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I. INTRODUCTION

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

Several proposal have been put forward as to where to look for the possible cause of the voicing effect (see Maddieson and Gandour, 1976, and Sóskuthy (2013) for an overview). Most of the proposed accounts place the source of the voicing effect in properties of speech production.[1] One of these production accounts, which will be the focus of this study, relates the voicing effect to some constant property of speech that is held constant across contexts while the local property of voiceless vs. voiced obstruents varies, thus creating a trade-off solution within the constant property. Lindblom (1967), Slis and Cohen (1969a), Slis and Cohen (1969b), and Lehiste (1970) (among others) argue that the relevant invariant property of speech is a constant durational interval within which segments of different duration results in different duration of other segments. Both the syllable/VC sequence

(Lindblom) and the word (Lehiste, Slis) has been proposed as the fixed interval. The closure of voiced stops is shorter than that of voiceless stops. It follows that vowels followed by shorter closures (like in the case of voiced stops) are longer than vowels followed by longer closures (like in the case of voiceless stops).

However, Chen (1970) and Maddieson and Gandour (1976) criticise the compensatory temporal adjustment account on empirical grounds. Chen (1970) shows that the duration of the syllable is affected by consonant voicing (compatible with findings in Jacewicz *et al.*, 2009), contrary to Lindblom's expectations. Maddieson and Gandour (1976) reject any compensatory account based on data from a parallel of the voicing effect, the aspiration effect, by which vowel tend to be longer when followed by aspirated stops than when followed by non-aspirated stops. They 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 consonant are different.

A. The present study

An exploratory study of acoustic data from Italian and Polish was conducted to investigate the relationship between vowel duration and consonant voicing in two languages that reportedly differ in the magnitude of the voicing effect. Italian has been unanimously reported as a voicing effect language (Caldognetto *et al.*, 1979; Esposito, 2002; Farnetani and Kori, 1986). The mean difference in vowel duration when followed by voiceless vs. voiced consonants ranges between 22 and 24 ms (with longer vowels followed by voiced consonants, Esposito, 2002; Farnetani and Kori, 1986).[2] On the other hand, Polish is subject to conflicting results regarding the presence and magnitude of the effect. While Keating (1984) reports no effect of voicing on vowel duration in data from 24 speakers, Nowak (2006) finds that vowels followed by voiced stops are 4.5 ms longer in the 4 speakers recorded. Moreover, Malisz and Klessa (2008) argue based on data from 40 speakers that the magnitude of the voicing effect in Polish is highly idiosyncratic, and claim their results to be inconclusive.

I couldn't find evidence for a different magnitude of the effect of voicing on vowel duration in Italian and Polish. However, the data support a compensatory temporal adjustment account by which the placement of the closure onset within an interval which is invariant between voiceless and voiced contexts (which is insensitive to C2 voicing) determines the respective durations of the vowel and the stop closure. While the data from the present study confirms that word is not affected as shwon in …, a problem of that account is that they don't discuss the internal structure of the word. While it is true that the duration of words is not affected by C2 voicing, I will show that the interval between two consecutive releases corresponds to a more elegant view, which is in turn compatible with current theories of gestural timing (which fits with current views on gestural timing [add references to C-centre]). I will show that the Release to Release is invariant and that this is compatible with a gestural timing in which the C2 is right-edge aligned with C1/V. I will also offer an interpretation of Maddieson and Gandour (1976) that is compatible with a compensatory temporal adjustment account.

II. METHOD

A. Participants

Seventeen subjects in total participated to this exploratory study. Eleven participants were native speakers of Italian (5 female, 6 male), while six were native speakers of Polish (3 female, 3 male). The Italian speakers were from the North and Centre of Italy (8 speakers from Northern Italy, 3 from Central Italy). The Polish group had 2 speakers from Poznań and 4 speakers from Eastern Poland. For more information on the speakers, see Appendix A. Ethical clearance was obtained for this study from the University of Manchester (REF 2016-0099-76). The participants signed a written consent and received a monetary compensation.

B. Equipment

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

C. Materials

The target stimuli were disyllabic words with $C_1V_1C_2V_2$ structure, where C_1 = /p/, V_1 = /a, o, u/, C_2 = /t, d, k, g/, and $V_2 = V_1$ (e.g. /pata/, /pada/, /poto/, etc.). 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. These sentences were chosen in order to keep the placement of stress and emphasis similar across languages, so to ensure comparability of results.

D. Procedure

The participant was asked to read the sentences with the target words which were sequentially presented on the computer screen. The order of the sentence stimuli was randomised for each participant. Each participant read the list of randomised sentence stimuli six times. Due to software constraints, the order of the list was kept the same across the six repetitions within each participant. Each speaker read a total of 72 sentences, with a grand total of 576 tokens (288 per language). The reading task lasted between 15 and 20 minutes, with optional short breaks between one repetition and the other.

E. Data processing and measurements

The audio recordings were exported from AAA in `.wav` format for further processing. A forced aligned transcription was accomplished through the SPeech Phonetisation Alignment and Syllabi-

TABLE I. List of measurements as extracted from acoustics.

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

fication software (SPPAS) (Bigi, 2015). The outcome of the automatic annotation was manually corrected when necessary, according to the criteria in Table I. The releases of C1 and C2 were detected automatically by means of a Praat scripting implementation of the algorithm described in Ananthapadmanabha *et al.* (2014). The durations in milliseconds of the following intervals were extracted from the annotated acoustic landmarks with Praat scripting: sentence duration, word duration, vowel duration (V1 onset to V1 offset), consonant closure duration (V1 offset to C2 burst), and Release-to-Release duration (RR duration, C1 release to C2 release). Syllable rate (syllables per second) was used as a proxy to speech rate (Plug and Smith, 2018) for duration normalisation, and was calculated as the number of syllables divided by the duration of the sentence (8 syllables in Italian, 6 in Polish).

F. Statistical analysis

Given the exploratory nature of the study, all statistical analyses reported here are to be considered data-driven or hypothesis-generating rather than hypothesis-driven (Kerr, 1998). The durational measurements were analysed with linear mixed-effects models using `lme4` v1.1-17 in R v3.5.0 (Bates *et al.*, 2015; Team, 2018). All factors were coded as treatment contrasts. *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). *P*-values below the alpha level 0.05 were considered significant. The estimates of the relevant effects are then calculated by refitting the models including only the significant terms (step-down approach, Diggle *et al.*, 2002; Zuur *et al.*, 2009, pp. 121–122). Bayes factors were used to specifically test the null hypotheses that word and RR duration are not affected by C2 voicing (i.e., the effect of C2 voicing on duration is `0`). For each set of null/alternative hypotheses, a full model (with the predictor of interest) and a null model (excluding it) were fitted separately using Maximum Likelihood estimation (Bates *et al.*, 2015, p. 34). The BIC approximation was then used to obtain Bayes factors (Jarosz and Wiley, 2014; Raftery, 1995, 1999; Wagenmakers, 2007). The approximation is calculated according to the equation in 1 (Wagenmakers, 2007, p. 796).

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

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

III. RESULTS

Only the most relevant terms will be presented. For the others see tables and appendixes.

A. Vowel duration

A linear mixed-effects model was fitted with the following terms: vowel duration as the outcome variable; fixed effects for C2 voicing (voiceless, voiced), 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: C2 voicing, vowel, language, and speech rate. No interaction was significant. The vowel /a/ (when followed by voiceless stops) has a duration of 202.5 ms (se = 8.5 ms). The vowel /o/ is 9.5 ms shorter (se = 3 ms), while the vowel /u/ is 30.5 ms shorter (se = 3). Vowels are 11 ms longer (se = 3) when followed by a voiced stop. Polish has on average shorter vowels than Italian ($\hat{\beta}$ = -28 ms, se = 8 ms), although the effect of voicing is estimated to be the same in both languages (the interaction of 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 ($\hat{\beta}$ = -15 ms, se = 1 ms).

B. Consonant closure duration

The same maximally specified model as with vowel duration has been fitted to consonant closure durations as the outcome variable. Only C2 voicing and speech rate were significant. Stop closure is 13 ms shorter (se = 3 ms) if the stop is voiced. Finally, faster speech rates correlate with shorter closure durations ($\hat{\beta}$ = -8 ms, se = 1 ms).

C. Vowel and closure duration

The full model was specified 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 when the vowel is /a/ ($\hat{\beta}$ = -0.2 ms, se = 0.06 ms). The effect with the vowel /o/ does not significantly differ from the one with /a/, while with /u/ the effect is -0.5 ms ($\hat{\beta}$ = -0.3 ms, se = 0.06 ms). In general, then, closure duration is inversely correlated with vowel duration after controlling for speech rate. However the correlation is quite weak. A 1 ms increase in closure duration corresponds to a 0.2–0.5 ms decrease in vowel duration.

D. Word duration

The following full and null models were fitted to test whether word duration is affected by C2 voicing. In the full model, I entered as fixed effects: C2 voicing, C2 place, vowel, speech rate, and language. The model also included by-speaker and by-word random intercepts, plus a by-speaker random slope for C2 voicing. The null model was the same as the full model, with the exclusion of the fixed effect of C2 voicing. The Bayes factor of the null model against the full model is 21.5. Thus, the null model (in which the effect of C2 voicing is 0) is 21.5 times more likely under the observed data than the full model. This indicates that there is strong evidence for word duration not being affected by C2 voicing.

E. Release to Release interval (RR) duration

The models specifications for the RR duration were the same as for word duration. The Bayes factor of the null model against the full model for RR duration is 19, which means that the null model (without C2 voicing) is 19 times more likely than the full model. The data suggests there is positive evidence that duration of the RR interval is not affected by C2 voicing.

IV. DISCUSSION

In this exploratory study of Italian and Polish acoustic data, I found that the duration of interval between the releases of two consecutive consonants is insensitive to the phonological voicing of the second consonant. The difference in vowel duration before voiceless vs. voiced stops derives from differences in placement of the closure onset within the fixed interval between the releases of C1 and C2.

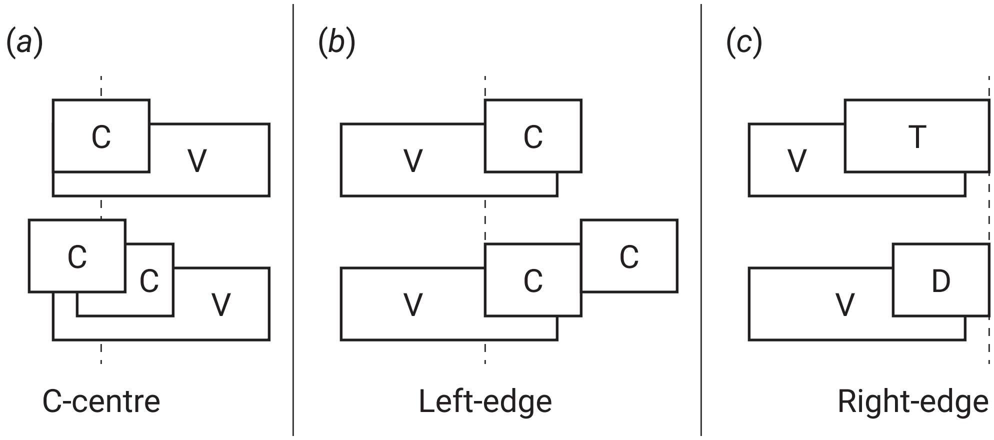

FIG. 1. Gestural organisation patterns for onsets (a), codas (b), heterosyllabic onsets (c). See Section IV A for details. Based on Marin and Pouplier (2010).

A. Gestural alignment

According to the model of gestural coupling (ref …), articulatory gestures can be timed according to two coupling modes: in-phase mode, by which two gestures start in synchrony, or anti-phase mode, in which one gesture starts when the preceding gesture has reached its target. These two modes of coupling can be applied to the gestural timing of segments within a syllable. Marin and Pouplier (2010) showed that onset consonants in American English are in-phase with the vowel nucleus and anti-phase with each other in the case of onset clusters. Such phasing pattern establishes a stable relation between the centre of the consonant or consonant cluster and the following vowel. Independent of the number of onset consonants, the midpoint of the onset, the so-called 'C-centre', is maintained at a fixed distance from the vowel, such that increasing number of consonants in the onset does not change the C-center/vowel distance. On the other hand, coda consonants are timed anti-phase with the preceding vowel and between themselves. Stability in codas is seen in the lag between the vowel and the left-most edge of the coda, which is not affected by the number of coda consonants.

Onset consonants can thus be said to follow a C-centre organisation pattern, while coda consonants follow a left-edge organisation pattern. Of course, in both cases, 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) consonant. The results from this acoustic study on Italian and Polish are compatible with a right-edge organisation pattern for onset consonants. The release of C2 (which is the onset of the seconds in CVCV words), which can be thought as the acoustic parallel of the articulatory right edge of C2, is invariantly timed relative to V1 (which is the nucleus of the first syllable).

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

de Jong (1991) reports that the closing gesture of consonants following stressed vowels is quicker in voiceless consonants than in voiced ones, and that also it is timed earlier than that of voiced consonants. The difference in vowel duration are, according to de Jong (1991), driven by the timing of the consonantal closing gesture relative to the vocalic opening gesture. The view proposed above reflects these findings. Moreover, the data in de Jong (1991) show that the final portion of the vocalic opening gesture is prolonged before voiced stops. This finding corresponds to what Raphael (1975) reported based on electromyographic data. The electromyographic signal corresponding to the vocalic gesture reaches its plateaux at the same time in the voiceless and voiced context, but the plateaux is held for longer in the case of vowels followed by voiced stops, indicating that muscular activation is kept for longer.

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

B. Limitations

It is difficult given the present data to disambiguate between two interpretations: either C2 is timed relative to a gestural epoch of V1 (possibly the gesture onset)—and the invariance of RR would follow from the fact that C1 is held constant— or the motor plan for CVCV words is structured is such a way to directly keep the RR duration invariant.

C. A reinterpretation of Maddieson and Gandour (1976)

Before concluding/Finally, I would like to offer a reinterpretation of the results in Maddieson and Gandour (1976). A major drawback of the analysis in Maddieson and Gandour (1976) is that the consonant duration in fact was measured from the closure of the relevant consonant to the release of the following consonant, due to difficulties in detecting the release of the consonant of interest (e.g., in *ab sāth kaho*, the duration of /t^h/ in *sāth* was calculated as the interval between the closure of /t^h/ and the release of /k/). This measure includes the burst and (eventual) aspiration of the consonant. Slis and Cohen (1969a), however, states that the inverse correlation between vowel duration and the following consonant raises when consonant *closure* duration is taken into account, and not entire *consonant* duration. If the correlation exists between vowel and closure duration, the inclusion of burst/aspiration duration clearly alters this relationship.

ACKNOWLEDGMENTS

Thanks to...

APPENDIX A: SOCIO-LINGUISTIC INFORMATION OF PARTICIPANTS

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

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

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TABLE II. Participants' sociolinguistic information.

ID	Age	Sex	Native L	Other Ls	City of birth	Spent most time in	> 6 mo
it01	29	Male	Italian	English, Spanish	Verbania	Verbania	Yes
it02	26	Male	Italian	Friulian, English, Ladin-Venetan	Udine	Tricesimo	Yes
it03	28	Female	Italian	English, German	Verbania	Verbania	No
it04	54	Female	Italian	Calabrese	Verbania	Verbania	No
it05	28	Female	Italian	English	Verbania	Verbania	No
it07	29	Male	Italian	English	Tradate	Cairate	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

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