosodic hierarchy in Estonian. Peak nasal flow, amplitude and duration were measured for /n/ in initial position of four domains: the syllable, the word, the phrase and the utterance. These four prosodic positions were cross-classified by two stress levels: stressed and unstressed. To test the importance of the foot as a prosodic constituent in determining segmental durations in Estonian, two types of data were examined. First, the duration of vowels in different positions within the foot and the word were examined to test the hypothesis that feet are isochronously timed in Estonian. A second experiment tested the hypothesis that the longest type of syllable (the overlong syllable) may, under some conditions, constitute a monosyllabic foot, another manifestation of isochrony. Several results emerged from the experiments. First, data from the nasals provided phonetic evidence for the view that utterances in Estonian consist of progressively larger domains or constituents: the syllable, the word, and the phrase. Not all of these domains, however, are equally well differentiated in terms of the phonetic properties examined in this paper. Second, tentative results suggest that certain durational properties are determined by the foot, while others appear to be a function of domains larger than the foot, in particular the word. Finally, stressed syllables are differentiated from unstressed syllables along subtle and typologically unusual, but nevertheless consistent, acoustic and articulatory parameters.*

1. INTRODUCTION. The acoustic and articulatory properties of segments may vary depending on prosodic position. In particular, there are two aspects of prosody which affect segments markedly: stress and prosodic phrasing. The effects of stress manifests themselves along many different acoustic and articulatory parameters: duration (e.g. Fry 1955), voice-onset-time (e.g. Cooper 1991), amplitude (e.g. Fry 1955), fundamental frequency (e.g. Fry 1958), tongue position (e.g. de Jong 1995) and jaw position (e.g. Beckman et al. 1992), velum height (e.g. Krakow 1993), size of glottal opening (e.g. Cooper 1991), etc.

Less well-documented, but currently the subject of much research, is the effect of prosodic phrasing on segmental properties. By the term "prosodic phrasing" is meant the grouping of segments into a hierarchy of constituents such

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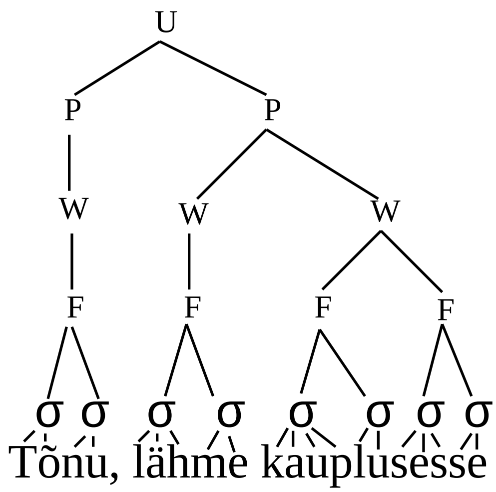
as the syllable, the foot, the word, the phrase, the utterance, etc. (Selkirk 1984). The prosodic hierarchy is shown in figure 1, using an Estonian example.



"Tõnu, let's go to the store."

FIGURE 1. The prosodic hierarchy in Estonian

Initial results of the research program examining the effects of prosodic phrasing on segments have yielded striking results, some of which are summarized below.

Probably the most familiar result is the lengthening effect seen in segments in the final position of prosodic domains (e.g. Oller 1973, Beckman et al. 1992, Wightman et al. 1992, etc.). Studies such as Wightman et al.'s indicate a general correlation between the level of the prosodic domain and the lengthening effect seen in final segments: the higher, or larger, the level, the greater the lengthening effect in general. Lengthening is also observed in domain initial segments (Oller 1973). Another parameter along which segments vary as a function of prosodic phrasing is VOT. VOT has been shown to be longer for phrase initial stops than for phrase medial stops in English (Pierrehumbert and Talkin 1992) and Korean (Jun 1993). Cooper (1991) has shown that word initial voiceless stops have a longer VOT than word medial, but syllable initial, voiceless stops in English. His data also shows that the peak glottal opening for voiceless stops is greater for word initial than for word medial stops.

There also appears to be a cross-linguistic tendency for the amplitude of domain initial nasal consonants to be smaller the higher the domain (Fougeron 1996). Nasal flow experiments conducted by Fougeron and Keating (1996a) have also shown that prosodic phrasing affects the amount of nasal flow in French. The higher the prosodic domain, the less nasal flow there is in domain initial nasal consonants. The decrease in nasal flow, they argue, is largely the result of the velum being in higher position which allows for less air to escape through the nose. Their results also show that the area of contact between the tongue and palate for the articulation of domain initial /t/ and /n/ in French (Fougeron and

Keating 1996a) and /n/ in English (Fougeron and Keating 1996b) is larger the higher the prosodic domain.

2. THE PRESENT STUDY. The goal of the present study was to examine the acoustic and articulatory correlates of different prosodic domains under differing stress conditions in Estonian. The five targeted domains were the utterance, the phrase, the word, the foot and the syllable and the two targeted stress levels were word-level primary stressed and unstressed. Three experiments were designed to examine these five domains and two stress levels.

The first experiment looked at four of the five prosodic domains and the two stress levels. The nasal /n/ was examined in initial position of four different prosodic domains: the *utterance*, the *phrase*, the *word* and the *syllable*, cross-classified by two stress levels: *unstressed* and *stressed*. This cross-classification of two stress levels by four prosodic levels yielded a total of eight different environments in which nasals were examined. These four prosodic domains examined were chosen, since they could easily be determined without a detailed study of Estonian prosodic phrasing. Utterance initial position corresponded to the commencement of speaking. Phrase-initial nasals followed a large intonation break after a vocative. Word initial nasals appeared at the beginning of orthographic (and also phonological) words, while syllable initial nasals were in syllable onset position in the middle of words. Crucially, a nasal which was in initial position of a domain is also in initial position of all lower domains. Thus, for example, a word-initial nasal is also in syllable-initial position, and a phrase-initial nasal also in word- and syllable-initial position. Three acoustic properties of /n/ were examined: nasal flow, acoustic amplitude and duration.

The next two experiments focused on the fifth domain, the foot, intermediate between the word and the syllable. These two experiments were undertaken largely because the same method of examining domain initial nasals could not be used for examining the acoustic correlates of the *foot*. The reason for this is that Estonian is a trochaic language (Lehiste 1965a) in which feet consist of a stressed syllable followed by one (or perhaps more) unstressed syllable. A syllable which is in foot-initial position in a trochaic language is also stressed, creating a confound of two factors: stress and foot position. In order to tease apart these two factors and examine the foot as a prosodic constituent independent of stress, a different hypothesis was tested, one advanced in earlier work on Estonian (e.g. Lehiste 1965b, Eek and Remmel 1974): namely, that there exists an inverse correlation between the durations of the two syllables of the foot: a tendency which results in a form of foot isochrony.

The first experiment designed to look at the foot, tested the extent to which feet are isochronous in Estonian. In tetrasyllabic words, the duration of the vowel in the second syllable of a disyllabic foot was measured as a function of the duration of the first vowel in the same foot, intra-foot timing. The hypothesis being tested was that the second vowel of the foot would be shorter, the longer the first syllable of the foot, because both vowels belong to the same foot. As a control, the third vowel was measured as a function of the second vowel. Because these two vowels belong to different feet, the hypothesis was that the third vowel would not vary in duration as a function of the second vowel's duration.

The final experiment examined another aspect of timing related to foot isochrony and based on stress data introduced by Hint (1973). Under Hint's account of stress, the longest type of syllable in Estonian (the overlong syllable) may constitute a monosyllabic foot in a disyllabic or longer word under certain conditions, unlike shorter syllable types which must belong to bisyllabic feet in polysyllabic words. As a diagnostic for determining whether a monosyllabic foot can occur in polysyllabic words, measurements were taken to ascertain whether a syllable following an overlong syllable receives secondary stress or not. Hint's stress judgments were used for this test, while the acoustic property most reliably associated with stress as determined from earlier work on Estonian, lengthening of consonants in the onset of stressed syllables, was used as the diagnostic for determining the location of stress.

3. EXPERIMENT ONE: PROSODIC CONSTITUENCY AND STRESS

3.1 METHODOLOGY. The nasal /n/ was examined in initial position of four different prosodic domains: the *utterance*, the *phrase*, the *word* and the *syllable*. Nasals in each of these prosodic positions occurred in both stressed and unstressed positions, yielding a total of eight different environments in which nasals were examined. Three different acoustic and articulatory parameters were examined for /n/: nasal flow, amplitude and duration. The speech of four native speakers of standard Estonian from the Tallinn area (one female and three males) was analyzed for the amplitude and duration phases of the experiment, three speakers (one female and two of the three male speakers examined in the amplitude and duration phases) for the nasal flow phase involving prosodic phrasing, and two speakers (one female and one male) for the nasal flow data involving stress.

The corpus for the experiment consisted of reiterant versions (Liberman and Streeter 1976) of Estonian words where the reiterant syllables consisted of /n/ and the vowel /a/. For example, instead of the word *kadanagi* [kátanàki] 'even a slingshot' essive sg., subjects said [nánanàna] with a stress pattern identical to that found in *kadanagi* . Likewise, instead of the real word *alpakana* [alpákana] 'alpaca' essive sg., subjects said [nanánana]. Subjects were primed using real words displaying stress patterns similar to those found in real words and told to mimic the prosodic patterns of the real words in their reiterant speech. Reiterant speech was used, since it allows for examination of prosodic aspects of speech without the confound of segmental perturbations varying througout the corpus. The corpus appears in table 1; the underlined nasals were measured. All of the targeted words were four syllables long, except for the one containing the syllable initial unstressed nasal which was three syllables long. In this case, the three syllable word was chosen, in order that the unstressed nasal would not be immediately preceded by a stressed vowel. Based on looking at a number of tokens in a pilot study, it was clear that the amplitude peak associated with primary stress typically follows a stressed short vowel in an open syllable and falls on the onset of the following syllable. This increase in amplitude associated with stress would have confounded the results, if unstressed nasals in tetrasyllabic words had been examined. The targeted words were placed in frame sentences consisting of real words. Between eight and ten repetitions of each sentence were recorded for all phases of the experiment.

Primary stress in native Estonian words falls predictably on the initial syllable. A large number of borrowed words, however, possess non-initial stress. For this reason, reiterant speech with non-initial stress was produced with relatively little difficulty for most speakers. However, reiterant words with non-initial stress were not measured for speaker M2. As a result of this omission, only three of the eight conditions were examined for speaker M2: utterance initial stressed, phrase initial stressed, and word initial stressed. Syllable initial unstressed nasals were not examined, since they differed from the other examined nasals in both stress and phrasing, and hence would not have allowed for examination of these factors independently of each other. The corpus is discussed further in section 3.2.2 which deals with acoustic amplitude.

utterance initial, stressed:	*Nánanana on sõna* [sØna].
utterance initial, unstressed:	*Nanánana on sõna.*
	'N..... is a word.'
phrase initial, stressed:	*Paul, nánanana on sõna.*
phrase initial, unstressed:	*Paul, nanánana on sõna.*
	'Paul, n..... is a word.'
word initial, stressed:	*See nánanana on sõna.*
word initial, unstressed:	*See nanánana on sõna.*
	'This n..... is a word.'
syllable initial, stressed:	*Nanánana on sõna.*
syllable initial, unstressed:	*Nánana on sõna.*
	'N..... is a word.'

TABLE 1: Corpus for experiment 1.

An attempt was made to keep the target nasal approximately the same distance from the beginning of the utterance in order to control for overall declination during the course of the utterance. Numerous studies have shown that declination may be a universal property of speech which potentially affects a number of acoustic and articulatory parameters, including amplitude (Vayra and Fowler 1992), jaw height (Vayra and Fowler 1992), velum height (Krakow 1993, Krakow et al. 1994), subglottal pressure (Gelfer et al. 1987), etc..

The results of the first experiment are presented in two parts. First, sections 3.2.1-3.2.3 discuss the effect of stress on peak nasal flow, acoustic amplitude and duration, respectively. In section 3.2.4. the acoustic properties associated with stress in Estonian are discussed in the context of the results from the present experiment as well as earlier work on Estonian. Sections 3.3.1-3.3.3 examine the results of the current experiment related to prosodic constituency. In section 3.3.4

the effects of prosodic level on nasals are summarized and compared to the results found for stress.

3.2. THE EFFECT OF STRESS ON NASALS

3.2.1. STRESS AND NASAL FLOW**.** The first phase of experiment one focused on peak nasal flow. Nasal flow was chosen as a diagnostic property largely because it allows for inferences to be drawn about an articulatory property, velum height, using a non-invasive technique. Following Fougeron and Keating, an increase in air flow through the nose suggests a lower velum position (all else being equal) which allows for more air to escape through the nose.

Flow was recorded using a Rothenberg split mask. The raw flow data were converted to an amplitude display on Kay's Computerized Speech Lab from which measures of the peak amount of nasal flow during the nasals were made. Results of the effect of stress on nasal flow appear in figure 2 for the two speakers examined. Error bars represent one standard deviation from the mean.

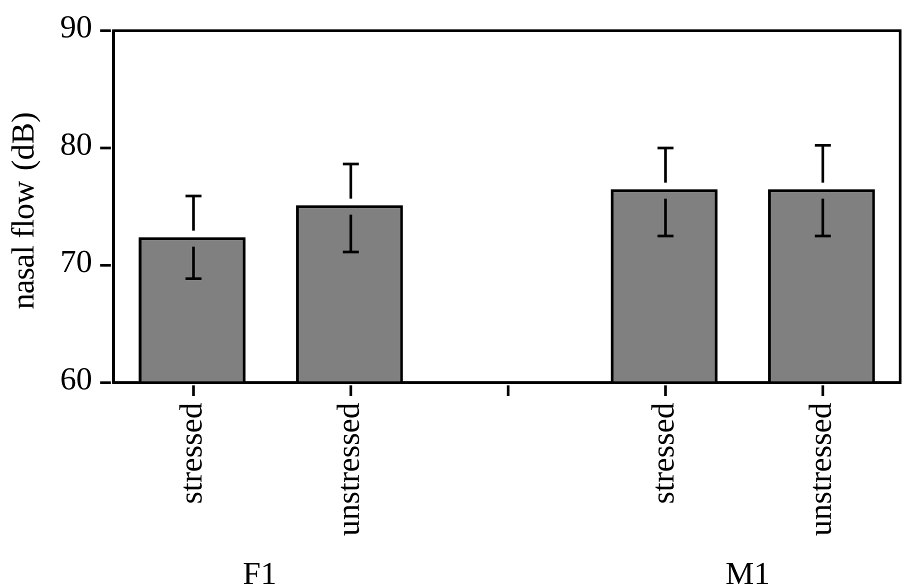


FIGURE 2. Peak nasal air flow as a function of stress

As is clear from figure 2, peak nasal flow only differs as a function of stress for speaker F1 but not for speaker M1. Speaker F1's stressed nasals are marked by less air flow than unstressed nasals. An ANOVA factorial revealed this difference to be highly significant [F (3, 69)=67.32, p<.0001]. The results for speaker F1 suggest that the velum is higher for nasals in the onset of stressed syllables than for nasals in the onset of unstressed syllables. In figure 3, the stress results are divided according to prosodic position.

Nasal flow for speaker F1 differs significantly as a function of stress at all four prosodic levels. However, this difference goes in two different directions. At the highest three levels (utterance, phrase and word), stressed nasals have less air flow than unstressed nasals. This pattern, however, is reversed at the syllable level, where stressed nasals actually are characterized by significantly *greater* flow relative to their unstressed counterparts.

Speaker M1's nasals do not differ in a consistent direction according to prosodic phrasing. The only significant result (p=.0003) was for word-initial stressed nasals to be marked by less flow than word-initial unstressed nasals.

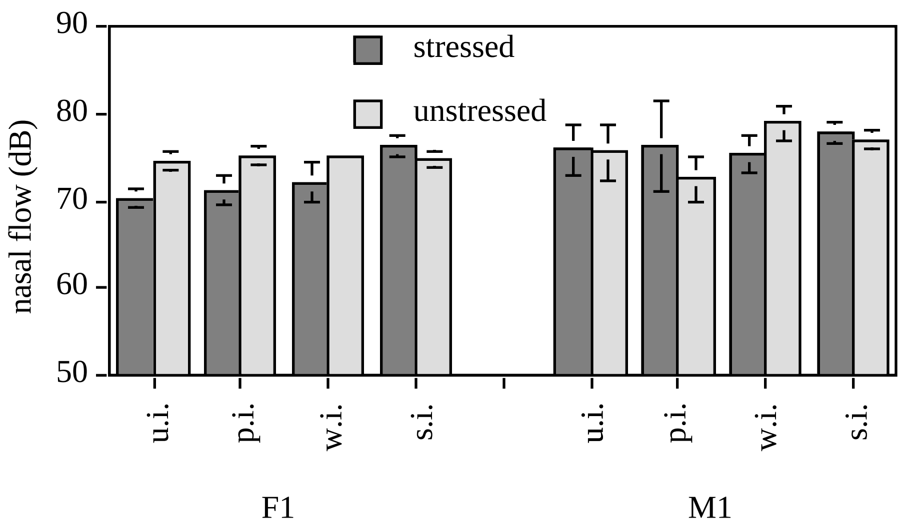


FIGURE 3. Peak nasal air flow as a function of stress by prosodic position (u.i = utterance initial, p.i. = phrase initial, w.i. = word initial, s.i. = syllable initial).

3.2.2. STRESS AND AMPLITUDE. Acoustic amplitude of nasals was measured in the next phase of the experiment. The same corpus was recorded in a sound booth *after* the nasal flow data was recorded, due to the filtering of higher frequencies by the Rothenberg mask. Average RMS amplitude was calculated over the duration of the nasal as segmented from a waveform in conjunction with a spectrogram. In order to control for random fluctuations in speaking level, the average amplitude value for the nasal was subtracted from the average amplitude of the *first stressed* vowel in the examined word. The measured nasals and the first stressed vowel in each token are shown in table 2. The target nasal is underlined; the reference vowel is bold-faced.

utterance initial, stressed:	*N**á**nanana on sõna.*
utterance initial, unstressed:	*Nan**á**nana on sõna.*
phrase initial, stressed:	*Paul, n**á**nanana on sõna.*
phrase initial, unstressed:	*Paul, nan**á**nana on sõna.*
word initial, stressed:	*See n**á**nanana on sõna.*
word initial, unstressed:	*See nan**á**nana on sõna.*
syllable initial, stressed:	*Nan**á**nana on sõna.*
syllable initial, unstressed:	*N**á**nana on sõna*

TABLE 2. Corpus for amplitude experiment. The amplitude of the reference **vowel** was subtracted from the amplitude of the target nasal.

The first stressed vowel and not the vowel immediately following the nasal was chosen because the vowel immediately following the targeted nasal was sometimes stressed and sometimes unstressed. Thus, any differences in relative nasal amplitude could be confounded by differences in the amplitude of the reference vowel due to stress. An attempt was made to keep the target nasal and the control vowel close to each other, in order to control for possible declination effects (see section 3.1). In virtually all tokens in the corpus, the target nasal follows the reference vowel. Positioning the target nasal *after* the control vowel was necessary, however, for the syllable initial, unstressed conditions, in order to satisfy the conflicting goals of not measuring the nasal immediately following the stressed vowel (due to the late amplitude peak associated with stress in Estonian; see section 3.1), while simultaneously keeping the target nasal approximately the same distance from the beginning of the utterance as nasals in other tokens.

Results for the different stress conditions pooled over different prosodic positions appear in figure 4. Bear in mind when considering figure 4, that the higher the bar, the greater the difference in amplitude between the examined nasal and the first stressed vowel; i.e. the higher the bar, the less amplitude the nasal has relative to the vowel.

Stress was shown by a two-factor ANOVA (stress and prosodic phrase position) to have a significant effect on nasal amplitude for two of the three speakers. For speakers F1 and M3, nasals in the onset of stressed syllables have significantly ($p<.01$) greater amplitude relative to the first stressed vowel than nasals in the onset of unstressed syllables. Speaker M1 does not differentiate stressed and unstressed nasals in terms of amplitude.

Figure 5 shows relative nasal amplitude as a function of both stress level and size of the prosodic level. Phrase-initial nasals were not examined for speaker M3. Syllable initial nasals could not be examined for speaker M2 for reasons elaborated earlier in section 3.1.

For speaker F1, stressed nasals have greater relative amplitude than their unstressed counterparts in phrase, word, and syllable initial position. These differences are statistically significant at the $p<.01$ level as revealed by unpaired t-tests. The difference between unstressed and stressed nasals in syllable initial position is nearly significant: $p=.089$. While the pattern observed at the syllable level could be due to the location of the syllable initial unstressed nasal after the reference vowel (which could reduce the relative amplitude of the nasal), this

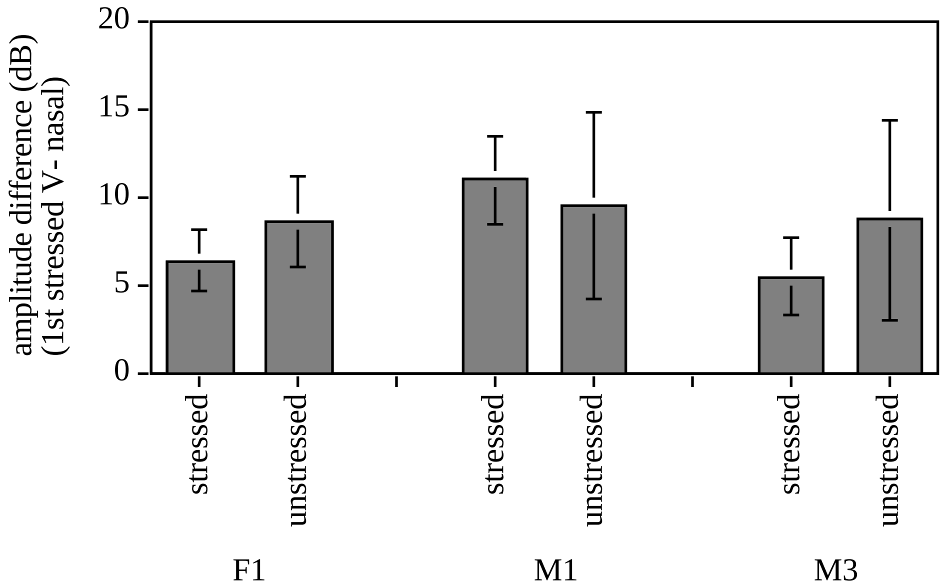


FIGURE 4. Amplitude difference between [n] and the 1st stressed vowel as a function of stress level. Higher values of the difference reflect relatively lower amplitude of the nasal.

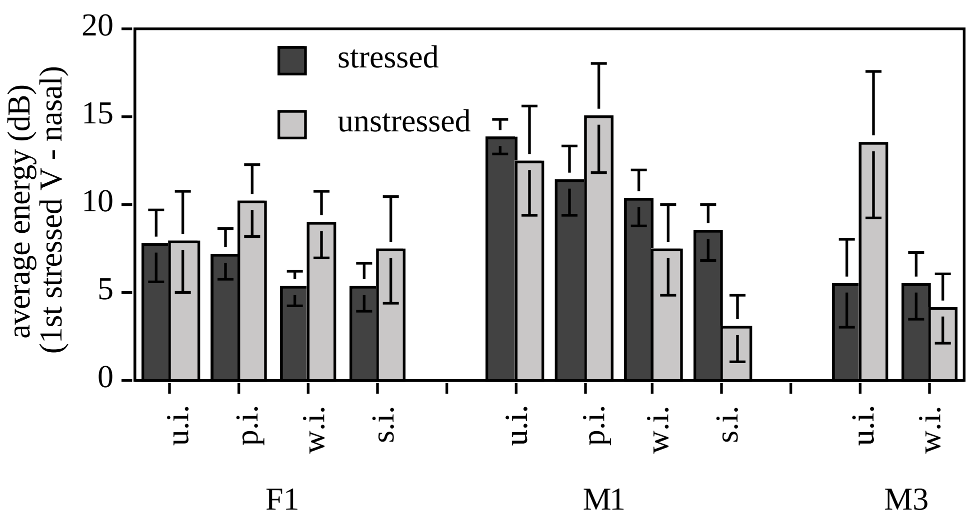


FIGURE 5. Amplitude difference between [n] and the 1st stressed vowel as a function of stress level and domain level. Higher values of the difference reflect relatively lower amplitude of the nasal (u.i = utterance initial, p.i. = phrase initial, w.i. = word initial, s.i. = syllable initial).

would not account for the word and phrase level data, where no such confounding factor exists.

Speaker M1 distinguishes stressed and unstressed nasals in terms of amplitude at phrase, word and syllable levels; all results are significant at least the p<.05 level, with the syllable level difference significant at the p<.0001 level. However, at the word and syllable level, stressed and unstressed nasals are differentiated in exactly the *opposite* pattern from speaker F1: speaker M1's stressed nasals have *lesser* amplitude than their stressed counterparts.

Finally, speaker M3 shows a different pattern for utterance and word-initial nasals. However, only the utterance level difference between stressed and unstressed nasals, the one following the predominant pattern across speakers, according to which stressed nasals have less relative amplitude than unstressed nasals, was statistically significant.

3.2.3. STRESS AND DURATION. The next phase of the first experiment examined the effect of stress on nasal duration. Duration was measured from a waveform with reference to a spectrogram. The effect of stress on duration pooled over different prosodic positions is considered in figure 6.

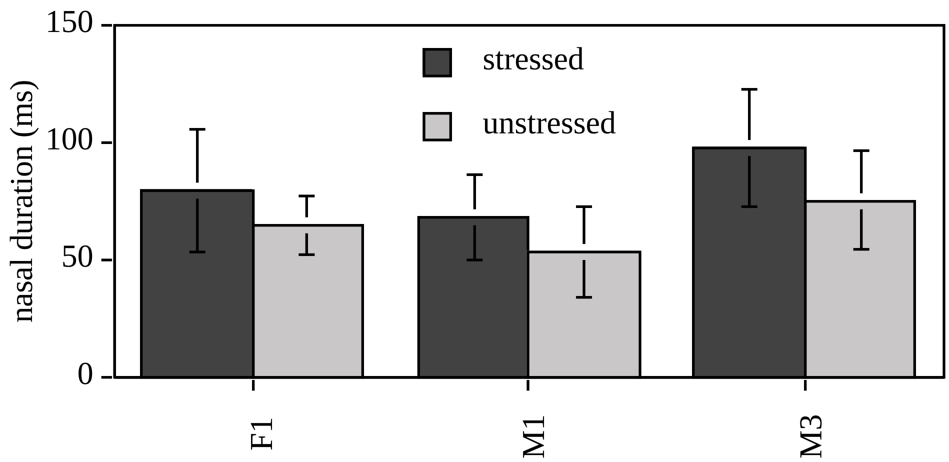


FIGURE 6. Nasal duration as a function of stress.

The result is clear for all three speakers examined. Nasals in the onset of stressed syllables are significantly longer than nasals in the onset of unstressed syllables, replicating earlier results (Lehiste 1966; Gordon 1995). Though the differences are not particularly large (15ms for speaker F1, 16ms for speaker M1, and 23ms for speaker M3), they are nevertheless consistent and significant for all speakers. The difference between stressed and unstressed nasals, however, is not observed at all prosodic levels for all speakers, as figure 7 shows.

For all levels except phrase initial position, stressed nasals are significantly longer than unstressed nasals for speaker F1. M1 differentiates stressed and unstressed nasals in terms of duration in utterance and phrase initial position (p<.05 for both levels), with the stressed nasals being longer than their unstressed counterparts in both positions. Word-initial and syllable initial nasals, however, do not differ in duration as a function of stress level for M1. Speaker M3 shows the same pattern for stressed nasals to be longer than unstressed nasals at all levels. Results, however, did not reach significance at the word-level: p=.17.

3.2.4. THE EFFECT OF STRESS ON NASALS: SUMMARY AND DISCUSSION. The phonetic parameter on which stress seems to exert the largest and most consistent influence across speakers is duration. Nasals in the onset of stressed syllables were significantly longer for all speakers examined. Stress also influenced nasal flow and amplitude, though the results were not as consistent as the duration result. One speaker (F1) showed decreased nasal flow in nasals in the onset of stressed syllables relative to nasals in the onset of unstressed syllables, suggesting a higher velum position in stressed syllables. The other speaker's (M1) stressed nasals, however, were not marked by decreased air flow relative to his unstressed nasals. Using a velotrace, Krakow (1993) found that the velum was raised higher for /t/ in stressed syllables compared to /t/ in unstressed syllables. Both Krakow's

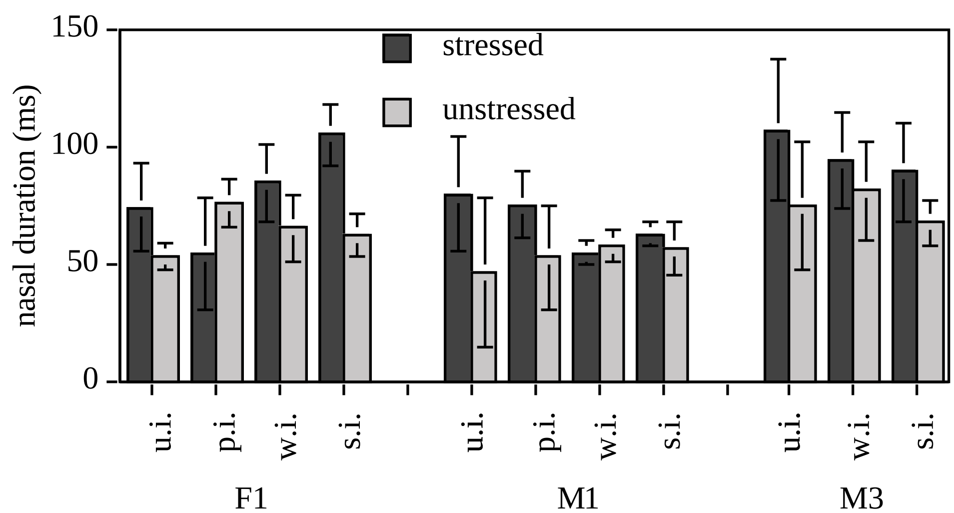


FIGURE 7. Nasal duration as a function of stress and prosodic level (u.i = utterance initial, p.i. = phrase initial, w.i. = word initial, s.i. = syllable initial).

data and the current results for Estonian nasal air flow seem to be compatible with the view that the sonority profile of a stressed syllable is enhanced relative to that of an unstressed syllable, as proposed for the syllable nucleus by Beckman et al. (1992). Syllables have an optimal sonority profile if they contain a maximally non-sonorant onset consonant followed by a maximally sonorant vowel nucleus, as argued by Clements (1990). Enhancement of the sonority profile of a syllable may target either the onset of the syllable or the nucleus of the syllable, or a combination of both. The sonority profile of the syllable as a whole is enhanced by *decreasing* the sonority of the onset consonant, but *increasing* the sonority of the nucleus. Raising the velum for a stressed consonant, whether a nasal or an oral consonant may be viewed as one means of increasing the consonantal properties of the nasal, thereby decreasing its sonority.

This sonority based explanation, however, does not account for the increase in amplitude of stressed nasals compared to unstressed nasals for speaker F1, the same speaker whose stressed nasals were marked by a decrease in peak nasal air flow. A strictly sonority based hypothesis would predict *decreased* amplitude in nasals in the onset of stressed nasals relative to nasals in the onset of unstressed syllables. The increase in amplitude seems sensible, however, when one considers that stressed syllables typically are often marked by greater amplitude in many languages. Thus, in the case of nasals, the goal of decreasing the sonority of the stressed nasal conflicts with the increase in amplitude caused by stress.

More generally, one might have expected that the decrease in air flow for speaker F1 would be associated with a decrease in amplitude for nasals under the assumption that amplitude of nasal flow is correlated with the amount of air flow through the nasal cavity. The greater the volume of air, the greater the amplitude of the nasal. Conversely, the less the volume of air, the smaller the amplitude of the nasal. This apparent contradiction is plausibly due to a difference in air flow through the *glottis* between nasals in stressed and unstressed positions. An increase in air flow associated with stress would presumably raise the overall amplitude of the nasal. It thus seems plausible that the discrepancy between amplitude in stressed and unstressed nasals is due to a difference in the amount of transglottal air flow rather than a difference in the amount of air flow through the nasal cavity. A measure of energy differentiated by frequency would perhaps shed light on this matter.

The effect of stress on nasal amplitude was found to be speaker dependent. Stressed nasals had greater amplitude than unstressed nasals for two of the three speakers (F1 and M3) examined, perhaps in keeping with the tendency for stressed syllables to be marked by greater amplitude cross-linguistically. The other speaker, however, showed no significant difference in amplitude based on stress.

3.3. PROSODIC LEVEL AND NASALS

3.3.1. PROSODIC LEVEL AND NASAL AIR FLOW**.** The effect of prosodic phrasing on nasal flow is shown in figure 8 which combines stressed and unstressed nasals. Recall from section 3.2.1 that data were converted to an amplitude scale. Syllable initial nasals were not examined for speaker M2 for reasons explained in section 3.1.

If we first consider the three lowest prosodic groupings, the syllable, word and phrase, a consistent trend is clear for both of the speakers for whom all levels were examined: the larger the prosodic constituent, the less the amount of air flow for domain-initial nasals. Speaker M2 also displays the same pattern for phrase and word initial nasals: phrase initial nasals have less flow than word initial nasals. All differences involving the lower three levels of the hierarchy are statistically significant at the $p<.05$ level, except for phrase vs. word-initial for speaker F1 and word vs. syllable-initial for speaker M1.

Utterance-initial nasals, however, do not behave as might be expected given the position of the utterance at the top of the prosodic hierarchy. Only speaker F1's utterance initial nasals have the least amount of flow of the four phrasing conditions. Utterance-initial nasals for speakers M1 and M2 display greater flow than phrase-initial nasals. In the case of speaker M2, this difference is highly significant at the $p<.01$ level.

Looking back at figure 3, an interesting difference between speakers F1 and M1 is apparent. Nasal flow for speaker F1 hardly varies at all as a function of phrasing for unstressed nasals. All levels, however, are distinguished for stressed nasals. In contrast, speaker M1 shows, in general, greater differentiation in unstressed than in stressed nasals.

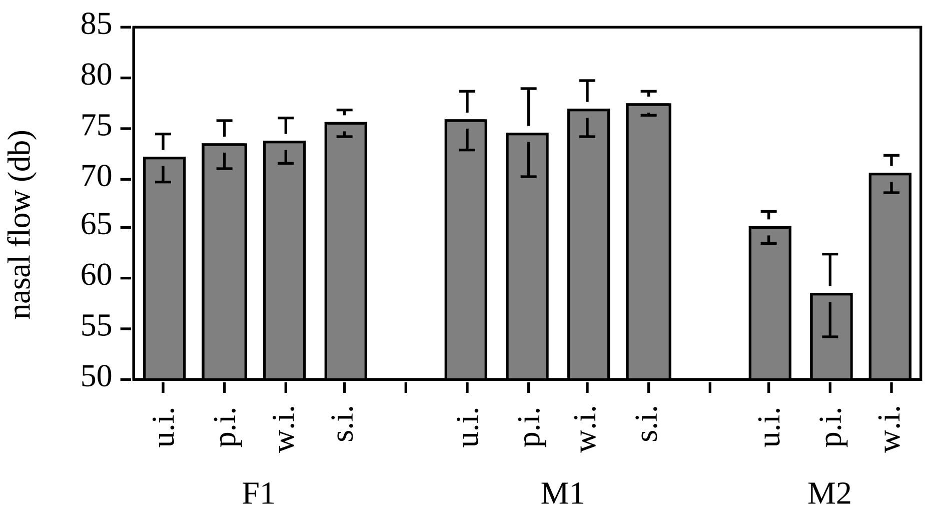


FIGURE 8. Peak nasal flow as a function of prosodic phrasing (u.i = utterance initial, p.i. = phrase initial, w.i. = word initial, s.i. = syllable initial).

3.3.2. PROSODIC LEVEL AND AMPLITUDE. The effect of prosodic level on the amplitude of domain initial nasals relative to the first stressed vowel in the target words is depicted in figure 9, which collapses both stress conditions. The higher the bar, the greater the difference in amplitude between the examined nasal and the first stressed vowel.

All four speakers distinguish at least two levels in the prosodic hierarchy, and in the same direction: nasals in initial position of higher prosodic domains possess less amplitude relative to the first stressed vowel than nasals in initial position of lower prosodic boundaries. Phrase and word initial nasals were significantly different ($p<.05$) from each other for all of the speakers for whom nasals in both of these positions were examined (speakers F1, M1 and M2). Phrase and syllable initial nasals were also differentiated ($p<.05$) for all speakers for whom the relevant nasals were examined (speakers F1 and M1). Speakers M1 and M3 also displayed a significant difference ($p<.05$) between word and syllable initial nasals. Speaker F1 showed a similar, but non-significant, trend for word initial nasals to have less amplitude than syllable initial nasals. None of the speakers distinguish utterance and phrase initial nasals in terms of amplitude.

Looking back at figure 5, speakers for the most part differentiated between prosodic level for both stressed and unstressed nasals, at least for the lowest three prosodic levels. In general, however, it is the unstressed nasals which show greater differentiation in terms of amplitude at different prosodic levels. It is also interesting to note that unstressed nasals in utterance initial position have greater relative amplitude compared to unstressed nasals in phrase initial position for speakers F1 and M1.

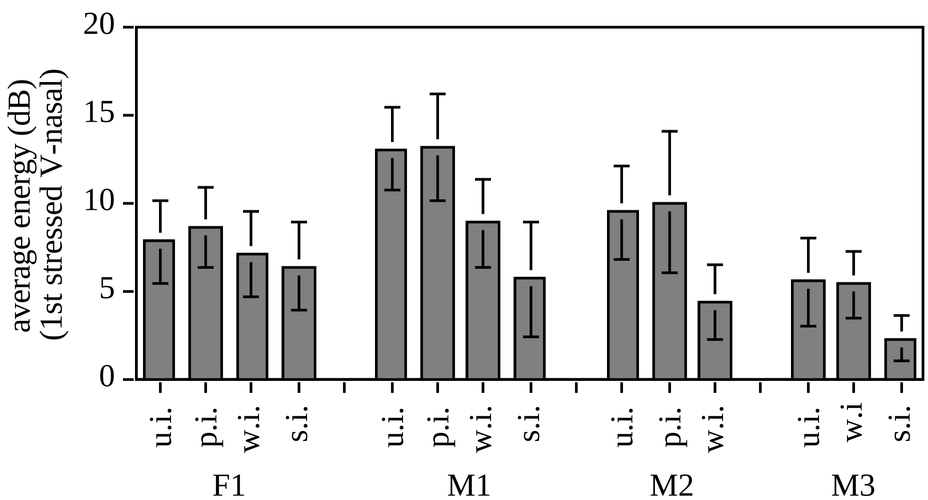


FIGURE 9. Amplitude difference between [n] and the 1st stressed vowel as a function of prosodic position. Higher values of the difference reflect relatively lower amplitude of the nasal.

3.3.3. PROSODIC LEVEL AND DURATION**.** The effect of phrase level on duration is far less clear than that of amplitude and nasal air flow, as shown in figure 10. For two speakers (M2 and M3), there is a consistent pattern of increased duration, the larger the prosodic domain. Note, however, given the small number of tokens, none of these differences fall under the $p<.05$ level of significance, although the difference between utterance initial and word-initial nasals for speaker M2 and the difference between utterance initial and syllable initial nasals for speaker M3 approach significance: $p<.0757$ and $p<.0715$, respectively. None of the differences for speaker M1 are significant. The strongest results come from speaker F1, for whom the size of the prosodic domain is *inversely* correlated with nasal duration. The differences between utterance initial and syllable initial and between phrase initial and syllable initial nasals are highly significant at the $p<.01$ level for speaker F1, while all other differences are nearly significant ($p<.10$), except for the difference between utterance and phrase initial nasals.

Looking at figure 7 in section 3.2.3, it is evident that much of the duration pattern seen in figure 10 for speaker F1 is due to the stressed nasals. Speaker F1's stressed nasals are generally shorter the larger the prosodic domain.

3.3.4. THE EFFECT OF PROSODIC LEVEL ON NASALS: SUMMARY AND DISCUSSION**.** Measurements of peak nasal air flow and amplitude of nasals in Estonian suggest a general trend for domain initial nasals to be "strengthened" the higher the domain which they begin. This strengthening is manifested either as a decrease in the amplitude of the nasal or in the amount of air flowing through the nose, or a combination of both, depending on the speaker.

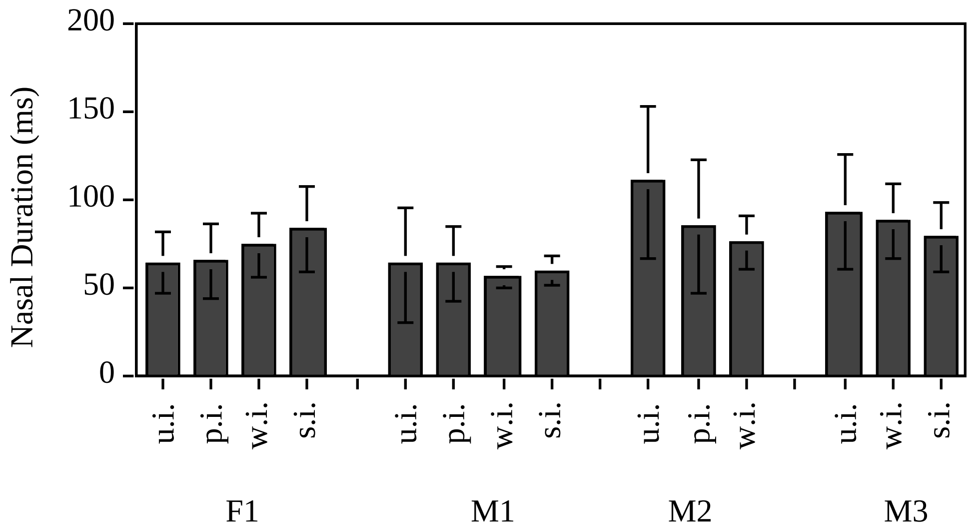


FIGURE 10. Nasal duration as a function of prosodic level (u.i = utterance initial, p.i. = phrase initial, w.i. = word initial, s.i. = syllable initial).

Those parameters which were least consistently correlated with stress, nasal flow and acoustic amplitude, turned out to be precisely the properties most consistently associated with differences in prosodic level. With the exception of utterance initial nasals, domain initial nasals had lesser flow, the higher the domain. While nasal air flow for all speakers did not distinguish every prosodic level on a consistent basis, all speakers did distinguish at least two levels, and always in the predicted direction. Acoustic amplitude of domain initial nasals for all speakers is also correlated with the size of the domain: the larger the domain the greater the difference in amplitude between the nasal and the first stressed vowel of the examined word. In other words, the larger the domain, the less the amplitude of the nasal. The decrease in amplitude and nasal air flow is compatible with the view discussed in section 3.2.4 that the overall sonority profile of the syllable is stronger in initial position of higher domains. This optimization of the domain initial syllable is achieved by making the initial consonant more consonantal-like, thereby maximizing the sonority difference between the initial consonant and the following vowel.

Interestingly, the property most closely linked to stress, duration, was the property which least reliably differentiated prosodic levels. Two speakers (M2 and M3) tended to lengthen nasals at the boundary of higher domains, while one speaker (F1) did just the opposite and shortened nasals at the boundary of higher domains. Yet another speaker (M1) did not display a consistent correlation between prosodic level and duration.

3.5. FUNCTIONAL LOAD AND THE MARKING OF STRESS AND PROSODIC DOMAIN. The tendency for a phonetic property to be consistently correlated with either stress or phrasing level but not both suggests that functional load plays a role in the exploitation of various phonetic parameters to signal stress or phrasing level. Where a property is closely involved with the demarcation of either stress or phrasing level, it will be less available for serving other functions. Thus, because onset duration carries such an important load in the marking of stress in Estonian, it is less available for signaling phrase boundaries. Conversely, velum height and amplitude is used to distinguish prosodic levels, and is thus not as readily available for manipulation in cueing stress. Assuming that avoidance of functional overload is at work in Estonian, as well as in other languages, then we would expect that a language with different properties associated with stress might also display differences in the properties associated with phrase level. For example, a language which does not signal stress by increasing the duration of the onset might be expected to vary duration more as a function of phrasing level. However, while the functional load explanation may offer some answers to why certain properties but not others are manipulated as a function of phrasing or stress, such an explanation does not account for all the data across languages. For example, VOT is correlated with stress in English (Cooper 1991), yet it also varies as a function of the size of the prosodic domain in which it occurs in initial position. More data from other languages is necessary to examine the extent to which languages try to avoid using a single parameter to signal both stress and prosodic level.

4. EXPERIMENT 2: THE FOOT AS A PROSODIC DOMAIN. The next two experiments were designed to examine the durational properties of the foot and to determine the extent to which segmental durations are a property of the foot. The first experiment, discussed in section 4.1, focused on the issue of foot isochrony in Estonian. In particular, the experiment sought to examine the extent to which durational properties of segments are predictable on the basis of foot structure or by other considerations external to the foot. The second experiment, considered in section 4.2, examined the evidence that a single overlong syllable may form a canonical foot on its own, thereby violating the more standard disyllabic foot template in Estonian.

4.1. FOOT TIMING. A corpus of tetrasyllabic nonsense words were constructed with all possible permutations of consonant and vowel durations adhering to word structures characteristic of native Estonian words *not containing an overlong first syllable.* These words were placed in a frame sentence. All words began with /s/, while all four vowels were /a/ and all word-internal consonants were oral dental stops. The duration of the first vowel was manipulated (either short or long), as was the duration of intervocalic consonants (also either short or long). The first half of a long consonant belongs to the same syllable as the immediately preceding vowel, resulting in a closed syllable (CVC or CVVC). For the male speaker, /saat/ in the first syllable was replaced by /saas/. The final syllable of the word was always open. Manipulating all possible combinations of length produced a corpus of sixteen target words, which appear in table 3 in Estonian orthography followed by the phonetic transcription.

In all words in the corpus, the first two syllables form one foot while the second two syllables form another foot. Two speakers, M3 and a female speaker not analyzed in the first experiment (labeled F2) repeated each sentence between eight and ten times in randomized order. The duration of the vowel in the second syllable and the vowel in the third syllable were each measured as a function of

See sadadada [sátatàta] *on sõna.*
See satadada [sátːatàta] *on sõna.*
See sadatada [sátatːàta] *on sõna.*
See sadadata [sátatàtːa] *on sõna.*
See satatada [sátːatːàta] *on sõna.*
See sadatata [sátatːàtːa] *on sõna.*
See satatata [sátːatːàtːa] *on sõna.*
See satadata [sátːatàtːa] *on sõna.*
See saadadada [sáːtatàta] *on sõna.*
See saatadada [sáːtːatàta] *on sõna.*
See saadatada [sáːtatːàta] *on sõna.*
See saadadata [sáːtatàtːa] *on sõna.*
See saatatada [sáːtːatːàta] *on sõna.*
See saadatata [sáːtatːàtːa] *on sõna.*
See saatatata [sáatːatːàtːa] *on sõna.*
See saatadata [sáːtːatàtːa] *on sõna.*

‘This __________ is a word.’

TABLE 3. Corpus used to examine the effect of foot structure on segment duration.

the types of syllables which preceded. Thus, the second vowel was measured as a function of whether the first syllable was CV, CVC, CVV or CVVC, while the third vowel was measured as a function of both the first syllable and whether the immediately preceding syllable was CV or CVC. Additionally, the target vowel was examined as a function of whether its syllable was open or closed by a consonant. The working hypothesis was that the second syllable should vary as a function of the first syllable (intrafoot timing), while the third syllable should not vary as a function of the second syllable (transfoot timing). In particular, it was hypothesized that the second vowel would be longer the shorter the first syllable, but that the second syllable would not influence the duration of the third vowel.

Thus, if the hypothesis were confirmed, the second vowel would be longer following a CV first syllable than following a CVC or CVV first syllable (which have similar durational profiles to each other). The second vowel would be expected to be still shorter following a CVVC first syllable. A short pilot study had indicated that durations of the first syllable from smallest to largest were CV, CVC and CVV, and CVVC. The results for the second vowel considered as a function of the type of the first syllable appear in figure 11.

Confirming the working hypothesis, there is a general inverse correlation between the length of the first syllable and that of the second syllable. Thus, the second vowel is longest following a CV first syllable (except for open second syllables for speaker M3), intermediate in duration following CVC and CVV first syllables, and shortest following a CVVC first syllable. The effect of the preceding syllable type was found to be highly significant for both speakers by a

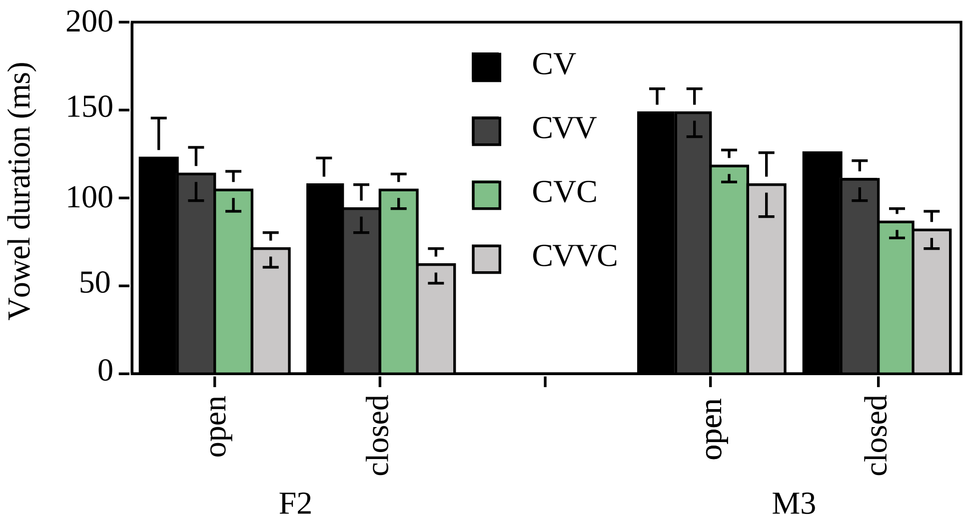


FIGURE 11. Duration of the second vowel as a function of whether it occurs in an open or closed syllable and as a function of the structure of the first syllable (CV, CVV, CVC, CVVC).

two-factor ANOVA with the preceding syllable and the syllable type (open vs. closed) of the target syllable as factors. In all cases, except for vowels in closed syllables for speaker F2, vowels following a CVV initial syllable were longer than those following a CVC initial syllable. Another pattern which emerges, also highly significant for both speakers, is for vowels in open syllables to be longer than those in closed syllables. This pattern conforms to the general cross-linguistic tendency for vowels in open syllables to be longer than those in closed syllables (Maddieson 1985). There is yet another effect which becomes apparent when comparing the duration of vowels in feet in which the first syllable is CV. Values (in milliseconds) for short vowels in open and closed first and second syllables appear in table 4. Values are for the underlined vowels.

The general pattern is for the vowel of the second syllable following a CV first syllable to be longer than a short vowel in the first syllable. This is the "half-long vowel" effect observed by many researchers of Estonian (e.g. Must 1959, Lehiste 1965b, Eek 1975, etc.) and also found in some dialects of Finnish (Wiik and Lehiste 1965). In the data considered in the current experiment, for vowels in structurally identical syllables (either open or closed), the lengthening effect is about 12-19% percent depending on the speaker and whether the first and second syllable are open or closed. However, when the first two syllables are [CVCVC], there is either no lengthening of the second vowel (speaker M3: 2nd vowel=.126, 1st vowel=.131) or only a very insignificant lengthening effect (speaker F2: 2nd vowel=.107, 1st vowel=.103). It thus seems that the presence of the final consonant in the foot contributes to the duration of the second syllable, and thus to the isochronous timing of the foot.

Speaker F2

CVCV(C)	.103	CVCV CVCVC	.123 .107

Speaker M3

CVCV(C)	.131	CVCV CVCVC	.148 .126

TABLE 4. Duration (in milliseconds) of vowels in the first and second syllables of tetrasyllabic words (speakers F2, M3).

Next the vowel of the third syllable was examined as a function of the second syllable. Results appear in figure 12.

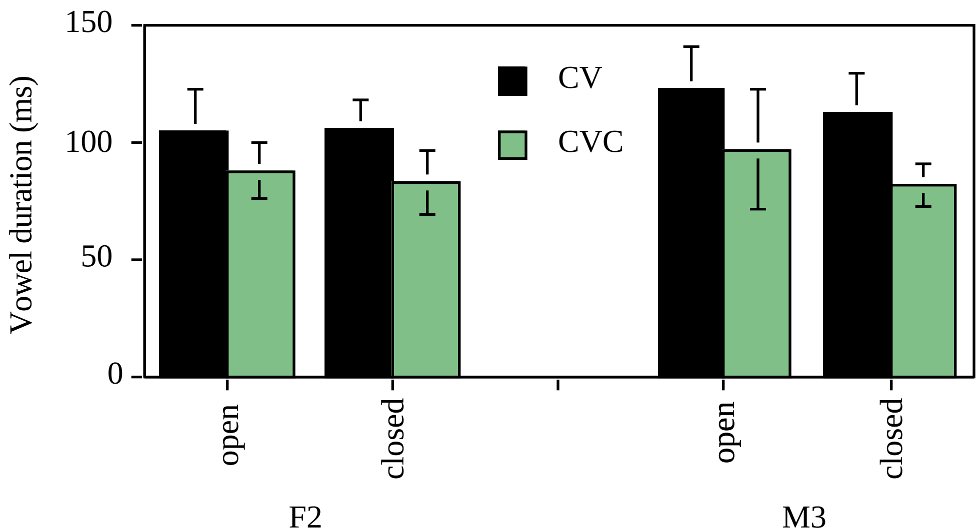


FIGURE 12. Duration of the third vowel as a function of whether it occurs in an open or closed syllable and as a function of the structure of the second syllable (CV, CVC).

First, there is a general trend, stronger for speaker M3 than for speaker F2, for vowels to be longer in an open third syllable than in a closed third syllable, in keeping with the overall effect of syllable structure on vowel duration in Estonian. Second, and more interestingly, there is a highly significant effect (p<.0001 for both speakers) of the second syllable on the duration of the third vowel, even though the second and third syllables belong to different feet. The third vowel is longer following a CV second syllable than following a CVC second syllable, a similar relationship to the one observed between the second vowel and the first syllable in figure 11. This piece of data suggests that segment duration is a function of not only foot-internal structure, but also is influenced by syllables in other feet. What is unclear based on the data seen so far, is if the observed durational patterns are the result of a general linear effect whereby one syllable influences the duration of the immediately following syllable or whether the observed data are the result of a word-level isochrony effect which shortens individual segments the longer the word is an a whole. In order to offer a tentative answer to this question, the duration of the third vowel was measured as a function of the structure of the first syllable. Results appear in figure 13.

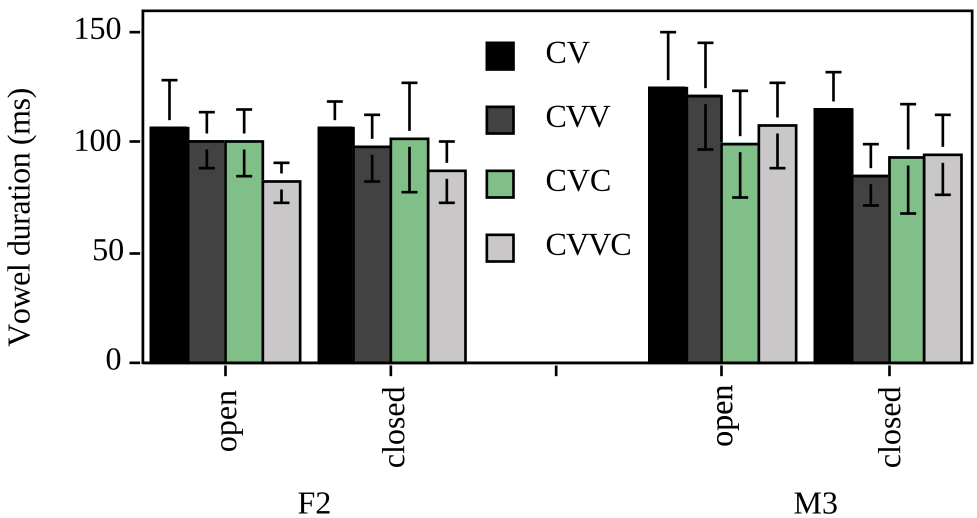


FIGURE 13. Duration of the third vowel as a function of whether it occurs in an open or closed syllable and as a function of the structure of the first syllable (CV, CVV, CVC, CVVC).

For both speakers, the type of the first syllable was found to have a highly significant effect on the duration of the third vowel. For speaker F2, significance reached the p<.0001 level, while the significance level was p=.0087 for speaker M3. The graph for F2 in figure 13 bears close resemblance to the one in figure 11 depicting the influence of the first syllable on the duration of the second vowel. The graph for speaker M3 in figure 13 also basically resembles the one in figure 11 for the same speaker, though some of the large differences in figure 11 are much smaller or non-existent in figure 13. The data in figure 13 thus offers evidence against the hypothesis that duration is linearly affected by the immediately preceding syllable, and offers support for the view that isochrony applies at the word level: i.e. that segment duration is inversely correlated with the overall length of the word. This latter hypothesis finds some support in Krull's (1992) data on Estonian as well as data from the related language Sámi (Engstrand 1987) which suggest similar inverse relationships between word duration and segment duration. A topic for further research would be to examine, perhaps by comparing actual syllable durations on a token by token basis, the relative strength of the effect of the second syllable on the third syllable compared to the effect of the first syllable on the second syllable. Both effects were found to be highly significant at the $p<.0001$ for both speakers in the current experiment, but this result is based on syllable types rather than actual syllable durations.

4.2. SECONDARY STRESS FOLLOWING AN OVERLONG FIRST SYLLABLE. The final experiment was designed to test the hypothesis that an overlong first syllable in certain polysyllabic word types may form a monosyllabic foot, whereas a short or long first syllable may never constitute a foot on its own in a polysyllabic word. This is the view advanced in Hint (1973)[1], who suggests that in words like *ausate* [(aúː)(sàtˑe)] 'honest, honorable' genitive pl. and *ausaks* [(aúː)(sàks)] 'honest, honorable' translative sg. with an overlong first syllable, the first syllable forms a canonical foot on its own and the second syllable begins a new foot. (Feet are indicated by parentheses.) As a reflection of this, the second syllable in these words receives secondary stress. However, an overlong first syllable is not the only prerequisite for secondary stress on the immediately following syllable. The placement of secondary stress is contingent upon the weight of the second syllable. Disyllabic words like *raadad* [(ráːtat)] 'cultivate' 2sg. pres. ind. with and overlong first syllable and a singly closed final syllable, however, do not receive secondary stress on the second syllable and thus consist of only one foot, according to Hint. Nor is there secondary stress on the second syllable in words which are structurally identical to a word with an overlong first syllable and secondary stress on the second syllable, except for their having a long first syllable: e.g. *saadate* [sáˑtatˑe] 'send' 2pl. present indicative and *saadaks* [sáˑtaks] 'send' 3sg. present conditional.

If it turned out that a syllable immediately following an overlong first syllable is able to attract secondary stress, whereas a syllable immediately following a non-overlong first syllable does not receive secondary stress, this would offer some support for the notion of foot isochrony under the view that feet have an optimal duration which can be achieved by an overlong single syllable. Following this logic, the failure of the second syllable to receive secondary stress in *raadad* [ráːtat] would be due to its being too *short* to form an independent foot. Thus, according to the hypothesis of foot isochrony, the desire to have feet of an optimal duration, not too short and not too long, is operative in Estonian. Based on the two forms *raadad* [ráːtat] vs. *raadaks* [ráːtàks], it seems that it is more

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[1] Hint's stress judgments may pertain to a southern variety of Estonian or an earlier form of the language.

important not to have a foot which is too short than it is to avoid feet which are too long.

A small corpus was constructed to test the extent to which foot isochrony is supported by stress patterns in words with an overlong first syllable. The corpus for all five speakers consisted of three words, one with a long first syllable, one with an overlong first syllable and a second syllable which is *stressed* in Hint's account, and one with an overlong first syllable and a second syllable which is *unstressed* in Hint's account. The number of syllables in the target words were slightly different as were the actual words examined for two different speaker groups, although the stress judgments being tested were the same for all speakers. The reason for the differences in the corpus between the two groups was that the data from one group were collected as part of a different experiment.

The corpus for speakers F2 and M3 consisted of reiterant nonsense words of three types: trisyllabic words with a long first syllable and an accordingly unstressed second syllable, trisyllabic words with an overlong first syllable and a CVC second syllable (stressed in Hint's account) and disyllabic words with an overlong first syllable and a CVC second syllable (unstressed according to Hint). Because some of the words with overlong and long first syllables were orthographically identical, subjects were prompted on which length was to be used by presenting them with a prosodically similar real word with the appropriate quantity. The target words were imbedded in the carrier sentence *See* __________ *on sõna*, "This __________ is a word." The corpus for speakers F2 and M3 appears in table 5.

Word	**Transcript.**	**Description**
saadata	[sáːtatːa]	long 1st syllable and unstressed 2nd syllable
saadad	[sáːːtat]	overlong 1st syllable and unstressed 2nd syllable
saadata	[sáːːtàtːa]	overlong 1st syllable and stressed 2nd syllable

TABLE 5. Corpus to examine secondary stress in words with an overlong syllable (speakers F2, M3).

The corpus for the other three speakers consisted of real Estonian words of three types, all disyllabic: disyllabic words with a long first syllable and a CVCC second syllable (unstressed), disyllabic words with an overlong first syllable and a CVCC second syllable (secondarily stressed in Hint's account), and disyllabic words with an overlong first syllable and a CVC second syllable, unstressed according to Hint. The target words were placed in the same frame sentence used by the first group of speakers: *See* __________*on sõna*, "This __________ is a word." The corpus for the second group of speakers is in table 6.

Word	**Transcript.**	**Gloss**	**Description**
laadaks	[láːtaks]	‘fair’ translat. sg.	long 1st syllable and unstressed 2nd syllable
raadad	[ráːːtat]	‘make land arable’ 2sg. pres. ind.	overlong 1st syllable and unstressed 2nd syllable
raadaks	[ráːːtàks]	‘make land arable’ 3sg. pres. cond.	overlong 1st syllable and stressed 2nd syllable

TABLE 6. Corpus to examine secondary stress in words with an overlong syllable (speakers M1, M2, and F1).

Stress was used as a diagnostic for determining foot structure: a stressed syllable was assumed to be the first syllable in a foot, following the assumption that Estonian is basically a trochaic language. Earlier research on Estonian (Lehiste 1966, Eek 1982, Liiv 1985, Gordon 1995) has indicated that stress is associated with two principal phonetic correlates: certain fundamental frequency contours and lengthening of consonants in the onset of stressed syllables. The second of these correlates, used to mark both secondary and primary stress, was discussed in greater detail in section 3.2.3. The first of these two properties, fundamental frequency, has slightly different manifestations in primary and secondary stressed syllables. Primary stressed syllables are marked by a rise in fundamental frequency for at least part of the duration of the stressed syllable (Liiv 1985). The length of this rise depends on the quantity of the stressed syllable. Secondary stress is marked by an interruption in the fundamental frequency decline (Eek 1982, Gordon 1995). The fundamental frequency properties associated with stress seem to be linked primarily to phrase level intonation properties and often vanish when words are not read in isolation, particularly in non-overlong syllables, as pointed out by Eek (1982) and others. In a pilot study, the present author found that the fundamental frequency cues to stress may disappear in a phrasal context, even when the word receives primary phrasal stress.

Because of the less clear role of fundamental frequency in the signaling of secondary stress, onset lengthening was chosen as the diagnostic for determining the location of secondary stress in the present experiment. Prior to beginning the present experiment, measurements of onset duration for all five speakers were taken from tetrasyllabic words *without an overlong first syllable*, in order to check that all speakers did in fact use onset lengthening to signal secondary stress. The results of this preliminary experiment confirmed to earlier results demonstrating that secondary stressed syllables have longer onsets than unstressed syllables.

The duration of /t/ in the onset of the second syllable in words containing an overlong first syllable and in words containing a long first syllable was then measured using the words in tables 5 and 6. Results appear in table 7. Durations of /t/ in the onset of syllables which are stressed in Hint’s account appear in bold.

There is a fair amount of interspeaker variation in the data. The most robust and consistent trend is for syllables following an overlong first syllable to have longer onset consonants than those following a non-overlong first syllable. This is true of all speakers except F1. Results from t-tests comparing all three word types with each other were significant at the p<.05 level for all speakers except F1 and M2, though M2's results approached significance (p<.05 *raadaks* vs. *laadaks*, p<.13 *raadad* vs. *laadaks*). Based on the general pattern of results, it thus seems plausible that, at least for some speakers, a syllable immediately following an overlong syllable is more stressed than one immediately following a non-overlong syllable. This result would seem to offer support for the view that overlong syllables may form a foot on their own, a notion which accords with the foot isochrony hypothesis.

Concerning the second hypothesis, that the second syllable following an overlong first syllable receives secondary stress *only in certain word types*, the results are less consistent across speakers and less robust for individual speakers. Three speakers (M1, M2, and M3) show a trend for syllables following overlong first syllables which are stressed in Hint's account to have longer onsets than syllables following overlong first syllables which are unstressed in Hint's account.

The differences, however, are quite small and statistically insignificant (55.1ms vs. 52.5ms for speaker M1, 68.9ms vs. 66.1ms for speaker M2, 64ms vs. 59ms for speaker M3). The only statistically significant difference between stressed and unstressed syllables following an overlong first syllable is found for speaker F2 (p<.05). However, her pattern is exactly the opposite of the expected

Spea-ker	**Second syllable**	**First syllable**			
		Normal	**Std.dev.**	**Overlong**	**Std.dev.**
F1	stressed			**36.5**	4.2
	unstressed	38.6	3.3	39.4	2.4
F2	stressed			**42.0**	8.0
	unstressed	34.0	7.0	57.0	10.0
M1	stressed			**55.1**	1.4
	unstressed	31.6	6.8	52.5	1.3
M2	stressed			**68.9**	9.5
	unstressed	57.4	11.9	66.1	10.1
M3	stressed			**64.0**	12.0
	unstressed	47.0	4.0	59.0	9.0

TABLE 7. Duration of /t/ (in ms) in the onset of syllables following overlong and long first syllables.

pattern. Unstressed syllables have longer onsets than stressed syllables in her data. On the basis of this data and the use of onset lengthening as a diagnostic for stress, we do not find particularly strong evidence for the hypothesis that the placement stress following an overlong first syllable is contingent upon the weight of the second syllable in standard Estonian.

5. CONCLUSION. This paper has examined the effect of several aspects of prosody on various acoustic and articulatory features in Estonian. Phonetic evidence from nasals suggests the presence of a prosodic hierarchy in Estonian consisting of the phrase, the word and the syllable, and perhaps also the utterance at the top of the hierarchy. Nasals in initial positions of different domains possess different properties depending on the level of the domain. Nasals in initial position of higher domains are marked by decreased amplitude and nasal air flow relative to their counterparts in initial position of lower domains. The decrease in nasal air flow suggests a higher velum position in higher domains, which supports the view that consonants are more consonantal in higher positions, a form of "strengthening". Stress also influences segments, principally with respect to durational patterns: consonants in the onset of stressed syllables are longer than those in the onset of unstressed syllables. The fact that stress and domain level influence different acoustic and articulatory parameters suggests that there are limits on the effectiveness with which a single phonetic parameter can serve two prosodic functions.

Evidence from durational measurements suggests that two types of isochrony are at work in Estonian: foot isochrony and word isochrony. Finally, the question of the location of secondary stress in words with an overlong first syllable was examined. Results suggest that the syllable immediately following an overlong first syllable is more stressed than the syllable immediately following a non-overlong first syllable, offering support for the view that feet are isochronously timed to some extent. However, there was no strong evidence that the weight of the second syllable plays a role in standard Estonian in determining the location of secondary stress in words with an overlong first syllable.

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