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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; Laeuffer, 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 /t / 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](#)

44 [Kori, 1986](#)). The mean difference in vowel duration when followed by voiceless vs. voiced
 45 consonants ranges between 22 and 24 ms (with longer vowels followed by voiced consonants,
 46 [Esposito, 2002](#); [Farnetani and Kori, 1986](#)).² On the other hand, Polish is subject to con-
 47 flicting results regarding the presence and magnitude of the effect. While [Keating \(1984\)](#)
 48 reports no effect of voicing on vowel duration in data from 24 speakers, [Nowak \(2006\)](#) finds
 49 that vowels followed by voiced stops are 4.5 ms longer in the 4 speakers recorded. Moreover,
 50 [Malisz and Klessa \(2008\)](#) argue based on data from 40 speakers that the magnitude of the
 51 voicing effect in Polish is highly idiosyncratic, and claim their results to be inconclusive.

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

V₁, 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 C₂, 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.

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)

E. Data processing and measurements

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

of the algorithm described in [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).

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

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.

185 IV. DISCUSSION

186 [Marin and Pouplier \(2010\)](#) showed that coda consonants in American English are timed
 187 relative to the preceding vowel in such a way that the left-edge of the coda consonant is
 188 stable across contexts. On the other hand, onset consonants follow a C-centre pattern, by
 189 which is the mid-way distance between the left and the right edge of the consonant that
 190 is stable. To the best of my knowledge, no study has been done on the timing of onset
 191 consonants relative to the *preceding* (heterosyllabic) consonant. The data of this study are
 192 compatible with a right-edge alignment account. The right edge of the C2 consonant, i.e. the
 193 release, in Italian and Polish is invariantly timed relative to V1, such that difference in C2
 194 closure duration do not affect the distance between V1 and the release of C2.

195 A right-edge alignment account is compatible with findings by [Raphael \(1975\)](#), [de Jong](#)
 196 [\(1991\)](#), and [Celata *et al.* \(2018\)](#).

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

201 Finally, I would like to offer a reinterpretation of the results in [Maddieson and Gandour](#)
 202 [\(1976\)](#). A major drawback of the analysis in [Maddieson and Gandour \(1976\)](#) is that the
 203 consonant duration in fact was measured from the closure of the relevant consonant to
 204 the release of the following consonant, due to difficulties in detecting the release of the
 205 consonant of interest (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. [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

¹Two 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.* \(1988\)](#).

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

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Participant ID	Age	Sex	Native language	Other languages	City of birth	Spoken language
it01	29	Male	Italian	English, Spanish	Verbania	V
it02	26	Male	Italian	Friulian, English, Ladin-Venetan	Udine	T
it03	28	Female	Italian	English, German	Verbania	V
it04	54	Female	Italian	Calabrese	Verbania	V
it05	28	Female	Italian	English	Verbania	V
it07	29	Male	Italian	English	Tradate	C
it09	35	Female	Italian	English	Vignola (MO), Italy	V
it11	24	Male	Italian	english	Monza	M
it13	20	Female	Italian	English, French, Arabic, Farsi	Ancona	C
it14	32	Male	Italian	English, Spanish	Frosinone	F
pl02	32	Female	Polish	English, Norwegian, French, German, Dutch	Koło	P
pl03	26	Male	Polish	Russian, English, French, German	Nowa Sol	P
pl04	34	Female	Polish	Spanish, English, French	Warsaw	W
pl05	42	Male	Polish	English, French	Przasnysz	W
pl06	33	Male	Polish	English	Zgierz	Z
pl07	32	Female	Polish	English, Russian	Bielsk Podlaski	B

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