ACOUSTIC CORRELATES OF PRIMARY WORD STRESS IN ESTONIAN

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Abstract. This study investigates the acoustic correlates of primary word stress in Estonian. The results contribute to several open questions concerning the acoustic correlates of word stress: Does fixed word stress have acoustic correlates? Can duration be the primary acoustic correlate of word stress in a language with contrastive segment length? Is F0 an exclusive correlate of phrase stress or does it also correlate with word stress? The study finds that despite being fixed, Estonian word stress significantly correlates with acoustic features. The primary correlate is F0, followed by vowel quality, overall intensity, duration and spectral tilt. The results support the functional load hypothesis which predicts that duration is not the primary acoustic correlate of word stress in languages with contrastive segment length. The results do not support the assumption that F0 exclusively correlates with phrasal stress and intonational pitch accents.

Keywords: Estonian, speech acoustics, fixed word stress, functional load hypothesis, quantity, phrasal stress

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1. Introduction

This paper reports an attempt to identify the acoustic correlates of Estonian primary word stress independently of phrasal stress and intonational pitch accents, on the one hand, and the Estonian three-way quantity distinction, on the other hand.

Estonian has fixed primary word stress on the first syllable of the word. Exceptions to word-initial stress occur in certain interjections and onomatopoeic words, e.g., *aitäh* [ɑit.ˈtæhː] 'thank you', a considerable number of (generally more recent) loan words, e.g., *foneetika* [fo.ˈneːt.tik.kɑ] 'phonetics' (Asu et al. 2016: 127), and derived words with certain suffixes, e.g., the feminine suffix *-lanna*, as in *lätlanna* [læt.ˈlan.na] 'Latvian.F.SG'. In tetrasyllabic and longer words secondary stress falls on every second or third syllable, e.g., *magamata* [ˈmɑ.ka.ˌmɑtː.tɑ] 'without sleeping' (Asu et al. 2016: 127). The primary-stressed syllable is the exclusive domain of several phonological categories (with exceptions in loan words), which thus contribute to signal it. The categories mainly restricted to primary-stressed syllables include four of the Estonian nine vowels, most diphthongs, and long vowels (Asu et al. 2016). On the phrasal level, the primary-stressed syllable, usually together with the following or preceding unstressed syllable, serves as the anchoring point for intonational pitch accents (Asu 2004).

Existing cross-linguistic studies have repeatedly found that fixed word stress does not have strong acoustic correlates (e.g. Dogil & Williams 1999 for Polish; Vogel et al. 2016 for Turkish and Hungarian; see also van Heuven & Turk 2020: 161). On the other hand, the existence of exceptions from the regular fixed stress position – which are relatively numerous in Estonian – has been associated with stronger acoustic correlates (Vogel et al. 2016). Also, based on an overview of 110 studies on word stress, Gordon & Roettger (2017) conclude that acoustic evidence of word stress has been found in languages both with predictable and distinctive stress. The goal of the present study is to test whether Estonian primary-stressed syllables correlate with the main acoustic features that have been found to signal lexical stress cross-linguistically.

1.1. Cross-linguistic correlates of word stress

Duration has been found to be the primary cross-linguistic acoustic correlate of word stress, in particular, the lengthening of the vowel of the stressed syllable (e.g. van Heuven & Turk 2020: 155; van Heuven 2018; Gordon & Roettger 2017; Lehiste 1970). In some languages only consonant and not vowel duration has been found to distinguish the stress level (Gordon & Roettger 2017). However, it is a debated issue whether duration can be the primary correlate of word stress also in a language with contrastive segment length, such as Estonian. According to the functional load hypothesis as applied to stress by Berinstein (1979: 2), increased duration is predicted to be superseded by change in F0 and increased intensity in the hierarchy of perceptual stress cues in a language with contrastive segment length. Vogel et al. (2016) developed the functional load hypothesis further into three subhypotheses, all of which were confirmed by their study. Their results predict that properties involved in phonemic contrasts will not be the strongest acoustic correlates of word level prominence nor phrase level prominence, and that the strongest acoustic correlates of word and phrase level prominence will not coincide.

On the other hand, the hypothesis that languages with contrastive segment length do not employ duration as the primary acoustic correlate of word stress was disconfirmed by the study of Lunden et al. (2017). As noted by Turk (2012: 250), duration is regularly used for many different purposes. The likely reason why duration can simultaneously fulfill different functions is that it can be implemented differently in each function: it can apply in different domains, in different magnitudes, using different articulatory strategies, or in different combinations with other cues (Turk 2012: 250–252). A further factor that could support the use of an acoustic feature in different functions is the possibility that speakers may develop a greater perceptual sensitivity to features that play a contrastive role in their language. This hypothesis was proposed and tested by Lehiste and Fox (1992) with regard to the sensitivity of Estonian-speakers to duration. They hypothesised that speakers of Estonian, a quantity language, are more sensitive to durational differences than speakers of a stress language (English) in the perception of prominence, and their results supported the hypothesis. Similarly, Šimko et al. (2015) found that speakers with different language backgrounds showed a different sensitivity to duration. The possibility that speakers may develop a perceptual specialisation to particular phonetic features gives rise to an opposite hypothesis to the functional load hypothesis: when speakers are particularly atuned to a specific feature, this feature can be used in a more nuanced way and can thus acquire a larger functional load.

In Estonian, duration has already been found to have different functions at several levels. The Estonian quantity system comprises three quantity degrees realised through a binary length distinction at segmental level in combination with three distinct duration ratios of stressed and unstressed syllables at foot level, e.g., *ude* [uteˑ] ‘down’, *uude* [uːte] ‘innovation’, *uude* [uːːtĕ] ‘new.ILL.SG’ (for an overview see Metslang et al. 2023: 74–81; Asu et al. 2016; Lippus et al. 2013; Prillop 2013; Lehiste 1960). On the phrasal level, duration is employed in preboundary lengthening (Plüschke & Harrington 2013; Krull 1997), as the primary dynamic correlate of phrasal stress (Lehiste 1968, 1970; Mihkla & Sahkai 2017), and as the primary correlate of emphatic phrasal stress distinguishing narrow focus from broad focus (Suomi et al. 2013; Mihkla et al. 2015; Sahkai et al. 2015). Measurements have shown that both pre-boundary lengthening (Plüschke & Harrington 2013) and lengthening as a correlate of non-emphatic (Lehiste 1968, 1970) and emphatic (Sahkai et al. 2015) phrasal stress apply in a way that preserves the characteristic foot-level duration ratios of the three quantity degrees. Furthermore, a comparison of the measurements in Plüschke & Harrington (2013) and Sahkai et al. (2015) shows that pre-boundary lengthening and emphatic lengthening partly apply in different domains. In particular, emphatic lengthening always affects the word-initial onset consonant while pre-boundary lengthening virtually never does. Nevertheless, pre-boundary lengthening restricts emphatic lengthening: in utterance-final position, the duration difference between emphatic and non-emphatic phrasal stress is smaller than in a non-final position (Sahkai et al. 2015).

In the present study, we will test whether duration additionally serves as an acoustic correlate of word stress in Estonian, and if it does, whether it is a primary or secondary correlate of word stress.

The second main cross-linguistic correlate of word stress is considered to be increased **overall intensity** (van Heuven &Turk 2020; Lehiste 1970; van Heuven 2018). However, Gordon and Roettger (2017) note that word stress studies that control for phrasal stress have rarely found intensity to be a strong correlate of word stress. Some studies have found that overall intensity varies together with F0 rather than word stress (e.g. Ortega-Llebaria & Prieto 2007; Sluijter & van Heuven 1996). This can be related to the fact that an increase of subglottal pressure causes an increase both in intensity and frequency (Lehiste 1970: 143–144; Ladefoged & Johnson 2011: 250). On the other hand, Lehiste (1970: 144) concludes that despite various dependence relationships, F0 and intensity can be considered at least to some extent independent.

In addition to overall intensity, **spectral tilt** has been found to be a minor correlate of word stress, with a larger increase of intensity at higher frequencies (e.g. van Heuven & Turk 2020; Gordon & Roettger 2017; Sluijter & van Heuven 1996). However, some studies have concluded that it correlates with vowel quality rather than word stress (e.g. Ortega-Llebaria & Prieto 2010).

A further relatively weak correlate of word stress is the **spectral expansion** of the stressed syllable vowel (e.g. van Heuven & Turk 2020; Lehiste 1970; van Heuven 2018). According to the overview of Gordon and Roettger (2017), this effect has not been found in studies that control for phrasal stress and is usually limited to certain vowels and/or only one formant.

Finally, **fundamental frequency** has been found to be a further correlate of word stress. More recently, these findings have been attributed to the fact that word stress has been examined in words also receiving a phrasal stress aligned with an intonational pitch accent. Several authors have therefore underlined the need to study the correlates of word stress independently of phrasal stress and intonation (e.g. Suomi et al. 2003; Ortega-Llebaria & Prieto 2007; Gordon 2014; van der Hulst 2014: 7; Vogel et al. 2016; Roettger & Gordon 2017; van Heuven 2018; van Heuven & Turk 2020: 152). On the other hand, Vogel et al. (2016), while controlling for phrasal stress, found F0 to be the main correlate of word stress in all four languages examined in their study (Spanish, Greek, Hungarian and Turkish). We will therefore include F0 as a potential correlate of word stress to be examined in the present study.

1.2. Acoustic correlates of word and phrase stress in Estonian

The above-mentioned features have also been tested as potential correlates of **Estonian word stress** by several studies, but usually without controlling for phrasal stress and pitch accent. Overall, it has been concluded that Estonian does not have strong word stress correlates, which has been attributed to the fixed position of the primary word stress (Lippus et al. 2014).

Estonian primary-stressed syllables have been found to be cued by the longer **duration** of the onset consonant (Gordon 1997; Asu & Lippus 2018) as well as by the duration of the vowel. The vowel of the primary-stressed syllable may be longer or shorter than the vowel of the unstressed syllable of the primary-stressed foot, depending on the quantity degree, but it is longer than the vowels of secondary stressed and unstressed syllables outside the primary-stressed foot (Lippus et al. 2014; Asu & Lippus 2018). Within secondary-stressed feet, duration does not distinguish between stressed and unstressed syllables (Asu & Lippus 2018).

The stressed syllable of a primary-stressed foot has been found to have higher mean **intensity** than the unstressed syllable of the same foot in all quantity degrees and both in words with and without phrasal stress (Sahkai & Mihkla 2019a,b). This result differs from those of some earlier studies that did not find a significant intensity difference between the stressed and unstressed syllables (Asu & Lippus 2018), or found it only in certain quantity degrees (Eek & Meister 1997; Kalvik & Mihkla 2010). Mean intensity was not found to distinguish between stressed and unstressed syllables of secondary-stressed feet (Asu & Lippus 2018).

Asu & Lippus (2018) further found that Estonian primary-stressed syllables showed smaller average **spectral balance**. **Spectral emphasis** did not distinguish the primary-stressed syllable from the unstressed syllable of the primary-stressed foot, but did distinguish it from the remaining syllables. Spectral features did not distinguish between the stressed and unstressed syllables of secondary-stressed feet (Asu & Lippus 2018).

Vowel quality has been found to distinguish between Estonian stressed and unstressed syllables primarily in spontaneous speech where unstressed syllables are strongly reduced; the reduction varies however depending on the quantity degree and the vowel (Asu et al. 2016: 40–42, 128).

Estonian primary-stressed syllables have also been found to correlate with **F0 features**, but without controlling for phrase stress and pitch accent (Lippus et al. 2014; Asu & Lippus 2018). Asu & Lippus (2018) found that primary-stressed syllables were distinguished by the average F0, the standard deviation of F0, and the F0 slope in the vowel; these features did not distinguish between the stressed and unstressed syllables of secondary-stressed feet.

Previous studies have also examined the acoustic correlates of **Estonian phrasal stress**. Phrasal stress in Estonian has been found to correlate with increased F0 maximum, larger F0 range (F0 features were measured only in words carrying a H*L pitch accent), longer duration and increased intensity level, but not with the intensity range within the word, spectral expansion of the stressed syllable vowel of the phrase-stressed word, or spectral emphasis (Mihkla & Sahkai 2017). **Emphatic phrasal stress** distinguishing narrow focus from broad focus has been found to correlate with lengthening as well as with increased F0 maximum and intensity level of the target word in relation to the preceding phrase-stressed word; the relative increase of the F0 maximum compared to the preceding phrase-stressed word was significant only in target words that did not immediately precede a phrase boundary, and the F0 and intensity range of the target word in itself did not correlate with emphatic phrase stress (Mihkla et al. 2015; Sahkai et al. 2015).

1.3. Research questions

The goal of the present study is to test the correlates of Estonian primary word stress independently of phrasal stress and quantity. The following parameters will be examined: duration, overall intensity, spectral emphasis and tilt, vowel quality, and F0. More specifically, we aim to elucidate the following points.

1. We will examine whether Estonian word stress correlates with duration, and if yes, whether duration is a primary or secondary correlate of word stress. This will help to elucidate the more general question whether duration can serve as the primary acoustic correlate of word stress in a language with contrastive segment length.

2. Lengthening of the onset consonant of the primary stressed syllable has been found to correlate both with word stress (Gordon 1997; Asu & Lippus 2018) and with emphatic phrasal stress (Sahkai et al. 2015). However, word stress has been studied without controlling for phrasal stress. We aim to clarify whether the lengthening of the onset emerges as a correlate of word stress also when controlling for phrasal stress.

3. We will verify whether intensity correlates with word stress in Estonian, as was found by Sahkai and Mihkla (2019b). The previous study compared lexically stressed and unstressed syllables syntagmatically within a foot, while the present study will apply a paradigmatic comparison.

4. Spectral parameters have been found to correlate with Estonian word stress (without controlling for phrasal stress) (Asu & Lippus 2018), but not with phrasal stress (Mihkla & Sahkai 2017; Sahkai & Mihkla 2019a). This suggests that they may be independent correlates of word stress, which we will verify.

5. We will verify the previous findings that vowel quality is not a general correlate of word stress in Estonian (Asu et al. 2016: 40–42, 128).

6. Word stress examined in words receiving phrasal stress has been found to correlate with pitch cues (Lippus et al. 2014; Asu & Lippus

2018). We aim to verify this result while controlling for phrasal stress. The results will contribute to the more general question whether F0 is an exclusive correlate of phrasal stress or whether it can also signal word stress.

7. More generally, we aim to test the prediction that Estonian word stress, being fixed, does not have strong acoustic correlates, as has been found by Lippus et al. (2014). The results will contribute to the more general question regarding the acoustic signalling of fixed word stress.

2. Data and method

2.1. Method

The most reliable method for the identification of the acoustic correlates of word stress is considered to be the paradigmatic comparison of the same syllable in the same position with and without stress, for instance, in words like ˈ*import* vs. *im*ˈ*port* (van Heuven 2018; van Heuven & Turk 2020: 152). This method cannot be applied in a language with fixed word stress like Estonian. In order to maximally approximate the paradigmatic method we compared word-initial stressed syllables with segmentally identical word-initial unstressed syllables of a certain type of loan words with non-initial stress, an approach also applied by Gordon (1997). In particular, we used pairs of segmentally identical stressed and unstressed word-initial syllables in words like ˈ***ma****nuse* ‘attachment.GEN.SG’ vs. ***ma***ˈ*neeži* ‘riding.school.GEN.SG’. In the unstressed condition we used loan words in which the primary-stressed syllable was preceded by a single unstressed syllable, making thus sure that the examined syllables did not receive secondary stress. The examined syllable pairs were not perfect minimal pairs. The position of the target syllable with respect to the prosodic foot structure of the word was different in the two conditions: the stressed syllable was both in a word- and foot-initial position while the unstressed syllable was word-initial, but not foot-initial: $_{\omega}$($_{\mathrm{Ft}}$(ˈ**mɑ**.nu.se)$_{\mathrm{Ft}}$)$_{\omega}$ vs. $_{\omega}$(**mɑ**. $_{\mathrm{Ft}}$(ˈneː.ʃi)$_{\mathrm{Ft}}$)$_{\omega}$. Thus it cannot be excluded that the potential differences found between the two conditions are related to the presence vs. absence of a foot boundary in addition to the presence vs. absence of stress. This mismatch cannot be avoided as feet are always trochaic in Estonian. The chosen approach is nevertheless preferable to a syntagmatic comparison of stressed and unstressed syllables within a foot. The syntagmatic comparison would likewise imply a different placement of the compared syllables with respect to foot and word boundaries (cf. van Heuven & Turk 2020: 152). As an additional drawback, the syntagmatic approach would make it impossible to test duration as a correlate of stress, as the relative duration of stressed and unstressed syllables in a foot is determined by quantity: in a first quantity foot, the stressed syllable is shorter than the unstressed syllable, while in second and third quantity feet the stressed syllable is longer than the unstressed syllable, see e.g. Lippus et al. (2014), Asu & Lippus (2018).

A question that may arise is the status of the exceptional test words with non-initial stress with respect to the Estonian phonological system. It has been suggested by van der Hulst (1999: 16) that loan words with an exceptional stress pattern can be considered as an integral part of the stress system of the language if they are otherwise pronounced in accordance with the phonetics of the language and if they are in normal use because there are no non-foreign equivalents. The words with non-initial stress included in the present study conform to this description. In addition, they display the characteristic phonological and morphophonological features of Estonian words. First of all, the initial unstressed syllable of the type of words used in the unstressed condition is an integral part of the prosodic word. This is evidenced by contexts where the initial unstressed syllable ends with a vowel and the following primary-stressed syllable starts with a long consonant, for instance, in a word like *muˈtandi* 'mutant.GEN.SG'. In Estonian, intervocalic long onsets undergo gemination across the syllable boundary within a prosodic word (Asu et al. 2016: 122). The same process occurs in the type of words included in the study. Accordingly, a word like *muˈtandi* is pronounced /mut.ˈtɑn.ti/, with gemination of the second syllable onset across the syllable boundary. Secondly, the primary-stressed foot following the initial unstressed syllable is a regular trochaic foot that has a quantity degree and shows morphologically meaningful quantity alternations that are typical of the Estonian morphophonological system, for example, /mut.ˈtɑn.ti/ 'mutant.GEN.SG' vs. /mut.ˈtɑntː.ti/ 'mutant.PAR.SG'. Finally, words with non-initial primary stress are not a rare occurrence in Estonian as their number is well over 10,000 according to the Combined Dictionary of the Institute of the Estonian Language (Langemets et al. 2023).

2.2. Materials

The materials of the study included ten target syllables. We used segmentally and structurally different syllables in order to ensure sufficient representativity. We used an equal number of open and closed syllables to examine in more detail the segmental distribution of potential lengthening effects. The ten target syllables are listed in (1).

(1) /mɑ/, /me/, /li/, /vo/, /mu/, /mɑk/, /met$^{(j)}$/, /mil^{j}(ː)/, /nor/, /mus(ː)/

In two instances, /mil^{j}(ː)/ and /mus(ː)/, the length of the coda consonant differs in the two conditions. The potential effects of this mismatch were mitigated by the fact that the measurements were made in the vowel or, in the case of duration, separately for each segment.

Each target syllable was embedded in two words, in one word as the initial stressed syllable and in the other as the initial unstressed syllable. All the words in both conditions had three syllables. In the stressed condition, the words consisted of a single primary-stressed foot. In the unstressed condition, the initial syllable was unparsed and the second and the third syllable constituted the primary-stressed foot.

Each target word was embedded in a sentence. All the sentences consisted of four words. In order to avoid phrase boundary effects in the target word, it was always the third word of the sentence. All the sentences had the structure [subject – auxiliary – (in)direct object – participial main verb]. The subject was always a two-syllable proper name and the auxiliary was always *oli*, the third person past tense form of the verb *olema* ‘be’; the object and the main verb varied. The target word was always the object. The sentence pairs including the stressed and the unstressed version of a target syllable were identical up to the second syllable of the target word (including the onset of the second syllable), see ex. (2).

(2) a. Stressed condition

Aino	oli	ˈ**me**lonid	toonud.
Aino	be.PST.3SG	melon.NOM.PL	bring.PST.PTCP

‘(I heard) Aino brought the melons.’

b. Unstressed condition

Aino	oli	**me**ˈlissid	toonud.
Aino	be.PST.3SG	balm.NOM.PL	bring.PST.PTCP

‘(I heard) Aino brought the balms.’

In order to avoid phrasal stress and intonational pitch accents in the target words, the target words were elicited in a post-focal position. In many works, pre-focal words repeated from the preceding context have been taken to provide the suitable data for studying word stress independently of phrasal stress (van Heuven & Turk 2020: 152; Vogel et al. 2016; Suomi et al. 2013). However, pre-focal given information is not necessarily deaccented, see e.g. Rochemont (2016: 45). In Estonian, pre-focal given information has been found to be accented (Sahkai & Mihkla 2017), while post-focal elements following a contrastive focus have been found to be predominantly deaccented (Sahkai et al. 2013). Therefore, the target words were elicited post-focally in the present work, although the post-focal position may induce other undesirable effects like the compression of pitch range (cf. Roettger & Gordon 2017).

In order to elicit the target words in a post-focal position, the subject of each carrier sentence was elicited as a corrective narrow focus via a preceding context sentence, see ex. (3). All the context and target sentences can be found in the Appendix.

(3) a. Context sentence

Viivi	oli	melonid	toonud.
Viivi	be.PST.3SG	melon.NOM.PL	bring.PST.PTCP

‘(I heard) Viivi brought the melons.’

b. Target sentence

Aino	oli	melonid	toonud.
Aino	be.PST.3SG	melon.NOM.PL	bring.PST.PTCP

‘(I heard) Aino brought the melons.’

In addition to the 20 target sentences, the materials included 60 filler sentences which were likewise preceded by a context sentence and elicited different information structural conditions.

2.3. Procedure and analysis

The data were recorded from 9 subjects (5 women and 4 men) at the recording studio of the Institute of the Estonian Language. The data were elicited via a production task. The 20 target sentences and 60 filler sentences appeared one by one on the computer screen together with the context sentence. The subjects were instructed first to silently read both sentences on the screen and then to produce the target sentence as a reaction to the context sentence, as they would do in a spontaneous conversation. Each sentence appeared once and each subject saw all the sentences in a different randomised order. The subjects went through the sentences at their own pace and could repeat a sentence if they wanted to. In the middle of the task there was a pause with distracting pictorial information. One sentence of each pair always appeared before the pause and the other after the pause.

In total 90 syllable pairs were recorded. The recordings were automatically segmented using the forced aligner of the Tallinn University of Technology (Alumäe et al. 2018) and manually checked in Praat (Boersma & Weenink 2020).

Each target word was verified in order to make sure that it had not been produced with a pitch accent. To do this, we measured the difference between the F0 maximum of the target word and that of the preceding auxiliary. The auxiliary being a function word, we assumed it to be deaccented. If the difference exceeded 2.8 semitones, the target syllable and its stressed or unstressed counterpart in the same speaker's data were excluded from the study. 2.8 semitones was chosen as the cut-off value because previous studies have shown that the F0 maximum of phrase-stressed words is on average 2.8 semitones higher than in words that do not receive phrasal stress in Estonian (Mihkla & Sahkai 2017). As a result, 27 syllable pairs were excluded from the analysis.

We measured the following acoustic parameters of the target syllables:
- the duration of the syllable and its constituent segments;
- the values of the following F0 and intensity parameters: the maximum, minimum and mean in the vowel, and the location of the maximum in the syllable. The same values were measured for F0 and intensity to confirm that they vary independently of each other;
- the spectral parameters in the vowel: emphasis and tilt;
- formant values in the vowel: F1 and F2.

All the values were measured and calculated using a Praat script. For the purpose of the analysis, the absolute values were normalised. The durations of the target syllables and their constituent segments were normalised with respect to the identical portions of the carrier sentences (including the subject, the auxiliary, and the target syllable). We first equalised the speech rate of the identical portion of each pair of carrier sentences and then calculated the durations of the target syllables and their segments. F0 and intensity levels in the vowel of the target syllable were normalised with respect to the F0 and intensity levels in the preceding word (the auxiliary). For each minimal pair of each speaker, the mean of the normalised duration, F0 and intensity values across the two conditions was then calculated. As the next step, the value of each member of the pair was calculated as the difference between its normalised value and the mean value of the pair.

The position of the F0 and intensity maximum within the target syllable was calculated as the percentage with respect to the beginning of the syllable (the value of the position of the maximum is 0% when it is located at the beginning of the syllable, and 100% when it is located at the end of the syllable).

Spectral emphasis in the vowel of the target syllable was calculated as the difference between the spectral energy in the frequency bands 500–2000 Hz and 0–5000 Hz. Spectral tilt in the vowel of the target syllable was calculated as the difference between the spectral energy in the frequency bands 0–1000 Hz and 1000–5000 Hz. The values of the formants F1 and F2 were converted into Bark and normalised as the Euclidean distance from the central point of the vowel space for every target syllable pair.

We used ANOVA to determine the signficance of each examined parameter. To answer the questions whether Estonian word stress has strong acoustic correlates and what is the strongest correlate, we used Classical Discriminant Analysis in order to determine the classification strength of each significant parameter, as recommended by van Heuven and Turk (2020: 151) and van Heuven (2018). SYSTAT 13 statistics software was used to run the statistical analyses.

3. Results

As the first stage of the analysis, we used two-factor ANOVAs to test the effect of stress and syllable structure (CV vs. CVC) on the acoustic parameters. Stress had a significant effect on all the acoustic variables except spectral emphasis. Syllable structure had a significant effect on the position of the F0 maximum ($F[1, 124] = 23.1$; $p < 0.001$) and on the position of the intensity maximum ($F[1, 124] = 74.4$; $p < 0.001$) in the target syllable. For these parameters as well as for the syllable and segment durations the results will be presented separately for the CV- and CVC-syllables.

3.1. Duration

The primary-stressed syllables were significantly longer than the unstressed syllables. The primary-stressed CV-syllables were on average 9.3 ms (6.5%) longer than the unstressed syllables ($F[1, 62] = 14.3$; $p < 0.001$). The primary-stressed CVC-syllables were 14.4 ms (6.6%) longer than the unstressed syllables ($F[1, 62] = 17.5$; $p < 0.001$). Figure 1 shows the segmental distribution of the lengthening. The lengthening was significant only in the vowel, being 6.7 ms and 10.3% in the CV-syllables ($F[1, 62] = 7.8$; $p = 0.0069$), and 10.6 ms and 15% in the CVC-syllables ($F[1, 62] = 16.7$; $p < 0.001$).

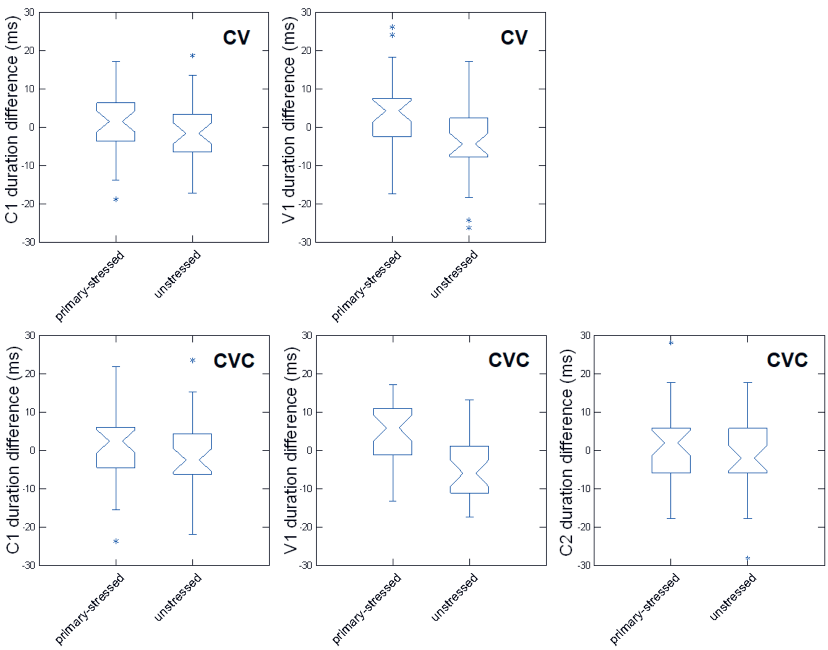

Figure 1. The relative lengthening/shortening of the constituent segments of the target CV-syllables (above) and CVC-syllables (below), depending on the stress condition. Asterisks mark outliers.

3.2. F0 and intensity

Table 1 represents the differences between the mean values of the F0 and intensity parameters (maximum, minimum and mean) in the stressed and unstressed syllables. As can be seen from Table 1, all the examined F0 parameters distinguished significantly between stressed and unstressed syllables. All the differences are positive, which means that all the F0 values were larger in the stressed syllables.

Table 1. The differences between the mean values of the F0 and intensity parameters of the stressed and unstressed syllables and corresponding p-values.

F0 and intensity parameters	differences	p-value
F0 max difference (st)	0.95	<0.001
F0 min difference (st)	0.71	0.0049
F0 mean difference (st)	0.89	<0.001
Intensity max difference (dB)	1.49	<0.001
Intensity min difference (dB)	1.03	0.0209
Intensity mean difference (dB)	1.38	<0.001

Figure 2 illustrates the difference between the F0 maxima in the stressed and unstressed syllable vowels. The mean value of the F0 maximum of the stressed syllable vowel was 0.95 semitones higher than that of the unstressed syllable vowel (F[1, 124]=106.9; p<0.001).

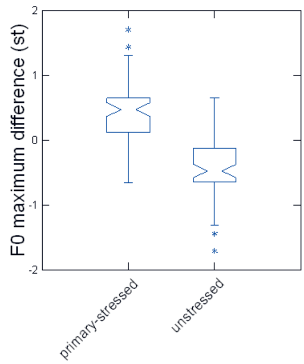

Figure 2. The difference between the F0 maxima of the stressed and unstressed syllable vowels (in semitones).

As for the intensity, Table 1 shows that all the examined parameters distinguished significantly between the stress conditions. The mean values of the intensity parameters were significantly higher in the stressed syllable vowels. For instance, the mean intensity of the stressed syllable vowel was 1.38 dB higher ($F[1, 124] = 37.7$; $p < 0.001$).

The locations of the F0 and intensity maxima within the syllable were influenced both by stress and syllable structure. The effect of syllable structure was due to the fact that the maxima tended to be located in the vowel. The F0 maximum of the CV-syllables was on average at 86% in the stressed condition and at 68% in the unstressed condition. In the CVC-syllables the F0 maximum was on average at 66% in the stressed condition and at 47% in the unstressed condition. The stress-induced difference in the relative position of the F0 maximum is significant both in the CV-syllables ($F[1, 62] = 11.4$; $p = 0.0013$) and the CVC-syllables ($F[1, 62] = 8.5$; $p = 0.0051$). The relative position of the intensity maximum in the target syllable likewise distinguished significantly between the stressed and unstressed syllables, as illustrated in Figure 3. In the primary-stressed syllable, the intensity maximum was located on average 11–16 percentage points further from the beginning of the syllable. In the CV-syllables, the maximum was located on average at 82% in the stressed syllable and at 71% in the unstressed syllable ($F[1, 62] = 5.1$; $p = 0.0384$). In the CVC-syllables, the respective locations were 55% and 39% ($F[1, 62] = 13.4$; $p = 0.0006$).

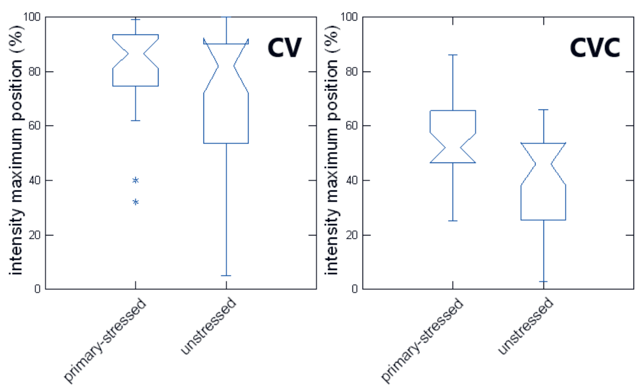

Figure 3. The location of the intensity maximum in the stressed and unstressed CV- and CVC-syllables (0% = the beginning of the syllable, 100% = the end of the syllable). Asterisks mark outliers.

The results also show that the F0 and intensity values did not coincide, suggesting that they varied independently of each other.

3.3. Spectral parameters and vowel quality

The differences between the values of the spectral emphasis in the stressed and unstressed syllable vowels were not significant ($F[1, 124] = 1.4$; $p = 0.2309$). Spectral tilt however correlated significantly with stress, being 1.01 dB less steep in the primary-stressed syllables ($F[1, 124] = 9.1$; $p = 0.0032$).

Stress had a significant effect on vowel quality ($F[1, 62] = 0.34$; $p = 0.5617$). The unstressed syllable vowels were on average 0.3 Bark closer to the centre of the vowel space.

3.4. The classification strength of the significant parameters

Figure 4 shows the results of the Classical Discriminant Analysis, which was applied to the significant parameters. From the various intensity and F0 parameters, only the most significant parameters were included in the analysis (intensity maximum and F0 maximum). Figure 4 shows the classification strength of the parameters between the stressed and unstressed syllables. F0 maximum was the strongest parameter, allowing to classify the primary-stressed and unstressed syllables with 83% accuracy. The next strongest parameter was vowel quality (79%), followed by intensity maximum (75%), duration (67%), and spectral tilt (62%).

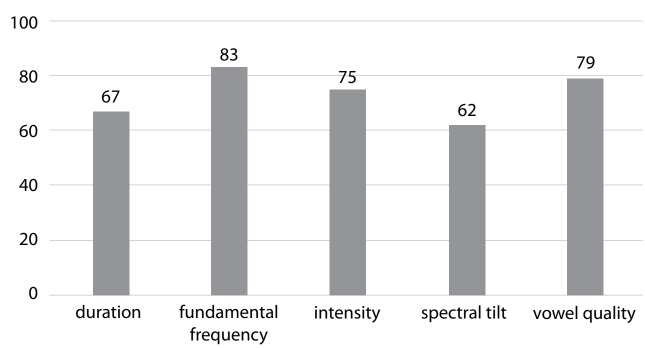

Figure 4. The classification strength (in percentages) of the significant parameters in the syllables based on CDA.

The overall classification strength of all the parameters taken together is 88%.

4. Discussion

The goal of the study was to identify the acoustic correlates of Estonian primary word stress independently of phrasal stress and intonational pitch accents, on the one hand, and the Estonian three-way quantity distinction, on the other hand.

Our first research question was whether Estonian word stress correlates with duration, which is cross-linguistically the primary correlate of word stress, and if yes, whether duration is a primary or secondary correlate of word stress. The results show that duration is indeed a significant correlate of word stress in Estonian, but not the primary correlate. Its classification strength was below 70%, which was lower than the classification strength of F0, vowel quality, and intensity. Also, compared to the results reported for other languages, stress-related lengthening is considerably smaller in Estonian. For example, English and Dutch stressed syllable vowels have been found to lengthen approximately 40–50% (van Heuven & Turk 2020: 153), while the lengthening found for Estonian in the present study was only 10–15%, depending on the syllable structure. Lengthening as a correlate of phrasal stress has likewise been found to be considerably smaller in Estonian, on average 10–15% depending on the quantity degree of the word (Mihkla & Sahkai 2017). These results are in accordance with the functional load hypothesis as formulated by Vogel et al. (2016). The hypothesis predicts that duration would not be the primary acoustic correlate of word stress in Estonian because it is contrastive at segmental level and, additionally, functions as the primary dynamic correlate of phrasal stress as well as the primary correlate of emphatic phrasal stress. The fact that both word and phrase stress are cued by a relatively small lengthening in Estonian can thus be explained by the fact that the stress-related lengthening must leave intact the segmental length distinctions and the foot-level distinctive duration ratios signalling the quantity degrees. At the same time, this does not exclude the possibility that lengthening is nevertheless an important perceptual stress cue, as the acoustic and perceptual ranking of cues need not overlap (van Heuven & Turk 2020: 160). It is possible that Estonian-speakers have developed a special perceptual sensitivity to duration because of its distinctive role, as has been suggested by Lehiste & Fox (1992). This could mean that smaller changes in duration are needed to achieve a perceptual effect.

Our second question concerned the segmental distribution of the stress-related lengthening. In previous studies, lengthening of the onset consonant of the primary-stressed syllable has been found to correlate both with word stress (Gordon 1997; Asu & Lippus 2018) and with emphatic phrasal stress (Sahkai et al. 2015) in Estonian. However, word stress had been studied without controlling for phrasal stress. We therefore aimed to clarify whether the lengthening of the onset emerges as a correlate of word stress also when controlling for phrasal stress. The present study only found significant lengthening in the stressed syllable vowel, but not in the onset or coda, suggesting that the lengthening of the onset is a correlate of phrasal rather than word stress. This result is in accordance with the suggestion of Turk (2012) that duration can serve many functions in a language because it applies somewhat differently in each function. In particular, our results suggest that lengthening as a correlate of phrasal vs. word stress partly applies in different domains.

The third goal of the study was to verify whether overall intensity correlates with word stress in Estonian, as was found by a previous study that compared lexically stressed and unstressed syllables syntagmatically within a foot (Sahkai & Mihkla 2019b), while the present study applied a paradigmatic comparison. The results confirm that overall intensity does indeed correlate with word stress in Estonian as it was found to be a significant correlate of stress, with a classification strength of 75%. The stress-related increase in intensity was however relatively small, less than 2 dB. This is in accordance with cross-linguistic findings according to which stress-related intensity differences are usually small (van Heuven 2014). According to Lehiste (1970: 121) the minimal perceivable intensity difference is 1 dB.

Our fourth goal was to confirm whether spectral tilt and emphasis are correlates of word stress, as spectral parameters have previously been found to correlate with word stress (without controlling for phrasal stress) (Asu & Lippus 2018), but not with phrasal stress (Mihkla & Sahkai 2017; Sahkai & Mihkla 2019a). In the present study, only spectral tilt turned out to be a significant correlate with a relatively low classification strength (62%).

The fifth aim was to verify the previous findings that vowel quality is not a general correlate of word stress in Estonian (Asu et al. 2016:40–42, 128). In the present study, vowel quality did turn out to be a significant parameter, with a classification strength of 79%.

The sixth goal was to examine the controversial question of F0 as a correlate of word stress. One the one hand, F0 has been found to correlate with word stress both in studies that did not control for phrasal stress (e.g. Lippus et al. 2014; Asu & Lippus 2018 for Estonian) as well as in those that did (Vogel et al. 2016). On the other hand, F0 has been considered to be an exclusive correlate of phrasal stress/pitch accents (e.g. van Heuven & Turk 2020: 152). According to the results of the present study, all the F0 parameters (minimum, maximum and mean F0 in the vowel of the target syllable and the position of the F0 maximum in the target syllable) were significant. Moreover, F0 maximum was the best performing feature with a classification accuracy of 83%. This result is in accordance with the results of Vogel et al. (2016). They identified F0 as the main phrase stress-independent cue of word stress in all four languages they examined: Spanish, Greek, Hungarian and Turkish. Still, the F0 differences between the conditions in the present study were very small, less than 1 st. This is in accordance with previous cross-linguisting findings, according to which F0 change (in semitones) under word stress is two to three times smaller than under phrasal stress (van Heuven 2018): in Estonian, the average increase of the F0 maximum in phrase-stressed words was found to be 2.8 st (Mihkla & Sahkai 2017).

Finally, we aimed to test the more general prediction that Estonian word stress, being fixed, does not have strong acoustic correlates, as suggested by earlier findings both on Estonian (Lippus et al. 2014) and other languages with fixed word stress (e.g. Dogil & Williams 1999 for Polish; Vogel et al. 2016 for Turkish and Hungarian). The classification strength of the significant parameters was between 62% and 83% and their combined strength was 88%. These results suggest that Estonian word stress does have strong acoustic cues. For example, the classification strength of the acoustic cues of word stress in American English was found to be between 60% and 80% (van Heuven 2018). On the other hand, as mentioned above, the differences between the conditions of the present study were relatively small: the lengthening ranged from 10% to 15%, the F0 difference was less than one semitone, the intensity difference was less than 2 dB, the difference in spectral tilt was 1.01 dB, and the formant value difference was 0.3 Bark.

5. Conclusion

This study examined the acoustic correlates of word-initial primary-stressed and unstressed syllables in Estonian independently of phrasal stress and quantity. Although Estonian has fixed word stress on the first syllable of the word, the acoustic correlates of word stress have a relatively high classification strength. The primary correlate is F0, followed by vowel quality, overall intensity, duration and spectral tilt. The results support the functional load hypothesis: duration, being distinctive at the segmental level, is not the primary acoustic correlate of word stress in Estonian. The results do not support the assumption that F0 exclusively correlates with phrasal stress and pitch accents as F0 turned out to be the primary stress cue.

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Kokkuvõte. Heete Sahkai, Meelis Mihkla: Eesti keele primaarse sõnarõhu akustilised korrelaadid. Artiklis tutvustatakse uurimust, mille eesmärk oli tuvastada eesti keele primaarse sõnarõhu akustilised korrelaadid sõltumatult vältest ja lauserõhust. Uurimuse tulemused täiendavad arutelu mitme lahtise küsimuse üle sõnarõhu akustiliste korrelaatide valdkonnas: kas ka fikseeritud sõnarõhul on akustilised korrelaadid? kas kestus saab olla sõnarõhu primaarne korrelaat keeles, kus on kontrastiivne häälikupikkus? kas põhitoon korreleerub ainult lauserõhu või ka sõnarõhuga? Uurimuses leitakse, et kuigi eesti keeles on fikseeritud esisilbirõhk, korreleerub see oluliselt akustiliste tunnustega. Sõnarõhu tugevaim korrelaat on põhitoon, millele järgnevad vokaalikvaliteet, üldintensiivsus, kestus ja spektri kalle. Tulemused toetavad funktsionaalse koormuse hüpoteesi, mille kohaselt kestus ei ole peamine sõnarõhu korrelaat kontrastiivse häälikupikkusega keeltes. Tulemused ei toeta aga eeldust, et põhitoon korreleerub ainult lauserõhu ja tooniaktsentidega.

Võtmesõnad: eesti keel, kõneakustika, fikseeritud sõnarõhk, funktsionaalse koormuse hüpotees, välde, lauserõhk

Appendix

The materials used in the study

Id	Context sentence	Target sentence
E1	Neeme oli manuse saatnud.	Aare oli **ma**nuse saatnud.
F1	Toomas oli maneeži avanud.	Aare oli **ma**neeži avanud.
E2	Liivo oli magneti kaotanud.	Aavo oli **mag**neti kaotanud.
F2	Jaana oli magnaadi valinud.	Aavo oli **mag**naadi valinud.
E3	Viivi oli melonid toonud.	Aino oli **me**lonid toonud.
F3	Reena oli melissid toonud.	Aino oli **me**lissid toonud.
E4	Teet oli metsise leidnud.	Peedu oli **met**sise leidnud.
F4	Uuno oli metseeni leidnud.	Peedu oli **met**seeni leidnud.
E5	Kaari oli volitust tahtnud.	Maara oli **vo**litust tahtnud.
F5	Siiri oli volangid teinud.	Maara oli **vo**langid teinud.
E6	Malle oli normingut muutnud.	Aadu oli **nor**mingut muutnud.
F6	Mati oli normaalsust maininud.	Aadu oli **nor**maalsust maininud.
E7	Teele oli mingit mulinat kuulnud.	Joonas oli **mu**linat kuulnud.
F7	Eevi oli mulati kutsunud.	Joonas oli **mu**lati kutsunud.
E8	Taavi oli muskuse andnud.	Eeva oli **mus**kuse andnud.
F8	Viiu oli muskaadi andnud.	Eeva oli **mus**kaadi andnud.
E9	Rein oli huvitava limuse leidnud.	Eero oli **li**muse leidnud.
F9	Triinu oli limiidi pannud.	Eero oli **li**miidi pannud.
E10	Tauno oli miljoni võitnud.	Eino oli **mil**joni võitnud.
F10	Tiiu oli miljööle mõelnud.	Eino oli **mil**jööle mõelnud.