Table 1: Sociolinguistic information on participants. The right-most column indicates whether the participant spent more than 6 consecutive months abroad.

id	sex	age	city	> 6 mo
IT01	m	28	Verbania	yes
IT02	m	26	Udine	yes
IT03	f	27	Verbania	no
IT04	f	54	Verbania	no
PL02	f	32	Poznań	yes
PL03	m	26	Poznań	yes
PL04	f	34	Warsaw	no
PL05	m	34	Przasnysz	no

The link between tongue root advancement and the voicing effect: an ultrasound study of Italian and Polish

Stefano Coretta[a,*]

[a] *University of Manchester, Linguistics and English Language*

1. Introduction

2. Methodology

2.1. Participants

Eight native speakers of Italian (2 females, 2 males) and Polish (2 females, 2 males) were recorded in Manchester and in Italy (Table 1). The Italian speakers were from Northern Italy (three from the North-west and one from Northeast). The Polish group was more heterogeneous, with two speakers from the North-west (Poznań), and two from the North-east (Warsaw and Przasnysz). Ethical clearance was obtained for this work from the University of Manchester (REF 2016-0099-76). The participants received a small monetary compensation.

2.2. Equipment set-up

An Articulate Instruments Ltd™ set-up was used for this study (Figure 1). The ultrasonic data was collected through a TELEMED Echo Blaster 128 unit with a TELEMED C3.5/20/128Z-3 ultrasonic transducer (20mm radius, 2-4 MHz). A synchronisation unit (P-Stretch) was plugged into the Echo Blaster unit and used for automatic audio/ultrasound synchronisation. A FocusRight pre-amplifier and a Movo LV4-O2 Lavalier microphone were used for audio recording. The acquisition of the ultrasonic and audio signals was achieved with the software Articulate Assistant Advanced (AAA, v2.17.2) running on a Hawlett-Packard ProBook 6750b laptop with Microsoft Windows 7. Stabilisation of the ultrasonic transducer was ensured by using a stabilisation headset produced by Articulate Instruments Ltd™ (Articulate Instruments Ltd 2008, not shown in figure).

2.3. Materials

Disyllabic words of the form $C_1V_1C_2V_2$ were used as targets, where C_1 = /p/, V_1 = /a, o, u/, C_2 = /t, d, k, g/, and V_2 = V_1 (e.g. /pata/, /pada/, /poto/, etc.), yielding a total of 12 target words. A labial stop was chosen as the first consonant to reduce influence on the following vowel (although see Vazquez-Alvarez and Hewlett 2007). Only coronal and velar stops were used as target consonants since labial consonants cannot be imaged with ultrasonography. The target words were embedded in a frame sentence. Prosodically similar sentences were used to ensure comparability between languages. The frame sentence was *Dico X lentamente* 'I say X slowly' for Italian, and *Mówię X teraz* 'I say X now' for Polish.

*Corresponding author
Email address: stefano.coretta@manchester.ac.uk (Stefano Coretta)
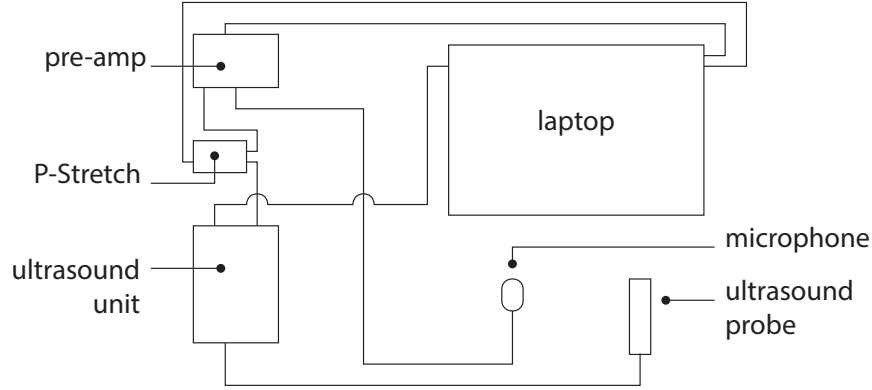
Figure 1: Schematic representation of the equipment setup (Articulate Instruments Ltd 2011, see text for details).

2.4. Procedure

The sentences with the target words were randomised for each participant, although the order was kept the same between repetitions within participant due to software constraints. Each participant repeated the list of randomised stimuli six times. A grand total of 576 tokens (288 per language) was recorded. The participant's occlusal plane was obtained using a bite plate (Scobbie et al. 2011), and the hard palate was imaged by asking the participant to swallow water (Epstein and Stone 2005). The frame rate of the acquisition of the ultrasonic data ranged between 43 and 68 frames per second. Other settings varied depending on the frame rate (scanlines = 88-114, pixel per scanline = 980-988, field of view = 71-93, pixel offset = 109-263, depth (mm) = 75-180). The audio signal was recorded at 22050 MHz (16-bit).

2.5. Data processing and analysis

Synchronisation of the ultrasonic and audio signal was achieved in post-processing, using a built-in procedure of AAA. The data were then subject to force alignment using the SPPAS force aligner (Bigi 2015). The outcome of the automatic annotation was then manually corrected, according to the criteria in Table 2. The onset of the target consonant burst (C2 burst) was detected automatically in Praat (Boersma and Weenink 2016), employing a implementation

of the algorithm described in Ananthapadmanabha et al. (2014). The durations of the following intervals were extracted from the acoustic landmarks using an automated procedure in Praat: vowel duration (V1 onset to V1 offset), consonant duration (V1 offset to V2 onset), and closure duration (V1 offset to C2 burst).

Spline curves were automatically fitted to the visible contours using the AAA batch tracking function. Manual correction was applied in those cases that showed clear tracking errors. The time of maximum tongue displacement within consonant closure was then calculated in AAA following the method in Strycharczuk and Scobbie (2015). A fan-like frame consisting of 42 equidistant radial lines was used as the coordinate system. The origin of the 42 fan-lines coincides with the centre of the ultrasonic probe, such that each fan-line is parallel to the direction of the ultrasonic signal. Tongue displacement was thus calculated as the displacement of the fitted splines along the fan-line vectors. The time of maximum tongue displacement was the time of greater displacement along the vector that showed the greatest standard deviation. The vector search area was restricted to the portion of the splines corresponding to the tongue tip for coronal consonants, and to the portion corresponding to the tongue dorsum for velar consonants.

The cartesian coordinates of the tongue contours were

Table 2: List of measurements as extracted from acoustics.

landmark		criteria
vowel onset	(V1 onset)	appearance of higher formants in the spectrogram following the burst of /p/ (C1)
vowel offset	(V1 offset)	disappearance of the higher formants in the spectrogram preceding the target consonant (C2)
consonant onset	(C2 onset)	corresponds to V1 offset
closure onset	(C2 closure onset)	corresponds to V1 offset
consonant offset	(C2 offset)	appearance of higher formants of the vowel following C2 (V2); corresponds to V2 onset
consonant burst onset	(C2 burst)	automatic detection (Ananthapadmanabha et al. 2014)

exported from two time points: the onset of C2 closure, and the time maximum tongue displacement (which is always within C2 closure). The contours were normalised by applying offsetting and rotation relative to the participant's occlusal plane (Scobbie et al. 2011). Durational measurements were analysed with linear mixed effects models using `lme4` in R (R Core Team 2017, Bates et al. 2015). Generalised additive mixed effects regression models (GAMMs, Wood 2006) were used for the statistical analysis of tongue contour data.

3. Results

3.1. Vowel duration and voicing

A linear mixed effects regression model was fitted to the Italian vowel duration data with DURATION as the outcome variable; VOWEL QUALITY (/a, o, u/), VOICING and PLACE OF ARTICULATION of the following consonant, SENTENCE DURATION as fixed effects; random intercepts by speaker and word, and by-speaker random slopes for voicing. An interaction between voicing and vowel quality was also included in the final model, since it significantly improved the model. P-values were obtained with likelihood ratio tests comparing the full model with a nested model without the tested predictor, and with `lmerTest` (Kuznetsova et al. 2016), which employs the Satterthwaite approximation to degrees of freedom. According to the full model as specified above,

Italian vowels are 22 milliseconds (SE = 6) longer if followed by a voiced stop ($\chi2(3) = 16.61$; $p < 0.001$). The following terms and interactions were also significant: place of articulation C2, vowel identity, sentence duration, and the interaction between C2 voicing and vowel identity.

For Polish, the same model structure was used, excluding the voicing-vowel interaction (which was not significant). Contrary to previous findings, the model reveals a significant 8 milliseconds effect (SE = 3) of consonantal voicing on the preceding vowel ($\chi2(1) = 5.4$, $p < 0.05$). Vowel identity and sentence duration were also significant. The place of C2 significantly improved the model ($\chi2(1) = 6.1$, $p < 0.05$), so it was included in the full model even though $p > 0.05$ according to the single predictor p-value. The inspection of the model residuals confirmed the assumptions of normality and homoscedasticity. The exploration of the random slopes for each speaker indicated that PL05 showed a particularly higher slope for voicing, meaning that the effect of voicing was stronger in his data, but removing this speaker from the model doesn't remove the effect. The estimated effect of voicing on vowel duration for PL05 was 14 milliseconds. These observations will become relevant when discussing about the results of the tongue contour data.
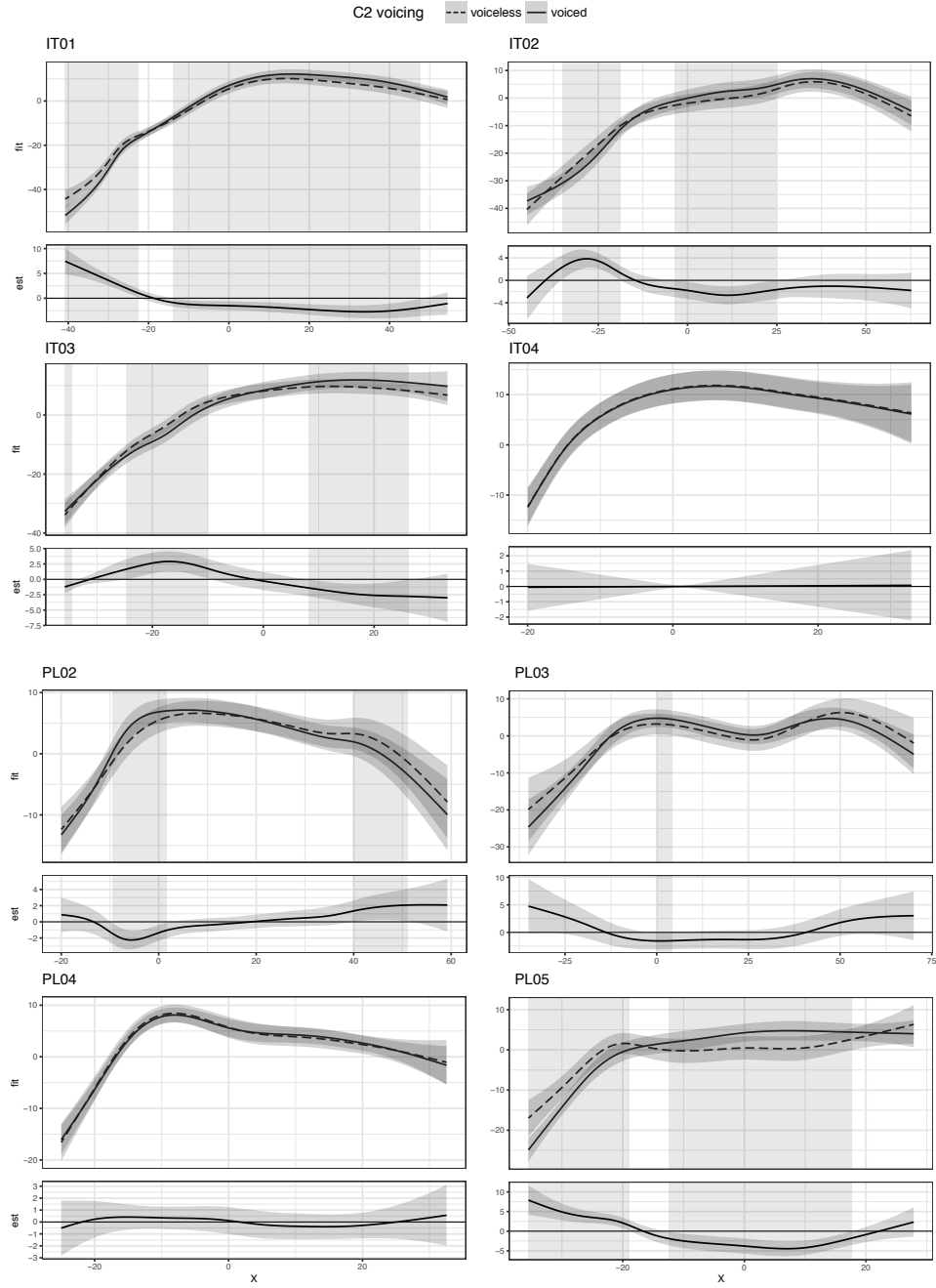
Figure 2: Comparison of tongue contours at the time of maximum tongue displacement (within C2 closure) in Italian (top half) and Polish (bottom half). The plotted contours are the estimated curves in the context of the vowel /a/ followed by coronal consonants. See Section 3.2 for more details.

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3.2. Tongue contours

The tongue contour data were analysed with GAMMs (Wood 2006). Individual GAMMs were fitted for each speaker: the Y-COORDINATES of the contours were included in the model as the outcome variable; the X-COORDINATES as the only parametric term. The following smooths were specified: a reference smooth term for the x-coordinates, three difference smooths for the x-coordinates by VOICING, VOWEL QUALITY, and PLACE of articulation of the following consonant respectively, and BY-WORD random smooths. A first-order autoregressive model was included to correct for the high autocorrelation residuals. Significance testing in GAMMs was achieved through model comparison and visual inspection of the difference smooth, as suggested in (Sóskuthy 2017). Given the poor quality of the ultrasonic data for /u/, this vowel was not included in the statistical analysis of tongue contours, hence the results reported in this section only refer to /a/ and /o/.

The analysis of the Italian ultrasonic data shows that voiced stops are produced with advancement of the root of the tongue, as expected based on previous research on English. Figure 2 (top half) shows the predicted tongue contours in voiceless (dashed line) and voiced stops (thick line) at maximum tongue displacement for each Italian speaker. Below each tongue contour panel, the difference smooth for voicing is also shown (black line, confidence interval in grey). Tongue contours are significantly different in those point in which the confidence interval of the difference smooth does not include 0 on the ordinate axis. The significantly different portions of the contours are also indicated in the figures by a shaded grey area.

In two participants out of four (IT01, IT02), the root was significantly more front in voiced stops in both vocalic contexts (/a, o/). On the other hand, one participant (IT03) had significant tongue root advancement only following /a/, while the fourth participant (IT04) didn't show advancement at all. For Polish (bottom half of Figure 2), three out of four speakers (PL02, PL03, PL04) did not have tongue root advancement, while the fourth speaker (PL05) had

significant advancement in voiced stops in both vocalic contexts.

Further contour analysis was carried out at C2 closure onset for the Italian and Polish speakers showing advancement. The tongue root at closure onset was found to be in advanced in voiced consonants (). Comparisons of tongue contours at C2 onset and at the time of maximum tongue displacement in voiced consonants further indicated that the degree of root advancement was larger at maximum displacement for the Italian speakers (IT01, IT02, IT03), but not for the Polish speaker (PL05). Figure 3 shows the results from IT01 as a representative example for Italian and from PL05.

The ultrasonic data showed that the tongue body was raised in speakers with tongue root advancement. The presence of this gesture in addition to root advancement makes sense from an anatomical point of view. Raising of the tongue body could be implemented as a way to counterbalance the compression of the tongue mass caused by the advancement of the root (Perkell 1969, Jackson 1988, Kingston et al. 1997, Fulop et al. 1998). It is not thus surprising to observe a raised tongue body in voiced stops accompanying root advancement.

4. Discussion

Based on the previously established link between tongue root advancement and voicing, it was proposed at the beginning of this paper that the presence of the voicing effect in a language should be correlated with the presence of tongue root advancement in voiced stops. To test the correlation between tongue root advancement and vowel durations, ultrasonic data were collected from two languages that differ in the presence/absence of the voicing effect, Italian and Polish respectively. It was predicted that voiced consonants should be produced with an advanced tongue root in Italian, but not in Polish. However, the results of this study point to a more fine-grained interpretation of the proposed link between tongue root and vowel duration.
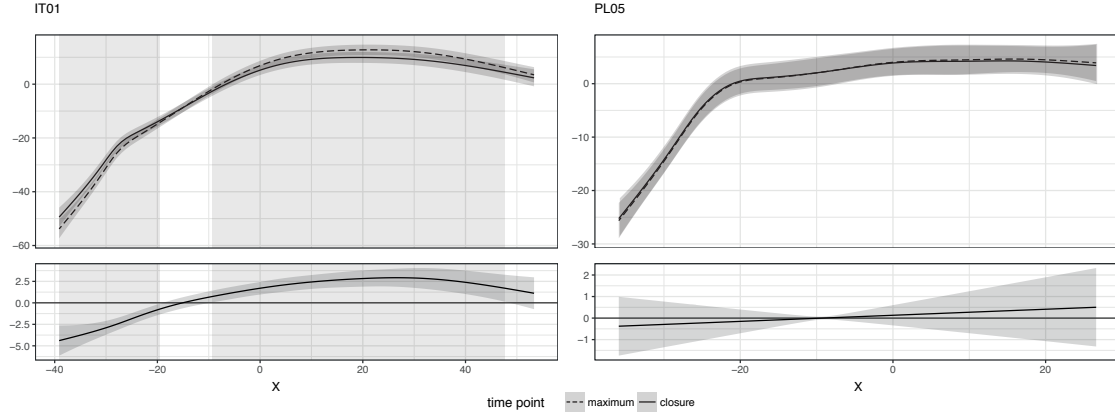
Figure 3: Comparison of tongue contours of voiced consonants at C2 closure onset and maximum tongue displacement (within C2 closure) in IT01 (Italian) and PL05 (Polish). See Section 3.2 for more details.
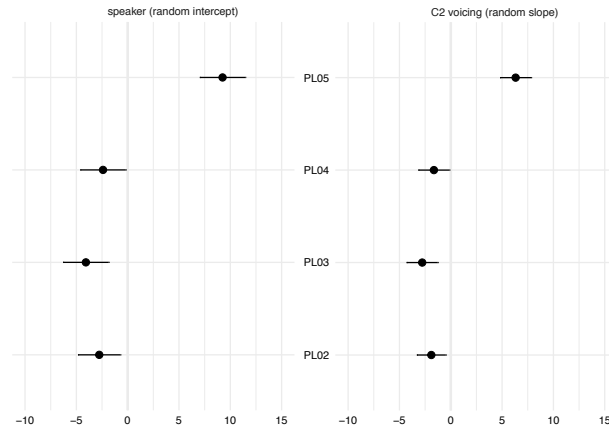

Figure 4: By-speaker random intercepts (left) and slopes (right) for the effect of C2 voicing on vowel duration in the Polish. The higher slope estimate (+6.3 ms) for PL05 indicates a relatively stronger effect of voicing on vowel duration for this participant.

The durational data of Polish indicate a small effect of voicing in this language, such that vowels followed by voiced stops are on average 8 milliseconds longer, contrary to previous findings in Keating (1984). The hypothesis that voiced consonants should not have tongue root advancement in Polish rests on the assumption that Polish is a non-voicing-effect language, which does not hold for the data of this study. The voicing effect was found to be stronger in one of the Polish speakers, PL05, who has a higher random slope estimate compared to the other Polish speakers (Figure 4). Note, however, that a model fitted to the Polish data with the exclusion of PL05 still indicates a difference of 6 milliseconds in vowel duration ($\chi2(1) = 8.28$; $p < 0.01$). Incidentally, though, PL05 is also the only Polish speaker who produced voiced consonants with an advanced tongue root, both at C2 closure onset and at the time of maximum tongue displacement.

This pattern is similar to that of the Italian speakers, who have both a relatively strong voicing effect and tongue root advancement. This is true for all the Italian speakers in this sample, except one (IT04), who had a 22 milliseconds difference in vowel duration but whose tongue root did not differ in voiced and voiceless stops. A possible interpretation of the different behaviour of IT04 as an age effect derives from the older age of this speaker (54 years old, vs

an average of 26 for the other speakers), although a more balanced sample is needed for confirmation.

Overall, the speakers who didn't produce voiced consonants with an advanced tongue root had a relatively weaker voicing effect. On the other hand, speakers with tongue root advancement showed a relatively strong effect, with estimates of the durational differences ranging between 15 and 30 milliseconds. This generalisation holds independently of the speaker's language. The fact that the degree of tongue advancement at C2 closure onset and at maximum displacement does not differ in PL05's voiced consonants could be linked to the relative weaker effect of voicing in this speaker. All things considered, it can be inferred that, other things being equal, if a speaker realises voiced consonants with concomitant advancement of the tongue root, then that same same speaker will also show a considerable durational difference in vowels, with longer vowels preceding voiced consonants.

The smaller effect of voicing in PL05 compared to the effect in Italian (14 vs 22 milliseconds) suggests that the relationship between tongue root advancement and vowel duration might be gradual rather then categorical (presence vs. absence). If this is the case, the magnitude of the voicing effect should correlate with the degree of tongue root advancement. More specifically, vowel duration is predicted to be directly correlated with the degree of advancement. Future work will set out to investigate the hypothetically gradient effect of tongue root advancement on vowel duration.

5. Conclusion

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