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

Keywords: vowel duration, closure duration, voicing effect, compensation, Italian, Polish

Abstract Over a century of phonetic research has established the cross-linguistic existence of the so called 'voicing effect', by which vowels tend to be shorter when followed by voiceless stops and longer when the following stop is voiced. However, no agreement is found among scholars regarding the source of this effect, and several causal accounts have been advanced. A notable one is the compensatory temporal adjustment account, according to which the duration of the vowel is inversely correlated with the stop closure duration (voiceless stops having longer closure durations than voiced stops). The compensatory account has been criticised due to lack of empirical support and its vagueness regarding the temporal interval within which compensation is implemented. The results from an exploratory study of Italian and Polish suggest that the duration of the interval between two consecutive stop releases in CVCV words in these languages is not affected by the voicing of the second stop. The durational difference of the first vowel then would follow from differences in closure durations of the following stop. While other factors (like perceptual biases and laryngeal effects) could also play a role in the development of the voicing effect, the data discussed here shed new light on a possible production account of voicing-related differences in vowel durations.

1 Introduction

Almost a hundred years of research have consistently shown that consonantal voicing has an effect on preceding vowel duration: vowels followed by voiced obstruents are longer than when followed by voiceless ones (Meyer 1904; Heffner 1937; House & Fairbanks 1953; Belasco 1953; Peterson &

Lehiste 1960; Halle & Stevens 1967; Chen 1970; Klatt 1973; Lisker 1974; Laeufer 1992; Fowler 1992; Hussein 1994; Lampp & Reklis 2004; Warren & Jacks 2005; Durvasula & Luo 2012). This so called 'voicing effect' has been found in a considerable variety of languages.[1] These include (but are not limited to) English, German, French, Spanish, Hindi, Russian, Italian, Arabic, and Korean (see Maddieson & Gandour 1976 for a more comprehensive, but still not exhaustive list).[2] Despite of the plethora of evidence in support of the *existence* of the voicing effect, agreement hasn't been reached regarding its *source*.

Several proposals have been put forward in relation to the possible source of the voicing effect (see Sóskuthy 2013 and Beguš 2017 for an overview). Some of the proposed mechanisms for the emergence of the voicing effect refer to properties of speech production. A notable production account, which will be the focus of this study, is based on compensatory temporal adjustments (Lindblom 1967; Slis & Cohen 1969b; a; Lehiste 1970b; a). According to this account, the voicing effect follows from the reorganisation of gestures within a unit of speech the duration of which is not affected by stop voicing. The duration of such unit is held constant across voicing contexts, while the duration of voiceless and voiced obstruents differs. The closure of voiceless stops is longer than that of voiced stops (Lisker 1957; Van Summers 1987; Davis & Van Summers 1989; de Jong 1991). As a consequence, vowels followed by voiceless stops (which have a long closure) are shorter than vowels followed by voiced stops (which have a short closure). Advocates of a compensatory mechanism propose two prosodic units as the scope of the temporal adjustment: the syllable (and, equivalently, the VC sequence or vowel-to-vowel interval, Lindblom 1967; Farnetani & Kori 1986), and the word (Slis & Cohen 1969b; a; Lehiste 1970b; a). However, the compensatory temporal adjustment account has been criticised in subsequent work.

Empirical evidence and logic challenge the proposal that the syllable or the word have a constant duration and hence drive compensation. First, Lindblom's 1967 argument that the duration of the syllable is constant is not supported by the findings in Chen (1970) and Jacewicz et al. (2009).

[1] One of the first attestations of the term 'voicing effect' can be attributed to Mitleb (1982). Another term used to refer to the same phenomenon is 'pre-fortis clipping', probably introduced by Wells (1990).

[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.

Chen (1970) rejects a syllable-based compensatory mechanism in the light of the fact that the duration of the syllable is affected by consonant voicing. Jacewicz et al. (2009) further show that the duration of monosyllabic words 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 /tʰ/ 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 /tʰ/ in *sāth* is calculated as the interval between the closure of /tʰ/ 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.

[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.

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 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.

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%). While the magnitude of the correlation is too 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, so that negative and positive misplacements would cancel each other out. Beguš (2017) argues that these findings support temporal compensation (although not univocally, see Beguš 2017: Section V, and Section 4.2 of this paper).

To summarise, a mechanism of compensatory temporal adjustment 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 mechanism gains credibility. However, issues about the actual implementation of the compensation mechanism still remain. While compensatory temporal adjustments are plausible ~~on the~~ in 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 (CV́CV) words in Italian and Polish.[4] This study 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. On the other hand, ~~they are both classified as voicing languages (languages in which the laryngeal opposition~~

[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`].

~~in consonants is between voiceless unaspirated and voiced consonants, Beckman 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~~ the typical realisation of phonological voiced stops in these languages are similar (but see Huszthy 2016 and Schwartz & Arndt 2018 for a phonological and phonetic discussion on laryngeal aspects of Italian and Polish respectively).[5] Cyran (2011) argues for a distinction between voicing and aspirating varieties of Polish, based on phonological arguments. Waniek-Klimczak (2011), on the other hand, cautiously argues that a possible change in progress in Polish is affecting the VOT values of voiceless stops in pre-stressed position.

The non-clear status of Polish laryngeal phonology/phonetics could be seen as a hindrance affecting the comparison with Italian. However, based on data from Italian, Kirby & Ladd propose that the distinction between voicing and aspirating languages itself (Beckman et al. 2013) cannot be straightforwardly mapped onto phonetics, and they remind us that 'the production of laryngeal contrasts of all kinds are considerably more complex' than generally described in the phonological literature (Kirby & Ladd 2016: 2409). Since this study focusses on the effect of post-stressed stops on preceding vowel durations, we believe that the comparison between Italian and Polish ~~share—on a general level—some~~ is still feasible, even in the case Polish voiceless pre-stressed stops are articulated with longer VOT values. Given that Italian and Polish share some features of the segmental and prosodic make-up of their phonological systems, the design of the experimental material and comparison of the results were facilitated. For these reasons, these languages offer an opportunity to investigate differences that could reveal mechanisms underlying the voicing effect, at least on a general level.

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) don't report estimates of vowel duration, just the direction of the effect, but the study is based on 10 speakers.

The results regarding the presence and magnitude of the effect in Polish are instead mixed. Slowiaczek & Dinnsen (1985) find that vowels followed

[5] ~~Note that, while Polish neutralises the voicing contrast word-finally, it is maintained word-medially (Strycharczuk 2012).~~

[5] Polish neutralises the voicing contrast word-finally, although the contrast is maintained word-medially (Strycharczuk 2012).

by word-final underlyingly voiced stops are 10–15 ms longer in 5 Polish speakers, although Jassem & Richter (1989) did not replicate their results. Similarly, Keating (1984) reports ~~no effect of voicing on~~ a difference of 2 ms in the duration of stressed vowels in disyllabic words from 24 speakers, which the author argues to be non-significant. On the other hand, 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 variety of results concerning the voicing effect in Polish could be related to differences in methodology. However, no clear pattern between studies which find a voicing effect and those which don't can be identified. For example, the studies reviewed here looked at either word-final or word-medial stops, controlled or read speech, speakers with a low or advanced proficiency in English. However, in all the individual cases both a positive and a negative result are reported depending on the study. What might be more relevant, though, is that the estimates of the difference in vowel duration are generally very low, between 3.5 and 15 ms. Given the small magnitude of the difference, it is likely that the failure to obtain significant *p*-values in some studies are due to low statistical power, rather than because of absence of the effect (as also hinted in Beguš 2017, see arguments in Roettger 2019 and Nicenboim et al. 2018).

The acoustic data from the 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.

2 Method

2.1 Participants

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 ~~Hawlett-Packard~~ 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

[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 [ɔː] (vowels in

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 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 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

penultimate stressed open syllables are long) rather than [oː] (Renwick & Ladd 2016). On the other hand, Polish has only a mid-low back vowel phoneme /ɔ/ (Gussmann 2007). For the 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)

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, 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 for further processing. The sample and bit rate were kept as upon recording (22050 Hz, 16-bit). A forced aligned transcription was accomplished through the

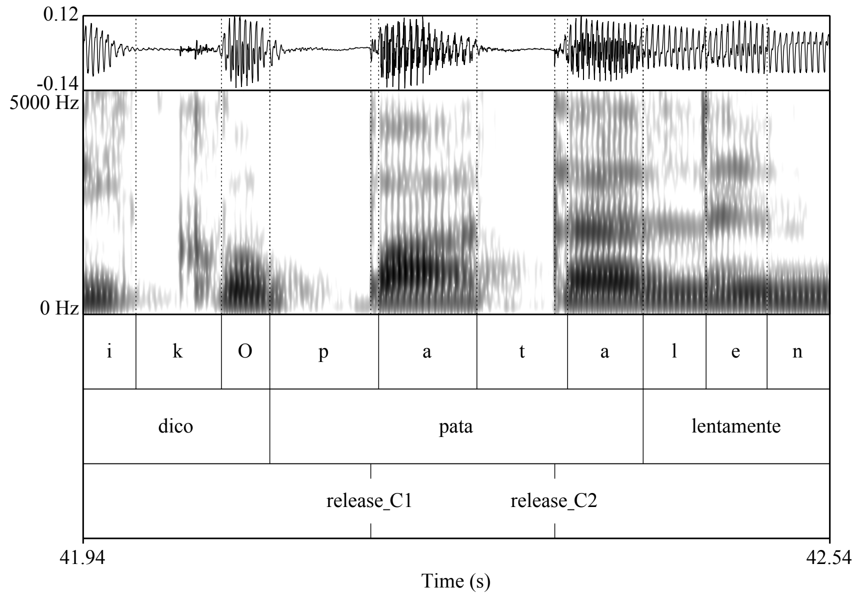
[7] ~~IT01 and IT02 (the first two participants of this study) also read sentences with words starting with /b/, which were later excluded from the experimental design. The data from /b/-initial words are not included in the analysis reported in this paper.~~

SPeech Phonetisation Alignment and Syllabification software (SPPAS, Bigi 2015). The outcome of the automatic 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).

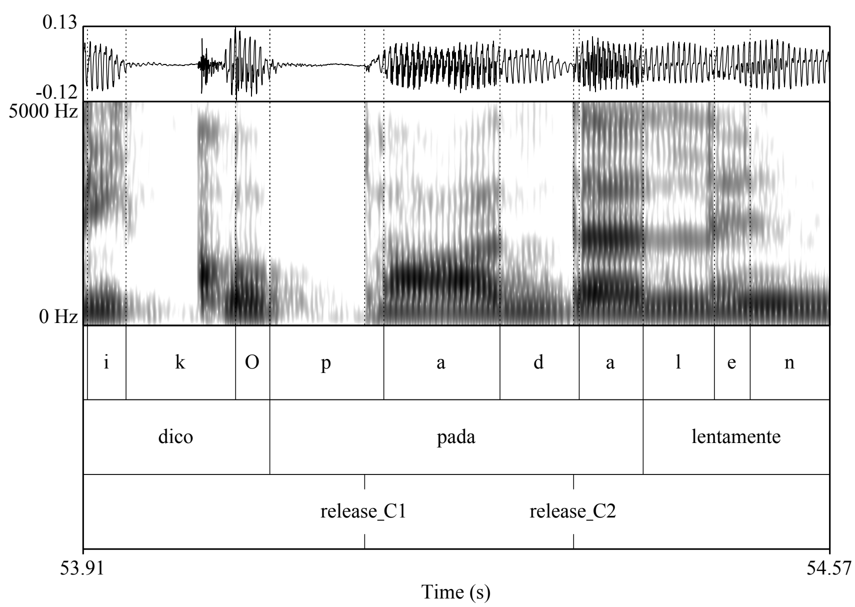
Moreover IT12 and IT14 produced several tokens of voiceless stops with voicing during closure (in some cases the closure was completely voiced). These tokens have been used in the analyses, because (1) the actual presence or absence of voicing during closure does not bear on the compensatory account 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).[7]

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~~.2 (R Core Team 2018; Wickham 2017).

[7] A reviewer makes interesting phonological remarks. The presence of lenition and voicing of voiceless stops in some varieties of Italian and its absence in Polish could be related to differences in laryngeal phonology and prosodic structure between these languages, namely the absence of a feature [voice] in Italian and the absence of true trochees in Polish. This hypothesis is compatible with work by Schwartz & Arndt (2018) and Schwartz (2016), to which the reader is referred.



(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).

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 estimates were extracted with the `effects` package v4~~.0-3~~.1-0 (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'. Inspection of residual plots and QQ plots of the models described below indicated absence of patterns in the residuals.

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).[8] 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

[8] The choice of Bayes factors over other information criteria, like AIC, is a practical one. First, Bayes factors can be used to identify the realative strength of the evidence for each hypothesis. The higher the Bayes factor of H_{01}, the stronger the evidence for H_0 according to the data. Second, a Bayes factor near 1 indicates that the data is compatible with both hypotheses (even when AIC indicates a preference of one over the other), in which case it is not possible to chose among them. Note that the AICs of the word duration and release to release duration models reported below are lower when C2 voicing is not included as a predictor than when it is included, although the difference in AIC between the null and full models is very small (below 2).

& Wiley 2014). The approximation is calculated according to the equation in 1 (Wagenmakers 2007: 796).

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

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.

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 http://bit.ly/2FItZe1.

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.

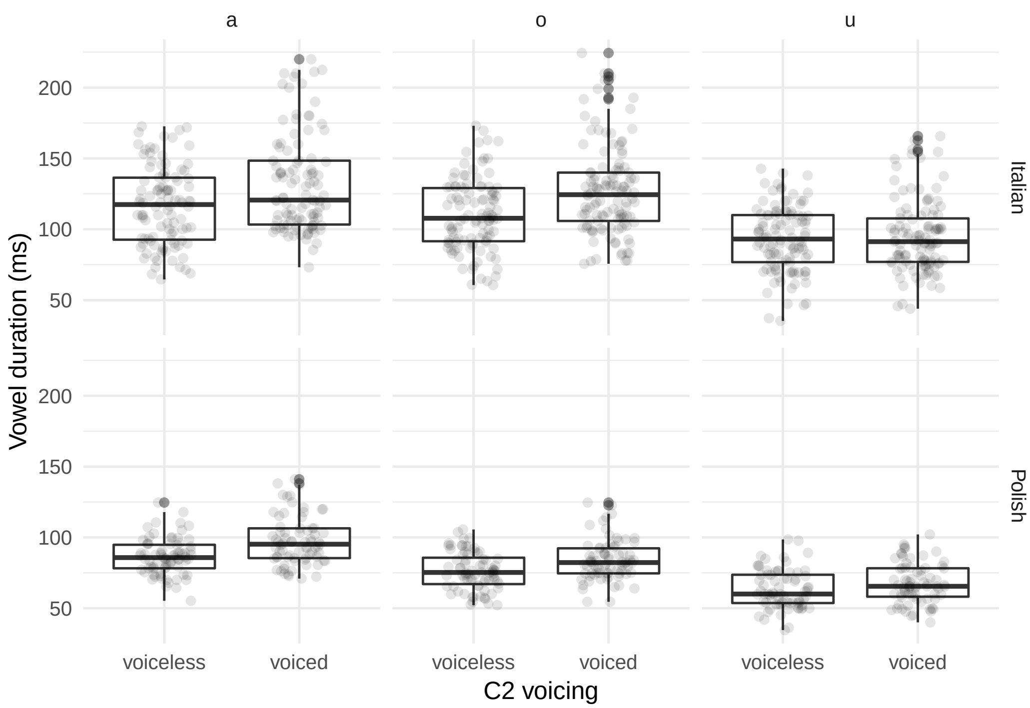


Figure 2: Raw data and boxplots of the duration in milliseconds of vowels in Italian (top row) and Polish (bottom row), for the vowels /a, o, u/ when followed by a voiceless or voiced stop.

~~Vowel~~ 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 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

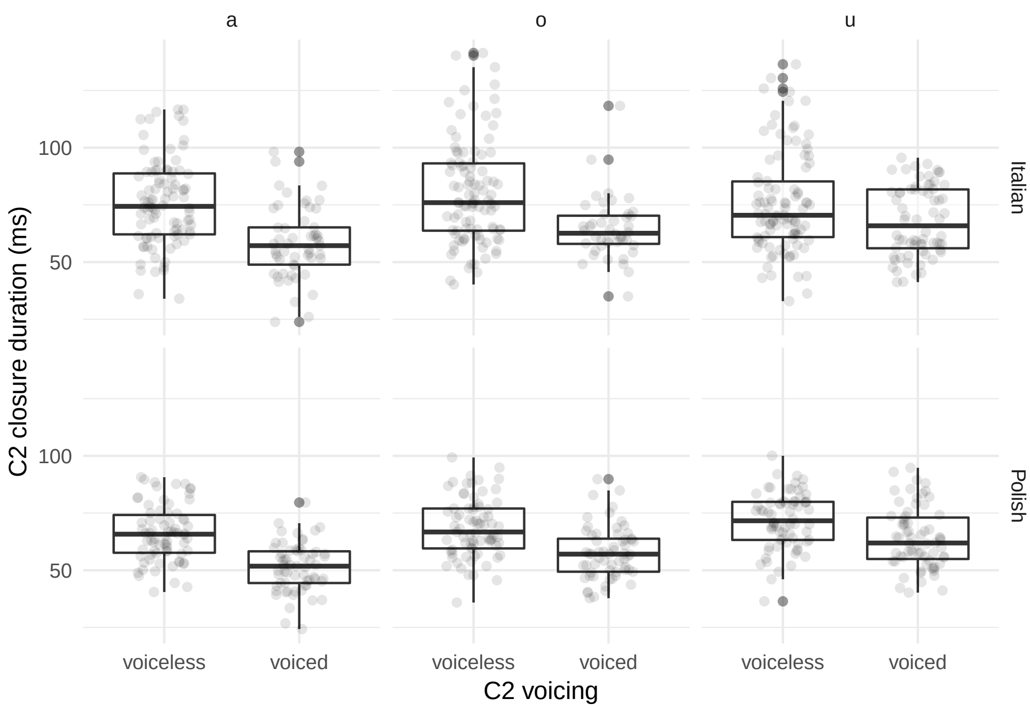


Figure 3: Raw data and boxplots of closure duration in milliseconds of voiceless and voiced stops in Italian (top row) and Polish (bottom row) when preceded by the vowels /a, o, u/.

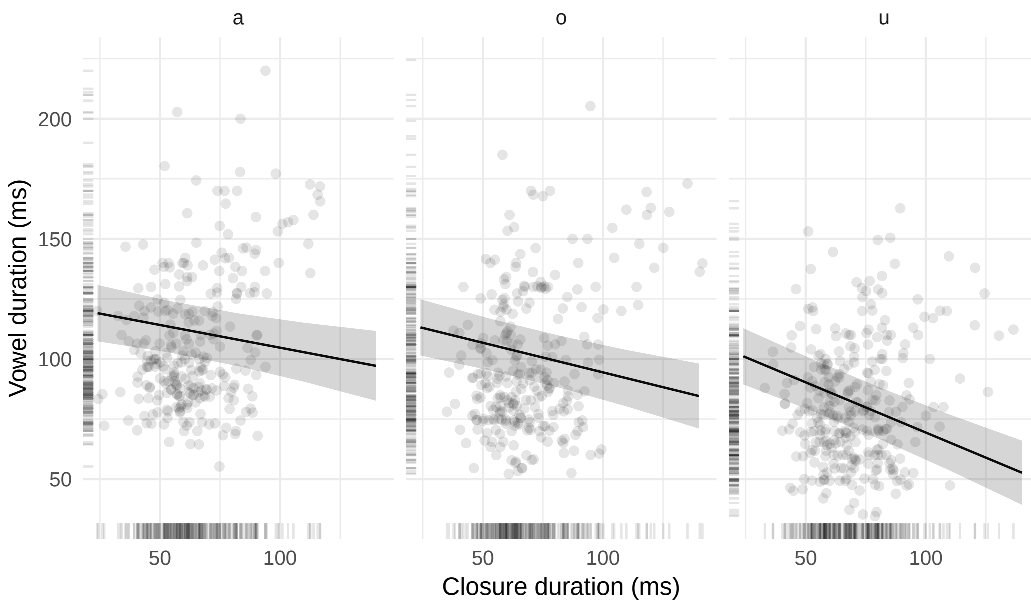


Figure 4: Raw data, estimated regression lines, and 95 per cent confidence intervals of the effect of closure duration on vowel duration for the vowels /a, o, u/ (from a mixed-effects model fitted to data pooled from Italian and Polish, see text for details).

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~~ 17.5 ms shorter (SE = ~~3~~4) 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).

3.3 *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 (centred); all logical interactions between closure duration, vowel, and speech rate; by-speaker and by-word random intercepts. Closure duration has a significant effect on vowel duration ($\hat{\beta}$ = -0.19 ms, SE = 0.06 ms).

The effect with /u/ is greater than with /a/ and /o/ ($\hat{\beta}$ = -0.23 ms, SE = 0.08 ms). In general, closure duration is inversely proportional to vowel duration. However, such correlation is quite weak, as shown by the small estimates. A 1 ms increase in closure duration corresponds to a 0.2–0.45 ms decrease in vowel duration. These estimates can be interpreted in terms of percentages of compensation, which range between 20 and 45%. Faster speech rates elicit a bigger effect than lower speech rates, as indicated by the significant interaction between closure duration and speech rate ($\hat{\beta}$ = -0.2 ms, SE = 0.06 ms). The effect of the interaction is reduced when the vowel is /u/ ($\hat{\beta}$ = 0.17 ms, SE = 0.08 ms). Figure 4 shows for each vowel /a, o, u/ the individual data points and the regression lines with 95% confidence intervals extracted from the mixed-effects model.

3.4 Word duration

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

3.5 Release to release interval duration

In Figure 5, boxplots and raw data points show the duration of the release to release interval in words with a voiceless vs. a voiced C2 stop, in Italian and Polish. It can be seen that the distributions, medians, and quartiles of the durations in the voiceless and voiced condition do not differ much in either language. In Italian, the mean duration of the release to release interval is 209.88 ms (SD = 43.84) if C2 is voiceless, and 208.6 ms (SD = 41.34) if voiced. In Polish, the mean durations are respectively 173.13 (SD = 22.44) and 172.67 (SD = 20.47) ms. The specifications of the null and full models

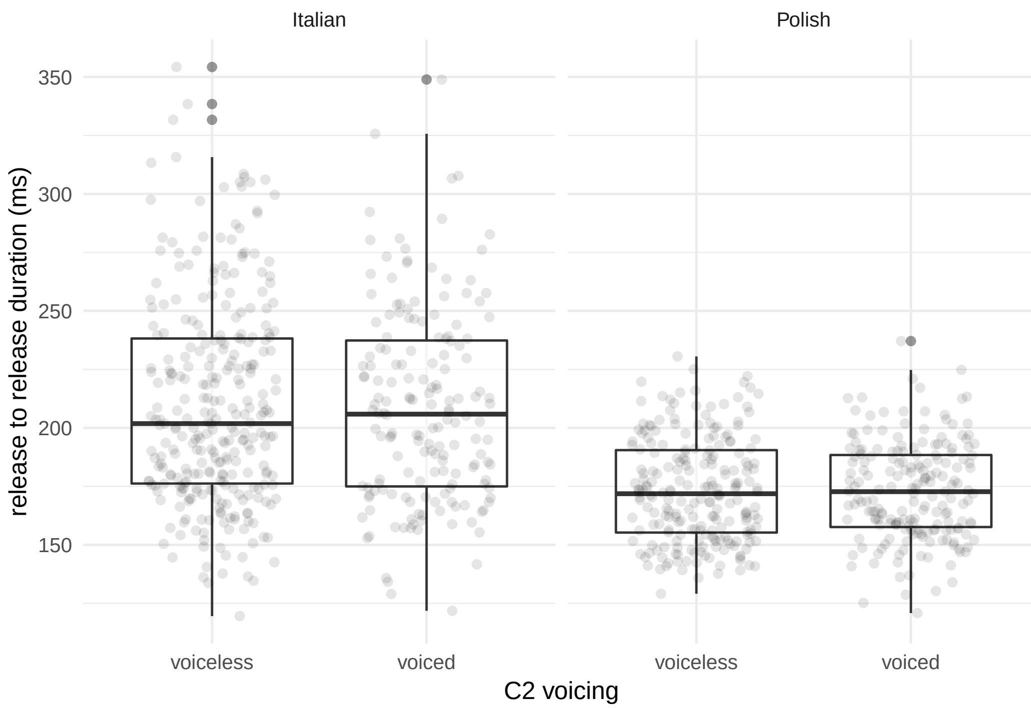


Figure 5: Raw data and boxplots of the duration in milliseconds of the release to release interval in Italian (left) and Polish (right) when C2 is voiceless or voiced.

for the release to release duration are the same as for word duration. The Bayes factor of the null model against the full model is 21, which means that the null model (without C2 voicing) is 21 times more likely than the model with C2 voicing as a predictor. The Bayes factor suggests there is strong evidence that duration of the release to release interval is not affected by C2 voicing.

4 Discussion

A study of articulatory and acoustic aspects of the effect of consonant voicing on vowel duration in Italian and Polish has been carried out to look for a possible source of such effect in speech production. Only the results from the acoustic part of the study bear on the main argument of this paper. The following sections discuss, in turn, the results regarding the effect of voicing on vowel duration in Italian and Polish and how the finding that the duration of the interval between the two consecutive consonant releases in CV́CV words is compatible with a compensatory temporal adjustment account of the voicing effect. The section concludes by discussing the limitations and open issues of this study.

4.1 *Voicing effect in Italian and Polish*

The results of vowel duration and C2 voicing indicate that vowels are longer when followed by voiced ~~then~~ than when followed by voiceless stops both in Italian and Polish. The estimated effect is around 16 ms when C2 is voiced for Italian. This value is not too far from the estimates of previous works on this language (Caldognetto et al. 1979; Farnetani & Kori 1986; Esposito 2002), the range of which is between 22 and 24 ms. The higher estimates 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 very similar magnitudes and 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 about 10.5 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, the raw mean difference of 7.5 ms in Polish—although still higher than what found in previous studies—might be more informative.

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), even if by just a small amount. 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. These patterns will need to be confirmed with a more balanced sample of Italian and Polish speakers.

On the other hand, while the estimated differences in vowel durations can be interpreted in reference to Italian and Polish as two independent linguistic objects, the patterns observed in the individual speakers does not indicate a systematic relation between magnitude of the effect and language. Figure 6 shows the random coefficients of the effect of C2 voicing on vowel duration for the individual speakers, extracted from the mixed-effects model presented in Section 3.1. Black indicates Italian speakers, while grey is for Polish speakers. As it can be seen, speakers of both languages are scattered along the values of the voicing effect. These results are in agreement with the idiosyncrasy found for the voicing effect of Polish in Malisz & Klessa (2008) . While large-scale studies could reveal clear language-level patterns, the data discussed here point to a scenario in which the speaker's individual behaviour is substantial. Future studies could thus look into the respective role of individual-level and community-level factors and how these contribute

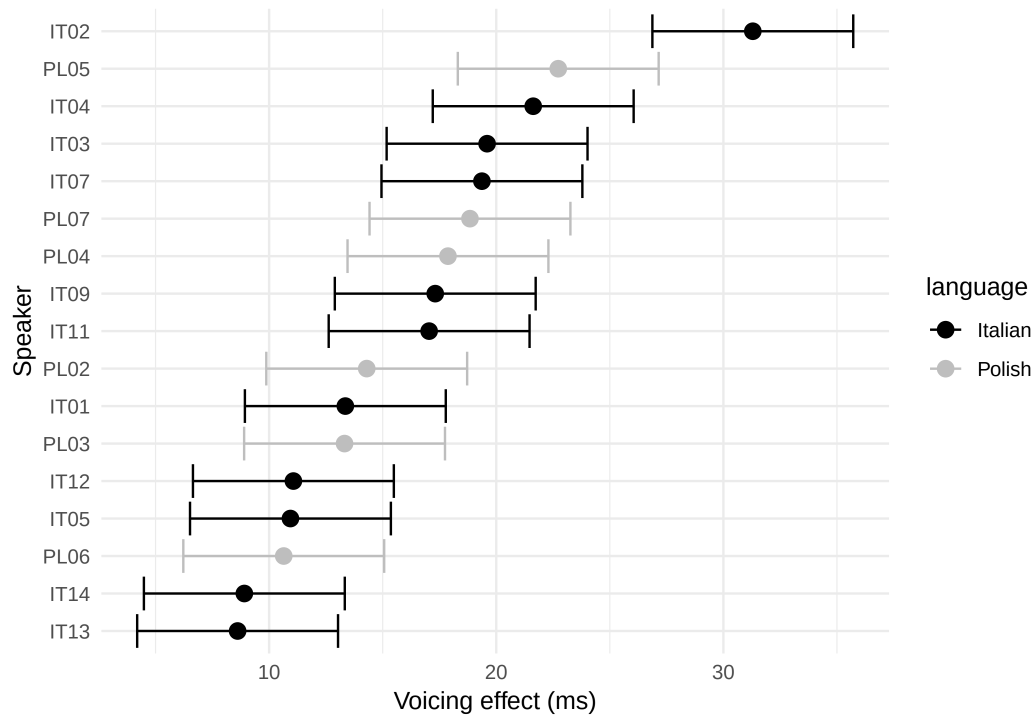


Figure 6: By-speaker random coefficients and error bars for the effect of C2 voicing on vowel duration, extracted from a mixed-effect model (Section 3.1)..

to the magnitude of the durational differences across speakers and languages.

4.2 *Compensatory temporal adjustment*

Vowels followed by voiced stops are long, while vowels followed by voiceless stops are short. The closure duration of voiced stops is short compared to that of voiceless stops. There seems to be an inverse relation between vowel duration and closure duration, by which a long vowel entails a short closure (and vice versa), and a short vowel entails a long closure (and vice versa).

The data and statistical analyses of this study suggest that the duration of the interval between the releases of two consecutive consonants in CV́CV words (the release to release interval) is not affected by the phonological voicing of the second consonant (C2) in Italian and Polish. In accordance with a compensatory temporal adjustment account (Slis & Cohen 1969a; Lehiste 1970b), the difference in vowel duration before voiceless vs. voiced stops can be seen as the outcome of differences in stop closure duration. In other words, the timing of the (acoustic) closure onset of C2 within the temporally stable release to release interval determines the duration of the preceding vowel. An earlier closure onset relative to the onset of the preceding vowel (like in the case of voiceless stops) causes the vowel to be shorter. On the other hand, a later closure onset (like with voiced stops) produces a longer vowel. Figure 7 illustrates the compensatory mechanism. Note that the term ‘temporal stability’ (and ‘temporally stable’) as used here means that the underlying statistical distribution of the interval duration is stable *across contexts of C2 voicing*. No specific statement is implied about the variance of the duration around the mean, across or within phonological contexts.

The invariance of the release to release interval allows us to refine the logistics of the compensatory account by narrowing the scope of the temporal adjustment action. A limitation of this account, as proposed by Slis & Cohen (1969a) and Lehiste (1970b), is the lack of a precise identification of the word-internal mechanics of compensation. As already discussed in Section 1, it is not clear why the adjustment should target the preceding stressed vowel, rather ~~then~~ than the following unstressed vowel or any other segment in the word. Since the release to release interval includes just the vocoid gesture between the release of C1 and the onset of the closure of C2 and the consonant closure, it follows that differences in closure duration

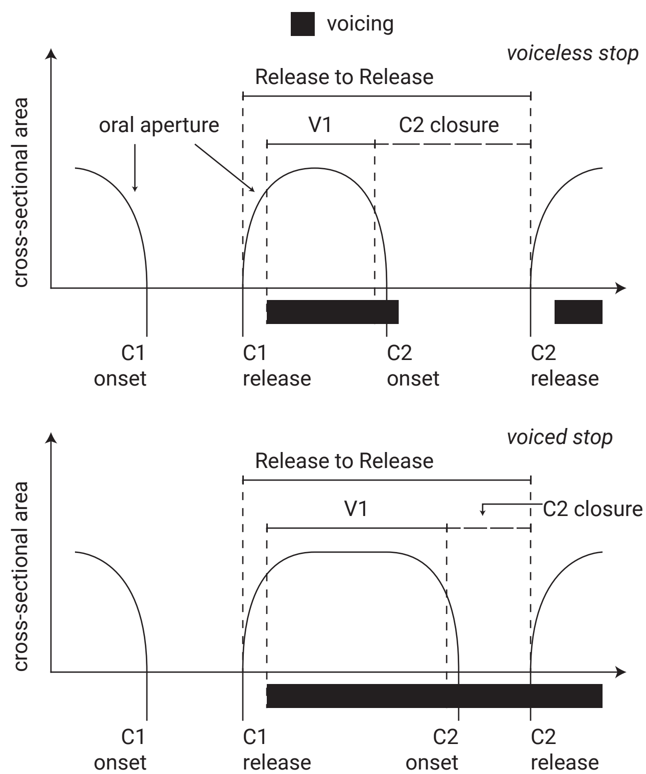


Figure 7: A schematic representation of the oral cavity cross-sectional area, as inferred from acoustics. Design based on Esposito (2002). The top panel shows a CV́C sequence with a voiceless C2, the bottom panel with a voiced C2. Oral cavity aperture (on the *y*-axis, as the inverse of oral constriction) 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.

must be reflected in differences in the duration of the preceding vocoid. ~~It is worth noting, though, that other accounts—which could be compatible with other aspects of production and perception—aren't ultimately ruled out. For example, perceptual factors might play a role in the enhancement of the effect (see Kingston & Diehl 1994, Port & Dalby 1982, and Luce & Charles-Luce 1985), and 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 ~~then~~ 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.

The non-exclusivity of the release to release interval is also shown by the fact that excluding the VOT from it still indicates that C2 voicing is not affecting the interval duration. The duration of the vowel onset to release interval (the release to release minus VOT) is stable across voicing contexts (Bayes factor = 9). However, the duration of release to release interval has relatively more cohesion than that of the vowel onset to release interval, as indicated by two measures of relative dispersion (the coefficient of variation CV and the coefficient of quartile variation CQV, see Bonett 2006).[9] On the other hand, the duration of the interval between the vowel onset of V1 to the vowel onset of V2 does change depending on C2 voicing (the interval it's around 20 ms longer if C2 is voiceless). This fact is simply a consequence of including the VOT of C2 in the measure. Voiceless stops have longer VOT values, which increases the duration of the interval. The difficulty in identifying a clear-cut time point corresponding to vowel onset could explain the relative higher dispersion of the vowel onset to release interval duration. For these reasons, the release to release interval is probably a better measure of temporal stability than the vowel onset to release, given its inherent higher cohesion.

[9] The CV of the release to release duration is 0.203, while that of the vowel onset to release duration is 0.232. The CQV is 0.127 for the release to release and 0.136 for the vowel onset to release. Lower values mean less dispersion/more cohesion.

It could be argued that the temporal stability of the release to release interval could be the result of lengthening vowels followed by voiced stops which have shorter closure durations (or, vice versa, of shortening vowels followed by voiceless stops), so that such stability would not necessarily follow from a compensatory mechanism. However, what it is claimed here is that the stability of the interval is a logical antecedent, while the different vowel/closure durations follow as a consequence of the differential timing of closure onset within the temporally stable interval. This interpretation seems more natural in light of accounts of gestural phasing like the one proposed by Tilsen (2013). Under this account, the stability of the release to release interval could follow from the relative phasing of the vowels in CVCV words (see Figure 6 in Tilsen 2013). The stability of the temporal distance between vowels in Italian is preliminarily supported by the acoustic data in Celata & Mairano (2014). While beyond the scope of this paper, articulatory 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 and in other durational phenomena.

Finally, it is worth noting that other accounts—which could be compatible with other aspects of production and perception—aren't ultimately ruled out. For example, perceptual factors might play a role in the enhancement of the effect (see Kingston & Diehl 1994, Port & Dalby 1982, and Luce & Charles-Luce 1985), and other perceptual explanations of the voicing effect have been proposed in Javkin (1976) and Kluender et al. (1988). Moreover, Beguš (2017) finds that even when C2 closure duration is controlled for, C2 phonation (ejective, voiceless, voiced) in Georgian is still a significant predictor. Beguš argues for a separate laryngeal effect, which operates in addition to the closure duration effect. In the present study, C2 voicing (voiceless, voiced) and its interactions are not significant when included in the model discussed in section Section 3.3, which has vowel duration as outcome and C2 closure duration as one of the predictors.[10]

Even when multicollinearity between predictors is minimal, statistical significance of multiple terms cannot unequivocally inform us on the actual contribution of those terms, since it is possible that unknown relations between terms mask underlying mechanisms (for a discussion see McElreath 2015). For example, it is possible that, through time, different phonation categories (like ejective, voiceless, and voiced stops) can develop different closure duration sub-distributions (Sóskuthy 2013). This can result in the ability for the phonation predictor to capture variance in vowel durations, even if

[10] Multicollinearity is not an issue here, since the VIFs are all below 3 (Zuur et al. 2010).

the original mechanism directly involved closure durations only (this kind of reasoning is compatible with exemplar theories of speech perception and production, see among others Johnson 1997; Sóskuthy et al. 2018; Ambridge 2018; Todd et al). Since opposite results have been obtained in relation to the significance of C2 phonation in addition to C2 closure durations, these results need to be replicated in future studies, although to ascertain whether they are artefacts of statistical procedures or if they reflect an underlying state of affairs might still prove difficult (cf. the correlation vs. causation problem).

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 mechanism proposed 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; Laeufer 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.

Some concern could be raised in relation to possible influences of English on the native productions of participants recorded in the English-speaking context of the University of Manchester Laboratory. However, as reported in Section 2.4, conversations during the session prior to the experiment and instructions were in the participant's native language. Antoniou et al. (2010) show that, in a situational language context study of Greek-English bilinguals, being exposed to the native language during the experiment elicited Greek native-like phonetic values even when the dominant language at the time of recording was English (the bilingual speakers acquired English as a second language, being Greek their first). A small effect of L2 could persist in proficient L2 speakers, as found by Schwartz et al. (2015). The five Polish speakers with a highly proficient level of English investigated in that study showed a 10 ms increase in VOT values compared to the quasi-monolingual base level. While previous studies focussed on VOT, future work should directly test the influence of English on the magnitude of the voicing effect of one's native language.

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~~ this exploratory study of 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 CV́CV words.

The temporal invariance of the release to release interval, together with a difference in stop closure duration of voiceless and voiced stops, ~~causes~~ can cause 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).

As discussed in Section 4.2, the temporal patterns reported here do not univocally exclude other possible sources for the duration differential. Multiple mechanisms (both articulatory and perceptual) could conspire together to produce the observed patterns. Such pluralist view has already been proposed, for example, for incomplete neutralisation in Winter & Röttger 2011 (for a review of explanatory pluralism in the cognitive sciences, see Dale et al. 2009 and references therein). A hybrid account which synthesises aspects of multiple accounts is probably warranted, given the diversity of results obtained so far. 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 prosodic structures and different laryngeal contrasts on the release to release interval, and in relation to other attributes of consonant effects on vowel duration.

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8 Competing interests

The author has no competing interests to declare.

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	$< \alpha$
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 × /o/	2.09	5.54	-8.77	12.96	10.18	0.38	0.71	
Voiced × /u/	-13.09	5.56	-23.99	-2.20	10.30	-2.36	0.04	*
Voiced × Polish	-5.73	6.61	-18.69	7.23	18.00	-0.87	0.40	
/o/ × Polish	-2.50	5.66	-13.60	8.60	11.09	-0.44	0.67	
/u/ × Polish	1.12	5.68	-10.01	12.26	11.23	0.20	0.85	
Voiced × /o/ × Polish	-6.16	8.00	-21.85	9.53	11.06	-0.77	0.46	
Voiced × /u/ × Polish	6.40	8.03	-9.34	22.13	11.19	0.80	0.44	

A Output of statistical models

See Table 2, Table 3, and Table 4.

B Socio-linguistic information of participants

See Table 5.

C Target words

See Table 6.

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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 × /o/	1.91	4.88	-7.65	11.47	11.80	0.39	0.70	
Voiced × /u/	10.88	4.79	1.50	20.27	10.97	2.27	0.04	*
Voiced × Polish	2.30	6.07	-9.59	14.19	19.83	0.38	0.71	
/o/ × Polish	-1.04	4.67	-10.19	8.10	9.94	-0.22	0.83	
/u/ × Polish	6.94	4.68	-2.24	16.12	10.09	1.48	0.17	
Voiced × /o/ × Polish	1.36	6.84	-12.04	14.77	11.44	0.20	0.85	
Voiced × /u/ × Polish	-3.08	6.77	-16.35	10.20	11.01	-0.45	0.66	

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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 × /o/	-0.06	0.08	-0.22	0.10	829.38	-0.71	0.48	
Closure × /u/	-0.23	0.08	-0.39	-0.07	831.49	-2.82	0.00	*
C2 closure × sp. rate	-0.20	0.06	-0.32	-0.08	826.97	-3.18	0.00	*
/o/ × sp. rate	-3.75	5.19	-13.92	6.42	819.79	-0.72	0.47	
/u/ × sp. rate	-10.13	5.50	-20.91	0.64	822.55	-1.84	0.07	
Closure × /o/ × sp. rate	0.09	0.07	-0.06	0.23	820.74	1.17	0.24	
Closure × /u/ × sp. rate	0.17	0.08	0.01	0.32	823.88	2.14	0.03	*

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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

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