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## I. INTRODUCTION

Almost 100 years of research have repeatedly shown that consonantal voicing has an effect on preceding vowel duration: vowels followed by voiced obstruents are longer than when followed by voiceless ones (Belasco, 1953; Chen, 1970; Durvasula and Luo, 2012; Esposito, 2002; Farnetani and Kori, 1986; Fowler, 1992; Halle and Stevens, 1967; Heffner, 1937; House and Fairbanks, 1953; Hussein, 1994; Javkin, 1976; Klatt, 1973; Kluender *et al.*, 1988; Laeufer, 1992; Lampp and Reklis, 2004; Lisker, 1974; Maddieson and Gandour, 1976; Peterson and Lehiste, 1960; Raphael, 1975; Warren and Jacks, 2005). Evidence for such so called 'voicing effect' has been found in a variety of languages, including (but not limited to) English, German, Hindi, Russian, Italian, Arabic, and Korean (see Maddieson and Gandour, 1976, for a more comprehensive, but still not exhaustive list). Despite of the plethora of evidence in support of the *existence* of the voicing effect, still after 100 years agreement hasn't been reached regarding the source of this effect.

Several proposal have been put forward as to where to look for the possible cause of the voicing effect (see Sóskuthy, 2013, and Beguš (2017) for an overview). Most of the proposed accounts place the source of the voicing effect in properties of speech production.[1] One of these production accounts, which will be the focus of this study, relates the voicing effect to some constant property of speech that is held constant across contexts while the local property of voiceless vs. voiced obstruents varies, thus creating a trade-off solution within the constant property. Lindblom (1967), Slis and Cohen (1969b), and Lehiste (1970b) (among others) argue that the relevant invariant property of speech is a constant durational interval within which segments of different duration results in different duration of other segments. Both the syllable/VC sequence (Lindblom, 1967) and the word (Lehiste, 1970a·b; Slis and Cohen, 1969a,b) has been proposed as the fixed interval. The closure of voiced stops is shorter than that of voiceless stops. It follows that vowels followed by shorter closures (like in the case of voiced stops) are longer than vowels followed by longer closures (like in the case of voiceless stops). However, the compensatory temporal adjustment account has been criticised in several occasions.

The proposal of the syllable or the word as the targets for compensation and encounter difficulties when confronted with empirical evidence and when scrutinised by logic. First, Lindblom's (1967) argument that the syllable is the interval within which compensation happens is not supported by the findings in Chen (1970) and Jacewicz *et al.* (2009). Chen (1970) rejects a syllable-based compensatory account on the light of the fact that the duration of the syllable is affected by consonant voicing. More recently, Jacewicz *et al.* (2009) further shows that the duration of monosyllabic words in American English does not change dependent on the voicing of the coda consonant. Second, although the results in Slis and Cohen (1969b) confirm that the word does not change in duration whether the stop following the stressed vowel is voiceless or voiced, it does not follow from this fact that compensation should necessarily target the stressed vowel. Indeed, it is possible that, for example, the following unstressed vowel could be the target of the compensation.

Maddieson and Gandour (1976) reject any compensatory account for the voicing effect based on data from Hindi on the so called 'aspiration effect', by which vowels are longer when followed by aspirated stops than when followed by non-aspirated stops. Vowels before voiceless unaspirated stops are the shortest, followed by vowels before voiced unaspirated and voiceless aspirated stops, which have similar duration between each other, followed by vowels before voiced aspirated stops, which are the longest. Maddieson and Gandour (1976) find no compensatory pattern between vowel and consonant duration: the consonant /t/, which has the shortest duration, is preceded by the shortest vowel, and vowels before /d/ and /$t^h$/ have the same duration although the durations of the two consonant are different.

However, an reevaluation of the way consonant duration is measured in Maddieson and Gandour (1976) might actually turn the situation in favour of a compensatory account. Consonant duration is in fact measured from the closure of the relevant consonant to the release of the following consonant, due to difficulties in detecting the release of the consonant of interest (e.g., in *ab sāth kaho*, the duration of /$t^h$/ in *sāth* was calculated as the interval between the closure of /$t^h$/ and the release of /k/). This measure includes the burst and (eventual) aspiration of the consonant. Slis and Cohen (1969a), however, states that the inverse correlation between vowel duration and the following consonant raises when consonant *closure* duration is taken into account, and not the entire *consonant* duration. If the correlation exists between vowel and closure duration, the inclusion of burst/aspiration duration clearly alters this relationship. Indeed, the data in Durvasula and Luo (2012) show that closure duration, appropriately measured, decreases from voiceless unaspirated > voiced > voiceless aspirated > voiced aspirated, which closely resembles the order of increasing vowel duration in Maddieson and Gandour (1976).[2]

More recently, Beguš (2017) investigated the effect of three phonation types on vowel durations in Georgian and finds that vowels are short when followed by voiceless aspirated stops, longer before ejective stops, and longest when followed by voiced stops. Crucially, stop closure duration follows a symmetrical pattern: Closure duration is short in voiced stops, longer in ejectives, and longest in voiceless aspirated stops. Beguš (2017) argues that these findings support a temporal compensation account, although not univocally.

To summarise, a compensatory temporal adjustment account of the voicing effect remains possible after a careful review of the critiques advanced by Chen (1970) and Maddieson and Gandour (1976), and in face of the results in Beguš (2017), although issues about the actual implementation of the compensation still persist. In conclusion, for the compensatory account to gain plausibility, an invariant interval within which compensation is implemented needs to be better defined, on the light of empirical data.

### A. The present study

This paper reports on results from a broader exploratory study that investigates the relationship between vowel duration and consonant voicing from an articulatory perspective. Synchronised recordings of audio, ultrasound tongue imaging, and electroglottography were carried out to enable a data-driven approach to the analysis of features related to the voicing effect in the context of disyllabic (CVCV) words in Italian and Polish. The design of the study has been constrained by the use of these articulatory techniques (see Section II). Moreover, given the exploratory nature of the study, the experimental design was not implemented to directly test the compensatory account. Here, only the results from acoustic will be discussed.

Italian and Polish reportedly differ in the magnitude of the voicing effect. Italian has been unanimously reported as a voicing effect language (Caldognetto *et al.*, 1979; Esposito, 2002; Farnetani and Kori, 1986). The mean difference in vowel duration when followed by voiceless vs. voiced consonants ranges between 22 and 24 ms (with longer vowels followed by voiced consonants, Esposito, 2002; Farnetani and Kori, 1986).[3] On the other hand, the results regarding the presence and magnitude of the effect in Polished are mixed. While Keating (1984) reports no effect of voicing on vowel duration in data from 24 speakers, Nowak (2006) finds that vowels followed by voiced stops are 4.5 ms longer in the 4 speakers recorded. Moreover, Malisz and Klessa (2008) argue based on data from 40 speakers that the magnitude of the voicing effect in Polish is highly idiosyncratic, and claim their results to be inconclusive on this matter. The difference in presence or magnitude of the voicing effect in Italian vs. Polish should enable us to find an underlying property that differs in the two languages and that might indicate a possible source for the voicing effect.

The acoustic data from the exploratory study reported here reveal that the duration of the interval between the releases of the two consonants in CVCV words (the Release to Release interval) is not affected by the voicing of the second consonant. This finding is compatible with a compensatory temporal adjustment account by which the timing of the stop closure onset within said interval determines the respective durations of the vowel and the stop closure. I further propose that the invariant duration of the Release to Release interval is congruent with current views on gestural timing (Goldstein and Pouplier, 2014) and I discuss the insights it provides in relation to our understanding of gestural organisation in speech.

## II. METHOD

### A. Participants

Seventeen subjects in total participated to this exploratory study. Eleven participants were native speakers of Italian (5 female, 6 male), while six were native speakers of Polish (3 female, 3 male). The Italian speakers were from the North and Centre of Italy (8 speakers from Northern Italy, 3 from Central Italy). The Polish group had 2 speakers from Poznań and 4 speakers from Eastern Poland.

For more information on the speakers, see Appendix B. Ethical clearance was obtained for this study from the University of Manchester (REF 2016-0099-76). The participants signed a written consent and received a monetary compensation of £10.

### B. Equipment

The acquisition of the audio signal was achieved with the software Articulate Assistant Advanced™ (AAA, v2.17.2) running on a Hawlett-Packard ProBook 6750b laptop with Microsoft Windows 7, with a sample rate of 22050 MHz (16-bit) in a proprietary format. A FocusRight Scarlett Solo pre-amplifier and a Movo LV4-O2 Lavalier microphone were used for audio recording.

### C. Materials

The target stimuli were disyllabic words with $C_1V_1C_2V_2$ structure, 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.). Most are nonce words, although inevitably some combinations lead to real words both in Italian (4 words) and Polish (2 words, see Appendix C). The lexical stress of the target words was placed by speakers of both Italian and Polish on $V_1$, as intended. The make-up of the target words was constrained by the design of the experiment, which included ultrasound tongue imaging (UTI). Front vowels are difficult to image with UTI, since their articulation involves tongue positions which are particularly far from the ultrasonic probe, hence reducing the visibility of the tongue contour. For this reason, only central and back vowels were included. Since one of the variables of interest in the exploratory study was the closing gesture of $C_2$, only lingual consonants were used. A labial stop was chosen as the first consonant to reduce possible coarticulation with the following vowel (although see Vazquez-Alvarez and Hewlett 2007). The target words were embedded in a frame sentence, *Dico X lentamente* 'I say X slowly' in Italian (following Hajek and Stevens, 2008), and *Mówię X teraz* 'I say X now' in Polish, and presented according to the respective writing conventions. These sentences were chosen in order to keep the placement of stress and emphasis similar across languages, so to ensure comparability of results.

### D. Procedure

The participant was asked to read the sentences with the target words which were sequentially presented on the computer screen. The order of the sentence stimuli was randomised for each participant. Each participant read the list of randomised sentence stimuli 6 times. Due to software constraints, the order of the list was kept the same across the six repetitions within each participant. Each speaker read a total of 12 sentences for 6 times (with the exceptions of IT02, who repeated the 12 sentences 5 times, and IT07, with whom words containing /u/ were not recorded due to technical difficulties relating to the ultrasound data collection).[4] with a grand total of 1224 tokens (792 from Italian, 432 from Polish). The reading task lasted between 15 and 20 minutes, with optional short breaks between one repetition and the other.

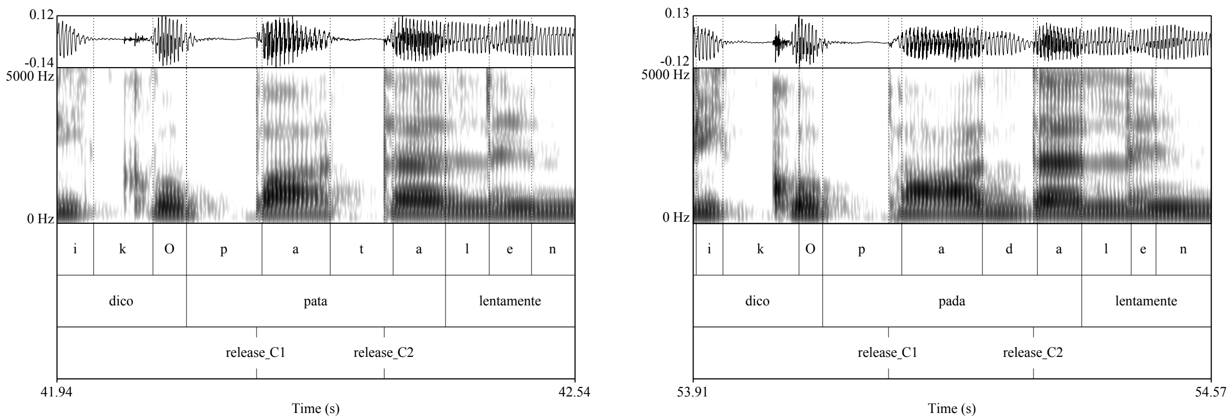
### E. Data processing and measurements

The audio recordings were exported from AAA in `.wav` format for further processing. A forced aligned transcription was accomplished through the SPeech Phonetisation Alignment and Syllabification software (SPPAS) (Bigi, 2015). The outcome of the automatic annotation was manually corrected when necessary, according to the criteria in Table I. The releases of C1 and C2 were detected automatically by means of a Praat scripting implementation of the algorithm described in

TABLE I. 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 release | (C1/C2 release) | automatic detection + manual correction (Ananthapadmanabha *et al.*, 2014) |

Ananthapadmanabha *et al.* (2014). The durations in milliseconds of the following intervals were extracted from the annotated acoustic landmarks with Praat scripting: sentence duration, word duration, vowel duration (V1 onset to V1 offset), consonant closure duration (V1 offset to C2 burst), and Release-to-Release duration (RR duration, C1 release to C2 release). Figure 1 shows an example of the segmentation of /pata/ (a) and /pada/ (b) from an Italian speaker. Syllable rate (syllables per second) was used as a proxy to speech rate (Plug and Smith, 2018) for duration normalisation, and was calculated as the number of syllables divided by the duration of the sentence (8 syllables in Italian, 6




(a) (b)

FIG. 1. Segmentation example.

in Polish). All further data processing and visualisation was done in R v3.5.0 (R Core Team, 2018; Wickham, 2017).

### F. Statistical analysis

Given the exploratory nature of the study, all statistical analyses reported here are to be considered data-driven or hypothesis-generating rather than hypothesis-driven (Gelman and Loken, 2013; Kerr, 1998). The durational measurements were analysed with linear mixed-effects models using `lme4` v1.1-17 in R (Bates *et al.*, 2015), and model estimates were extracted with the `effects` package v4.0-2 (Fox, 2003). All factors were coded with treatment contrasts and the following reference levels: voiceless (vs. voiced), /a/ (vs. /o/, /u/), coronal (vs. velar), Italian (vs. Polish). The estimates in the results section refer to these reference levels unless interactions are discussed. *P*-values for the individual terms were obtained with `lmerTest` v3.0-1, which uses the Satterthwaite's approximation to degrees of freedom (Kuznetsova *et al.*, 2017; Luke, 2017). A result is considered significant if the *p*-value is below the alpha level ($\alpha = 0.05$).[5]

Bayes factors were used to specifically test the null hypotheses that word and RR duration are not affected by C2 voicing (i.e., the effect of C2 voicing on duration is 0). For each set of null/alternative hypotheses, a full model (with the predictor of interest) and a null model (excluding it) were fitted separately using Maximum Likelihood estimation (Bates *et al.*, 2015, p. 34). The BIC approximation was then used to obtain Bayes factors (Jarosz and Wiley, 2014; Raftery, 1995, 1999; Wagenmakers, 2007). The approximation is calculated according to the equation in 1 (Wagenmakers, 2007, p. 796).

$$BF_{01} \approx exp(\Delta BIC_{10}/2) \tag{1}$$

where $\Delta BIC_{10} = BIC_1 - BIC_0$, $BIC_1$ is the BIC of the full model, and $BIC_0$ is the BIC of the null model. Values of $BF_{01} > 1$ indicate a preference of $H_0$ over $H_1$. The interpretation of the Bayes factors follows the recommendations in Raftery (1995, p. 139).

The extracted measurements were filtered before statistical analysis. Measures of vowel duration, closure duration, word duration, and RR duration that are 3 standard deviations lower or higher than the respective means were excluded from the final dataset. This operation yields a total of 920 tokens of vowel and closure durations, 1176 tokens of word duration, and 848 tokens of RR duration.

## III. RESULTS

The following sections report the results of the study in relation to the durations of vowels, consonant closure, word, and the Release to Release interval. When discussing the output of statistical modelling, only the relevant predictors and interactions will be presented. To avoid the cluttering

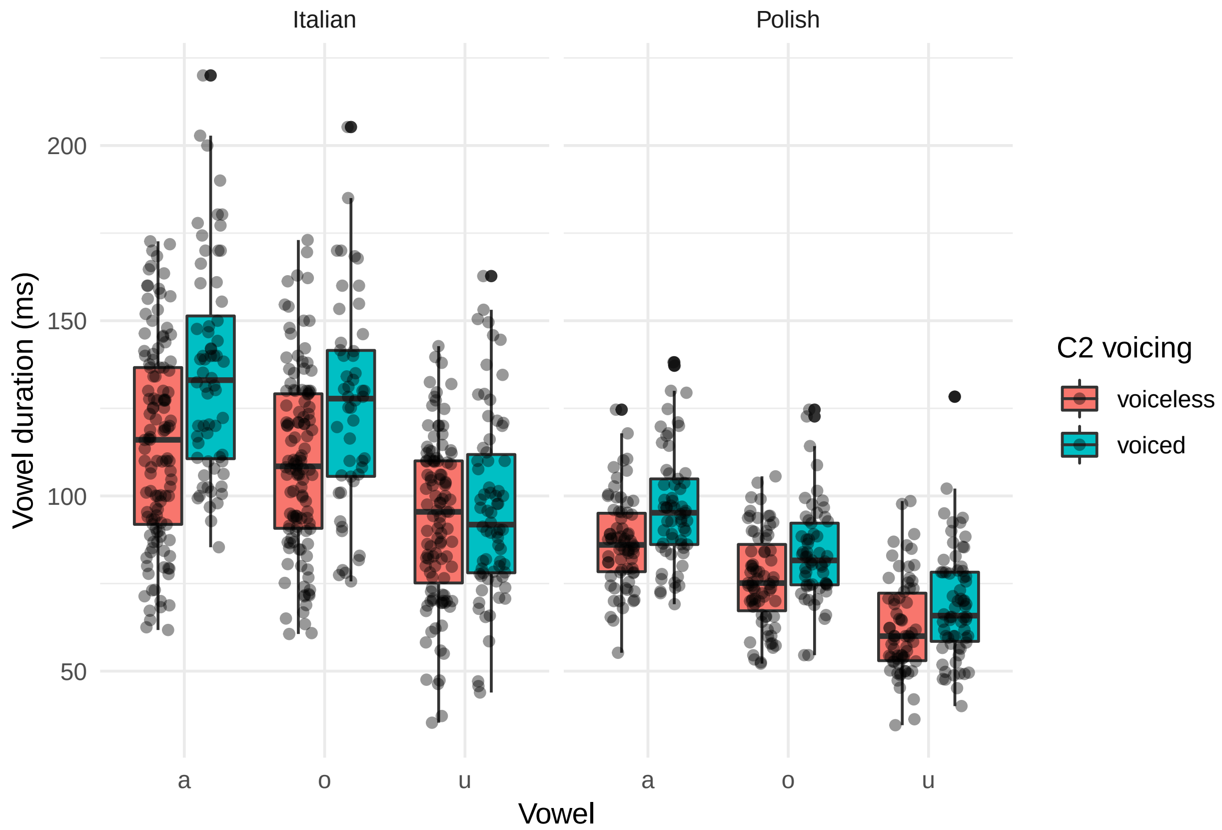



FIG. 2. Vowel duration in Italian and Polish.

generated by model parameters and alleviate the reader, the full output of statistical models and respective *p*-values are included in Appendix A.

### A. Vowel duration

Figure 2 shows boxplots and the raw data of vowel duration in Italian (on the left) and Polish (on the right) for the three vowels /a, o, u/. Vowel tend to be longer when followed by a voiced stop both in Italian and Polish. The effect appears to be greater in Italian than in Polish, especially for the vowels /a/ and /o/. There is no clear effect of C2 voicing in /u/ in Italian, but the effect is discernible in Polish /u/. In Italian, vowels have a mean duration of 106 ms (sd = 27) before voiceless stops, and a mean duration of 118 ms (sd = 33) before voiced stops. Polish vowels are on average 75 ms long (sd = 16) when followed by a voiceless stop, and 83 ms long (sd = 19) if a voiced stop follows. The difference in vowel duration based on the raw means is 12 ms in Italian and 8 ms in Polish.

A linear mixed-effects model with vowel duration as the outcome variable was fitted with the following predictors: fixed effects for C2 voicing (voiceless, voiced), C2 place of articulation (coronal, velar), vowel (a, o, u), language (Italian, Polish), and speech rate (as syllables per second); by-speaker and by-word random intercept with by-speaker random slopes for C2 voicing. All possible interactions between C2 voicing, vowel, and language were included. The following terms are significant according to *t*-tests with Satterthwaite's approximation to degrees of freedom: C2 voicing, vowel, language, and speech rate. Only the interaction between C2 voicing and vowel is significant. Vowels are 19 ms longer (se = 4.4) when followed by a voiced stop (C2 voicing). The effect of C2 voicing is smaller with /u/ (around 5 ms, $\hat{\beta}$ = -14.4 ms, se = 6). Polish has on average shorter vowels than Italian ($\hat{\beta}$ = -28 ms, se = 8), and the effect of voicing is estimated to be about 11 ms (although recall that the interaction between language and C2 voicing is deemed not significant). Speech rate has unsurprisingly a negative effect on vowel duration, such that faster rates correlate with shorter vowel durations ($\hat{\beta}$ = -15 ms, se = 1).

### B. Consonant closure duration

Figure 3 illustrates stop closure durations with boxplots and individual raw data points. A pattern opposite to that with vowel duration can be noticed: Closure duration is shorter for voiced than for voiceless stops. The closure of voiceless stops in Italian is 77 ms long (sd = 20), while the voiced stops have a mean closure duration of 63 ms (sd = 15). In Polish, the closure duration is 69 ms (sd =

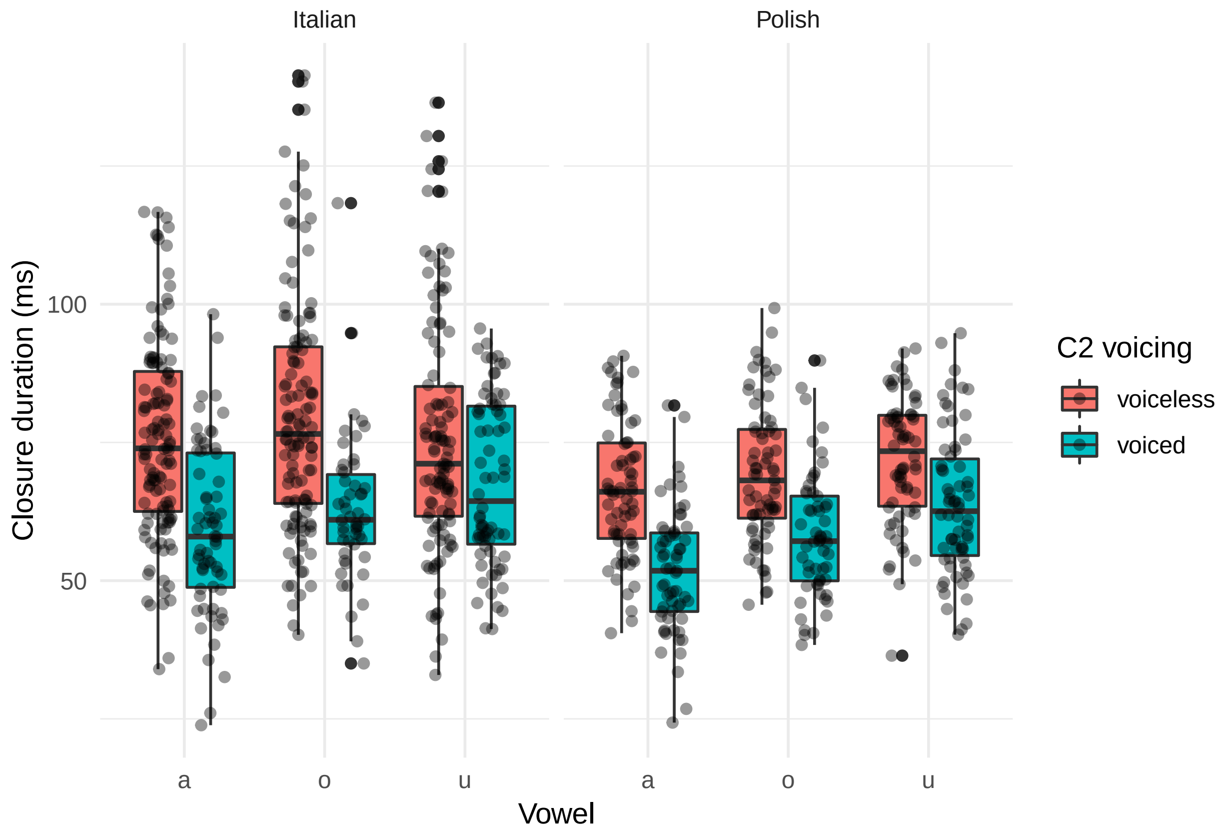



FIG. 3. Stop closure duration in Italian and Polish.

12) in voiceless stops and 58 ms (sd = 13) in voiced stops. The difference in closure duration based on the raw means is 14 ms in Italian and 11 ms in Polish. The same model specification as with vowel duration has been fitted with consonant closure durations as the outcome variable. C2 voicing, C2 place, and speech rate are significant. Stop closure is 16.5 ms shorter (se = 3) if the stop is voiced and 3.5 ms longer (se = 1.5) if velar. Finally, faster speech rates correlate with shorter closure durations ($\hat{\beta}$ = -8.5 ms, se = 1 ms).

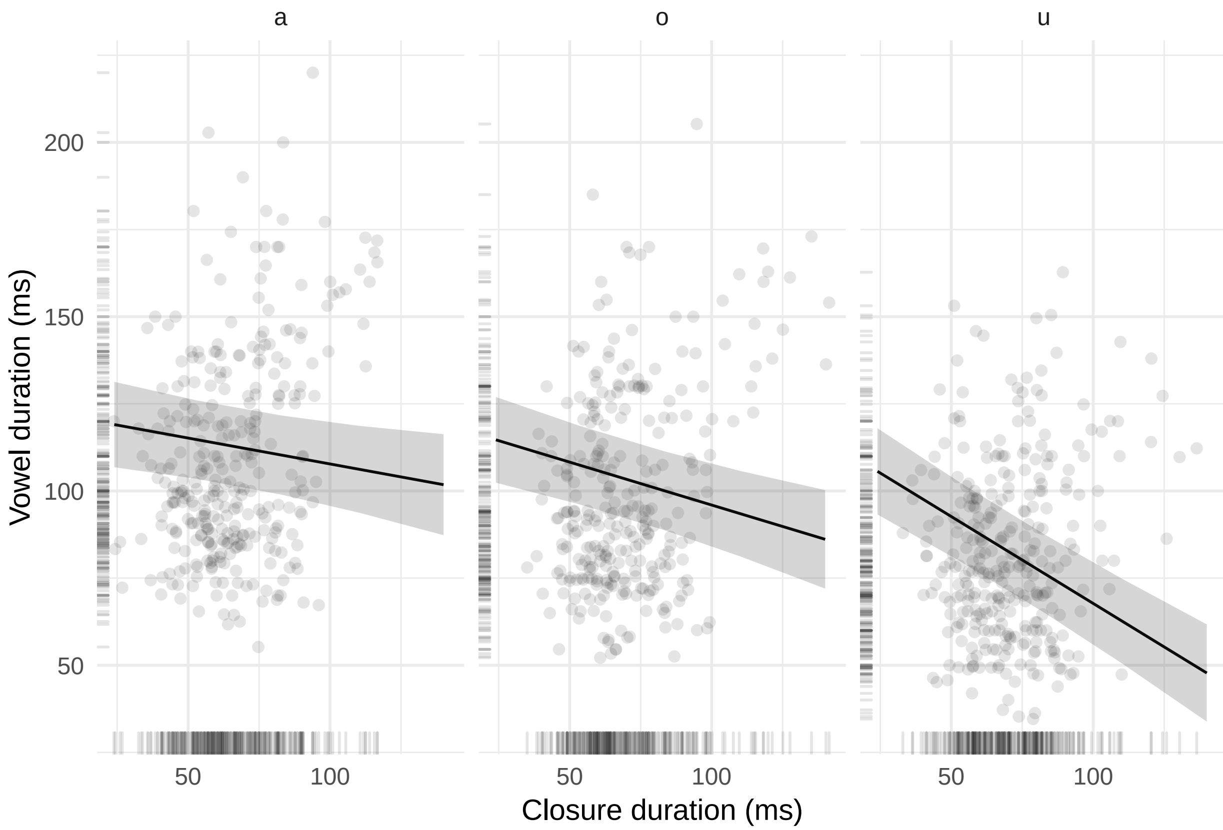



FIG. 4. Linear regression of closure and vowel duration per vowel.

### C. Vowel and closure duration

A model addressing the relationship between vowel and stop closure duration was fitted with the following terms and interactions: vowel duration as the outcome variable; as fixed effects, closure duration, vowel, speech rate; an interaction between closure duration and vowel; by-speaker and by-word random intercepts, and by-speaker random slopes for C2 voicing. Closure duration has a significant effect on vowel duration ($\hat{\beta}$ = -0.15 ms, se = 0.06 ms). The effect with /u/ is greater than with /a/ and /o/ ($\hat{\beta}$ = -0.35 ms, se = 0.06 ms). In general, closure duration is inversely correlated with vowel duration. However such correlation is quite weak. A 1 ms increase in closure duration corresponds to a 0.2–0.5 ms decrease in vowel duration. Figure 4 shows for each of /a, o, u/ the individual data points and the regression lines with confidence intervals extracted from the linear model.

### D. Word duration

Words with a voiceless stop are on average 397 ms long (sd = 81) in Italian and 356 ms long (sd = 39) in Polish. Words with a voiced stop have a mean duration of 396 ms (sd = 72) in Italian and 362 ms (sd = 39) in Polish. The following full and null models were fitted to test for the effect of C2 voicing on word duration. The full model has the following fixed effects: C2 voicing, C2 place, vowel, speech rate, and language. The model also includes by-speaker and by-word random intercepts, and a by-speaker random slope for C2 voicing. The null model excludes the fixed effect of C2 voicing. The Bayes factor of the null model against the full model is 24. Thus, the null model (in which the effect of C2 voicing is 0) is 24 times more likely under the observed data than the full model. This indicates that there is strong evidence for word duration not being affected by C2 voicing.

### E. Release to Release interval duration

In Figure 5, boxplots show the durations of the Release to Release interval in words with a voiceless vs. a voiced C2 stop, in Italian (left side) and Polish (right side). It can be seen, also from the single data points, that the distributions and main statistics of the durations in the two conditions do not differ much within both languages. In Italian, the mean duration of the Release to Release interval is 210 ms (sd = 44) if C2 is voiceless, and 209 ms (sd = 41) if C2 is voiced. In Polish, the means are respectively 173 (sd = 22) and 172 (sd = 21) ms. The models specifications for the Release to Release duration are the same as for word duration. The Bayes factor of the null model against the

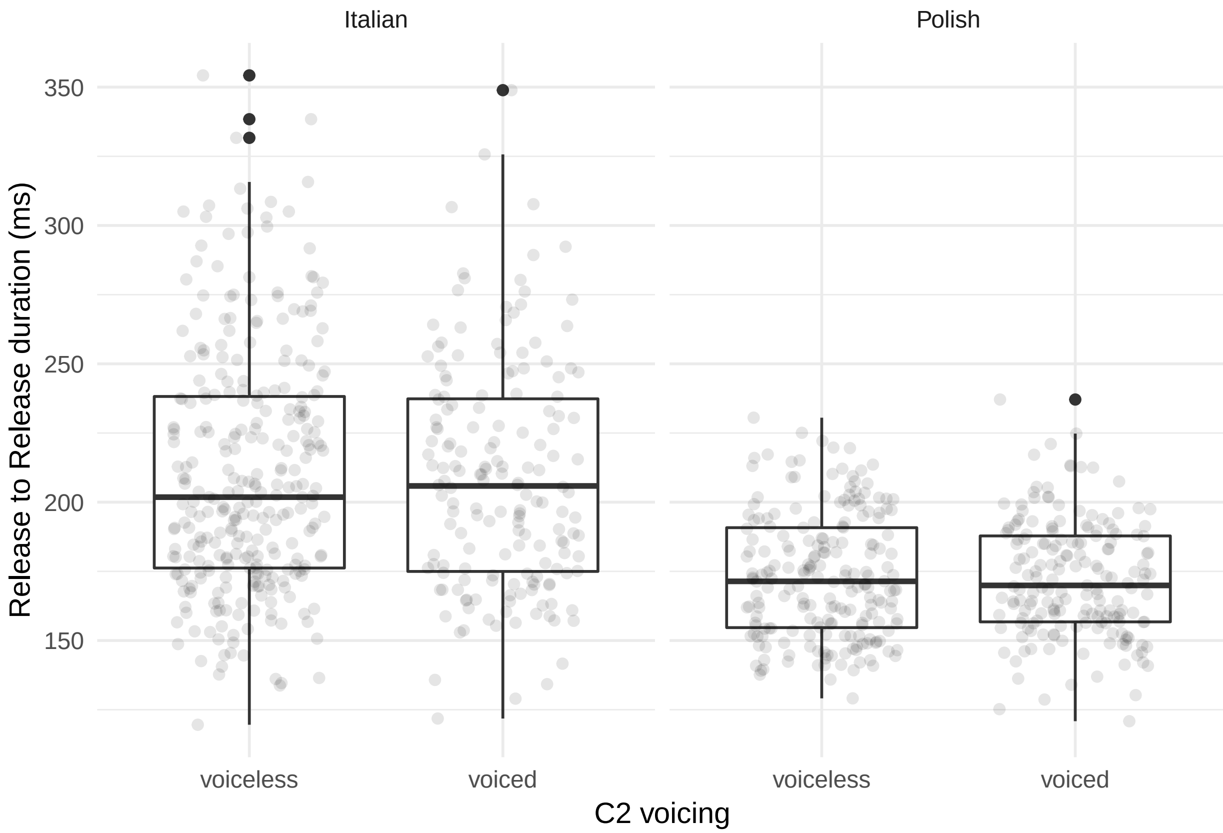



FIG. 5. Release to Release interval duration.

full model is 23, which means that the null model (without C2 voicing) is 23 times more likely than the full model. The data suggests there is positive evidence that duration of the RR interval is not affected by C2 voicing.

## IV. DISCUSSION

The data and statistical analysis presented in the previous section indicate that the duration of interval between the releases of two consecutive consonants in CV́CV words (the Release to Release interval) is insensitive to the phonological voicing of the second consonant (C2). In accordance with a compensatory temporal adjustment account (Lehiste, 1970b; Slis and Cohen, 1969b), the difference in vowel duration before voiceless vs. voiced stops is the outcome of differences in stop closure duration. More specifically, the timing of the closure onset of C2 within the invariant Release to Release interval determines the duration of the preceding vowel. An earlier closure onset (like in the case of voiceless stops), relative to the onset of the preceding vowel, causes the vowel to be shorter. On the other hand, a later closure onset (like with voiced stops) produces a longer vowel. Hence, the voicing effect can be seen as a product of gestural timing, rather then a consequence of characteristics of voicing *per se*.

A limitation of the compensatory temporal adjustment account, in the variant of Slis and Cohen (1969b) and Lehiste (1970b), is the lack of a precise identification of the internal structure of the word as the unit within which the compensation happens. It is not clear, for example, why compensation should target the preceding stressed vowel, rather then the following unstressed vowel or any other segment in the word. The invariance of Release to Release interval allows us to formulate a better defined internal organisation of the word. Since the Release to Release interval contains (in a simplified view) just the vowel (broadly defined as a vocoid gesture) and the consonant closure, it follows by logic that differences in closure duration must affect the preceding vowel.

The invariance of the Release to Release interval can be seen as the explanans of the voicing effect, and it gives the compensatory account a more logical consistency by narrowing the scope of the temporal adjustment action. On the other hand, the Release to Release invariance becomes in turn an explanandum and it thus requires to be motivated. In the following section, I offer a gestural organisation account that allows the invariance or such interval to follow from the relative timing of the articulatory gestures in a CV́C sequence.

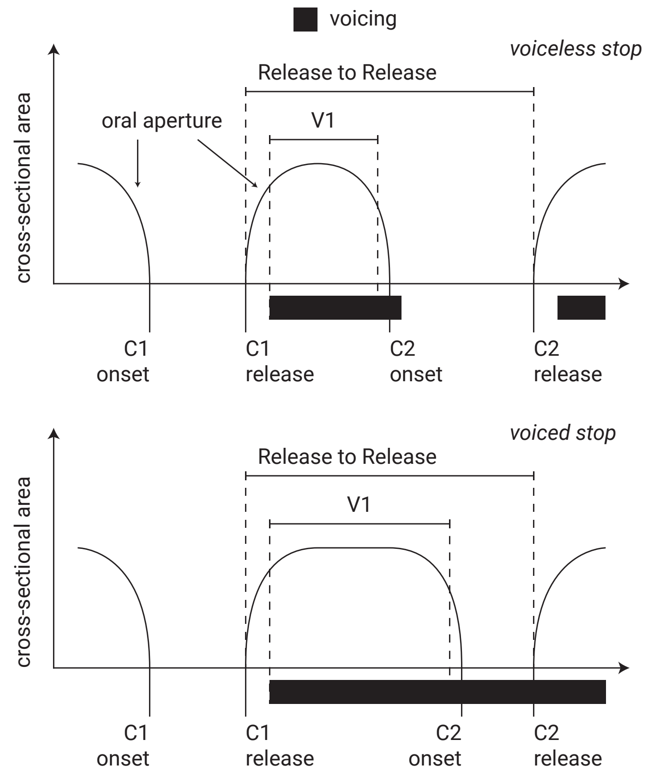



FIG. 6. A schematic representation of the voicing effect as a compensatory temporal adjustment phenomenon. The schematic show the gestural unfolding of a CV́C sequence when C2 is voiceless (top panel), or voiced (bottom panel). Oral cavity aperture (on the *y*-axis, as the inverse of oral constriction) through time (on the *x*-axis) is represented with a changing black line that represents the movement trajectory of an articulator. Lower values represent a more constricted oral tract (a contoid configuration), while higher values indicate a more open oral tract (a vocoid configuration). The black bars below the time axis represent voicing (vocal fold vibration). Various landmarks and intervals are indicated in the schematic.

### A. Gestural alignment

According to the coupled oscillator model of syllabic structure (Browman and Goldstein, 1988, 2000; Goldstein *et al.*, 2006; Goldstein and Pouplier, 2014), articulatory gestures can be timed ac-

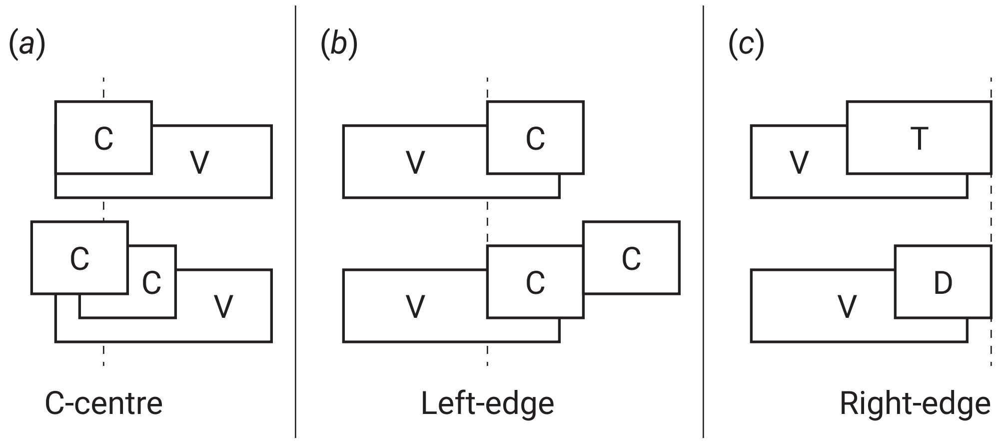



FIG. 7. Gestural organisation patterns for onsets (a), codas (b), heterosyllabic onsets (c). See Section IV A for details. Based on Marin and Pouplier (2010).

cording to two coupling modes: in-phase (synchronous) mode, by which two gestures start in synchrony, or anti-phase (sequential) mode, in which one gesture starts when the preceding one has reached its target. Marin and Pouplier (2010) showed that onset consonants in American English are in-phase with the vowel nucleus and anti-phase with each other. Such phasing pattern establishes a stable relationship between the centre of the consonant or consonant cluster and the following vowel. Independent of the number of onset consonants, the midpoint of the onset, the so-called 'C-centre', is maintained at a fixed distance from the vowel, such that increasing number of consonants in the onset does not change the C-centre/vowel distance (Figure 7(a)). On the other hand, coda consonants are timed anti-phase with the preceding vowel and between themselves. Stability in codas is seen in the lag between the vowel and the left-most edge of the coda, which is not affected by the number of coda consonants (Figure 7(b)). Other studies found further evidence for the synchronous and sequential coupling modes (see extensive review in Marin and Pouplier (2010) and Marin and Pouplier

(2014)), although the use of one mode over the other depends on the language and the consonants under study.

Consonants can thus be said to follow either a C-centre organisation pattern or a left-edge organisation pattern. In both cases, of course, the pattern is relative to the tautosyllabic vowel (the following vowel for onsets, the preceding vowel for codas). To the best of my knowledge, no study has reported the timing of onset consonants relative to the *preceding* (heterosyllabic) vowel. The results from this acoustic study on Italian and Polish are compatible with a right-edge organisation pattern for onset consonants and preceding stressed vowels Figure 7(c). The release of C2 (which is the onset of the second syllable in CV́CV words)—which can be thought as the acoustic parallel of the articulatory right edge of C2—is invariantly timed relative to V1 (which is the nucleus of the first syllable).

A consequence of a right-edge organisation pattern of C2 relative to V1 in CV́CV words is that differences in C2 closure duration do not affect the lag between V1 and the release of C2, as shown by the results of this study. The invariance of the lag between the release of C1 and that of C2 then can be seen to follow from the invariance in timing between, on the one hand, C1 (which is always /p/ in this study) and V1, and, on the other, between V1 and the right edge of C2.

A right-edge organisation account is compatible with findings from electromyographic, x-ray microbeam, and ultrasonic data by, respectively, Raphael (1975), de Jong (1991), and Celata *et al.* (2018). Celata *et al.* (2018) show that vowels before tautosyllabic clusters have the same duration as before heterosyllabic clusters. However, vowels followed by geminates are shorter than when followed by singletons, although from a syllabic structure point of view geminates correspond to heterosyllabic clusters and singletons to tautosyllabic clusters (i.e., V-final syllables followed by singletons and tautosyllabic clusters are open, while those followed by geminates and heterosyllabic clusters are closed). Celata *et al.* (2018) argue that these results corroborate a rhythmic account in which the relevant unit is the rhythmic syllable, i.e. the VC(C) sequence (independent of the traditional syllabic structure), which is kept constant. Such view reflects a gestural timing view in which the timing of the right edge of the consonant is held constant relative to the vowel.

de Jong (1991) reports that the closing gesture of voiceless stops (following stressed vowels) is faster than that of voiced stops, and that also it is timed earlier with respect to the opening gesture of the stressed vowel. According to de Jong (1991), the differences in vowel duration are driven by the timing of the consonantal closing gesture relative to the vocalic opening gesture (also see Hertrich and Ackermann 1997). Moreover, the data in de Jong (1991) show that the final portion of the vocalic opening gesture is prolonged before voiced stops. This finding corresponds to what Raphael (1975) reported based on electromyographic data. The electromyographic signal corresponding to the vocalic gesture reaches its plateaux at the same time in the voiceless and voiced context, but the plateaux is held for longer in the case of vowels followed by voiced stops, indicating that muscular activation is kept for longer.

These studies taken together, plus the results from this study, bring evidence to the view that two factors contribute to the difference in vowel duration observed before consonants varying in their voicing specification. These two factors are: (1) the right-edge alignment of coda consonants following stressed vowels relative to the latter, and (2) the differential timing of the closing gesture onset for voiceless vs. voiced stops. These two factors together can be synthesised into a compensatory temporal adjustment account, in which the fixed interval is generated by factor (1) and the temporal adjustment is brought about by factor (2).

### B. Limitations and future work

The generalisations reported in this paper strictly apply to disyllabic words with a stressed vowel in the first syllable. It is possible that the organisation pattern found in this context does not occur in sequences including an unstressed vowel. For example, it is known that the difference in closure duration between voiceless and voiced stops is not stable when the stops precede a stressed vowel, although the vowels preceding the pre-stress stops have different durations (Davis and Van Summers, 1989). According to the gestural interpretation given here, the absence in differences of closure duration should correspond to no difference in vowel duration. Data from different contexts and different languages is thus needed to assess the generality of the claims put forward in this paper.

The constraints on experimental material enforced by the use of ultrasound tongue imaging have been previously mentioned in Section II C. Given these constraints, temporal information from other vowels (like front vowels) and places of articulation is a desideratum. Section IV A discusses the interpretation of the Release to Release invariance in CV́CV words as a consequence of the timing of C2 rather than of a holistic CV́C motor plan in which the RR interval is held constant. Although beyond the scope of this paper, disambiguating between these two interpretations on articulatory grounds is fundamental for a general understanding of a theory of gestural organisation.

The compensatory temporal adjustment account presented here extends to other durational effects discussed in the literature. In particular, the account bears predictions on the direction of the durational difference led by phonation types different from voicing, like aspiration and ejection. For example, the mix of results with regard to the effect of aspiration (Durvasula and Luo, 2012) suggests that the conditions for a temporal adjustment might differ across the contexts and languages studied.

In light of the results in Beguš (2017), future studies will have to investigate the durational invariance of speech intervals in relation to a variety of phonation contrasts.

## V. CONCLUSION

## ACKNOWLEDGMENTS

Thanks to...

## APPENDIX A: OUTPUT OF STATISTICAL MODELS

### 1. Vowel duration

| term | estimate | std.error | df | statistic | p.value | conf.low | conf.high |
|---|---|---|---|---|---|---|---|
| (Intercept) | 202.5289 | 8.6169 | 134.7948 | 23.5036 | 0.0000 | 185.6400 | 219.4178 |
| c2_phonationvoiced | 18.9669 | 4.3898 | 12.7785 | 4.3207 | 0.0009 | 10.3631 | 27.5707 |
| vowelo | -6.1457 | 3.9512 | 8.6900 | -1.5554 | 0.1555 | -13.8899 | 1.5985 |
| vowelu | -26.3039 | 3.9772 | 8.9199 | -6.6136 | 0.0001 | -34.0991 | -18.5087 |
| languagePolish | -24.2194 | 8.1708 | 21.7230 | -2.9642 | 0.0072 | -40.2338 | -8.2050 |
| c2_placevelar | -8.1827 | 1.6984 | 10.5938 | -4.8178 | 0.0006 | -11.5116 | -4.8539 |
| syl_rate | -15.2920 | 1.2679 | 775.7483 | -12.0608 | 0.0000 | -17.7771 | -12.8070 |
| c2_phonationvoiced:vowelo | -2.0453 | 5.8662 | 10.5314 | -0.3487 | 0.7342 | -13.5428 | 9.4522 |
| c2_phonationvoiced:vowelu | -14.4536 | 5.8040 | 10.0977 | -2.4903 | 0.0318 | -25.8292 | -3.0780 |
| c2_phonationvoiced:languagePolish | -7.9928 | 6.4252 | 14.2528 | -1.2440 | 0.2336 | -20.5860 | 4.6005 |
| vowelo:languagePolish | -3.6121 | 5.7389 | 9.6704 | -0.6294 | 0.5437 | -14.8601 | 7.6360 |
| vowelu:languagePolish | 1.6149 | 5.7695 | 9.8777 | 0.2799 | 0.7853 | -9.6931 | 12.9230 |
| c2_phonationvoiced:vowelo:languagePolish | -2.9987 | 8.3627 | 10.8862 | -0.3586 | 0.7268 | -19.3894 | 13.3920 |
| c2_phonationvoiced:vowelu:languagePolish | 7.9601 | 8.3077 | 10.6040 | 0.9582 | 0.3593 | -8.3227 | 24.2428 |

## 2. Closure duration

| term | estimate | std.error | df | statistic | p.value | conf.low | conf.high |
|---|---|---|---|---|---|---|---|
| (Intercept) | 119.7338 | 7.2100 | 128.2742 | 16.6065 | 0.0000 | 105.6023 | 133.8652 |
| c2_phonationvoiced | -16.5825 | 4.3129 | 17.8144 | -3.8449 | 0.0012 | -25.0356 | -8.1294 |
| vowelo | 3.6830 | 3.4951 | 9.0918 | 1.0538 | 0.3192 | -3.1672 | 10.5333 |
| vowelu | -1.9898 | 3.5174 | 9.3243 | -0.5657 | 0.5849 | -8.8837 | 4.9041 |
| languagePolish | -6.9400 | 6.8688 | 22.0443 | -1.0104 | 0.3233 | -20.4027 | 6.5226 |
| c2_placevelar | 3.4024 | 1.4976 | 10.9532 | 2.2719 | 0.0443 | 0.4672 | 6.3376 |
| syl_rate | -8.4278 | 1.0550 | 557.6472 | -7.9887 | 0.0000 | -10.4954 | -6.3601 |
| c2_phonationvoiced:vowelo | 1.1040 | 5.1738 | 10.8916 | 0.2134 | 0.8350 | -9.0364 | 11.2445 |
| c2_phonationvoiced:vowelu | 9.9882 | 5.1257 | 10.4981 | 1.9486 | 0.0786 | -0.0581 | 20.0344 |
| c2_phonationvoiced:languagePolish | 1.6759 | 6.5019 | 20.0145 | 0.2578 | 0.7992 | -11.0675 | 14.4194 |
| vowelo:languagePolish | -0.2681 | 5.0672 | 10.0440 | -0.0529 | 0.9588 | -10.1997 | 9.6635 |
| vowelu:languagePolish | 7.1432 | 5.0932 | 10.2505 | 1.4025 | 0.1903 | -2.8393 | 17.1256 |
| c2_phonationvoiced:vowelo:languagePolish | 1.5022 | 7.3707 | 11.2269 | 0.2038 | 0.8422 | -12.9441 | 15.9485 |
| c2_phonationvoiced:vowelu:languagePolish | -3.2088 | 7.3279 | 10.9696 | -0.4379 | 0.6700 | -17.5711 | 11.1536 |

### 3. Vowel and closure duration

| term | estimate | std.error | df | statistic | p.value | conf.low | conf.high |
|---|---|---|---|---|---|---|---|
| (Intercept) | 219.3142 | 10.4477 | 123.5512 | 20.9917 | 0.0000 | 198.8371 | 239.7913 |
| closure_duration | -0.1487 | 0.0632 | 50.3807 | -2.3532 | 0.0226 | -0.2726 | -0.0249 |
| vowelo | -2.0462 | 5.4702 | 81.5530 | -0.3741 | 0.7093 | -12.7675 | 8.6751 |
| vowelu | -5.0236 | 5.5582 | 86.7938 | -0.9038 | 0.3686 | -15.9176 | 5.8703 |
| syl_rate | -17.5364 | 1.2855 | 896.1529 | -13.6415 | 0.0000 | -20.0559 | -15.0168 |
| closure_duration:vowelo | -0.0973 | 0.0615 | 876.5971 | -1.5835 | 0.1137 | -0.2178 | 0.0231 |
| closure_duration:vowelu | -0.3500 | 0.0619 | 895.3921 | -5.6582 | 0.0000 | -0.4712 | -0.2288 |

## APPENDIX B: SOCIO-LINGUISTIC INFORMATION OF PARTICIPANTS

## APPENDIX C: TARGET WORDS

[1]Two accounts that point to perceptual features are Javkin (1976) and Kluender *et al.* (1988). To the best of my knowledge, Javkin (1976)'s proposal remains empirically untested, while see Fowler (1992) for arguments against Kluender *et al.* (1988).

[2]Durvasula and Luo (2012) does not find a negative correlation between vowel duration and consonant closure duration, but rather a (small) positive effect: vowel duration increases with closure duration when including an voicing and aspi-

TABLE II. Participants' sociolinguistic information.

| ID | Age | Sex | Native L | Other Ls | City of birth | Spent most time in | > 6 mo |
|---|---|---|---|---|---|---|---|
| it01 | 29 | Male | Italian | English, Spanish | Verbania | Verbania | Yes |
| it02 | 26 | Male | Italian | Friulian, English, Ladin-Venetan | Udine | Tricesimo | Yes |
| it03 | 28 | Female | Italian | English, German | Verbania | Verbania | No |
| it04 | 54 | Female | Italian | Calabrese | Verbania | Verbania | No |
| it05 | 28 | Female | Italian | English | Verbania | Verbania | No |
| it09 | 35 | Female | Italian | English | Vignola | Vignola | Yes |
| it11 | 24 | Male | Italian | English | Monza | Monza | Yes |
| it13 | 20 | Female | Italian | English, French, Arabic, Farsi | Ancona | Chiaravalle | Yes |
| it14 | 32 | Male | Italian | English, Spanish | Frosinone | Frosinone | Yes |
| pl02 | 32 | Female | Polish | English, Norwegian, French, German, Dutch | Koło | Poznań | Yes |
| pl03 | 26 | Male | Polish | Russian, English, French, German | Nowa Sol | Poznań | Yes |
| pl04 | 34 | Female | Polish | Spanish, English, French | Warsaw | Warsaw | No |
| pl05 | 42 | Male | Polish | English, French | Przasnysz | Warsaw | No |
| pl06 | 33 | Male | Polish | English | Zgierz | Zgierz | Yes |
| pl07 | 32 | Female | Polish | English, Russian | Bielsk Podlaski | Bielsk Podlaski | Yes |

TABLE III. Target words.

| Italian | | | Polish | | |
|---|---|---|---|---|---|
| pata | poto* | putu | pata | poto | putu |
| pada | podo | pudu | pada* | podo | pudu |
| paca* | poco* | pucu | paka* | poko | puku |
| paga* | pogo | pugu | paga | pogo | pugu |

ration as fixed effects. However, it is likely that this result is a consequence of not controlling for speech rate, so it will not be discussed here.

[3]These estimates should be taken as a gross approximation. There are several issues: number of speakers, different contexts, statistical modelling.

[4]IT01 and IT02 (the first two participants of this study) read also sentences with words starting with /b/, which were later excluded from the experimental design. The data from /b/-initial words are not included in the analysis reported in this paper.

[5]Luke (2017) argues that the common approach of using likelihood ratio tests for statistical inference with mixed models leads to inflated Type I error rates. Luke (2017, 1501) also warns that 'results should be interpreted with caution, regardless of the method adopted for obtaining *p*-values'.

Ananthapadmanabha, T. V., Prathosh, A. P., and Ramakrishnan, A. G. (**2014**). "Detection of the closure-burst transitions of stops and affricates in continuous speech using the plosion index," The Journal of the Acoustical Society of America **135**(1), 460–471.

Bates, D., Mächler, M., Bolker, B., and Walker, S. (**2015**). “Fitting linear mixed-effects models using lme4,” Journal of Statistical Software **67**(1), 1–48.

Beguš, G. (**2017**). “Effects of ejective stops on preceding vowel duration,” The Journal of the Acoustical Society of America **142**(4), 2168–2184, doi: 10.1121/1.5007728.

Belasco, S. (**1953**). “The influence of force of articulation of consonants on vowel duration,” The Journal of the Acoustical Society of America **25**(5), 1015–1016.

Bigi, B. (**2015**). “SPPAS - Multi-lingual approaches to the automatic annotation of speech,” The Phonetician **111–112**, 54–69.

Browman, C. P., and Goldstein, L. (**1988**). “Some notes on syllable structure in articulatory phonology,” Phonetica **45**(2-4), 140–155.

Browman, C. P., and Goldstein, L. (**2000**). “Competing constraints on intergestural coordination and self-organization of phonological structures,” Bulletin de la communication parlée (5), 25–34.

Caldognetto, E. M., Ferrero, F., Vagges, K., and Bagno, M. (**1979**). “Indici acustici e indici percettivi nel riconoscimento dei suoni linguistici (con applicazione alle consonanti occlusive dell’italiano),” Acta Phoniatrica Latina **2**, 219–246.

Celata, C., Meluzzi, C., and Bertini, C. (**2018**). “Stressed vowel durational variations and articulatory cohesiveness: Italian data” Poster presented at LabPhon 16, Lisbon.

Chen, M. (**1970**). “Vowel length variation as a function of the voicing of the consonant environment,” Phonetica **22**(3), 129–159.

Davis, S., and Van Summers, W. (**1989**). “Vowel length and closure duration in word-medial VC sequences,” The Journal of the Acoustical Society of America **17**, 339–353.

de Jong, K. (**1991**). “An articulatory study of consonant-induced vowel duration changes in english,” Phonetica **48**(1), 1–17.

Durvasula, K., and Luo, Q. (**2012**). “Voicing, aspiration, and vowel duration in Hindi,” Proceedings of Meetings on Acoustics **18**, 1–10.

Esposito, A. (**2002**). “On vowel height and consonantal voicing effects: Data from Italian,” Phonetica **59**(4), 197–231.

Farnetani, E., and Kori, S. (**1986**). “Effects of syllable and word structure on segmental durations in spoken Italian,” Speech communication **5**(1), 17–34.

Fowler, C. A. (**1992**). “Vowel duration and closure duration in voiced and unvoiced stops: There are no contrast effects here,” Journal of Phonetics **20**(1), 143–165.

Fox, J. (**2003**). “Effect displays in R for generalised linear models,” ournal of Statistical Software **8**(15), 1–27, doi: 10.18637/jss.v008.i15.

Gelman, A., and Loken, E. (**2013**). “The garden of forking paths: Why multiple comparisons can be a problem, even when there is no “fishing expedition” or “p-hacking”and the research hypothesis was posited ahead of time,” Department of Statistics, Columbia University .

Goldstein, L., Byrd, D., and Saltzman, E. (**2006**). “The role of vocal tract gestural action units in understanding the evolution of phonology,” in *Action to Language via the Mirror Neuron System*, edited by M. A. Arbib (Cambridge: Cambridge University Press), pp. 215–249.

Goldstein, L., and Pouplier, M. (**2014**). “The temporal organization of speech,” in *The Oxford handbook of language production*, edited by V. Ferreira, M. Goldrick, and M. Miozzo (Oxford: Oxford University Press).

Hajek, J., and Stevens, M. (**2008**). "Vowel duration, compression and lengthening in stressed syllables in central and southern varieties of standard italian," ISCA.

Halle, M., and Stevens, K. (**1967**). "Mechanism of glottal vibration for vowels and consonants," The Journal of the Acoustical Society of America **41**(6), 1613–1613.

Heffner, R.-M. (**1937**). "Notes on the length of vowels," American Speech **12**, 128–134.

Hertrich, I., and Ackermann, H. (**1997**). "Articulatory control of phonological vowel length contrasts: Kinematic analysis of labial gestures," The Journal of the Acoustical Society of America **102**(1), 523–536.

House, A. S., and Fairbanks, G. (**1953**). "The influence of consonant environment upon the secondary acoustical characteristics of vowels," The Journal of the Acoustical Society of America **25**(1), 105–113.

Hussein, L. (**1994**). "Voicing-dependent vowel duration in Standard Arabic and its acquisition by adult american students," Ph.D. thesis, The Ohio State University.

Jacewicz, E., Fox, R. A., and Lyle, S. (**2009**). "Variation in stop consonant voicing in two regional varieties of American English," Journal of the International Phonetic Association **39**(3), 313–334, doi: 10.1017/S0025100309990156.

Jarosz, A. F., and Wiley, J. (**2014**). "What are the odds? a practical guide to computing and reporting Bayes factors," The Journal of Problem Solving **7**(1), 2–9, doi: 10.7771/1932-6246.1167.

Javkin, H. R. (**1976**). "The perceptual basis of vowel duration differences associated with the voiced/voiceless distinction," Report of the Phonology Laboratory, UC Berkeley **1**, 78–92.

Keating, P. A. (**1984**). "Universal phonetics and the organization of grammars," UCLA Working Papers in Phonetics **59**.

Kerr, N. L. (**1998**). "HARKing: Hypothesizing after the results are known," Personality and Social Psychology Review **2**(3), 196–217.

Klatt, D. H. (**1973**). "Interaction between two factors that influence vowel duration," The Journal of the Acoustical Society of America **54**(4), 1102–1104.

Kluender, K. R., Diehl, R. L., and Wright, B. A. (**1988**). "Vowel-length differences before voiced and voiceless consonants: An auditory explanation.," Journal of Phonetics **16**, 153–169.

Kuznetsova, A., Bruun Brockhoff, P., and Haubo Bojesen Christensen, R. (**2017**). "`lmerTest` package: Tests in linear mixed effects models," Journal of Statistical Software **82**(13), doi: 10.18637/jss.v082.i13.

Laeufer, C. (**1992**). "Patterns of voicing-conditioned vowel duration in French and English," Journal of Phonetics **20**(4), 411–440.

Lampp, C., and Reklis, H. (**2004**). "Effects of coda voicing and aspiration on Hindi vowels," The Journal of the Acoustical Society of America **115**(5), 2540–2540.

Lehiste, I. (**1970**a). "Temporal organization of higher-level linguistic units," The Journal of the Acoustical Society of America **48**(1A), 111–111.

Lehiste, I. (**1970**b). "Temporal organization of spoken language," in *Working Papers in Linguistics*, Vol. 4, pp. 96–114.

Lindblom, B. (**1967**). "Vowel duration and a model of lip mandible coordination," Speech Transmission Laboratory Quarterly Progress Status Report **4**, 1–29.

Lisker, L. (**1974**). "On "explaining" vowel duration variation," in *Proceedings of the Linguistic Society of America*, pp. 225–232.

Luke, S. G. (**2017**). "Evaluating significance in linear mixed-effects models in R," Behavior Research Methods **49**(4), 1494–1502, doi: 10.3758/s13428-016-0809-y.

Maddieson, I., and Gandour, J. (**1976**). "Vowel length before aspirated consonants," in *UCLA Working papers in Phonetics*, Vol. 31, pp. 46–52.

Malisz, Z., and Klessa, K. (**2008**). "A preliminary study of temporal adaptation in Polish vc groups," in *Proceedings of Speech Prosody*, pp. 383–386.

Marin, S., and Pouplier, M. (**2010**). "Temporal organization of complex onsets and codas in American English: Testing the predictions of a gestural coupling model," Motor Control **14**(3), 380–407.

Marin, S., and Pouplier, M. (**2014**). "Articulatory synergies in the temporal organization of liquid clusters in Romanian," Journal of Phonetics **42**, 24–36.

Nowak, P. (**2006**). "Vowel reduction in Polish," Ph.D. thesis, University of California, Berkeley.

Peterson, G. E., and Lehiste, I. (**1960**). "Duration of syllable nuclei in english," The Journal of the Acoustical Society of America **32**(6), 693–703.

Plug, L., and Smith, R. (**2018**). "Segments, syllables and speech tempo perception" Talk presented at the 2018 Colloquium of the British Association of Academic Phoneticians (BAAP 2018).

R Core Team (**2018**). "R: A language and environment for statistical computing" R Foundation for Statistical Computing, Vienna, Austria, https://www.R-project.org.

Raftery, A. E. (**1995**). "Bayesian model selection in social research," Sociological methodology 111–163.

Raftery, A. E. (**1999**). "Bayes factors and BIC: Comment on "A critique of the Bayesian information criterion for model selection"," Sociological Methods & Research **27**(3), 411–427.

Raphael, L. J. (**1975**). "The physiological control of durational differences between vowels preceding voiced and voiceless consonants in English," Journal of Phonetics **3**(1), 25–33.

Slis, I. H., and Cohen, A. (**1969**a). "On the complex regulating the voiced-voiceless distinction I," Language and speech **12**(2), 80–102.

Slis, I. H., and Cohen, A. (**1969**b). "On the complex regulating the voiced-voiceless distinction II," Language and speech **12**(3), 137–155.

Sóskuthy, M. (**2013**). "Phonetic biases and systemic effects in the actuation of sound change," Ph.D. thesis, University of Edinburgh.

Vazquez-Alvarez, Y., and Hewlett, N. (**2007**). "The 'trough effect': an ultrasound study," Phonetica **64**(2-3), 105–121.

Wagenmakers, E.-J. (**2007**). "A practical solution to the pervasive problems of p values," Psychonomic bulletin & review **14**(5), 779–804.

Warren, W., and Jacks, A. (**2005**). "Lip and jaw closing gesture durations in syllable final voiced and voiceless stops," The Journal of the Acoustical Society of America **117**(4), 2618–2618.

Wickham, H. (**2017**). "tidyverse: Easily install and load the 'tidyverse'" R package version 1.2.1., https://CRAN.R-project.org/package=tidyverse.