

An exploratory study of voicing-related differences in vowel duration as compensatory temporal adjustment in Italian and Polish

1 **Abstract** Over a century of phonetic research has established the cross-
2 linguistic existence of the so called ‘voicing effect’, by which vowels tend to
3 be shorter when followed by voiceless stops and longer when the following
4 stop is voiced. However, no agreement is found among scholars regarding
5 the source of this effect, and several causal accounts have been advanced.
6 A notable one is the compensatory temporal adjustment account, according
7 to which the duration of the vowel is inversely correlated with the stop clo-
8 sure duration (voiceless stops having longer closure durations than voiced
9 stops). The compensatory account has been criticised due to lack of empiri-
10 cal support and its vagueness regarding the temporal interval within which
11 compensation is implemented. The results from this exploratory study of
12 Italian and Polish suggest that the duration of the interval between two
13 consecutive stop releases in CVCV words in these languages is not affected
14 by the voicing of the second stop. The durational difference of the first
15 vowel then would follow from differences in closure durations of the fol-
16 lowing stop. While other factors (like perceptual biases) could also play a
17 role in the development of the voicing effect, the data discussed here shed
18 new light on a possible production account of voicing-related differences in
19 vowel durations.

20 **1 Introduction**

21 Almost a hundred years of research have consistently shown that consonan-
22 tal voicing has an effect on preceding vowel duration: vowels followed by
23 voiced obstruents are longer than when followed by voiceless ones (Meyer
24 1904; Heffner 1937; House & Fairbanks 1953; Belasco 1953; Peterson &
25 Lehiste 1960; Halle & Stevens 1967; Chen 1970; Klatt 1973; Lisker 1974;
26 Laeufer 1992; Fowler 1992; Hussein 1994; Lampp & Reklis 2004; Warren
27 & Jacks 2005; Durvasula & Luo 2012). This so called ‘voicing effect’ has

28 been found in a considerable variety of languages.¹ These include (but are
 29 not limited to) English, German, French, Spanish, Hindi, Russian, Italian,
 30 Arabic, and Korean (see Maddieson & Gandour 1976 for a more comprehen-
 31 sive, but still not exhaustive list).² Despite of the plethora of evidence in
 32 support of the *existence* of the voicing effect, agreement hasn't been reached
 33 regarding its *source*.

34 Several proposals have been put forward in relation to the possible source
 35 of the voicing effect (see Sóskuthy 2013 and Beguš 2017 for an overview).
 36 Some of the proposed accounts place the source of the voicing effect in prop-
 37 erties of speech production. A notable production account, which will be
 38 the focus of this study, is the compensatory temporal adjustment account
 39 (Lindblom 1967; Slis & Cohen 1969b; a; Lehiste 1970b; a). According to
 40 this account, the voicing effect follows from the reorganisation of gestures
 41 within a unit of speech the duration of which is not affected by stop voicing.
 42 The duration of such unit is held constant across voicing contexts, while the
 43 duration of voiceless and voiced obstruents differs. The closure of voiceless
 44 stops is longer than that of voiced stops (Lisker 1957; Van Summers 1987;
 45 Davis & Van Summers 1989; de Jong 1991). As a consequence, vowels
 46 followed by voiceless stops (which have a long closure) are shorter than
 47 vowels followed by voiced stops (which have a short closure). Advocates
 48 of the compensatory account propose two prosodic units as the scope of
 49 the temporal adjustment: the syllable (and, equivalently, the VC sequence
 50 or vowel-to-vowel interval, Lindblom 1967; Farnetani & Kori 1986), and
 51 the word (Slis & Cohen 1969b; a; Lehiste 1970b; a). However, the com-
 52 pensatory temporal adjustment account has been criticised in subsequent
 53 work.

54 Empirical evidence and logic challenge the proposal that the syllable or
 55 the word have a constant duration and hence drive compensation. First,
 56 Lindblom's 1967 argument that the duration of the syllable is constant is
 57 not supported by the findings in Chen (1970) and Jacewicz et al. (2009).
 58 Chen (1970) rejects a syllable-based compensatory account in the light of
 59 the fact that the duration of the syllable is affected by consonant voicing.
 60 Jacewicz et al. (2009) further show that the duration of monosyllabic words

¹ One of the first attestations of the term 'voicing effect' can be attributed to Mitleb (1982). Probably Wells (1990) introduced the term 'pre-fortis clipping', which can also be found in the literature.

² A typological note: Most languages reported having a voicing effect come from the Indo-European family. Others are from a pool of widely studied languages. It is thus of vital importance that future studies look at other language families and underdocumented/underdescribed languages.

in American English changes depending on the voicing of the coda consonant. Second, although the results in [Slis & Cohen \(1969a\)](#) suggest that the duration of disyllabic words in Dutch is constant whether the second stop is voiceless or voiced, it does not follow from this fact that compensation should necessarily target the vowel preceding the stop. Indeed, it is logically possible that the following unstressed vowel could be the target of the compensation, therefore differences in preceding vowel duration still call for an explanation.

The compensatory temporal adjustment account has been further challenged on the basis of the so called ‘aspiration effect’ ([Maddieson & Gandour 1976](#)), by which vowels are longer when followed by aspirated stops than when followed by unaspirated stops. In Hindi, vowels before voiceless unaspirated stops are short, vowels followed by voiced aspirated stops are long, and vowels followed by voiced unaspirated and voiceless aspirated stops are in between and have similar durations. [Maddieson & 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 consonants are different. [Maddieson & Gandour \(1976\)](#) argue that a compensatory explanation for differences in vowel duration cannot be maintained.

However, a re-evaluation of the way consonant duration is measured in [Maddieson & Gandour \(1976\)](#) might actually turn their findings in favour of a compensatory account. Due to difficulties in detecting the release of the consonant of interest, consonant duration in [Maddieson & Gandour \(1976\)](#) is measured from the closure of the relevant consonant to the release of the following, (e.g., in *ab sāth kaho*, the duration of /t^h/ in *sāth* is calculated as the interval between the closure of /t^h/ and the release of /k/). This measure includes the burst and aspiration (if present) of the consonant following the target vowel. [Slis & Cohen \(1969b\)](#), however, state that the inverse relation between vowel duration and the following consonant applies to *closure* duration, and not to the entire *consonant* duration.³ If an inverse relation exists between vowel and closure duration, the inclusion of burst and/or aspiration clearly alters this relationship.

Indeed, the study on Hindi voicing and aspiration effects conducted by [Durvasula & Luo \(2012\)](#) indicates that closure duration, measured from closure onset to closure offset, decreases according to the hierarchy voiceless

³ In this paper, I use the term *relation* to mean a categorical pattern of entailment (like in ‘a long vowel entails a short closure’), while the term *correlation* is reserved to a statistical correlation of two continuous variables.

unaspirated > voiced unaspirated > voiceless aspirated > voiced aspirated, which closely resembles the order of increasing vowel duration in Maddieson & Gandour (1976). Nonetheless, Durvasula & Luo (2012) do 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 voicing and aspiration are taken into account. However, as noted in Beguš (2017), it is likely that this result is a consequence of not controlling for speech rate. A small negative effect of closure duration can turn positive if the effect of speech rate (which is positive) is greater, given the cumulative nature of these effects (Beguš 2017: p. 2177).

de Jong (1991) finds partial support for a compensatory mechanism between vowel and closure duration in an electro-magneto-articulometric study of two American English speakers. The duration of vowels in nuclear accented, pre-, and post-nuclear accented position is weakly negatively correlated with closure duration (the slope coefficients range between -0.12 and -0.35, meaning that the amount of durational compensation is between 10% and 35%). Although it is difficult to draw definite conclusions based on the data of two speakers, and while the magnitude of the correlation is quite weak to univocally support compensation, the direction of the correlation is correct (i.e. a negative correlation).

Further evidence for a compensatory account and a negative correlation between vowel and closure duration comes from the effect of a third type of consonants, namely ejectives. Beguš (2017) finds that in Georgian (which contrasts aspirated, voiced, and ejective consonants) 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 the reversed pattern: closure is short in voiced stops, longer in ejectives, and longest in voiceless aspirated stops. Moreover, vowel duration is inversely correlated with closure across the three phonation types. Beguš (2017) mentions the possibility that the negative correlation is an artefact of the vowel and closure intervals sharing a boundary. This annotation bias could generate negative correlations (by which the vowel would shorten and the closure would lengthen by the same amount when, for example, the boundary is placed to the left of the ‘actual’ boundary). However, Beguš shows with a cross-annotator analysis that this was not the case. Moreover, I would like to add that, if misplacement of the V-C boundary is due to random error (which is a neutral assumption to make), the measured displacement from the ‘actual’ boundary will approximately follow a normal distribution with mean 0. Beguš (2017) argues that these findings support a

temporal compensation account (although not univocally, see [Beguš 2017: Section V](#)).

To summarise, a compensatory temporal adjustment account has been proposed as the pathway to the emergence of the voicing effect. According to such account, the difference in vowel duration before consonants varying in voicing (and possibly other phonation types) is the outcome of a compensation between vowel and closure duration. After reviewing the critiques advanced by [Chen \(1970\)](#) and [Maddieson & Gandour \(1976\)](#), and in face of the results in [Slis & Cohen \(1969a\)](#), [de Jong \(1991\)](#) and [Beguš \(2017\)](#), a temporal compensation account gains credibility. However, issues about the actual implementation of the compensation mechanism still remain. In conclusion, while the compensatory temporal adjustment account is plausible on the light of the reviewed literature, we are still left with the necessity of identifying a speech interval the duration of which is not affected by the voicing of the post-vocalic consonant, and within which compensation can be logically implemented.

1.1 The present study

This paper reports on selected results from a broader exploratory study that investigates the relationship between vowel duration and consonant voicing from both an acoustic and 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.⁴ This study, in its exploratory nature, was not designed to test the compensatory account, but rather to collect synchronised articulatory and acoustic data on the voicing effect. Moreover, the design of the study has been constrained by the use of ultrasound articulatory techniques (see Section 2). Since the tongue imaging and electroglottographic data don't bear on the main argument put forward here, only the results from acoustics will be discussed.

Italian and Polish reportedly differ in the magnitude (or presence) of the effect of stop voicing on vowel duration, while they are both classified as voicing languages (languages in which the laryngeal opposition in consonants is between voiceless unaspirated and voiced consonants, [Beckman](#)

⁴ As per [Cysouw & Good \(2013\)](#), the glossonyms *Italian* and *Polish* as used here to refer, respectively, to the languoids Italian [GLOTTOCODE: ital1282] and Polish [GLOTTOCODE: poli1260].

et al. 2013).⁵ For this reason, these two languages offer the opportunity to investigate differences that could reveal mechanisms underlying the voicing effect. Moreover, given that Italian and Polish share—on a general level—some features of the segmental and prosodic make-up of their phonological systems, the design of the experimental material and comparison of the results is facilitated.

Italian has been unanimously reported as a voicing-effect language (Caldognetto et al. 1979; Farnetani & Kori 1986; Esposito 2002). The mean difference in vowel duration when followed by voiceless vs. voiced consonants ranges between 22 and 24 ms in these studies, with longer vowels followed by voiced consonants. The mean differences are based on 3 speakers in Farnetani & Kori 1986 and 7 speakers in Esposito 2002. Caldognetto et al. 1979 does not report estimates of vowel duration, just the direction of the effect, but the study is based on 10 speakers. On the other hand, the results regarding the presence and magnitude of the effect in Polish 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. Malisz & Klessa (2008) argue based on data from 40 speakers that the magnitude of the voicing effect in Polish is highly idiosyncratic, and claim that their results are inconclusive on this matter. While they do not report estimates from the 40 speakers, a table with mean vowel durations from 4 suggests a mean difference before voiceless vs. voiced stops of 3.5 ms.

The acoustic data from the exploratory study discussed here suggests that (1) a voicing effect can be detected both in Italian and Polish, and that (2) the duration of the interval between two consecutive stop releases (the release to release interval) is not affected by the voicing of the second consonant in both languages. This finding is compatible with a compensatory temporal adjustment account by which the timing of the closure onset of the stop following the vowel within said interval determines the respective durations of vowel and closure.

⁵ Note that, while Polish neutralises the voicing contrast word-finally, it is maintained word-medially.

2 Method

2.1 Participants

For this exploratory study, a target of 10 speakers per language was set. A low target number of participants was required to keep the time needed for processing the ultrasound data at manageable levels, since it generally requires more time than in more standard acoustic analysis. The stopping rule for recruitment was to reach 10 speakers in both languages or to end data collection within 15 months from the start. This rule was chosen to comply with resources and time limits. Participants were sought in Manchester (UK), and in Verbania (Italy). Seventeen subjects in total participated in this study. Eleven subjects are native speakers of Italian (5 female, 6 male), while six are native speakers of Polish (3 female, 3 male). The Italian speakers are from the North and Centre of Italy (8 speakers from Northern Italy, 3 from Central Italy). The Polish group has 2 speakers from Western Poland, 3 speakers from Central Poland, and 1 speaker from Eastern Poland. For more information on the sociolinguistic details of the speakers, see Appendix B. Ethical clearance for this study was obtained from the University of Manchester (REF 2016-0099-76). The participants signed a written consent and received a monetary compensation of £10.

2.2 Equipment

The acquisition of the audio signal was achieved with the software Articulate Assistant Advanced™ (AAA, v2.17.2, [Articulate Instruments Ltd™ 2011](#)) running on a Hewlett-Packard ProBook 6750b laptop with Microsoft Windows 7. Audio recordings were sampled at 22050 Hz (16-bit) and saved in a proprietary format (.aa0). A FocusRight Scarlett Solo pre-amplifier and a Movo LV4-O2 Lavalier microphone were used for audio recording. The microphone was placed at the level of the participant's mouth on one side, at a distance of about 10 cm. The microphone was clipped onto a metal headset worn by the participant, which was part of the ultrasonic equipment.

2.3 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.).⁶ Most are nonce words, although inevitably some combinations produce 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 be imaged with UTI, since their articulation involves tongue surface 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 & Hewlett 2007](#)). The number of target words was kept low to reduce the time required for completing the task, since the ultrasonic equipment can get very uncomfortable for the speaker when worn for more than 15/20 minutes.

The target words were embedded in a frame sentence. Controlling for meaning, segmental and prosodic make-up between languages proved to be difficult. The frames are *Dico X lentamente* ‘I say X slowly’ in Italian (following [Hajek & Stevens 2008](#)), and *Mówię X teraz* ‘I say X now’ in Polish. These sentences were chosen in order to maintain a similar intonation contour across languages.

2.4 Procedure

The participant was asked to read the sentences with the target words which were presented on the computer screen. The order of the sentences was randomised for each participant. Participants 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. The reading task lasted between 15 and 20 minutes, with optional short breaks

⁶ Italian has both a mid-low [ɔ] and a mid-high [o] back vowel in its vowel inventory. These vowels are traditionally described as two distinct phonemes ([Krämer 2009](#)), although both their phonemic status and their phonetic substance are subject to a high degree of geographical and idiosyncratic variability ([Renwick & Ladd 2016](#)). As a rule of thumb, stressed open syllables in Italian (like the ones used in this study) have [ɔ:] (vowels in penultimate stressed open syllables are long) rather than [o:] ([Renwick & Ladd 2016](#)). On the other hand, Polish has only a mid-low back vowel phoneme /ɔ/ ([Gussmann 2007](#)). For sake of typographical simplicity, the symbol /o/ will be used here for both languages.

Table 1: Criteria for the identification of acoustics landmarks .

landmark		criteria
vowel onset	(V1 onset)	Appearance of higher formants in the spectrogram following the release 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)

between one repetition and the other. The total session time was around 45 minutes. Before the start of the experiment, the participants were spoken to in their mother tongue to try and reduce exposition to English prior to being recorded. Instructions were also given in their respective mother tongues. Each speaker read a total of 12 sentences for 6 times (with the exceptions of IT02, who repeated the 12 sentences 5 times), which yields to a grand total of 1212 tokens (792 from Italian, 420 from Polish).⁷

The experiment was carried out in two locations: in the sound attenuated booth of the Phonetics Laboratory at the University of Manchester (directed by Dr. Patrycja Strycharczuk), and in a quiet room in a field location in Italy (Verbania, Northern Italy). In both locations the equipment and procedures were the same. Data collection started in December 2016 and ended in March 2018.

2.5 Data processing and measurements

The audio recordings were exported from AAA in the .wav format at the same sample and bit rate 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

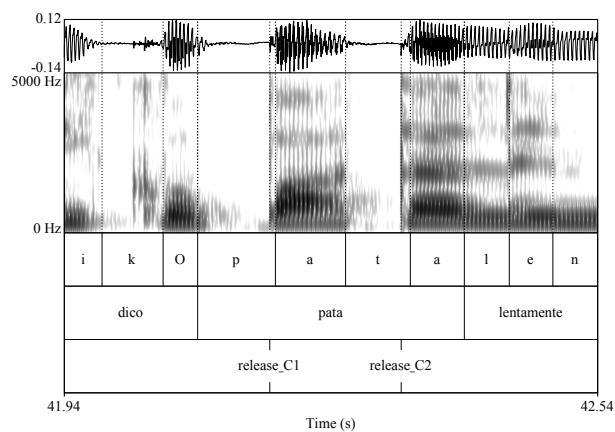
⁷ IT01 and IT02 (the first two participants of this study) also read sentences with words starting with /b/, which were later excluded from the experimental design. The data from /b/-initial words are not included in the analysis reported in this paper.

annotation was manually corrected for the relevant boundaries, according to the criteria in Table 1 based on Machač & Skarnitzl (2009). Segmentation boundaries not used in the analyses have not been checked to speed up processing. The releases of C1 and C2 were detected automatically by means of a Praat scripting implementation of the algorithm described in Ananthapadmanabha et al. (2014), and subsequently corrected if necessary. The identification of the stop release was not possible in 99 tokens (8%) of C1 and 265 tokens (22%) of C2 out of 1212. This was due either to the absence of a clear burst in the waveform and spectrogram, or the realisation of voiced stops as voiced fricatives. Most of the fricativised tokens come from three speakers of Central Italian, IT12, IT13, and IT14, a variety of Italian known to show processes of lenition (Hualde & Nadeu 2011). Moreover IT12 and IT14 produced several tokens of voiceless stops with voicing during closure (in some cases the closure was completely voiced). These tokens have been used in the analyses, because (1) the actual presence or absence of voicing during closure does not bear on the compensatory account discussed here (which concerns supraglottal gestures) and laryngeal gestures can be implemented almost entirely independently from oral gestures, and (2) the voicing effect has been shown to exist even in whispered speech, where vocal fold vibration is entirely absent (Sharf 1964).

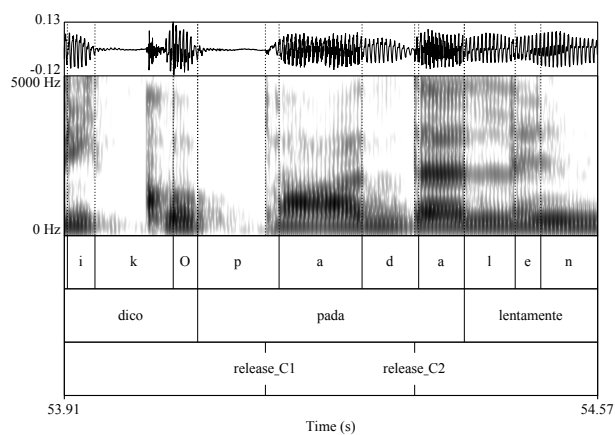
The durations in milliseconds of the following intervals were extracted with a series of custom Praat scripts from the annotated acoustic landmarks: word duration, vowel duration (V1 onset to V1 offset), consonant closure duration (V1 offset to C2 release), and release to release duration (C1 release to C2 release). Sentence duration was measured in seconds. 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 & Smith 2018), and was calculated as the number of syllables divided by the duration of the sentence in seconds (8 syllables in Italian, 6 in Polish). All further data processing and visualisation was done in R v3.5.1 (R Core Team 2018; Wickham 2017).

2.6 Statistical analysis

Given the data-driven nature of the study, all statistical analyses reported here are to be considered exploratory (hypothesis-generating) rather than confirmatory (hypothesis-driven, Kerr 1998; Gelman & Loken 2013; Roettger 2018). The durational measurements were analysed with linear mixed-effects models using lme4 v1.1-19 in R (Bates et al. 2015), and model es-



(a) /pata/



(b) /pada/

Figure 1: Segmentation example of the words *pata* and *pada* uttered by the Italian speaker IT09 (the times on the x-axis refer to the times in the concatenated audio file).

estimates were extracted with the `effects` package v4.0-3 (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). Speech rate has been centred when included in the models to make the intercept estimates more interpretable. The models were fitted by Restricted Maximum Likelihood estimation (REML). 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 ($\alpha = 0.05$). The choice of not using likelihood ratio tests for statistical inference is based on Luke (2017) who argues that this approach can lead to inflated Type I error rates. In any case, Luke (2017: 1501) also warns that 'results [from mixed-effects models] should be interpreted with caution, regardless of the method adopted for obtaining *p*-values'.

Bayes factors were used to test whether word and release to release 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 the Maximum Likelihood estimation (ML, Bates et al. 2015: 34). The Bayes Information Criterion (BIC) approximation was then used to obtain Bayes factors (Raftery 1995; 1999; Wagenmakers 2007; Jarosz & Wiley 2014). The approximation is calculated according to the equation in 1 (Wagenmakers 2007: 796).

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

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): 1–3 = weak evidence, 3–20 = positive evidence, 20–150 = strong evidence, > 150 = very strong evidence.

The extracted measurements were filtered before statistical analysis. Measures of vowel duration, closure duration, word duration, and release to release duration that are 3 standard deviations lower or higher than the respective means were excluded from the final dataset (this procedure generally corresponds to a loss of around 2.5% of the data). One sentence (sentence 48 of IT07, *Dico pada lentamente*) included a speech error and has been excluded. After excluding missing measurements, these operations

yield a total of 920 tokens of vowel and closure durations, 1176 tokens of word duration, and 848 tokens of release to release duration.

While the study has been devised to also allow comparison between Italian and Polish, the low number of Polish speaker (6, against 11 Italian speakers) makes statistical comparison difficult (see Kirby & Sonderegger 2018 and references therein for a discussion on statistical power). The raw mean differences, presented in conjunction with the estimates from statistical modelling, can still inform us on the cross-linguistic differences and thus they will contribute to the discussion of the results.

2.7 Open Science statement

Following recommendations for Open Science in Crüwell et al. (2018) and Berez-Kroeker et al. (2018) the data and code used to produce the analyses discussed in this paper are available on the Open Science Framework at https://osf.io/bfyhr/?view_only=391ef2dcc2834039a90f739ddb6f137a (Coretta 2018).

3 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. The full output of statistical models (including confidence intervals and p -values) are given in Appendix A.

3.1 Vowel duration

Figure 2 shows boxplots and raw data of vowel duration for the three vowels /a, o, u/ when followed by voiceless or voiced stops in Italian and Polish. Vowels tend to be longer when followed by a voiced stop in both languages. The effect appears to be greater in Italian than in Polish, especially for the vowels /a/ and /o/. There is no evident effect of C2 voicing in /u/ in Italian, but the effect is discernible in Polish /u/. In Italian, vowels have a mean duration of 106.16 ms (SD = 27.08) before voiceless stops, and a mean duration of 117.66 ms (SD = 34.63) before voiced stops. Polish vowels are on average 75.57 ms long (SD = 16.16) when followed by a voiceless stop, and 83.11 ms long (SD = 19.37) if a voiced stop follows. The difference in

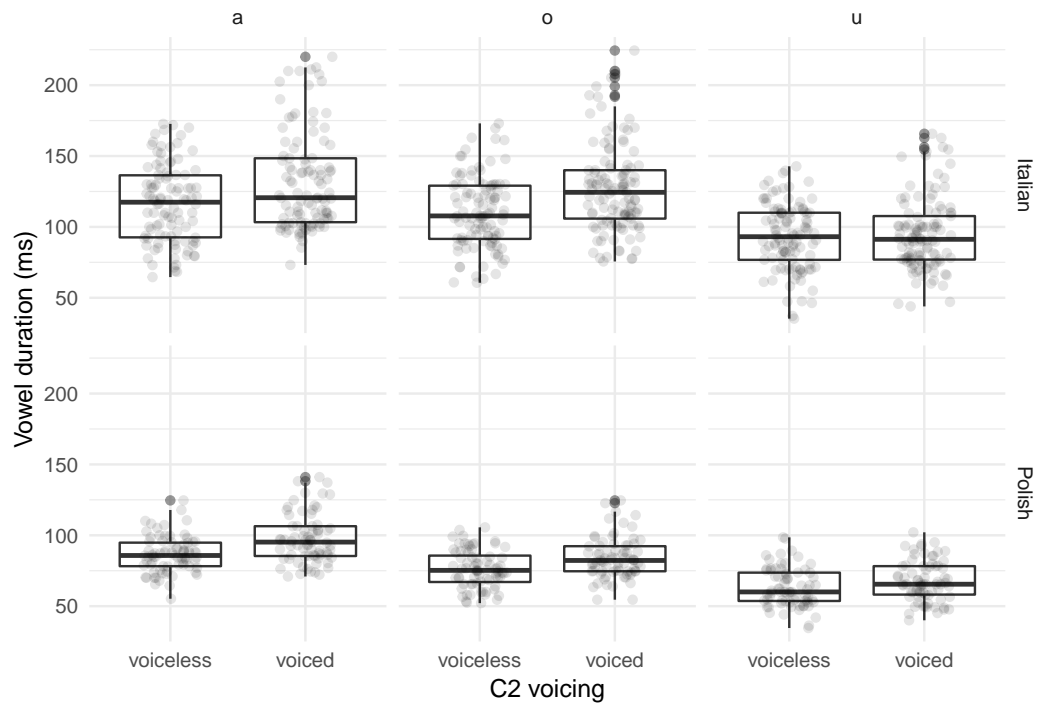


Figure 2: Raw data and boxplots of the duration in milliseconds of vowels in Italian (top row) and Polish (bottom row), for the vowels /a, o, u/ when followed by a voiceless or voiced stop.

vowel duration based on the raw means is 11.5 ms in Italian and 7.54 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, centred); by-speaker and by-word random intercepts 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, C2 place, vowel, language, and speech rate. Only the interaction between C2 voicing and vowel is significant. Vowels are 16.28 ms longer (SE = 4.42) when followed by a voiced stop (C2 voicing), and 8 ms shorter (SE = 1.63) when followed by a velar stop. The effect of C2 voicing is smaller with /u/ (around 3 ms, $\hat{\beta} = -13.1$ ms, SE = 5.56). Polish has on average shorter vowels than Italian ($\hat{\beta} = -24.05$ ms, SE = 7.83), and the effect of voicing is estimated to be about 10.55 ms (although note that the interaction between language and C2 voicing is not significant). Speech rate has a negative effect on vowel duration, such that faster rates correlate with shorter vowel durations ($\hat{\beta} = -16.23$ ms, SE = 1.26).

3.2 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 106.16 ms long (SD = 27.08), while the voiced stops have a mean closure duration of 117.66 ms (SD = 34.63). In Polish, the closure duration is 75.57 ms (SD = 16.16) in voiceless stops and 83.11 ms (SD = 19.37) in voiced stops. The difference in closure duration based on the raw means is 13.33 ms in Italian and 10.87 ms in Polish. The same model specification as with vowel duration has been fitted with consonant closure duration 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).

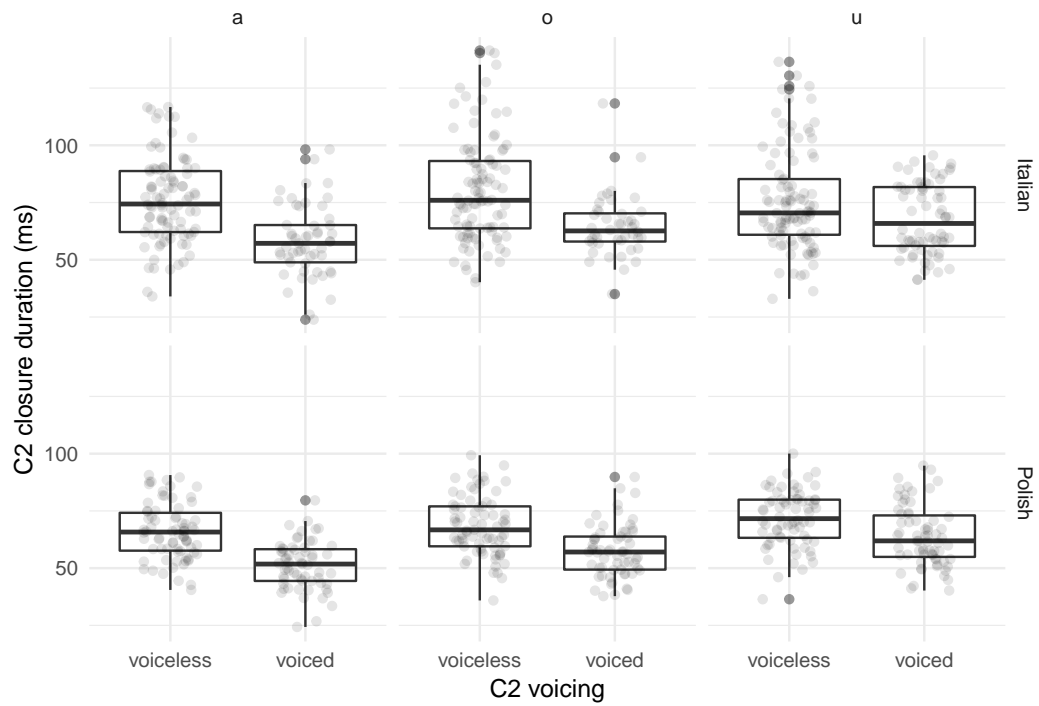


Figure 3: Raw data and boxplots of closure duration in milliseconds of voiceless and voiced stops in Italian (top row) and Polish (bottom row) when preceded by the vowels /a, o, u/.

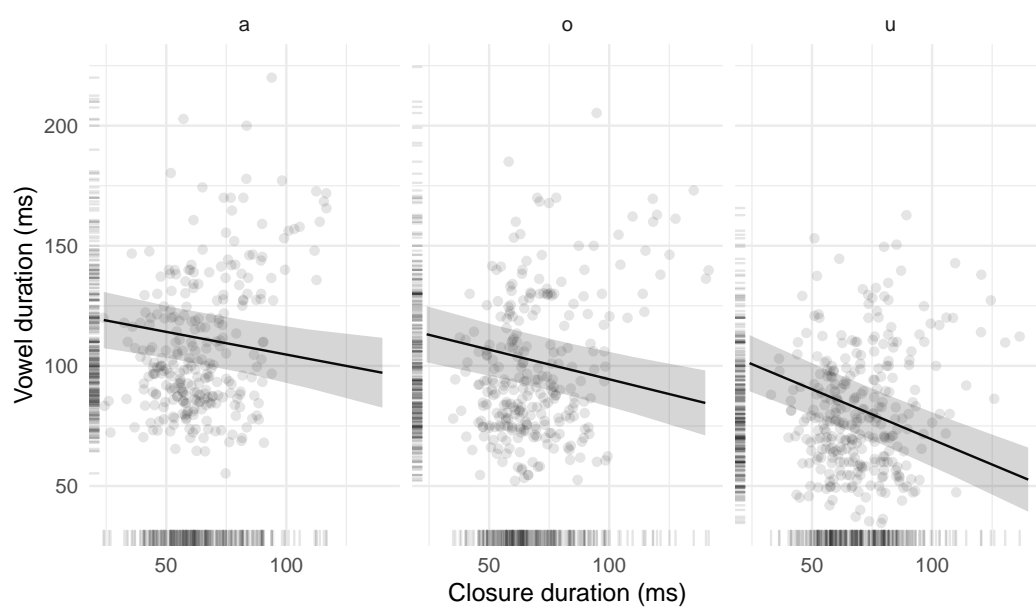


Figure 4: Raw data, estimated regression lines, and 95 per cent confidence intervals of the effect of closure duration on vowel duration for the vowels /a, o, u/ (from a mixed-effects model fitted to data pooled from Italian and Polish, see text for details).

422 **3.3 Vowel and closure duration**

423 A model addressing the relationship between vowel and stop closure dura-
 424 tion was fitted with the following terms and interactions: vowel duration
 425 as the outcome variable; as fixed effects, closure duration, vowel, speech
 426 rate (centred); all logical interactions between closure duration, vowel, and
 427 speech rate; by-speaker and by-word random intercepts. Closure duration
 428 has a significant effect on vowel duration ($\hat{\beta} = -0.19$ ms, SE = 0.06 ms).
 429 The effect with /u/ is greater than with /a/ and /o/ ($\hat{\beta} = -0.23$ ms, SE =
 430 0.08 ms). In general, closure duration is inversely proportional to vowel
 431 duration. However, such correlation is quite weak, as shown by the small
 432 estimates. A 1 ms increase in closure duration corresponds to a 0.2–0.45
 433 ms decrease in vowel duration. These estimates can be interpreted in terms
 434 of percentages of compensation, which range between 20 and 45%. Faster
 435 speech rates elicit a bigger effect than lower speech rates, as indicated by the
 436 significant interaction between closure duration and speech rate ($\hat{\beta} = -0.2$
 437 ms, SE = 0.06 ms). The effect of the interaction is reduced when the vowel
 438 is /u/ ($\hat{\beta} = 0.17$ ms, SE = 0.08 ms). Figure 4 shows for each vowel /a, o,
 439 u/ the individual data points and the regression lines with 95% confidence
 440 intervals extracted from the mixed-effects model.

441 **3.4 Word duration**

442 Words with a voiceless C2 are on average 393.72 ms long (SD = 79.05) in
 443 Italian and 387.72 ms long (SD = 73.45) in Polish. Words with a voiced
 444 stop have a mean duration of 357.07 ms (SD = 39.14) in Italian and 361.87
 445 ms (SD = 38.51) in Polish. The following full and null models were fitted
 446 to test the effect of C2 voicing on word duration. The full model is made
 447 up of the following fixed effects: C2 voicing, C2 place, vowel, language,
 448 and speech rate. The model also includes by-speaker and by-word random
 449 intercepts, and a by-speaker random slope for C2 voicing. The null model
 450 is the same as the full model with the exclusion of the fixed effect of C2
 451 voicing. The Bayes factor of the null against the full model is 19. Thus, the
 452 null model (in which there is no effect of C2 voicing, $\beta = 0$) is 19 times
 453 more likely under the observed data than the full model. This indicates that
 454 there is positive evidence for a null effect of C2 voicing on word duration.

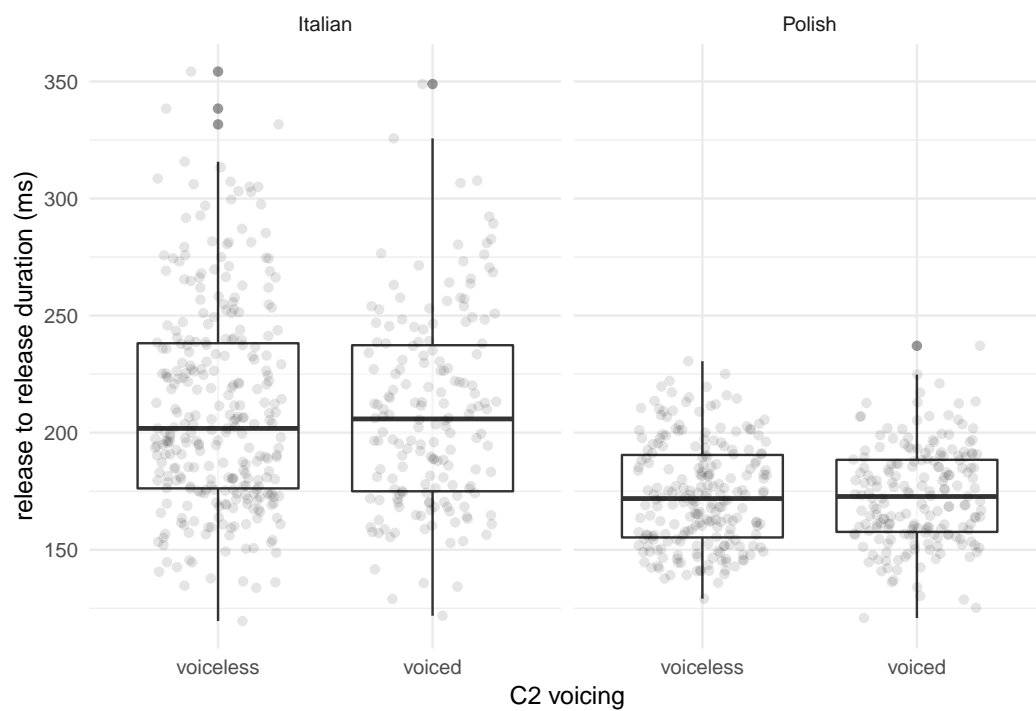


Figure 5: Raw data and boxplots of the duration in milliseconds of the release to release interval in Italian (left) and Polish (right) when C2 is voiceless or voiced.

455 **3.5 Release to release interval duration**

456 In Figure 5, boxplots and raw data points show the duration of the release to
 457 release interval in words with a voiceless vs. a voiced C2 stop, in Italian and
 458 Polish. It can be seen that the distributions, medians, and quartiles of the
 459 durations in the voiceless and voiced condition do not differ much in either
 460 language. In Italian, the mean duration of the release to release interval is
 461 209.88 ms (SD = 43.84) if C2 is voiceless, and 208.6 ms (SD = 41.34) if
 462 voiced. In Polish, the mean durations are respectively 173.13 (SD = 22.44)
 463 and 172.67 (SD = 20.47) ms. The specifications of the null and full models
 464 for the release to release duration are the same as for word duration. The
 465 Bayes factor of the null model against the full model is 21, which means that
 466 the null model (without C2 voicing) is 21 times more likely than the model
 467 with C2 voicing as a predictor. The Bayes factor suggests there is strong
 468 evidence that duration of the release to release interval is not affected by
 469 C2 voicing.

470 **4 Discussion**

471 An exploratory study of articulatory and acoustic aspects of the effect of
 472 consonant voicing on vowel duration in Italian and Polish has been carried
 473 out to look for a possible source of such effect in speech production. Only
 474 the results from the acoustic part of the study bear on the main argument
 475 of this paper. The following sections discuss, in turn, the results regard-
 476 ing the effect of voicing on vowel duration in Italian and Polish and how
 477 the finding that the duration of the interval between the two consecutive
 478 consonant releases in CVCV words is compatible with a compensatory tem-
 479 poral adjustment account of the voicing effect. The section concludes by
 480 discussing the limitations and open issues of this study.

481 **4.1 Voicing effect in Italian and Polish**

482 The results of vowel duration and C2 voicing indicate that vowels are longer
 483 when followed by voiced then when followed by voiceless stops both in
 484 Italian and Polish. The estimated effect is around 16 ms when C2 is voiced
 485 for Italian. This value is not too far from the estimates of previous works
 486 on this language (Caldognetto et al. 1979; Farnetani & Kori 1986; Esposito
 487 2002), the range of which is between 22 and 24 ms. The higher estimates
 488 of these studies compared to the one here could be related to differences

in experimental design, or Type M (magnitude) errors due to low statistical power in previous studies (see Kirby & Sonderegger 2018). The estimate of the effect of voicing on C2 closure duration is around -18 ms. Crucially, the effect of voicing on vowel and closure duration have similar magnitudes, but opposite signs. These results suggest a compensatory mechanism between vowel and closure duration.

Furthermore, the effect of voicing on the duration of Italian /u/ is smaller than with /a/ and /o/ (about 3 vs. 16 ms respectively), a fact already observed by Ferrero et al. 1978. While it is not clear why the duration of this particular vowel should not be affected by C2 voicing, the data reported here indicate that the magnitude of the difference in closure duration when the preceding vowel is /u/ is smaller than with /a/ and /o/ (about 7 vs. 17 ms respectively). If vowel duration compensates for closure duration, then a smaller difference in closure duration should correspond to a small difference in vowel duration, as the estimates seem to suggest.

The interpretation of the Polish results is less straightforward. Previous studies found either no voicing effect or a small effect in Polish (3.5–4.5 ms). In particular, Malisz & Klessa (2008) say that the effect seems to be very idiosyncratic in the 40 speakers of their analysis. The estimated effect found in the 6 Polish speakers of the present study is 10.54 ms, and the difference based on the means of the raw vowel durations is 7.5 ms. Recall, however, that the interaction between language and C2 voicing (which gives the estimate of 10.54) is not significant (see the full model summary in Table 2). It is likely, though, that the non-significance might be related to low power. Indeed, only 6 Polish speakers have been recorded, against 11 speakers of Italian. The raw mean difference of 7.5 ms in Polish—although still higher than what found in previous studies—might be more informative in this case.

More specifically, when one compares the raw mean duration differences of vowels with the raw mean duration differences of consonant closures, a pattern can be seen. The mean differences of Italian vowels and closures (11.5 and 13.33, respectively) are bigger than those of Polish (7.54 and 10.87), although by a small amount (about 3 ms). It is plausible that the smaller effect of C2 voicing on preceding vowel duration in Polish is related to the smaller effect on closure duration, if we assume a temporal mechanism of compensation between the closure and the vowel. Of course these patterns need to be confirmed with a more balanced sample of Italian and Polish speakers.

527 **4.2 Compensatory temporal adjustment**

528 Vowels followed by voiced stops are long, while vowels followed by voice-
529 less stops are short. The closure duration of voiced stops is short compared
530 to that of voiceless stops. There seems to be an inverse relationship between
531 vowel duration and closure duration, by which a long vowel entails a short
532 closure (and vice versa), and a short vowel entails a long closure (and vice
533 versa).

534 The data and statistical analyses of this exploratory study suggest that
535 the duration of the interval between the releases of two consecutive con-
536 sonants in CVCV words (the release to release interval) is not affected by
537 the phonological voicing of the second consonant (C2) in Italian and Pol-
538 ish. In accordance with a compensatory temporal adjustment account (Slis
539 & Cohen 1969a; Lehiste 1970b), the difference in vowel duration before
540 voiceless vs. voiced stops can be seen as the outcome of differences in stop
541 closure duration. In other words, the timing of the (acoustic) closure on-
542 set of C2 within the temporally stable release to release interval determines
543 the duration of the preceding vowel. An earlier closure onset relative to
544 the onset of the preceding vowel (like in the case of voiceless stops) causes
545 the vowel to be shorter. On the other hand, a later closure onset (like with
546 voiced stops) produces a longer vowel. Note that the term ‘temporal stabil-
547 ity’ (and ‘temporally stable’) as used here means that the underlying statisti-
548 cal distribution of the interval duration is stable *across contexts of C2 voicing*.
549 No specific statement is implied about the variance of the duration around
550 the mean, across or within phonological contexts. Figure 6 illustrates the
551 compensatory mechanism.

552 The invariance of the release to release interval allows us to refine the
553 logistics of the compensatory account by narrowing the scope of the tem-
554 poral adjustment action. A limitation of this account, as proposed by Slis
555 & Cohen (1969a) and Lehiste (1970b), is the lack of a precise identifica-
556 tion of the word-internal mechanics of compensation. As already discussed
557 in Section 1, it is not clear why the adjustment should target the preced-
558 ing stressed vowel, rather than the following unstressed vowel or any other
559 segment in the word. Since the release to release interval includes just the
560 vocoid gesture between the release of C1 and the onset of the closure of C2
561 and the consonant closure, it follows that differences in closure duration
562 must be reflected in differences in the duration of the preceding vocoid. It
563 is worth noting, though, that other accounts—which could be compatible
564 with other aspects of production and perception—aren’t ultimately ruled
565 out. For example, perceptual factors might play a role in the enhancement

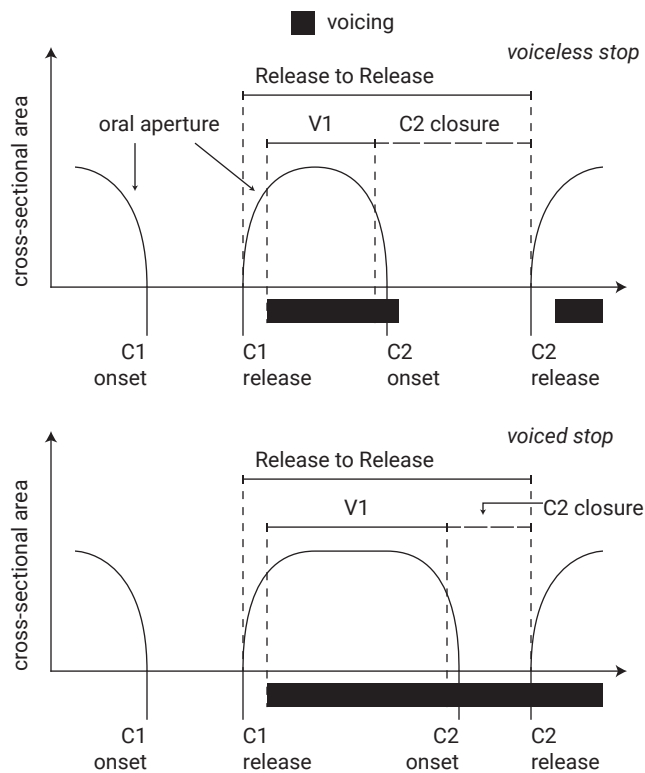


Figure 6: A schematic representation of the oral cavity cross-sectional area, as inferred from acoustics. Design based on [Esposito \(2002\)](#). The top panel shows a CVC sequence with a voiceless C2, the bottom panel with a voiced C2. Oral cavity aperture (on the y-axis, as the inverse of oral constriction) through time (on the x-axis) is represented by the black line. 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.

of the effect (see Kingston & Diehl 1994, Port & Dalby 1982, and Luce & Charles-Luce 1985). Other perceptual explanations of the voicing effect have been proposed in Javkin (1976) and Kluender et al. (1988).

Under an account of temporal compensation, the voicing effect can be interpreted as a by-product of gestural phasing, rather than a consequence of intrinsic features of voicing *per se*. The temporal stability of the release to release interval across voicing contexts allows us to refine the compensatory mechanism by providing a temporal anchor. On the other hand, it is important to note that the release to release interval should not necessarily have a special status in such compensatory account, but rather can be used as a proxy to the understanding of a full gestural mechanism of compensation. Indeed, the temporal stability of this interval should be derivable from a theory of gestural phasing, rather than one that simply states that the interval is stable across voicing contexts. While beyond the scope of this paper, work on the gestural coordination of sequences besides the traditional syllable might reveal a principled organisation that results in the temporal patterns observed in this study.

4.3 *Limitations and future work*

The generalisations put forward in this paper strictly apply to disyllabic words with a stressed vowel in the first syllable, flanked by single stops. First, it is possible that the 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 vowels preceding pre-stress stops have slightly different durations (Davis & Van Summers 1989). According to the interpretation given here, the absence of differences in closure duration should correspond to the absence of differences in vowel duration. Second, it is known that the magnitude of the effect of voicing is modulated by other prosodic characteristics, like the number of syllables in the word, presence/absence of focus, and position within the sentence (Sharf 1962; Klatt 1973; Laeuffer 1992; de Jong 2004). Third, the constraints on experimental material enforced by the use of ultrasound tongue imaging have been previously mentioned in Section 2.3. Given these constraints, temporal information from other vowels (like front vowels), places and manners of articulation is a desideratum. Data from different contexts and different languages is thus needed to assess the generality of the claims put forward in this paper.

Another issue is the interaction of the temporal compensation and speech rate. The magnitude of compensation between vowel and closure duration found in [de Jong \(1991\)](#) and here is somewhat small (between 12% and 40%). Ideally, given the temporal stability of the release to release interval relative to C2 voicing, the compensation rates should approximate 100%. However, it is possible that the correlation between vowel and closure duration is modulated in complex ways by the individual effects of speech rate on the vowel and the closure. For example, [Ko \(2018\)](#) finds that the vowel/closure ratio differs depending on speaking rate and that there is an interaction between the voicing of the consonant and speaking rate. When the consonant is voiceless, the vowel/closure ratio is smaller when speaking rate is slow, while slow speaking rate induces larger vowel/closure values when the consonant is voiced. Experimental work is required which addresses the differential effect of speaking rate on vowel and consonant closures, and how these interact with a possible compensatory mechanism.

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 & 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 also have to investigate the durational invariance of speech intervals in relation to a variety of phonation contrasts.

5 Conclusions

The results of an exploratory study on the effect of voicing on vowel duration are congruent with a compensatory temporal adjustment account of such effect. Acoustic data from seventeen speakers of Italian and Polish show that the temporal distance between two consecutive stop releases is not affected by the voicing of the second stop in CVCV words. The temporal invariance of the release to release interval, together with a difference in stop closure duration of voiceless and voiced stops, causes vowels to be shorter when followed by voiceless stops (which have a long closure) and longer when followed by voiced stops (the closure of which is short). Future work will need to investigate further aspects of the patterns found in this study, with a particular focus on the effects of different segmental and

Table 2: Summary of the linear mixed-effects model fitted to vowel duration (see Section 3.1).

Predictor	Estimate	SE	CI low	CI up	df	t-value	p-value	< α
Intercept	118.06	4.94	108.38	127.74	23.89	23.91	0.00	*
Voicing = voiced	16.28	4.42	7.62	24.95	15.38	3.68	0.00	*
Vowel = /o/	-7.50	3.93	-15.21	0.21	10.31	-1.91	0.08	
Vowel = /u/	-25.71	3.94	-33.44	-17.98	10.43	-6.52	0.00	*
Lang = Polish	-24.05	7.83	-39.40	-8.69	22.38	-3.07	0.01	*
Place = velar	-7.95	1.63	-11.15	-4.75	10.99	-4.87	0.00	*
Speech rate	-16.23	1.26	-18.69	-13.77	854.63	-12.91	0.00	*
Voiced \times /o/	2.09	5.54	-8.77	12.96	10.18	0.38	0.71	
Voiced \times /u/	-13.09	5.56	-23.99	-2.20	10.30	-2.36	0.04	*
Voiced \times Polish	-5.73	6.61	-18.69	7.23	18.00	-0.87	0.40	
/o/ \times Polish	-2.50	5.66	-13.60	8.60	11.09	-0.44	0.67	
/u/ \times Polish	1.12	5.68	-10.01	12.26	11.23	0.20	0.85	
Voiced \times /o/ \times Polish	-6.16	8.00	-21.85	9.53	11.06	-0.77	0.46	
Voiced \times /u/ \times Polish	6.40	8.03	-9.34	22.13	11.19	0.80	0.44	

639 prosodic structures and different laryngeal contrasts on the release to re-
 640 lease interval.

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651 **A Output of statistical models**

652 See Table 2, Table 3, and Table 4.

653 **B Socio-linguistic information of participants**

654 See Table 5.

Table 3: Summary of the linear mixed-effects model fitted to closure duration (see Section 3.2).

Predictor	Estimate	SE	CI low	CI up	df	t-value	p-value	< α
Intercept	73.25	4.28	64.86	81.63	22.38	17.11	0.00	*
Voicing = voiced	-17.70	4.06	-25.66	-9.74	18.63	-4.36	0.00	*
Vowel = /o/	3.75	3.26	-2.64	10.14	9.43	1.15	0.28	
Vowel = /u/	-1.91	3.27	-8.32	4.50	9.56	-0.58	0.57	
Lang = Polish	-7.03	6.82	-20.40	6.34	20.82	-1.03	0.31	
Place = velar	3.80	1.38	1.08	6.51	10.94	2.74	0.02	*
Speech rate	-7.86	1.13	-10.08	-5.64	488.55	-6.94	0.00	*
Voiced \times /o/	1.91	4.88	-7.65	11.47	11.80	0.39	0.70	
Voiced \times /u/	10.88	4.79	1.50	20.27	10.97	2.27	0.04	*
Voiced \times Polish	2.30	6.07	-9.59	14.19	19.83	0.38	0.71	
/o/ \times Polish	-1.04	4.67	-10.19	8.10	9.94	-0.22	0.83	
/u/ \times Polish	6.94	4.68	-2.24	16.12	10.09	1.48	0.17	
Voiced \times /o/ \times Polish	1.36	6.84	-12.04	14.77	11.44	0.20	0.85	
Voiced \times /u/ \times Polish	-3.08	6.77	-16.35	10.20	11.01	-0.45	0.66	

Table 4: Summary of the linear mixed-effects model for testing the correlation between vowel and closure duration (see Section 3.3).

Predictor	Estimate	SE	CI low	CI up	df	t-value	p-value	< α
Intercept	123.62	6.76	110.36	136.87	56.24	18.27	0.00	*
Closure dur.	-0.19	0.06	-0.32	-0.06	816.53	-2.93	0.00	*
Vowel = /o/	-4.54	6.31	-16.90	7.82	127.46	-0.72	0.47	
Vowel = /u/	-12.47	6.40	-25.00	0.07	134.64	-1.95	0.05	
Speech rate	-5.16	4.28	-13.55	3.23	827.04	-1.21	0.23	
Closure \times /o/	-0.06	0.08	-0.22	0.10	829.38	-0.71	0.48	
Closure \times /u/	-0.23	0.08	-0.39	-0.07	831.49	-2.82	0.00	*
C2 closure \times sp. rate	-0.20	0.06	-0.32	-0.08	826.97	-3.18	0.00	*
/o/ \times sp. rate	-3.75	5.19	-13.92	6.42	819.79	-0.72	0.47	
/u/ \times sp. rate	-10.13	5.50	-20.91	0.64	822.55	-1.84	0.07	
Closure \times /o/ \times sp. rate	0.09	0.07	-0.06	0.23	820.74	1.17	0.24	
Closure \times /u/ \times sp. rate	0.17	0.08	0.01	0.32	823.88	2.14	0.03	*

Table 5: Participants' sociolinguistic information. The column 'Spent most time in' gives the city in which the participant spent most of their life. The last column ('> 6 mo') indicates whether the participant has spent more than 6 months abroad .

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
IT12	26	Male	Italian	English	Rome	Rome	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 6: Target words. Asterisks indicate real 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

C Target words

See Table 6.

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