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Positional Effect in the Articulation and Acoustics of Stressed Vowels in Italian

Bowei Shao[1,2], *Philipp Buech*[2], *Anne Hermes*[2], *Maria Giavazzi*[1]

[1]Département d'études cognitives, École Normale Supérieure, Université PSL, Paris, France
[2]Laboratoire de Phonétique et Phonologie, UMR 7018, CNRS & Sorbonne Nouvelle, Paris, France

bowei.shao@ens.psl.eu, philipp.buech@sorbonne-nouvelle.fr,
anne.hermes@sorbonne-nouvelle.fr, maria.giavazzi@ens.psl.eu

Abstract

Lexical stress may be signalled through a large number of acoustic parameters. In Italian, stress is realized through (1) longer duration, (2) more peripheral vowels (F1/F2) , and (3) higher intensity. Moreover, duration has been shown to be sensitive to the position where stress occurs in the word: penultimate stressed syllables are longer than antepenultimate stressed syllables. Little is known however on other acoustic correlates and on articulatory correlates of this positional effect. Using EMA (AG501), we aim to investigate and to describe the interplay between the acoustic and articulatory parameters of this positional effect. The results show that (i) antepenultimate stressed vowels are shorter than penultimate ones, (ii) antepenultimate and penultimate stressed vowels show a comparable hyperarticulated pattern in tongue dorsum position and formant structure, (iii) while antepenultimate stress' intensity increases in accordance with lip aperture, penultimate stress' intensity peak occurs at the beginning of the vowel and is followed by a slope. This is not in accordance with the pattern of lip aperture. The findings are discussed within the hyperarticulation and the sonority expansion theories of prominence, and also within the framework of Articulatory Phonology.

Index Terms: Italian, stress, articulation, acoustics, EMA, prosody

1. Introduction

Lexically prominent positions are known in the phonological literature to be privileged, syllable nuclei bearing lexical prominence are generally realized with an ensemble of reinforced acoustic parameters: they are longer in duration, higher in $f0$, more peripheral and more intense than their unstressed counterparts [1]. Stressed vowels in Italian follow these typological generalizations, they are shown to be longer in duration, and have higher peak intensity compared to their unstressed counterparts [2, 3, 4, 5]. Their formant structure is also more peripheral when stressed [6]. Moreover, Italian has a language-specific stress correlate: duration is sensitive to the position in which main stress occurs: the penultimate stressed syllable is longer than the antepenultimate stressed one [7, 8]. This language-specific pattern has been argued to reflect an underlying phonological difference, in the sense that the stressed penultimate syllables are heavy [7]. Little is known however on other acoustic and articulatory correlates of this positional effect [9]. The aim of the present study is to shed light on acoustics as well as articulatory correlates of this positional effect in Italian.

The articulatory and acoustic correlates of lexical prominence are typically accounted for by (a) sonority expansion [10, 11] and (b) localized hyperarticulation [12]. These two accounts of prominence marking consider the phonetic nature of stress as an expansion of certain key articulatory features in space and time [13]. In terms of stressed vowels, the sonority expansion theory considers that jaw opening is larger in the accented syllable because the opening gesture of the accented vowel is fully realised without any truncation. An important consequence of this different jaw dynamics is that the total acoustic intensity should be substantially higher in the accented syllable. The hyperarticulation theory proposes that stress entails a range of production changes which enhance the perceptual clarity of the output.

In more current developments within Articulatory Phonology [14, 15], an abstract, expansionary, spatio-temporal modulation gesture tied to the stress domain has been suggested to model lexical stress [16, 17]. Specifically, the temporal discrepancies between stressed and unstressed syllables are seen as the outcome of a temporal μ-gesture that is active during a stressed syllable. The spatial μ-gesture, however, has not yet been clearly defined [13].

1.1. Aims of the study

This paper aims to fulfill the following three objectives through a re-analysis of an EMA data set on Italian we previously recorded [18, 6]: 1) Replication of the durational differences found in previous studies. 2) Relating stress-induced formant patterns to the tongue dorsum position over the time course of the stressed vowel. 3) Relating stress-induced intensity profiles to lip aperture during the stressed vowel. The findings will be discussed within the hyperarticulation and the sonority expansion theories of prominence, and further within the μ-gesture proposal [16] in Articulatory Phonology [14].

2. Method

2.1. Speakers, stimuli, and recording procedures

We recorded synchronized articulatory and acoustic data from 15 speakers from the northern regions of Italy based on their place of birth and primary school attendance. Amongst the speakers, 7 were female and 8 were male based on self-identification, the mean age was 24.7 (±4.3) years. Of the 15 speakers, 5 were excluded from the present study because their mid-front vowel quality categorically varied as a function of stress: when the mid-front vowel was stressed it was produced as [ɛ], whereas it was produced as [e] when unstressed. We thus included in the present study the remaining 10 speakers, who had consistent [e] in both stressed and unstressed contexts, i.e., those speaking the varieties of Northern Italian which neutralize the phonemic contrast between /e/ and /ɛ/ to [e] across the board [19].

The structure of the target nonce words was [$C_1V_1.C_2V_2.C_3V_3$], differing solely by the position of stress on the first or the second syllable. The V_1 and V_3

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positions were occupied by /i/. C_1 and C_2 were occupied by /p, t/ and V_2 was /a, e/. C_3 was /k, g, tʃ, dʒ/. (e.g., /ˈpi.ta.ki/, /pi.ˈta.ki/). The target words were transcribed using standard Italian orthography. The stressed syllables were denoted by placing an accent mark on the vowel, following the common convention for marking stress in unfamiliar nouns in Italian.

During the recording session, the target words were presented on a computer screen to the speakers within a carrier phrase. The screen displayed a map of Italy with a nonce target word (representing a village name), and below it was the carrier phrase "Pimpa parte da __ la mattina presto" (Engl.: "Pimpa leaves from __ early in the morning."). Phrasal level prominence was thus controlled for by using the same prosodic structure across all target words. The entire list of target words was repeated four times, which resulted in a total of 3840 utterances (64 targets × 4 repetitions × 15 speakers), among which 3635 (96.5%) utterances were usable. After exclusion of the 5 speakers mentioned above, the final token count was 2414.

2.2. Data acquisition, extraction, and statistical analysis

Articulatory and acoustic data were collected simultaneously using the Electromagnetic Articulograph (EMA) AG 501 (Carstens Medizinelektronik GmbH) and a head-mounted microphone. EMA sensors were placed on upper and lower lips, tongue tip, tongue mid, and tongue dorsum, with additional sensors behind the left and right ear for head correction. The articulatory signal was recorded with a sample rate of 1250 Hz and filtered using a Butterworth lowpass filter with a cut-off frequency of 25 Hz and order 5. The acoustic signal was recorded at a sample rate of 48 kHz and 32-bit float.

The utterances of the acoustic signals from the EMA recording were pre-segmented using Audacity v3.1.3 [20]. They were then extracted and automatically annotated using the Montreal Forced Aligner v2.0.6 [21] and manually inspected in Praat v6.3.10 [22]. The EMA data were analyzed using ema2wav [23] based on the annotations from acoustic signals.

To measure the acoustic profile of stressed and unstressed vowels, we chose to analyse the following parameters: vowel duration, their dynamic intensity profile over time and their formant structure. The duration of each vowel was extracted and modeled in Bayesian hierarchical linear regression models. In the model, we entered `STRESS` condition as common level effect. As group level effect, we had by-`SPEAKER` random slopes and intercepts for the effect of `STRESS`. We reported the posterior means of the common level effects along with the lower and upper limits of 95% credible intervals.

For the intensity measurement, acoustic signals were scaled using scale function in Praat [22] to a mean intensity of 55 dB, in order to control for inter-recording difference. Intensity was then measured by taking ten equal-distanced time-points across the entire duration of the vowels (including onset and offset), to account for its dynamic profile over time. The time-series data of intensity was then modeled using Generalized Additive Mixed Models (GAMMs) constructed using the mgcv package (1.8-40) in R (4.2.2) [24, 25], and visualized using Tidyverse (1.3.2) and Tidymv (3.3.2) [26, 27]. The GAMMs were performed on each vowel with `STRESS` condition as fixed effect and smoothing parameters, with by-`STRESS` factor smooths for `SPEAKER` as random effect. We chose to use the `bam` function due to the considerable volume of the data set.

The formant structure of F1 and F2 was measured as the mean value of each formant using the mid-50% time window, scaled into Bark [28] and modeled in Bayesian hierarchical linear regression models (brms, 2.20.4) [29] for each vowel and each formant, in order to compare stressed to unstressed conditions. The Bayesian models were constructed using the same structure as for duration.

To measure the absolute tongue dorsum position in both the high-low (vertical) and the front-back (horizontal) dimension during the vowels, we applied the window method [30, 31], in which a part of the acoustic segment is used as a time window to measure the corresponding averaged absolute tongue dorsum position. Since the targets were all vowels, the mean position values of the tongue dorsum movement was calculated over the mid-50% to capture the representative tongue dorsum position. The extracted mean position data were then normalized by speakers utilizing z-standardization. Note that in the front-back dimension, lower values indicate more fronted tongue positions; in the high-low dimension, lower values indicate lowered tongue positions. A Bayesian hierarchical linear regression model (brms, 2.20.4) [29] was run for each vowel and each dimension, in order to compare stressed to unstressed condition using the same model structure as for the formants.

To measure the kinematics of lip aperture over time, we chose to perform a dynamic analysis on the Euclidean distance between higher lip and lower lip. The Euclidean distance from the acoustic onset to offset of each vowel was extracted and modeled using GAMMs, as for intensity. Given the left-skewed distribution of the position data, the use of the scaled-*t* family was warranted.

3. Results

3.1. Vowel duration

The duration of the stressed vowels is affected by their position. Antepenultimate stressed vowels have a mean duration of 106.37 ms (±27.24), which is shorter than that of the penultimate stressed vowels (mean duration 147.85±39.53 ms). This difference is confirmed by the hierarchical linear regression model, which estimated it as 40.45 ms [20.38, 60.68] across all vowel types.

Interestingly, a reversed positional effect is observed when we compare corresponding unstressed positions. An unstressed penultimate vowel is shorter than an unstressed antepenultimate vowel by -10.82 ms [-17.03, -4.62].

That is to say, when the antepenultimate position is stressed, the mean duration of the vowel increases from 81.07 ms to 106.37 ms, which is an increase of 31%. When the penultimate position is stressed, the mean duration of the vowel increases from 66.09 ms to 147.85 ms, which is an increase of 124%. Our data show that the main stress in Italian has a clear positional effect with respect to duration.

3.2. Formant structure and tongue dorsum position

The analyses of the acoustic vowel space and the tongue dorsum position reveal a position- and vowel-dependent pattern (reported in Table 1). The formant structure of penultimate vowels indicates that [a] is lowered and acoustically more posterior when it is stressed. The formant structure of [e] is not influenced by stress in F1 and slightly fronted in F2. As for the vowel [i] in antepenultimate position, there are no observable stress-related changes in tongue dorsum position in F1, whereas F2 is slightly higher when the vowel is stressed. In the penultimate position, the tongue dorsum in [a] is lowered and fronted when the vowel is stressed. As for [e], the tongue dorsum's position shows slight raise along the high-low dimension and a retraction along the front-back dimension.

In sum, acoustically, the stressed [i] is slightly fronted, the stressed [e] is fronted, whereas the stressed [a] is lowered and more back. Articulatorily, the stressed [e] is slightly raised and retracted, whereas the stressed [a] is lowered and fronted. These stressed vowels conform to the typical stress patterns observed in languages worldwide, meaning that they are acoustically more peripheral and articulatorily hyperarticulated.

Table 1: *Common level effects of Bayesian hierarchical linear regression models conducted on tongue dorsum position and formant structure of unstressed vs. stressed vowels. V_1 and V_2 indicate the position of the vowel in the stimuli structured as $C_1V_1.C_2V_2.C_3V_3$. Tongue dorsum (TD) is reported in both high-low (y) and front-back (x) dimensions. Formant structure is reported in Bark scale. $\hat{\beta}$ values are reported with their lower and upper boundaries of 95% Credible Intervals*

			$\hat{\beta}$	**lower**	**upper**
V_1 [i]	TD	y	0.03	0.006	0.07
		x	0.04	-0.03	0.10
	Formant	F1	-0.03	-0.17	0.12
		F2	0.20	0.08	0.32
V_2 [a]	TD	y	-1.06	-1.22	-0.90
		x	-0.64	-0.84	-0.43
	Formant	F1	1.55	1.35	1.75
		F2	-1.37	-1.71	-1.03
V_2 [e]	TD	y	0.14	0.02	0.26
		x	0.32	0.14	0.50
	Formant	F1	0.04	-0.20	0.28
		F2	0.34	0.16	0.52

3.3. Intensity and lip aperture

Our data reveal an interesting pattern: The intensity profiles of the two stress positions show a positional effect, but lip aperture does not.

3.3.1. Intensity profile

With respect to the vowel's intensity profile, we found a consistent pattern presented in Figure 1: only the antepenultimate positioned [i] has higher overall intensity when it is stressed, [e, a] in the penultimate position do not have higher intensity profile when they are stressed.

However, the two stress positions behave differently in their respective intensity profiles. When stress is on the antepenultimate position, the intensity peak is located in the middle of the vowel, as can be seen from the V_1 [i] in Figure 1 (red dashed line). However, when stress is on the penultimate position, the peak is located near the acoustic onset of the vowel, as can be seen from the V_2 [e, a] in Figure 1 (blue solid lines). The dynamic intensity profile thus shows an important divergence not observed in previous studies.

This behaviour, however, cannot be directly linked to the lip aperture profile.

3.3.2. Lip aperture profile

The lip aperture profiles of the vowels are presented in Figure 2: across the two stress positions, stressed, [i, e, a] all have larger lip aperture compared to their unstressed counterparts. There is a consistent difference between stressed and unstressed vowels, even for the high close vowel [i] in antepenultimate position.

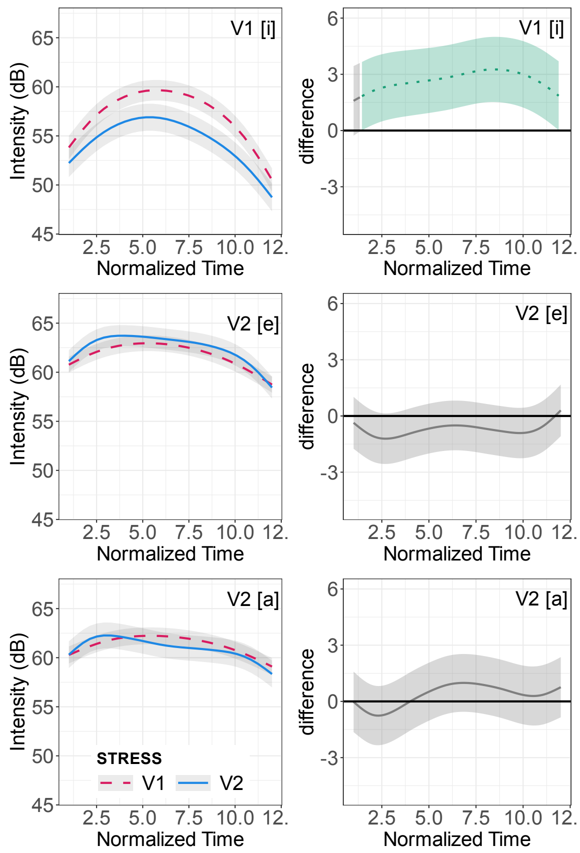

Figure 1: *GAMM fitted intensity (dB) trajectories in V_1 and V_2, by normalized time (left), with estimated differences (right). The blue solid lines represent when the stress is on the penultimate position (here [e, a]), the red dashed lines represent when the stress is on the antepenultimate position (here [i]). Estimated differences are presented with 95% confidence intervals by time (normalized). The green dotted lines represent the significant difference between stressed vs. unstressed vowels in the same position.*

In the case of antepenultimate stress, lip aperture is clearly related to the vowel's intensity profile. We can see this relation by comparing the vowel [i] in Figure 2 to the same vowel in Figure 1, in which the opening-closing pattern of lip aperture in both stressed and unstressed conditions seems to behave in accordance with intensity, in the sense that larger lip aperture is related to higher intensity.

In the case of penultimate stress, lip aperture is inconsistent with the intensity profile [31], as can be seen by comparing Figure 2 [e, a] to the same vowels in Figure 1: the intensity profile does not follow the lip aperture one, in the sense that the peak of lip aperture does not coincide the peak of intensity. The peak of intensity, as reported earlier, occurs early in the vowel near its acoustic onset; the peak of lip aperture occurs near the acoustic middle of the vowels.

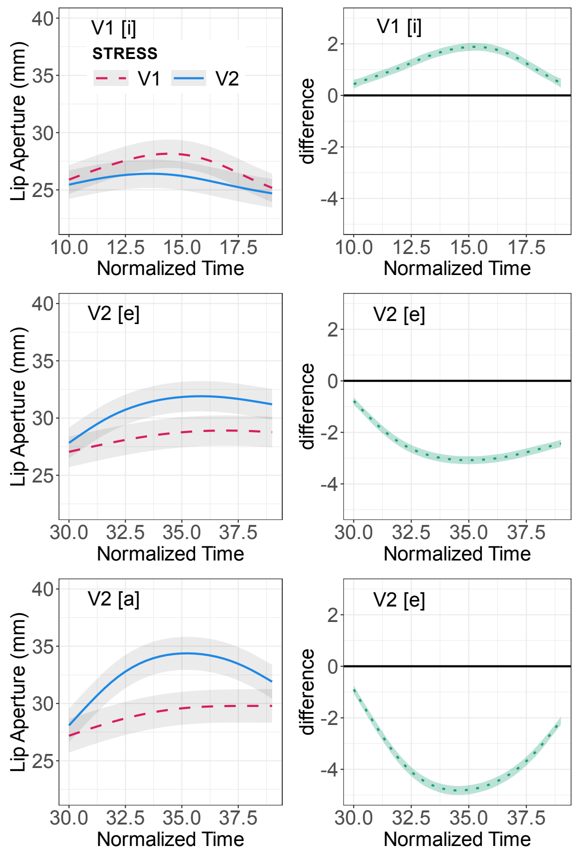

Figure 2: *GAMM fitted lip aperture (LA) trajectories (mm) in V_1 and V_2, by normalized time (left), with estimated differences (right). The blue solid lines represent when the stress is on the penultimate position (here [e, a]), the red dashed lines represent when the stress is on the antepenultimate position (here [i]). Estimated differences are presented with 95% confidence intervals by time (normalized). The green dotted lines represent the significant difference between stressed vs. unstressed vowels in the same position.*

4. Discussion

This study shows that the phonetic correlates of main lexical stress in Italian have a clear positional effect, which is observed in the duration and in the intensity profile of the stress-bearing vowel. Further, penultimate stress entails longer vowel duration than antepenultimate stress, and it has an earlier intensity peak near the acoustic onset of the stress-bearing vowel. This earlier intensity peak cannot be simply accounted for by larger lip aperture.

Our data confirmed an earlier study [7] which showed that main stress has a positional effect in duration: the antepenultimate vowel had a mean duration of 149 ms, and that of penultimate vowel was 177 ms.

Our data seem to further suggest that the production of stressed vowels involves both hyperarticulation [12] and sonority expansion [11]. Our data, especially the vowel [i] in the antepenultimate position, illustrates a case of sonority expansion [11] under stress. The acoustic intensity measured at the lips is related to the general openness of the vocal tract, and we observe that the total acoustic intensity is significantly higher in the stressed [i].

As for [e, a] in the penultimate position, they are acoustically more peripheral and articulatorily hyperarticulated, confirming the observation made for English accented vowels [12]. Their production also involves larger lip aperture, which however does not straightforwardly translate into higher intensity. Moreover, the stressed and unstressed vowels in penultimate position do not show a general intensity difference. The earlier peak of intensity observed in the stressed vowels at this position indicates that the sound pressure at this stress-position may be regulated by the source pressure at the glottis, rather then by the general openness of the vocal tract.

We may infer from our data that both sonority expansion and hyperarticulation are mechanisms of the production of main stress in Italian, but not systematically for both stress positions and for all articulators (i.e., lips and tongue dorsum). Antepenultimate stress seems to be mainly sonority-based, in the sense that the stressed vowel is mainly distinguished by its systematically higher intensity, relatable to larger lip aperture. Penultimate stress, on the other hand, seems to be mainly hyperarticulation-based, in the sense that the stressed vowel is hyperarticulated with a very specific intensity setting which is not exactly reflected in lip aperture.

In Articulatory Phonology, lexical stress is modulated by an abstract, spatio-temporal expansionary gesture: the μ-gesture [16]. Recent studies have shown that spatial and temporal effects may be independent from each other [32, 33]. Our data further show that the two modulations are not only independently specified in phonology (in the sense that they do not share the same temporal and spatial target), they are also differently specified in the two stress positions in Italian. The μ-gesture proposal should take this positional effect into account.

This study is based on a re-analysis of a previous data set, which comes with clear limitations. The most important limitation was the unbalanced vowels between penultimate and antepenultimate positions. This unbalanced design does not enable us to do a direct comparative study between the two stress positions. An on-going study is designed to overcome this limitation.

5. Conclusions

This study confirms that antepenultimate and penultimate stress positions in Italian behave differently in terms of 1) duration, 2) hyperarticulation, and 3) intensity. The stress vowels [e, a] in penultimate position are longer and hyperarticulated, but do not show higher intensity overall. The stressed vowel [i] in antepenultimate position is longer (though not as long as the penultimate ones), and overall more intense. These results suggest that the phonetic implementation of the main lexical stress in Italian involves both sonority expansion and hyperarticulation, but not to the same extend for antepenultimate and penultimate stress positions.

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