It is a robust cross-linguistic observation that acoustic distances between vowels are greater in stressed syllables, compared to unstressed ones. This phenomenon has been modelled in the framework of vowel undershoot [4], localised hyperarticulation [3], sonority expansion [1, 2], and stress-conditioned coarticulatory resistance [6, 7]. Although these models invoke articulatory mechanisms, they have subsequently largely been tested based on their acoustic predictions, e.g. [8, 9]. In this paper, we present combined articulatory and acoustic data on vowel reduction in Polish that inform models of reduction in ways that acoustic data alone cannot.

The data are time-synchronised audio and midsagittal ultrasound recordings from 8 native speakers of Polish (7 females, mean age = 32). We elicited vowel reduction in two ways: by manipulating stress (e.g. mi\_mo, /mi.mol/ ‘despite’ vs. mi\_moza, /mi.mo.za/ ‘mimosa’), and by manipulating speech rate through instruction to participants (slow, normal and fast). The segmental environment was controlled for. All six oral vowel phonemes were included (/i/, /e/, /a/, /o/, /u/, /y/), appearing in stressed, and pre-stressed positions. 144 tokens were collected from each participant. Formants were extracted automatically in Praat at acoustic midpoint and normalised using z-score. Midsagittal tongue contours were extracted at the same time point in Cartesian coordinates. They were then submitted to a Principal Component Analysis, applied by-speaker [10], and reduced to two PCs, which typically accounted for more than 90% of the variance. In order to standardise the rotation of the PCs, the PCs were entered as predictors in linear models of normalised f1 and f2 (for each speaker; see [5] for a similar approach). We used the model predictors, labeled comp1 and comp2, as abstract normalised articulatory exponents of f1 and f2. We modelled the measurements, along with V1 duration using lme4.

Figures 1-3 are based on model estimates. Both speech rate and stress exert a systematic effect on vowel duration, although the two also interact (Fig 1). Accordingly, the acoustic vowel space is systematically contracted from slow, through normal, to fast speech rate, and from stressed syllables to unstressed ones (Fig 2). The difference is mostly apparent in non-high vowels, it primarily affects f1, and the magnitude of difference is similar for rate and stress manipulations. In contrast, only speech rate systematically affects the articulatory components 1 and 2. The interaction between stress and vowel, shown in the right panel of Fig 3, is not significant, and neither is the main effect of stress.

We interpret the articulatory components as related to tongue displacement in the ultrasound image. For speech rate manipulations, displacement differences are consistent with vowel undershoot, which is also reflected in the acoustic output. For stress manipulations, however, there is a systematic acoustic difference between stressed and unstressed vowel that cannot be attributed to the same articulatory mechanism. The stress effects we find could potentially be explained if the speakers raised their larynx to mark stressed syllables, which results in raising of both f0 and f1. This hypothesis is generally confirmed by the f0 patterns we find in the data, although there is some individual variation. We also note that the absence of lingual undershoot in unstressed vowels coexists with regular temporal reduction. This would suggest that stress-conditioned temporal reduction is phonologised in Polish, along with compensatory mechanisms that mitigate against spatial reduction.
Figure 1. Vowel duration

Figure 2. Normalised acoustic vowel spaces

Figure 3. Normalised articulatory vowel spaces

**References**


