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I. 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 (Belasco, 1953; Chen, 1970; Durvasula and Luo, 2012; Esposito, 2002; Farnetani and Kori, 1986; Fowler, 1992; Halle and Stevens, 1967; Heffner, 1937; House and Fairbanks, 1953; Hussein, 1994; Javkin, 1976; Klatt, 1973; Kluender *et al.*, 1988; Laeufer, 1992; Lampp and Reklis, 2004; Lisker, 1974; Maddieson and Gandour, 1976; Peterson and Lehiste, 1960; Raphael, 1975; Warren and Jacks, 2005). This so called 'voicing effect' has been found in a considerable variety of languages, including (but not limited to) English, German, Hindi, Russian, Italian, Arabic, and Korean (see Maddieson and Gandour 1976 for a more comprehensive, but still not exhaustive list). Despite of the plethora of evidence in support of the *existence* of the voicing effect, agreement hasn't been reached regarding its *source*.

Several proposal have been put forward as to where to search for the possible source of the voicing effect (see Sóskuthy 2013 and Beguš 2017 for an overview). The majority of the proposed accounts place the source of the voicing effect in properties of speech production.[1] A notable production account, which will be the focus of this study, is the compensatory temporal adjustment account (Lehiste, 1970a,b; Lindblom, 1967; Slis and Cohen, 1969a,b). According to this account, the voicing effect derives from the reorganisation of gestures within a unit of speech that 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. It is well known that the closure of voiceless stops is longer than that of voiced stops (Davis and Van Summers, 1989; De Jong, 1991; Lisker, 1957; Van Summers, 1987). 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 the compensatory account proposed two prosodic units as the scope of the temporal adjustment: the syllable (or, more neutrally, the VC sequence Lindblom 1967), and the word (Lehiste, 1970a,b; Slis and Cohen, 1969a,b). 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 findings in Chen (1970) and Jacewicz *et al.* (2009). Chen (1970) rejects a syllable-based compensatory account on the light of the fact that the duration of the syllable is affected by consonant voicing. Jacewicz *et al.* (2009) further show that the duration of monosyllabic words in American English changes dependent on the voicing of the coda consonant. Second, although the results in Slis and Cohen (1969b) 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, so 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 and Gandour, 1976), by which vowels are longer when followed by aspirated stops than when followed by non-aspirated stops. In Hindi, vowels before voiceless unaspirated stops are the shortest, followed by vowels before voiced unaspirated and voiceless aspirated stops, which have similar duration, followed by vowels before voiced aspirated stops, which are the longest. Maddieson and Gandour (1976) find no compensatory pattern between vowel and consonant duration: the consonant /t/, which has the shortest duration, is preceded by the shortest vowel, and vowels before /d/ and /t / have the same duration although the durations of the two consonant are different. Maddieson and 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 and 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 and 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 / in *sāth* was calculated as the interval between the closure of /t / and the release of /k/). This measure includes the burst and (eventual) aspiration of the consonant following the target vowel. Slis and Cohen (1969a), however, states that the inverse correlation between vowel duration and the following consonant applies to *closure* duration, and not the entire *consonant* duration. If a correlation exists between vowel and closure duration, the inclusion of burst and/or aspiration duration clearly alters this relationship.

Indeed, the study on Hindi voicing and aspiration effects conducted by Durvasula and Luo (2012) indicates that closure duration, properly measured, decreases according to the hierarchy voiceless unaspirated > voiced unaspirated > voiceless aspirated > voiced aspirated, which closely resembles the order of increasing vowel duration in Maddieson and Gandour (1976). Nonetheless, Durvasula and 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).

Further evidence for a compensatory account 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 duration is short in voiced stops, longer in ejectives, and longest in voiceless aspirated stops. Moreover, vowel duration is inversely correlated with closure duration across the three phonation types. 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 to explain 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 a careful review of the critiques advanced by Chen (1970) and Maddieson and Gandour (1976), and in face of the results in Slis and Cohen (1969b) and Beguš (2017), a compensatory 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 left with the necessity of finding a constant speech interval within which compensation is logically implemented.

A. 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 and 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.[2] Given its exploratory nature, this study was not devised to test the compensatory account, but rather to collect articulatory and acoustic data on the voicing effect.[3] Moreover, the design of the study has been constrained by the use of such articulatory techniques (see Section II). 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 of the effect of stop voicing on vowel duration. Italian has been unanimously reported as a voicing-effect language (Caldognetto *et al.*, 1979; Esposito, 2002; Farnetani and Kori, 1986). The mean difference in vowel duration when followed by voiceless vs. voiced consonants ranges between 22 and 24 ms, with longer vowels followed by voiced consonants.[4] 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. Moreover, Malisz and Klessa (2008) argue based on data from 40 speakers that the magnitude of the voicing effect in Polish is highly idiosyncratic, and claim their results are inconclusive on this matter.

The acoustic data from the exploratory study discussed here confirms the existence of a voicing effect in Italian and Polish, and suggests that 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 stop closure onset within said interval determines the respective durations of vowel and closure. I further propose that the constant duration of the Release to Release interval is congruent with current views on gestural timing (Goldstein and Pouplier, 2014) and I discuss the insights such account provides in relation to our understanding of the gestural organisation of speech.

II. METHOD

A. Participants

Seventeen subjects in total participated in this exploratory 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 Poznań and 4 speakers 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.

B. 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 ProBook 6750b laptop with Microsoft Windows 7. Recordings were made at sample rate of 22050 MHz (16-bit), 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 around at the level of the participant's mouth on one side, at a distance of 10 cm.[5]

C. Materials

The target stimuli were disyllabic words with $C_1V_1C_2V_2$ structure, where C_1 = /p/, V_1 = /a, o, u/, C_2 = /t, d, k, g/, and $V_2 = V_1$ (e.g. /pata/, /pada/, /poto/, etc.).[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 image with UTI, since their articulation involves tongue positions which are particularly far from the ultrasonic probe, hence reducing the visibility of the tongue contour. For this reason, only central and back vowels were included. Since one of the variables of interest in the exploratory study was the closing gesture of C_2, only lingual consonants were used. A labial stop was chosen as the first consonant to reduce possible coarticulation with the following vowel (although see Vazquez-Alvarez and Hewlett 2007).

The target words were embedded in a frame sentence, *Dico X lentamente* 'I say X slowly' in Italian (following Hajek and Stevens, 2008), and *Mówię X teraz* 'I say X now' in Polish, and presented according to the respective writing conventions. These sentences were chosen in order to keep the placement of stress and emphasis similar across languages.

D. Procedure

The participant was asked to read the sentences with the target words which were sequentially presented on the computer screen. The order of the 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 experiment time lasted around 45 minutes. Each speaker read a total of 12 sentences for 6 times (with the exceptions of IT02, who repeated the 12 sentences 5 times, and IT07, with whom words containing /u/

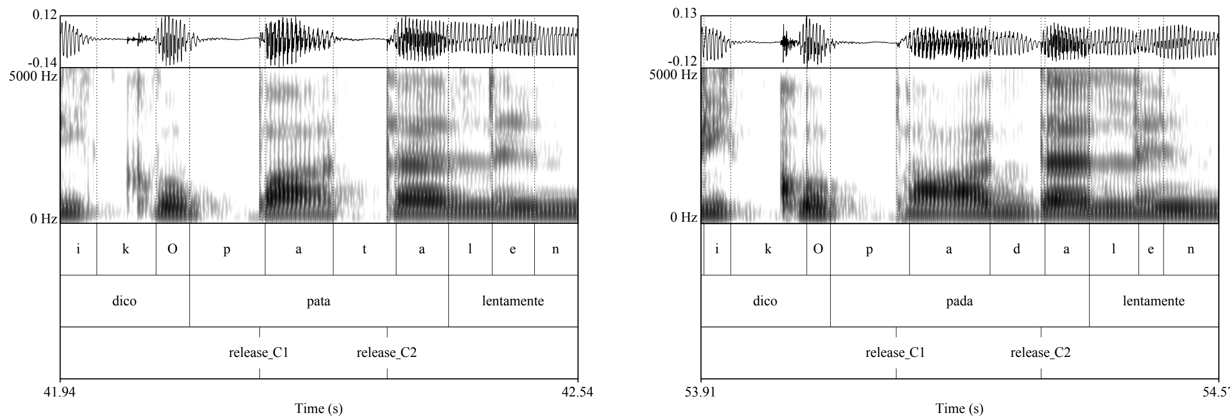
TABLE I. List of measurements as extracted from acoustics.

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)

were not recorded due to technical difficulties relating to ultrasound data collection), which yields to a grand total of 1224 tokens (792 from Italian, 432 from Polish).[7]

E. Data processing and measurements

The audio recordings were exported from AAA in `.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).



(a) (b)

FIG. 1. Segmentation example.

The outcome of the automatic annotation was manually corrected, according to the criteria in Table I. The releases of C1 and C2 were detected automatically by means of a Praat scripting implementation of the algorithm described in Ananthapadmanabha *et al.* (2014). The durations in milliseconds of the following intervals were extracted with Praat scripting 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 and 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 v3.5.0 (R Core Team, 2018; Wickham, 2017).

F. 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) (Gelman and Loken, 2013; Kerr, 1998; Roettger, 2018). The durational measurements were analysed with linear mixed-effects models using `lme4` v1.1-17 in R (Bates *et al.*, 2015), and model estimates were extracted with the `effects` package v4.0-2 (Fox, 2003). All factors were coded with treatment contrasts and the following reference levels: voiceless (vs. voiced), /a/ (vs. /o/, /u/), coronal (vs. velar), Italian (vs. Polish). The 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 ($\alpha = 0.05$).[8]

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

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

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

The extracted measurements were filtered before statistical analysis. Measures of vowel duration, closure duration, word duration, and RR duration that are 3 standard deviations lower or higher than the respective means were excluded from the final dataset. This operation (which generally corresponds to a loss of around 2.5% of the data) yields a total of 920 tokens of vowel and closure durations, 1176 tokens of word duration, and 848 tokens of RR duration.

III. RESULTS

The following sections report the results of the study in relation to the durations of vowels, consonant closure, word, and the Release to Release interval. When discussing the output of statistical modelling, only the relevant predictors and interactions will be presented. To avoid the visual cluttering of parameters tables and alleviate the burden of the reader, the full output of statistical models (including confidence intervals and *p*-values) are given in Appendix A.

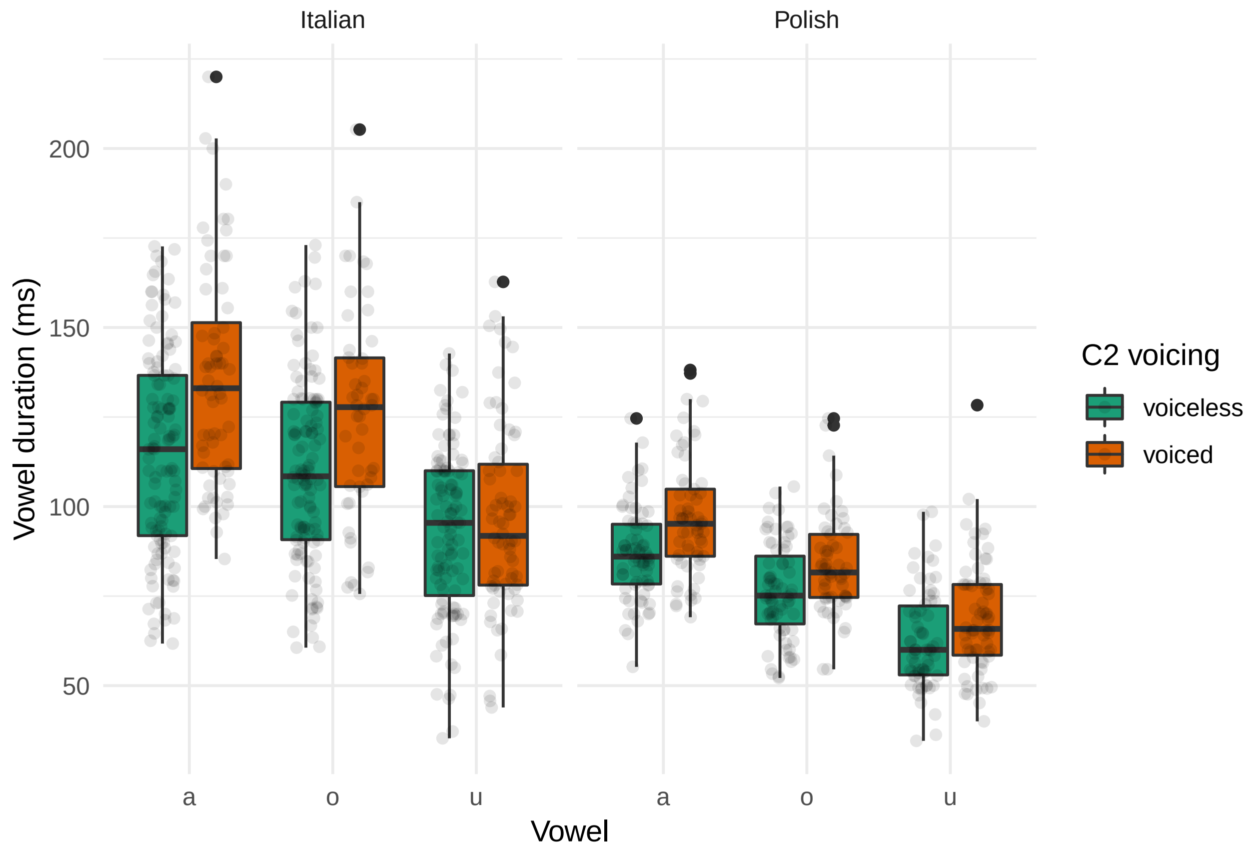


FIG. 2. Raw data and boxplots of the duration in milliseconds of vowels in Italian (left) and Polish (right), for the vowels /a, o, u/ when followed by a voiceless (green) or voiced (orange) stop.

A. 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. Vowel 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 ms (sd = 27) before voiceless stops, and a mean duration of 118 ms (sd = 33) before voiced stops. Polish vowels are on average 75 ms long (sd = 16) when followed by a voiceless stop, and 83 ms long (sd = 19) if a voiced stop follows. The difference in vowel duration based on the raw means is 12 ms in Italian and 8 ms in Polish.

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

B. Consonant closure duration

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

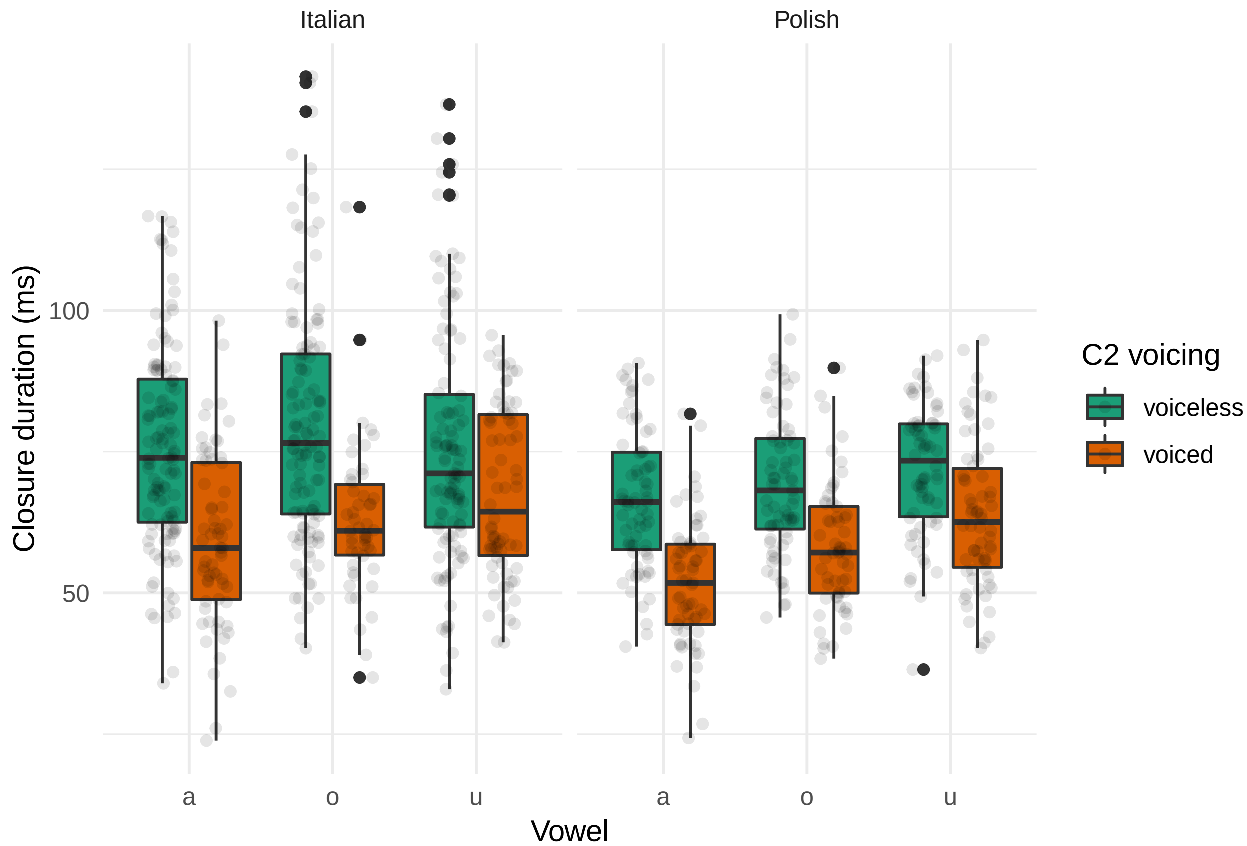


FIG. 3. Raw data and boxplots of closure duration in milliseconds of voiceless (green) and voiced (orange) stops in Italian (left) and Polish (right) when preceded by the vowels /a, o, u/.

the closure duration is 69 ms (sd = 12) in voiceless stops and 58 ms (sd = 13) in voiced stops. The difference in closure duration based on the raw means is 14 ms in Italian and 11 ms in Polish. The same model specification as with vowel duration has been fitted with consonant closure durations as the outcome variable. C2 voicing, C2 place, and speech rate are significant. Stop closure is 16.5 ms shorter (se = 3) if the stop is voiced and 3.5 ms longer (se = 1.5) if velar. Finally, faster speech rates correlate with shorter closure durations ($\hat{\beta}$ = -8.5 ms, se = 1 ms).

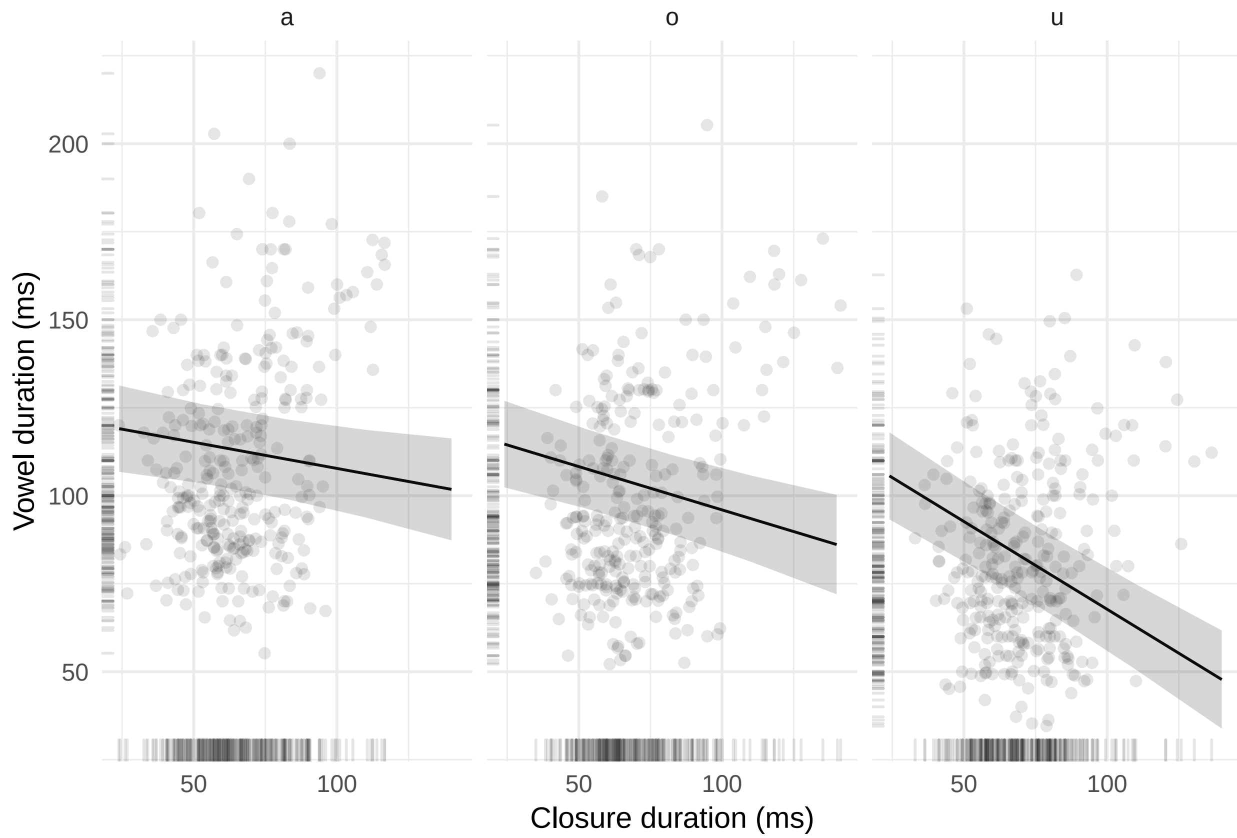


FIG. 4. Raw data and estimated regression lines of the effect of closure duration on vowel duration for the vowels /a, o, u/ (from a mixed-effects model fitted to data pooled from Italian and Polish).

C. Vowel and closure duration

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

D. Word duration

Words with a voiceless C2 are on average 397 ms long (sd = 81) in Italian and 356 ms long (sd = 39) in Polish. Words with a voiced stop have a mean duration of 396 ms (sd = 72) in Italian and 362 ms (sd = 39) in Polish. The following full and null models were fitted to test 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 24. Thus, the null model (in which there is no effect of C2 voicing, $\beta = 0$) is 24 times more likely under the observed data than the full model. This indicates that there is strong evidence for a null effect of C2 voicing on word duration.

E. 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

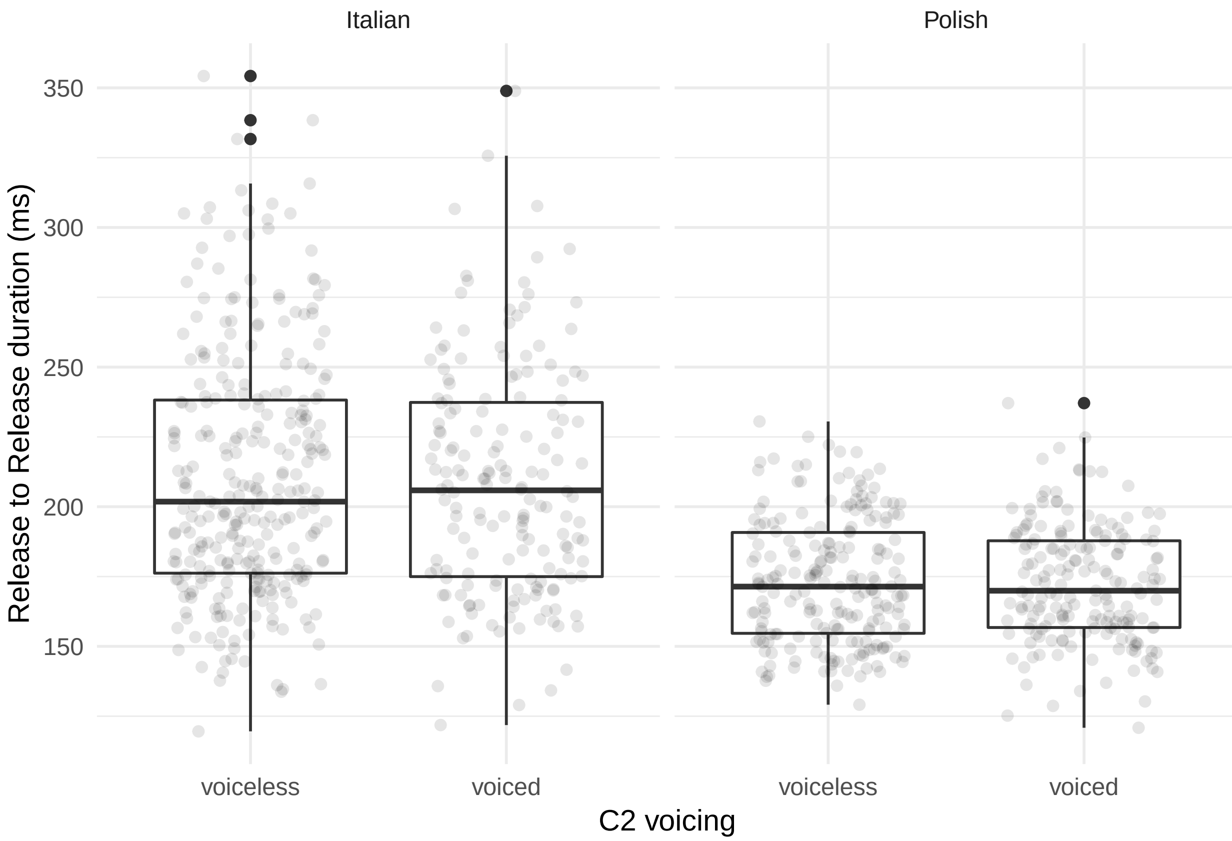


FIG. 5. Raw data and boxplots of the duration in milliseconds of the Release to Release interval in Italian (left) and Polish (right) when C2 is voiceless or voiced.

condition do not differ much in either language. In Italian, the mean duration of the Release to Release interval is 210 ms (sd = 44) if C2 is voiceless, and 209 ms (sd = 41) if voiced. In Polish, the mean durations are respectively 173 (sd = 22) and 172 (sd = 21) ms. The specifications of the null and full models 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 23, which means that the null model (without C2 voicing) is 23 times more likely than the model with C2 voicing as a predictor. The data suggests there is positive evidence that duration of the RR interval is not affected by C2 voicing.

F. Summary

Seventeen participants were recorded while reading CVCV words embedded in a frame sentence. The stressed vowel was either /a, o, u/, and C2 was one of /t, d, k, g/. Of the seventeen participants, 11 are native speakers of Italian and 6 of Polish. Vowel, stop closure, word, and Release to Release vowel duration were measured from the acoustic signal. The analyses of the durational data suggest that:

(a) Stressed vowels in C_1VC_2V words in Italian and Polish are 19 ms longer (se = 4.4) when C2 is voiced.

(b) C2 closure is 16.5 ms shorter (se = 3) if the stop is voiced.

(c) Vowel duration negatively correlates with closure duration, such that shorter closures correspond to longer vowels.

(d) Both word duration and Release to Release duration are not affected by the underlying voicing specification of C2.

IV. DISCUSSION

The data and statistical analyses of this exploratory study suggest that the duration of the interval between the releases of two consecutive consonants in CVCV words (the Release to Release interval) is insensitive to the phonological voicing of the second consonant (C2) in Italian and Polish. In accordance with a compensatory temporal adjustment account (Lehiste, 1970b; Slis and Cohen, 1969b), the difference in vowel duration before voiceless vs. voiced stops can be seen as the outcome of differences in stop closure duration. More specifically, the timing of the closure onset of C2 within the invariant Release to Release interval determines the duration of the preceding vowel. An earlier closure onset 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 6 illustrates this mechanism.

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 and Cohen (1969b) and Lehiste (1970b), is the lack of a precise identification of the word-internal mechanics of compensation. As already discussed in Section I, it is not clear, for example, why the adjustment should target the preceding stressed vowel, rather then the following unstressed vowel or any other segment in the word. Since the Release to Release interval includes just the vowel (broadly defined as a vocoid gesture) and the consonant closure, it follows that differences in closure duration must be reflected in differences in the duration of the preceding vowel.

On the one hand, the voicing effect can be re-interpreted as a by-product of gestural timing, rather then a consequence of intrinsic features of voicing *per se*, with a constant Release to Release interval as the explanans. On the other hand, the Release to Release invariance is in turn an explanandum. In the following section, I offer a gestural organisation account that allows the invariance of such interval to follow from the relative timing of the articulatory gestures in a CVC sequence.

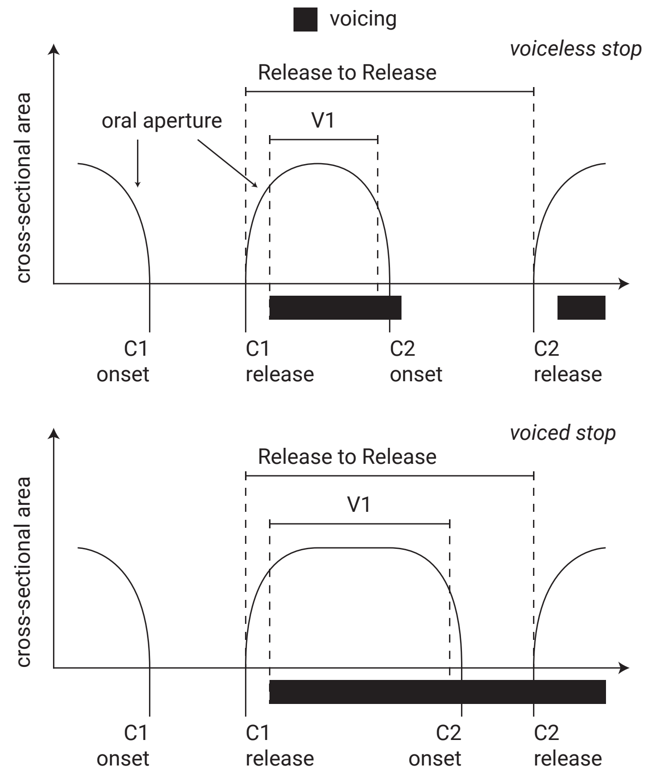


FIG. 6. A schematic representation of the voicing effect as a compensatory temporal adjustment phenomenon. The schematic shows the gestural unfolding of a CVC sequence when C2 is voiceless (top panel), or voiced (bottom panel). Oral cavity aperture (on the y-axis, as the inverse of oral constriction) through time (on the x-axis) is represented 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. Design based on Esposito (2002).

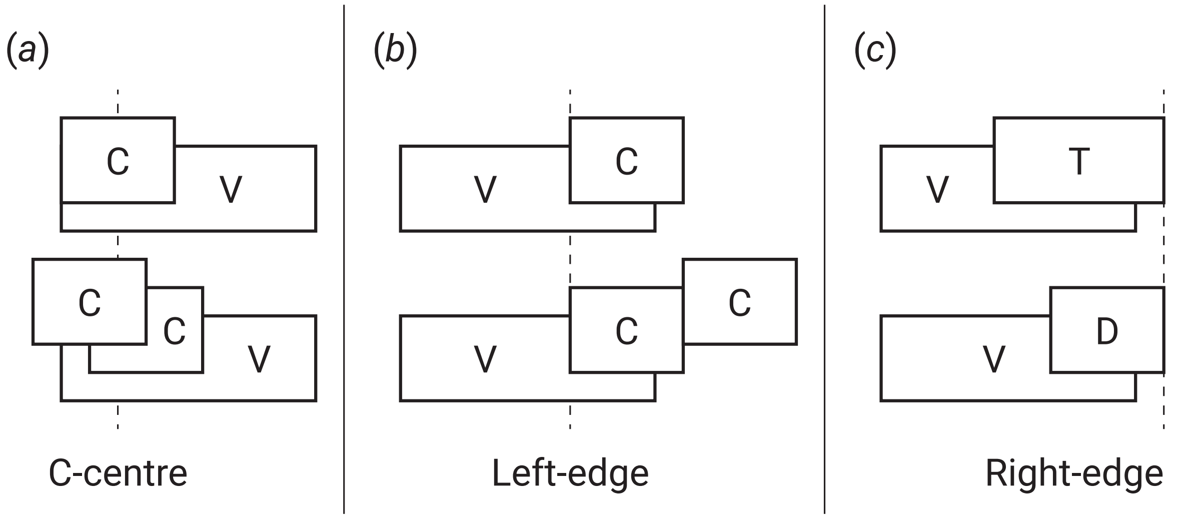


FIG. 7. Gestural organisation patterns for onsets (a), codas (b), heterosyllabic onsets (c). C = consonant, V = vowel, T = voiceless stop, D = voiced stop. See Section IV A for details. Based on Marin and Pouplier (2010).

A. Gestural alignment

According to the coupled oscillator model of syllabic structure (Browman and Goldstein, 1988, 2000; Goldstein *et al.*, 2006; Goldstein and Pouplier, 2014), articulatory gestures can be timed according to two coupling modes: in-phase (synchronous) mode, by which two gestures start in synchrony, or anti-phase (sequential) mode, in which a gesture starts when the preceding one has reached its target. Marin and Pouplier (2010) showed that onset consonants in American English are in-phase with respect to the vowel nucleus and anti-phase with each other. Such phasing pattern establishes a stable relationship between the centre of the consonant (or consonants in a cluster) and the following vowel. Independent of the number of onset consonants, the temporal midpoint of the onset (the so-called ‘C-centre') is maintained at a fixed distance from the vowel, such that an increasing number of consonants in the onset does not change the distance between the vowel and the onset C-centre (Figure 7a). On the other hand, coda consonants are timed anti-phase with the preceding vowel and between themselves. Temporal stability in codas is found in the lag between the vowel and the left-most edge of the coda, which is not affected by the number of coda consonants (Figure 7b). Other studies found further evidence for the synchronous and sequential coupling modes (see extensive review in Marin and Pouplier 2010 and Marin and Pouplier 2014), although the use of one mode over the other depends on the language and the consonants under study.

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

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

A right-edge organisation account is compatible with findings from electromyographic, x-ray microbeam, and ultrasonic data by, respectively, Raphael (1975), De Jong (1991), and Celata *et al.* (2018). Celata *et al.* (2018) show that vowels followed by single consonants are longer than when followed by geminates (for example, /ba.ta/ vs. /bat.ta/). However, vowels followed by a tautosyllabic cluster have the same duration as vowels followed by a heterosyllabic cluster (/pa.tron/ vs. /bat.man/). Celata *et al.* (2018) argue that these results corroborate a rhythmic account in which the relevant unit is what they call the rhythmic syllable (i.e. the VC(C) sequence), and not the traditional syllable. The duration of the rhythmic syllable is constant across the phonological contexts, while that of the traditional syllable is not. This reflects a gestural timing view in which the timing of the right edge of the consonant is fixed relative to the vowel.

De Jong (1991) reports that the closing gesture of voiceless stops (following stressed vowels) is faster than that of voiced stops, and that also it is timed earlier with respect to the opening gesture of the stressed vowel. According to De Jong (1991), the differences in vowel duration are driven by the timing of the consonantal closing gesture relative to the vocalic opening gesture (also see Hertrich and Ackermann 1997). Moreover, the data in De Jong (1991) show that the final portion of the opening gesture is prolonged before voiced stops.

This pattern fits to the one reported in an electromyographic study by Raphael (1975). The electromyographic signal corresponding to the vocalic gesture reaches its plateau at the same time relative to the preceding consonant in the voiceless and voiced context, but the plateau is held for longer in the case of vowels followed by voiced stops. This indicates that muscular activation in the vocalic gesture before voiced stops is held for longer. Raphael (1975) further notes that the durational difference in muscular activation corresponds to the difference in the acoustic duration of vowels before voiceless vs. voiced stops.

The results of the studies just discussed, together with the results from this study, bring support to a view in which two aspects of gestural organisation contribute to the difference in vowel duration observed before consonants varying in their voicing specification. These aspects are: (1) the *right-edge alignment* of coda consonants following a stressed vowel relative to the latter, and (2) the *differential timing of the closing gesture onset* for voiceless vs. voiced stops. The interplay of these two aspects can be synthesised into a compensatory temporal adjustment account, which requires a temporally constant interval, produced by (1), and a temporal reorganisation, brought about by (2).

B. Limitations and future work

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

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

The compensatory temporal adjustment account presented here extends to other durational effects discussed in the literature. In particular, the account bears predictions on the direction of the durational difference led by phonation types different from voicing, like aspiration and ejection. For example, the mix of results with regard to the effect of aspiration (Durvasula and Luo, 2012) suggests that the conditions for a temporal adjustment might differ across the contexts and languages studied. In light of the results in Beguš (2017), future studies will have to investigate the durational invariance of speech intervals in relation to a variety of phonation contrasts.

V. CONCLUSION

The results of an exploratory study on the effect of voicing on vowel duration bring support for 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). I proposed that the Release to Release invariance is a consequence of the gestural organisation of the CVC sequence, in which the lag between the right-edge of the second consonant and the preceding stressed vowel is fixed.

TABLE II. Summary of the linear mixed-effects model fitted to vowel duration.

term	Estimate	SE	CI low	CI up	df	t-value	p-value <
Intercept	202.5289	8.6169	185.6400	219.4178	134.7948	23.5036	0.0000 *
C2 voi: voiced	18.9669	4.3898	10.3631	27.5707	12.7785	4.3207	0.0009 *
Vow: /o/	-6.1457	3.9512	-13.8899	1.5985	8.6900	-1.5554	0.1555
Vow: /u/	-26.3039	3.9772	-34.0991	-18.5087	8.9199	-6.6136	0.0001 *
Lang: Polish	-24.2194	8.1708	-40.2338	-8.2050	21.7230	-2.9642	0.0072 *
C2 place: velar	-8.1827	1.6984	-11.5116	-4.8539	10.5938	-4.8178	0.0006 *
Syl. rate	-15.2920	1.2679	-17.7771	-12.8070	775.7483	-12.0608	0.0000 *
Voiced, /o/	-2.0453	5.8662	-13.5428	9.4522	10.5314	-0.3487	0.7342
Voiced, /u/	-14.4536	5.8040	-25.8292	-3.0780	10.0977	-2.4903	0.0318 *
Voiced, Polish	-7.9928	6.4252	-20.5860	4.6005	14.2528	-1.2440	0.2336
/o/, Polish	-3.6121	5.7389	-14.8601	7.6360	9.6704	-0.6294	0.5437
/u/, Polish	1.6149	5.7695	-9.6931	12.9230	9.8777	0.2799	0.7853
Voiced, /o/, Polish	-2.9987	8.3627	-19.3894	13.3920	10.8862	-0.3586	0.7268
Voiced, /u/, Polish	7.9601	8.3077	-8.3227	24.2428	10.6040	0.9582	0.3593

TABLE III. Summary of a linear mixed-effects model fitted to closure duration.

term	Estimate	SE	CI low	CI up	df	t-value	p-value	<
Intercept	119.7338	7.2100	105.6023	133.8652	128.2742	16.6065	0.0000	*
C2 voi: voiced	-16.5825	4.3129	-25.0356	-8.1294	17.8144	-3.8449	0.0012	*
Vow: /o/	3.6830	3.4951	-3.1672	10.5333	9.0918	1.0538	0.3192	
Vow: /u/	-1.9898	3.5174	-8.8837	4.9041	9.3243	-0.5657	0.5849	
Lang: Polish	-6.9400	6.8688	-20.4027	6.5226	22.0443	-1.0104	0.3233	
C2 place: velar	3.4024	1.4976	0.4672	6.3376	10.9532	2.2719	0.0443	*
Syl. rate	-8.4278	1.0550	-10.4954	-6.3601	557.6472	-7.9887	0.0000	*
Voiced, /o/	1.1040	5.1738	-9.0364	11.2445	10.8916	0.2134	0.8350	
Voiced, /u/	9.9882	5.1257	-0.0581	20.0344	10.4981	1.9486	0.0786	
Voiced, Polish	1.6759	6.5019	-11.0675	14.4194	20.0145	0.2578	0.7992	
/o/, Polish	-0.2681	5.0672	-10.1997	9.6635	10.0440	-0.0529	0.9588	
/u/, Polish	7.1432	5.0932	-2.8393	17.1256	10.2505	1.4025	0.1903	
Voiced, /o/, Polish	1.5022	7.3707	-12.9441	15.9485	11.2269	0.2038	0.8422	
Voiced, /u/, Polish	-3.2088	7.3279	-17.5711	11.1536	10.9696	-0.4379	0.6700	

TABLE IV. Summary of a linear mixed-effects model fitted to vowel duration with closure duration as predictor.

term	Estimate	SE	CI low	CI up	df	t-value	p-value	<
Intercept	219.3142	10.4477	198.8371	239.7913	123.5512	20.9917	0.0000	*
C2 closure	-0.1487	0.0632	-0.2726	-0.0249	50.3807	-2.3532	0.0226	*
Vow: /o/	-2.0462	5.4702	-12.7675	8.6751	81.5530	-0.3741	0.7093	
Vow: /u/	-5.0236	5.5582	-15.9176	5.8703	86.7938	-0.9038	0.3686	
Syl. rate	-17.5364	1.2855	-20.0559	-15.0168	896.1529	-13.6415	0.0000	*
C2 closure, /o/	-0.0973	0.0615	-0.2178	0.0231	876.5971	-1.5835	0.1137	
C2 closure, /u/	-0.3500	0.0619	-0.4712	-0.2288	895.3921	-5.6582	0.0000	*

TABLE V. Participants' sociolinguistic information.

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

TABLE VI. Target words.

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

APPENDIX A: OUTPUT OF STATISTICAL MODELS

1. Vowel duration

2. Closure duration

3. Vowel and closure duration

APPENDIX B: SOCIO-LINGUISTIC INFORMATION OF PARTICIPANTS

APPENDIX C: TARGET WORDS

[1]Two accounts that posit a perceptual cause are the ones by Javkin (1976) and Kluender *et al.* (1988). To the best of my knowledge, Javkin (1976)'s proposal remains to be empirically tested, while see Fowler (1992) for arguments against Kluender *et al.* (1988).

[2]As per Cysouw and Good (2013), the glossonyms *Italian* and *Polish* as used here refer, respectively, to the languoids Italian [Glottocode: `ital1282`] and Polish [Glottocode: `poli1260`].

[3]To the best of my knowledge, this is the first attempt to gather synchronised acoustic, tongue imaging and electroglottographic data in relation to the voicing effect.

[4]The mean differences are based on 3 speakers in Farnetani and Kori 1986 and 7 speakers in Esposito 2002. Caldognetto *et al.* 1979 does not report estimates of vowel duration, but the study is based on 10 speakers.

[5]The microphone was clipped onto a metal headset wore by the participant, which is part of the ultrasound equipment.

[6]Italian has both a mid-low [ ] and a mid-high [o] back vowel in its vowel inventory. These vowels are traditionally described as two distinct phonemes (Kramer, 2009), although both their phonemic status and

their phonetic substance are subject to a high degree of geographical and idiosyncratic variability Renwick and Ladd (2016). As a rule of thumb, stressed open syllables in Italian (like the ones used in this study) have [ ] (vowels in penultimate stressed open syllables are long) rather than [o] Renwick and Ladd (2016). On the other hand, Polish has only a mid-low back vowel phoneme / / (Gussmann, 2007). For sake of typographical simplicity, the symbol /o/ will be used here for both languages.

[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.

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

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