TITLE: Temporal (in)stability in English monosyllabic and disyllabic words: Insights on the effect of voicing on vowel duration

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Abstract

English is one in the wide range of languages in which the duration of vowels is modulated by the voicing of the following consonant: Vowels are shorter when followed by voiceless stops, and longer when followed by voiced stops. The so-called voicing effect has been attributed to a variety of mechanisms. Temporal compensation between the duration of the vowel and the following stop closure is one of these mechanisms. Based on acoustic data from Italian and Polish disyllabic words, the compensatory mechanism has been proposed to be a consequence of the temporal stability of the interval between the consonant releases flanking the vowel. The timing of the VC boundary within this interval determines the respective durations of the vowel and the stop closure. In this paper, it is shown that the duration of the release-to-release interval is not affected by the voicing of the second consonant in English disyllabic words, but that it is in monosyllabic words. It is argued that the stability of the interval can be derived from the isochronous phasing of the vocalic gestures in the VCV sequence of disyllabic words. The absence of the temporal anchor of a second vowel in monosyllabic words, on the other hand, allows the vocalic and the consonant gesture durations to be modified independently. Other aspects of production and perception behind the voicing effect can coexist with a temporal compensation mechanism and cannot be excluded.

Keywords: voicing effect, vowel duration, compensatory adjustment, English

1 Introduction

A well-known cross-linguistic tendency is that vowels have shorter durations when followed by voiceless stops and longer durations when followed by voiced stops. This so-called 'voicing effect' has been long documented in a wide range of languages across different linguistic families (Maddieson & Gandour 1976; Beguš 2017). Several hypotheses have been proposed as to the origin of this phenomenon, from articulatory mechanisms to perceptual biases; however, no one particular account has gained universal support.

One such hypothesis, the compensatory temporal adjustment account, states that the voicing effect involves a compensatory mechanism between vowel and consonant closure duration. Vowels are shorter when followed by voiceless stops because the latter have longer closure durations, and, vice versa, vowels are longer before voiced stops because the latter have shorter closure durations. However, the compensatory account fails to clearly identify a speech interval within which compensation is implemented. Both the syllable (Lindblom 1967; Farnetani & Kori 1986) and the word (Slis & Cohen 1969a,b; Lehiste 1970a,b) have been proposed as such intervals, but these have been subsequently criticised on empirical and logical grounds (Chen 1970; Jacewicz et al. 2009; Maddieson & Gandour 1976; Coretta 2019b).

In an exploratory study of acoustic durations in Italian and Polish trochaic CV́CV words, Coretta (2019b) finds that the duration of the interval between the the release of C1 and the release of C2 (the release-to-release interval) is not affected by the voicing status of the second consonant. The duration of the release-to-release interval in words where the second consonant is voiceless (like /pata/) is not significantly different from that in words where the second consonant is voiced (for example, /pada/).[1] The temporal stability of the release-to-release interval is compatible with a compensatory temporal adjustment account of the voicing effect (Lindblom 1967; Slis & Cohen 1969a,b; Lehiste 1970a,b), and it offers a resolution to the drawbacks of previous versions of the account.

Given the temporal stability of the release-to-release interval, the timing of the acoustic vowel/consonant (VC) boundary (corresponding to the acoustic vowel offset and the acoustic consonant closure onset) within that interval determines the respective durations of vowel and consonant closure. Since the VC boundary in voiceless stops is timed earlier within the release-to-release relative to voiced stops, the vowel is shorter and closures is longer when the post-vocalic stop is voiceless than when it is voiced. This interpretation agrees with known differences of closure durations in voiceless vs. voiced stops (Lisker 1957; Summers 1987; Davis & Summers 1989; de Jong 1991), namely that voiceless closures are longer than voiced ones. Thus, a possible diachronic pathway to the voicing effect is one in which vowel and closure duration differences emerge from changes in the timing of the VC boundary within the release-to-release interval.

Note that the release-to-release interval in itself does not have a special status in the account put forward here. The proposed account of compensatory temporal adjustment can be understood in relation to the *acoustic* duration of vowels, hence the scope of compensation can (but need not) be defined in terms of acoustic intervals. As reviewed above, the interval found to be temporally stable across voicing contexts in disyllabic words in Italian and Polish is the release-to-release interval (Coretta 2019b). However, it is desirable to derive the isochrony of this acoustic interval from properties of articulatory coordination. A tentative account of the underlying gestural coordination from which the release-to-release isochrony can be derived is offered here.

[1] Note that the release-to-release interval is not equivalent to the VC interval, since the latter does not include the VOT from the consonant preceding the vowel. See Coretta (2019b) for further details.

1.1 A gestural account of the voicing effect

According to Öhman (1966, 1967), the speech stream is composed by a series of continuous vocalic gestures interrupted by gestures of oral constriction (consonants). Fowler (1983) further proposes that the vocalic gestures of a VCV sequence are characterised by a cyclic pattern of production, so that the temporal distance between the two vowels is constant, independent of the nature of the intervening consonant. While the temporal distance of the V-to-V interval is modulated by the number of intervening consonants (Zmarich et al. 2011; Zeroual et al. 2015), the distance can still be expected to be stable within the context of disyllabic words with a single intervocalic consonant that alternates in voicing.

The task-dynamic model (Saltzman et al. 2008) of Articulatory Phonology (Ohala et al. 1986; Browman & Goldstein 1988, 1992), based on the coupled oscillators model (O'Dell & Nieminen 2008), states that any two gestures can be implemented according to two modes. Either they are initiated in synchrony or they are implemented sequentially. These modes of gestural phasing (in-phase and anti-phase) can account for a variety of patterns of articulatory timing. Onset consonants are generally produced in-phase with the following vowel, meaning that the vocalic and consonantal gestures are initiated together. This same mechanism also gives rise to the so-called C-centre effects observed with onsets, by which the acoustic duration of a vowel depends on the number of onset consonants (Browman & Goldstein 1988; Marin & Pouplier 2010; Hermes et al. 2013; Marin & Pouplier 2014). On the other hand, coda consonants tend to be produced anti-phase relative to the preceding vowel and to each other, meaning that they are articulated in sequence. The duration of vowels has been found to be insensitive to the number of coda consonants following them (Marin & Pouplier 2010, 2014)

Further evidence for a vowel-based rhythmic gestural implementation comes from work by Farnetani & Kori (1986) and Celata & Mairano (2014). These studies investigate the relation between vowel duration and syllable structure in Italian. In the first study, it was found that vowels followed by a singleton stop (for example in /la.da/) are longer than vowels followed by a tautosyllabic cluster (/la.dra/). This pattern can easily be derived from a scenario in which the distance between the vowels is the same in the two contexts (/la.da/ and /la.dra/), and the onset consonants follow a C-centre alignment. The onset of the first consonant in the /dr/ cluster is shifted towards the vowel, making the latter shorter. Celata & Mairano (2014) also show that the duration of the consonant/consonant cluster is negatively correlated with the duration of the preceding vowel (although the magnitude of the correlation is low to moderate).

Under the gestural account proposed in this paper, the combined action of the isochrony of the vowel-to-vowel interval and the in-phase alignment of the onset consonant is responsible for the isochrony of the release-to-release interval in

CVCV words. The first consonant and vowel are produced in-phase with each other, and these are sequentially followed by the second consonant and vowel, again produced in-phase with each other. Then, the differential duration found in the voicing effect would be a consequence of the different velocity of the closing gesture in voiceless vs. voiced consonants.

Summers (1987) shows that the closing gesture of voiceless stops has greater velocity than that of voiced stops. Assuming that the closing gesture of both voiceless and voiced stops is initiated in synchrony with that of the following vowel (as per the in-phase alignment), full oral closure is achieved earlier in voiceless stops relative to its timing in voiced stops. The result is, everything else being equal, a shorter vowel and a longer (full) closure in voiceless stops, and a longer vowel and a shorter closure in voiced stops. Warren & Hay (2006) offer some evidence from lip data, where the lip closing gestures (together with the jaw gesture) accounts for about 80% of the vowel duration difference.

A similar chain of reasoning applies to the context of coda consonants. If coda consonants are produced anti-phase with the preceding vowel and the closing gesture of the consonant starts at a specific time after the production of the vowel independent of consonant voicing, then the greater velocity of the closing gesture in voiceless stops would result in a shorter vowel and a longer closure relative to voiced stops. However, the articulatory data in de Jong (1991) suggests that the timing of the onset of the stop closing gesture differs depending on voicing in English monosyllabic words. Section 4.3 will discuss a possible solution based on perceptual mechanisms that could reconcile the articulatory predictions put forward here and the empirical data.

1.2 The voicing effect in English

English is one of the most investigated languages in relation to the voicing effect (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; Ko 2018). English is also the language in which the voicing effect reportedly has the greatest magnitude relative to that of other languages. This special status of English is traditionally attributed to the phonologisation of the voicing effect in this language (Sharf 1964; de Jong 2004). Vowel duration and the vowel-to-consonant duration ratio are considered to be among the most stable cues to consonantal voicing (Peterson & Lehiste 1960; Raphael 1972; Port & Dalby 1982). Kluender et al. (1988) proposed that the difference in vowel duration before voiceless vs. voiced stops could have been enhanced and exploited to cue the voicing contrast. This could explain the greater effect of English compared for example to the effect in Italian, in which voicing is most robustly cued by vocal fold vibration during closure (Pape & Jesus 2014).

As it is the case, previous studies on English have reported a difference in vowel duration before voiceless vs. voiced stops which ranges between 20 and 150 ms, while the values for the effect in Italian are lower, between 15 and 25 ms (Magno Caldognetto et al. 1979; Farnetani & Kori 1986; Esposito 2002; Coretta 2019b). A Bayesian meta-analysis of the voicing effect based on estimates obtained from 15 studies suggests that the effect of voicing in English monosyllabic words ranges between 55 and 95 ms at 95% probability, with a meta-analytical mean of 75 ms (see Supplement A). On the other hand, the meta-analytical estimate of the voicing effect for disyllabic words is lower, at about 25 ms (around 50 ms less than in monosyllabic words). This estimate is closer to the effect sizes reported for Italian. Note, however, that the Italian values refer to the effect as observed in disyllabic words.

Nevertheless, it is possible that the alleged differences in magnitude between English and other languages are a product of the different contexts under examination (Laeufer 1992). Ko (2018), in a more recent investigation of the voicing effect in English monosyllabic words, finds a substantially lower difference in vowel duration (35 ms). The Bayesian meta-analysis (Supplement A) further suggests a potential for publication bias towards bigger effects, which means that the meta-analytical estimate (75 ms) could be an overestimation. Finally, the surveyed studies have a very low number of participants (mean = 3.4, SD = 2.5), which can lead to so-called Type M errors (estimate magnitude errors) and overestimation of the effect (Kirby & Sonderegger 2018; Roettger 2019). In sum, it is generally assumed that the voicing-driven differences in vowel duration are greater in English than in other languages, although the empirical foundation of this conception is not entirely straightforward. Although not the focus of this study, arguments based on differences in effect size will become relevant when discussing the results.

1.3 Research hypotheses

One of the aims of this study is to test whether the same temporal stability observed for the release-to-release interval in Italian and Polish disyllabic words can also be observed in English. English makes a good object of enquiry since much work on the voicing effect has been done on this language, and the phonological structure of the language allows us to directly compare onset and coda stops in disyllabic and monosyllabic words respectively. While the temporal stability of the release-to-release interval is expected in English disyllabic words, monosyllabic words are predicted not to show such stability. As discussed above, an essential component of the release-to-release temporal stability in disyllabic words is the presence of a direct relation between the two vowels in these type of words. Since monosyllabic words don't have a second vowel, there is no direct vowel-to-vowel relation to derive the release-to-release stability from.

Furthermore, Jacewicz et al. (2009) report that, in American English, monosyllabic words are longer when the second consonant is voiced. Based on this finding, it is expected that the release-to-release duration should be longer when C2 is voiced. Jacewicz et al. (2009) attribute the difference in monosyllabic word duration to the difference in vowel duration before voiceless vs. voiced stops. Thus, we can expect the magnitude of the difference in release-to-release duration in monosyllabic words to be close to the difference in vowel duration. This hypothesis also fits with the reported greater effect of voicing on vowel duration in monosyllabic than disyllabic words (with the caveats discussed in Section 1.2).

The data in Coretta (2019b) suggests that the intrinsic duration of vowels and consonants can contribute to the duration of the release-to-release interval. In particular, release-to-release intervals containing a high vowel have shorter durations than those with a low vowel. This is not surprising, given the well-known tendency of high vowels to be shorter than low vowels (Hertrich & Ackermann 1997; Esposito 2002; Mortensen & Tøndering 2013; Toivonen et al. 2015; Kawahara et al. 2017). As for the consonantal place of articulation, the release-to-release is shorter in Italian and Polish when the second consonant is velar compared to when it is coronal. This could be a consequence of the fact that the closure of velar stops is shorter than that of other stops. For example, Sharf's (1962) data on closure duration in English suggests that the closure of labial stops (60-90 ms) is about 10 ms longer than that of velar stops (55-75 ms). It can be expected that release-to-release intervals with a velar stop in English will be about 10 ms shorter than intervals with a labial stop.

Another set of objectives concerns the effect of voicing on vowel and closure durations. A conceptual replication of previous studies' effect sizes is sought, with special attention to differences between monosyllabic and disyllabic words. Only a few studies directly compare the effect on vowel durations in different syllabic positions (for example, Sharf (1962) and Klatt (1973)). The reported effects are in the range of 50-55 ms in word-final (closed-syllable) position and 20-25 in word-medial (open-syllable) position. The Bayesian meta-analysis of the voicing effect indicates a mean difference of 50 ms (75 ms in word-final position vs. 25 ms word-medially). As for the duration of stop closure, the data in Sharf (1962) and Luce & Charles-Luce (1985) indicates that voiced closures are 10-13 ms shorter than voiceless closures.

While directly investigating the statistical relationship between vowel and closure durations might seem more appropriate for assessing whether a compensation exists between the two, this was not done for three reasons. First, as discussed by Ohala & Lyberg (1976) and Beguš (2017), interpreting the correlations between two temporal intervals that share a boundary is problematic, unless one uses two independent sources for the measurements of vowel and closure durations, such as multiple annotators (Beguš 2017) or articulatory data from different articulators (de Jong 1991). Neither of these options were available for this study due to time and resources constraints. Second, as discussed in Coretta (2019b), less is known about the interplay between segment durations, speech rate, and the vowel/closure relation, making interpretation of data on correlation difficult in most cases. A third reason for not correlating vowel and closure durations is that the main focus of this study was to assess word-level gestural phasing via acoustic measures. Future work will have to be carried out in which the vowel/closure correlation is investigated using robust and unambiguous methods.

To summarise, the following research questions and respective hypotheses can be formulated:

1. Is the duration of the interval between two consecutive stop releases (the release-to-release interval) in monosyllabic and disyllabic words affected by the voicing of C2 in English?
   - H1a: The duration of the release-to-release interval is not affected by C2 voicing in disyllabic words.
   - H1b: The release-to-release interval is longer in monosyllabic words with a voiced C2 than in monosyllabic words with a voiceless C2.
2. Is the duration of the release-to-release interval affected by (a) the number of syllables of the word, (b) the quality of V1, and (c) the place of C2?
   - H2a: The release-to-release interval is longer in monosyllabic than in disyllabic words.
   - H2b: The duration of the release-to-release interval decreases according to the hierarchy /ɑː/, /ɜː/, /iː/.
   - H2c: The release-to-release interval is longer when C2 is labial.
3. What is the estimated difference in the effect of voicing on vowel and stop closure duration between monosyllabic and disyllabic words?
   - H3: The effect of voicing on vowel duration is greater in monosyllabic than in disyllabic words (no specific hypothesis for the effect of number of syllables on the effect of voicing on closure duration).

2 Methods

The following subsections describe the experimental and statistical methods of this study. The research design and data analyses were pre-registered on the Open Science Framework prior to data collection.[2] The research compendium of this paper

[2] The pre-registration can be found at this temporary link for peer-review: `https://osf.io/hwr94/?view_only=d994915422144efaae4a5915237cb386`.

with data (Coretta 2019a) and analysis scripts is also available on the Open Science Framework.[3] Choices on experimental design and analysis were made within the Bayesian framework of statistical inference (see Section 2.1 and Section 2.7 for details).

2.1 Sample size and stopping rule

Sample size and a stopping rule were decided prior to data collection with a Bayesian method of sample determination based on the Region Of Practical Equivalence (ROPE, Kruschke 2015; Vasishth et al. 2018b). A 'no-effect' region of values around 0 is first identified. This null region (the ROPE) can be thought of as a Bayesian 95% credible interval of a distribution, the values within which can be interpreted as a negligible or null effect. For this study, a ROPE between −10 and +10 ms has been chosen. The width of 20 ms is based on the estimates of the just noticeable difference in Huggins (1972) and Nooteboom & Doodeman (1980). Differences in release-to-release durations below 10 ms (either positive or negative) are interpreted as compatible with a null effect.

Once a ROPE width is set, the goal is to collect data during sequential testing until the width of the 95% credible interval (CI) of the tested effect is equal to or less than the ROPE width (in this study, 20 ms). In other words, the objective is to reach estimate precision, rather than significance (as in frequentist null hypothesis testing). Inference can then be made based on the credible interval of the sought effect. When the precision goal is reached (the CI width is equal or lower than the ROPE width), three possible scenarios can arise: (1) the CI of the effect completely overlaps with the ROPE around 0, in which case the data supports a practically equivalent null effect; (2) the CI of the effect completely lies outside the ROPE, which indicates that the data support the effect to be within that CI; (3) the CI partially overlaps with the ROPE, in which case no clear decision can be made on whether the data supports one hypothesis over the other, although it is still possible to infer the sign of the effect and the range of probable values (if the CI partially overlaps with the right side of the ROPE without including 0, there is evidence for a positive effect, while if the CI overlaps with the left side of the ROPE without including 0, there is evidence for a negative effect).

An initial minimum of 20 participants was chosen for sequential testing. Due to resource and time constraints specific to this particular study, a second condition had to be included in the stopping rule such that data collection would be have to stop on 5 April 2019, independent of the ROPE condition. The time target was hit before the ROPE target, and data collection had to stop at 15 participants.

[3] The analysis code can be found at this temporary link for peer-review: `https://osf.io/32fst/?view_only=2dc237b60f4c4c77b6ec10300b9e528e`.

Table 1: Test $C_1\acute{V}_1C_2$(VC) words.

teep	teepus	teek	teekus
teeb	teebus	teeg	teegus
terp	terpus	terk	terkus
terb	terbus	terg	tergus
tarp	tarpus	tark	tarkus
tarb	tarbus	targ	targus

2.2 Participants

The participants of this study were 15 native speakers of British English, who were born and raised in the Greater Manchester area. The speakers were all students at the University of Manchester with no reported hearing or speaking disorders, and with normal or corrected to normal vision. The participants signed a written consent form and received £5 for participation.

2.3 Equipment

Audio recordings were obtained in a sound-attenuated room in the Phonetics Laboratory of the University of Manchester, with a Zoom H4n Pro recorder and a RØDE Lavalier microphone, at a sample rate of 44100 Hz (16-bit, downsampled to 22050 Hz for analysis). The Lavalier microphone was clipped on the participants clothes, about 20 cm from the mouth, displaced a few centimetres to one side.

2.4 Materials

The test words were $C_1\acute{V}_1C_2$(VC) words, where C_1 = /t/, V_1 = /iː, ɜː, ɑː/, C_2 = /p, b, k, g/, and (VC) = /əs/. /əs/ was chosen for its lower parsability as a native suffix, in order to prevent morphological complexity in disyllabic words. This structure specification generates 24 test words, shown in Table 1. All of these are nonce words, with the exception of *turk* and *tarp*, and of *teek* via the homophone *teak*. Building stimuli from a structure template rather than from the lexicon ensures greater experimental and statistical control. Moreover, the use of nonce words removes or reduces confounds from some usage variables, like for example lexical frequency.[4] Each word was embedded in the following frame sentences: *I'll say X this Thursday*, *You'll say X this Monday*, *She'll say X this Sunday*, *We'll say X this*

[4]The three real words in the materials have low lexical frequency (Zipf 1-7 log-frequency: *tarp* 2.23, *teak* 2.76, and *turk* 2.91) according to the SUBTLEX-UK corpus (Van Heuven et al. 2014).

Friday, *They'll say X this Tuesday*. Each word + frame combination was included once in the stimuli list, so that each speaker read a total of 120 sentence stimuli (24 words × 5 frames). A total of 1800 observations were recorded (120 stimuli × 15 speakers).

2.5 Procedure

The experimental procedure was first explained to the participants prior to recording. The participants also familiarised themselves with the materials by reading them aloud. They were instructed not to insert pauses anywhere within the sentence stimuli and to keep a similar intonation contour for the total duration of the experiment. They were also given the chance to take any number of breaks at any point during recording. Misreadings or speech errors were corrected by asking the participant to repeat the stimulus. The reading task took around 6 to 10 minutes, while the total experiment session lasted about 25 minutes. Data collection started on 19 February 2019 and ended on 5 April 2019.

2.6 Data processing and measurements

A forced-aligned transcription was obtained with the SPeech Phonetisation Alignment and Syllabification software (SPPAS, Bigi 2015). The automatic annotation was corrected by the author according to the principles of phonetic segmentation detailed in Machač & Skarnitzl (2009). Vowel onset and offset were identified as the approximate time of respectively appearance and disappearance of higher formant structure (F2-F4) in the spectrogram. Consonant onset and stop closure onset correspond to vowel offset. A custom Praat script was written to automatically detect the release of the consonants in the test words, using the algorithm in Ananthapadmanabha et al. (2014). The output was checked and manually corrected by the author when necessary according to the following criterion. The stop release was identified as the time of onset of the release burst, which generally takes the form of a sudden short interval of irregular noise after the stop closure.

The following measures were obtained via a custom Praat script:

- Duration of the release-to-release interval: from the release of C1 to the release of C2.
- V1 duration: from appearance to disappearance of higher formant structure (F2-F4) in the spectrogram in correspondence of V1 (Machač & Skarnitzl 2009).
- C2 closure duration: from disappearance of higher formant structure in the V1C2 sequence to the release of C2 (Machač & Skarnitzl 2009).

- Speech rate: calculated as the number of syllables per second (number of syllables in the sentence divided by the sentence duration in seconds, Plug & Smith 2018).

2.7 Statistical analysis

The choice of Bayesian over frequentist statistics stems from a recent discussion of the problems associated with the reliance of *p*-values in statistical inference (Wagenmakers 2007; Munafò et al. 2017; Kirby & Sonderegger 2018; Roettger 2019). Bayesian statistics also offers a straightforward framework for investigating the absence of differences across conditions (a 'null effect') based on the ROPE (Section 2.1), as it is in part the case in this study. Another favourable aspect of Bayesian methods is that more focus is given to the distributions of the enquired effects, rather than on point estimates (which are less informative when matters of statistical power are taken into consideration, see a discussion of Type S-M errors in Kirby & Sonderegger 2018) and an arbitrary significance cut-off point. Furthermore, Bayesian inference is centred around an incremental procedure of reallocation of credibility between natural states and on evidence based on observed data (Kruschke 2015), rather than on a series of hypothetical experimental replications (Wagenmakers 2007).[5] For an introduction to Bayesian statistics in phonetics, see Vasishth et al. (2018a), and Nicenboim et al. (2018), while for a general introduction see Etz et al. (2018), McElreath (2015), Kruschke (2015), and references therein. While a thorough discussion of Bayesian methods would be beyond the scope of this paper, it is relevant to provide the less familiar reader with the basic tools for interpreting analyses and results.

Particular weight will be given to the estimated distributions of the sought effects in presenting the results of this study. The estimated distribution of an effect (or parameter) is the posterior distribution of that effect (or parameter). The posterior distribution is an approximation of the parameter distribution, and it takes into account the specified prior for that parameter, i.e. the theoretical probability of the parameter as known or derived by the researcher. The inclusion of priors in the analysis is at the heart of Bayesian modelling, which relies on prior knowledge for the estimation of parameter values. For each relevant term in the models, the 95% credible intervals (CI) should be taken as a summary of the posterior distribution, and inference should be based on the posterior rather than on the point estimate (the posterior mean, represented here with $\bar{\theta}$). A 95% CI can be interpreted as the 95% probability that a parameter lies within that interval range. For example,

[5] I am not advocating here against *p*-values in absolute terms. On the contrary, *p*-values are still useful in that they provide us with a practical solution in situations that involve, for example, decision-making.

if the 95% CI is between 10 and 30 ms, there is a 95% probability that the true parameter value is between 10 and 30 ms, with extreme values being less likely than values in the centre of the interval.

In each model, priors are specified for each of the parameters to be estimated. The priors are in the form of particular distributions, like the Gaussian (normal) or the Cauchy distribution. A prior defines the prior knowledge of where the parameter might lie within a range of values. For example, a prior as a normal distribution with mean 200 ms and standard deviation 50 indicates the researcher's belief that the parameter lies between 100 and 300 ms with 95% probability (i.e., the mean minus twice the standard deviation, and the mean plus twice the standard deviation).

Statistical analysis was performed in R v3.5.3 (R Core Team 2019). Bayesian regression models were fit with brms (Bürkner 2017, 2018). Each model was run with four MCMC chains and 2000 iterations per chain, of which 1000 for warm-up. A Gaussian (normal) distribution was used in all the models as the response distribution. All factors were coded using treatment contrasts (the first level in this list was set as the reference level): number of syllables (disyllabic, monosyllabic), vowel (/ɑː/, /ɜː/, /iː/), C2 voicing (voiceless, voiced), C2 place of articulation (velar, labial). Speech rate was centred when included in the models so that the intercept could be interpreted as the intercept at mean speech rate. A seed (1234) was set in all models to ensure reproducibility of the output. The priors used in the models reported here will be discussed along with the results in the following sections.

A concern could be raised that the priors might have greater influence on the posterior distributions than the observed data, which would be undesired. A sensitivity analysis based on posterior *z*-scores and shrinkage (Betancourt 2018) indicates that the posterior distributions discussed in this study are not just based on the priors, but are also informed by the data.

3 Results

This section reports the results of the Bayesian models, grouped by outcome variable (release-to-release, vowel duration, closure duration). A description of the model structure and priors is given for each model, followed by the presentation of the posterior distributions of the relevant terms. Each model is assigned a number (1 to 5), and the text refers to these.

Model convergence was reached in all the reported models ($\hat{R}$ = 1) and no major divergences in the MCMC chains were observed. The posterior predictive check plots indicate that the observed distributions are slightly positively skewed so that a log-normal distribution would have been more appropriate. Previous work has shown that speech-units duration does follow, as a general trend, a log-

Table 2: Summary of the Bayesian regression fitted to release-to-release duration (model 1, see Section 3.1)

Predictor	Mean	SD	Q2.5	Q97.5	CI width
Intercept	263.71	9.64	244.17	283.00	38.84
Voicing = voiced	-4.43	10.03	-23.86	15.45	39.30
Num. syll. = monosyllabic	17.34	9.76	-1.58	36.53	38.11
Speech rate (cntr.)	-36.10	2.06	-40.14	-32.13	8.01
voiced × monosyll.	16.53	12.72	-8.41	41.41	49.83

normal distribution (Rosen 2005; Ratnikova 2017), and the practice of transforming duration data to the logarithmic scale is not uncommon (Gahl & Baayen 2019). However, the deviations from a Gaussian distribution here were minimal, and an informal comparison of one of the models fitted with a log-normal distribution led to virtually identical results.

3.1 Release-to-release duration

A Bayesian regression was fit to model the duration of the release-to-release interval (model 1). The following terms were included as fixed effects: C2 voicing (voiceless, voiced), number of syllables (disyllabic, monosyllabic), centred speech rate, an interaction between C2 voicing and number of syllables. A by-speaker and by-word random intercept, and a by-speaker random coefficient for C2 voicing were entered as random effects. The following priors were used.[6] Two weakly informative priors based on the results from Coretta (2019b) were chosen for the intercept and the effect of C2 voicing. The former prior is a normal distribution with mean 200 ms and SD = 50, while the latter a normal distribution with mean 0 ms and SD = 25. A weakly informative prior as a normal distribution with mean 50 ms and SD = 25 was specified for the effect of number of syllables. The prior is based on differences in vowel duration between mono- vs. disyllabic words, which range between 30 and 100 ms (Sharf 1962; Klatt 1973). The same prior was used for the interaction between C2 voicing and number of syllables, based on the reported differences in voicing effect in mono- vs. disyllabic words (Sharf 1962; Klatt 1973). The prior for the effect of centred speech rate is a normal distribution with mean -25 ms and SD = 10, and is based on results from Coretta (2019b). For the random effects, a half Cauchy distribution (location = 0, scale = 25) was used for the standard deviation and the residual standard deviation, and a LKJ(2) distribution for the correlation among the random terms.

[6] A weakly informative prior is a prior that intentionally provides weaker information on the effect than what is known about that effect (Gelman 2006), while conversely a strongly informative prior is a prior that conveys greater information.

Table 3: Summary of the Bayesian regression fitted to release-to-release duration (model 2, see Section 3.1)

Predictor	Mean	SD	Q2.5	Q97.5	CI width
Intercept	289.05	8.14	273.01	305.09	32.08
Vowel = /ɜː/	-8.58	6.90	-21.90	4.87	26.78
Vowel = /iː/	-36.94	6.96	-50.10	-22.26	27.84
C2 place = labial	2.46	5.68	-9.15	13.28	22.44
Speech rate (cntr.)	-37.48	2.05	-41.51	-33.37	8.14

Table 2 gives the posterior mean, posterior standard deviation, 2.5 and 97.5 quantiles (lower and upper bounds of the 95% credible interval), and the credible interval's width of the fixed effects of model 1. The precision goal (CI width ≤ 20 ms, based on the ROPE) was reached only for centred speech rate (CI width = 8.14 ms). The posterior distribution of the estimated effect of C2 voicing on the release-to-release duration has a 95% credible interval (95% CI) between -23.86 and 15.45 ms (the mean is -4.43 ms, SD = 10.03). The 95% CI of the estimated interaction between C2 voicing and number of syllables tends towards positive values, between -8.41 and 41.41 ms ($\bar{\theta}$ = 16.53 ms, SD = 12.72). The difference in duration of the release-to-release interval between monosyllabic and disyllabic words is more clearly positive, between -1.58 and 36.53 ms (95% CI, $\bar{\theta}$ = 17.34, SD = 9.76). Speech rate has a strong negative effect on the release-to-release duration with 95% CI = [-40.14, -32.13].

A second Bayesian regression (model 2) was fitted with the release-to-release duration as the outcome variable to test the effects of vowel and C2 place of articulation, which were entered as terms in the model without interactions. Centred speech rate was also included. The random effects structure was the same as with the first model. The relevant priors from the first model were kept. For the effects of vowel (/ɜː/, /iː/) and place of articulation (labial), the very weakly informative prior used is a normal distribution with mean = 0 ms and SD = 30. This prior was based on duration differences depending on vowel height (Heffner 1937; House & Fairbanks 1953; Hertrich & Ackermann 1997) and labial place of articulation (Sharf 1962), which both range between 10 and 30 ms.

The summary of the fixed effects of model 2 are given in Table 3. As with model 1, only the CI width of speech rate reached the intended precision. The posterior distribution of the effect of the vowel /ɜː/ shows that this vowel tends to a negative effect, with a 95% CI between −21.90 and 4.87 ms ($\bar{\theta}$ = −8.58 ms, SD = 6.9). The vowel /iː/ has a more robust negative effect on release-to-release duration, with a 95% CI between −50.10 and −22.26 ($\bar{\theta}$ = −36.94 ms, SD = 6.96). Less clear is the effect of C2 place of articulation (velar vs. labial stop): The mean of the posterior is 2.46 ms (SD = 5.68), and the 95% CI is [−9.15, 13.28].

Table 4: Summary of the Bayesian regression fitted to release-to-release duration and predictors from model 1 and 2 (model 3, see Section 3.1)

Predictor	Mean	SD	Q2.5	Q97.5	CI width
Intercept	280.81	6.99	266.72	294.37	27.66
Voicing = voiced	-2.43	4.06	-10.45	5.65	16.10
Num. syll. = monosyllabic	16.03	3.32	9.17	22.48	13.31
Vowel = /ɜː/	-10.05	2.95	-15.92	-4.24	11.68
Vowel = /iː/	-39.03	2.99	-45.03	-32.76	12.27
C2 place = labial	2.46	2.39	-2.29	7.28	9.57
Speech rate (cntr.)	-36.10	1.99	-39.96	-32.24	7.72
voiced × monosyll.	11.67	4.71	2.65	20.98	18.33

The credible intervals of the effects in the models reported above have widths which are greater than the chosen ROPE width of 20 ms. The wide credible intervals indicate that the estimated posterior distributions of the effects have a somewhat high degree of uncertainty with them. This uncertainty is potentially due to not controlling for vowel and number of syllables in the first and second model respectively. An exploratory model (model 3) was thus fitted to the data, in which all the terms from the two models above were included. The same priors of the two separate models were used in the combined model.

Including all the relevant terms in the model (C2 voicing and place, vowel, number of syllables in interaction with C2 voicing) reduces the width of the credible intervals substantially. Figure 1 shows the posterior distributions of the model terms with a variety of credible intervals. The posterior distribution of the C2 voicing effect on release-to-release duration is tighter than that of model 1 (95% CI = [−10.45, 5.65], within the ROPE) while the mean (−2.43 ms, SD = 4.06) is virtually unchanged (−4.43 ms, only a 2 ms difference). The estimated effect of syllable number is robustly positive (95% CI = [9.17, 22.48], virtually completely outside the ROPE), with a mean (16.03 ms, SD = 3.32) similar to that in model 1. The posterior distribution of the interaction between number of syllables and C2 voicing (95% CI = [2.65, 20.98], partial overlap with the ROPE) suggests a positive and medium-sized interaction effect ($\bar{\theta}$ = 11.67 ms, SD = 4.71). This result indicates that the duration of the release-to-release is possibly greater in monosyllabic words with voiced C2 than in monosyllabic words with voiceless C2. The effects of vowel and place of articulation have similar means as in model 2, but the credible intervals are smaller. The release-to-release is on average 10.05 ms (SD = 2.95, 95% CI = [−15.92, −4.24], partial overlap with the ROPE) shorter if the vowel is /ɜː/ and 39.3 ms (SD = 2.99, 95% CI = [−45.03, −32.76]) shorter if the vowel is /iː/. C2 place of articulation (labial) has a negligible positive mean effect (2.6 ms, SD = 2.39, 95% CI = [−2.29, 7.28], complete overlap with the ROPE).

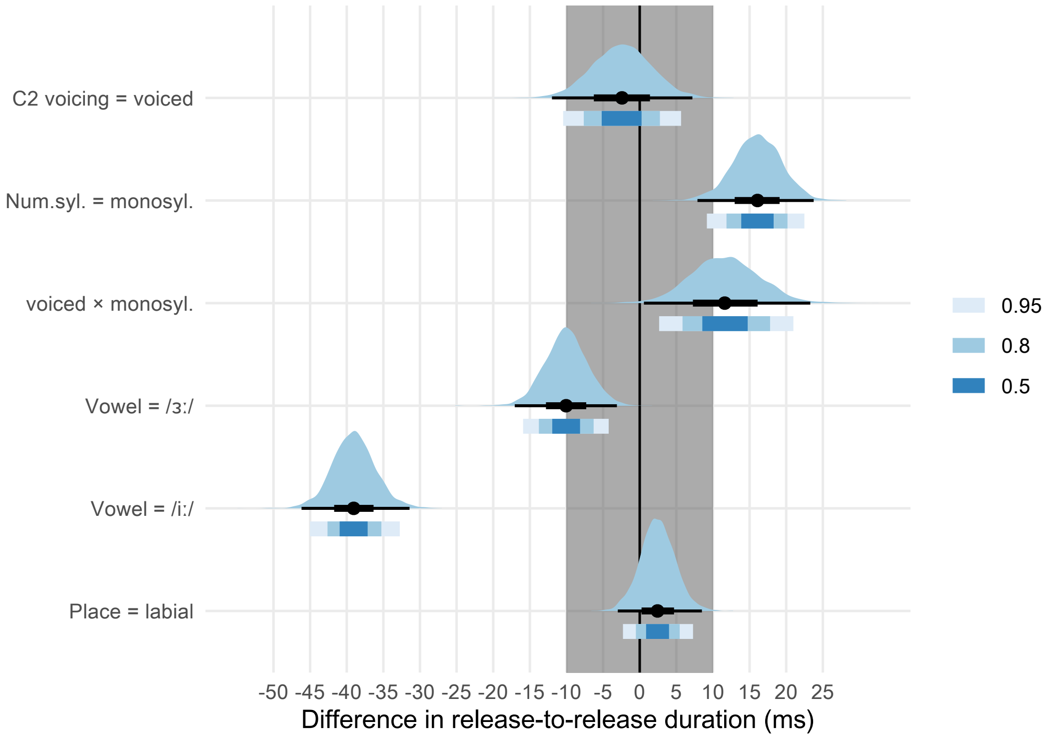

Figure 1: Posterior distributions and Bayesian credible intervals of the effects on release-to-release duration (model 3). For each effect, the thick blue-coloured bars indicate (from darker to lighter) the 50%, 80%, and 95% CI. The black point with bars are the posterior median (the point), the 98% (thin bar) and 66% (thicker bar) CI. The shaded grey area around 0 is the ROPE.

Table 5: Summary of the Bayesian regression fitted to vowel duration (model 4, see Section 3.2)

Predictor	Mean	SD	Q2.5	Q97.5	CI width
Intercept	124.91	5.96	112.94	136.77	23.83
Voicing = voiced	13.65	5.16	3.73	24.09	20.36
Vowel = /ɜː/	-9.03	5.13	-19.08	1.63	20.71
Vowel = /iː/	-36.77	5.00	-46.42	-26.67	19.74
Num. syll. = monosyllabic	14.91	5.07	5.15	25.14	19.99
Speech rate (cntr.)	-18.03	1.48	-20.93	-15.29	5.63
voiced × /ɜː/	0.24	6.83	-13.70	13.94	27.64
voiced × /iː/	6.73	6.59	-6.54	19.26	25.80
voiced × monosyll.	4.03	6.70	-8.98	17.69	26.67
/ɜː/ × monosyll.	0.53	7.07	-13.57	14.57	28.15
/iː/ × monosyll.	-16.07	6.93	-30.03	-2.68	27.35
voiced × /ɜː/ × monosyll.	-2.94	9.46	-21.37	15.77	37.14
voiced × /iː/ × monosyll.	14.46	9.18	-3.59	31.99	35.58

3.2 Vowel duration

A Bayesian regression model was fitted to test vowel duration (model 4). The following terms were entered: C2 voicing (voiceless, voiced), vowel (/ɑː/, /ɜː/, /iː/), number of syllables (disyllabic, monosyllabic), centred speech rate, all possible interactions between C2 voicing, vowel, and number of syllables. The same random structure as in the previous models was used (a by-speaker and by-word random intercept, and a by-speaker random coefficient for C2 voicing).

For the prior of the intercept of vowel duration, a normal distribution with mean 145 ms and standard deviation 30 was used (Heffner 1937; House & Fairbanks 1953; Peterson & Lehiste 1960; Sharf 1962; Chen 1970; Klatt 1973; Davis & Summers 1989; Laeufer 1992; Ko 2018). A normal distribution with mean 50 ms and standard deviation 20 was used as the prior for the effect of voicing on vowel duration (based on the above studies). A normal prior with mean 50 and standard deviation 25 was chosen instead for the effect of number of syllables and the interaction C2 voicing/number of syllables. For the effects of vowel, vowel/number of syllables interaction, and the three-way interaction vowel/number of syllables/C2 voicing, the prior was a normal distribution with mean 0 and standard deviation 30, based on differences reported in the studies above. A slightly more informative prior was used for the interaction between C2 voicing and vowel (mean = 0, SD = 20). The same priors as in the previous models were included for the random effects.

Table 5 reports the summary of model 4, while Figure 2 shows the posterior distributions and credible intervals. The precision target was reached in the non-interacting predictors (permitting a few milliseconds above 20), with the exeption of the intercept. All the interactions terms have CI widths above 25 ms. The

95% CI of the posterior distribution of the duration of /ɑː/ is included in the range 112.94–136.77 ms ($\bar{\theta}$ = 124.91 ms, SD = 5.96). The vowel /ɜː/ is 9.03 ms shorter (SD = 5.16) with CI = [−19.08, 1.63], while /iː/ is 36.77 ms shorter (SD = 5, 95% CI = [−46.42, −26.67]). C2 voicing has a small but somewhat robust positive effect on vowel duration in disyllabic words (only partial overlap with the ROPE without including 0). The posterior distribution of the effect of voicing on /ɑː/ (the reference level) has mean 13.65 ms (SD = 5.16) and 95% CI = [3.73, 24.09]. The posterior of the interaction of voicing with vowel when the vowel is /ɜː/ is quite spread out around 0, with the 95% CI between −13.70 and 13.94 ms. This indicates that /ɑː/ and /ɜː/ are similar in their behaviour of voicing-driven durational differences. On the other hand, the effect of voicing is on average 6.73 ms greater (SD = 6.59, 95% CI = [−6.54, 19.26]) when the vowel is /iː/, but the posterior overlaps with the ROPE and it includes 0.

The magnitude of the voicing effect in disyllabic vs. monosyllabic words is modulated by the identity of the vowel. The posterior distribution for the interaction C2 voicing/number of syllables when the vowel is /ɑː/ has mean 4.03 ms (SD = 6.7) and 95% CI [−8.98, 17.69]. This distribution indicates the possibility for a very small increase of the effect from disyllabic to monosyllabic words with /ɑː/, but the great overlap with the ROPE and inclusion of 0 makes it difficult to argue for or against a difference in effect. The three-way interaction C2 voicing/vowel/number of syllables suggests that the effect of voicing in monosyllabic words with /ɜː/ is very similar to that of monosyllabic /ɑː/-words ($\bar{\theta}$ = −2.94, SD = 9.46, 95% CI = [−21.37, 15.77]). On the other hand, the effect increases by 14.46 ms (SD = 9.18, CI = [−3.59, 31.99]) in monosyllabic words with /iː/ relative to disyllabic /iː/-words. Note that the credible intervals of these interaction effect are quite large, so that a wide range of values are probable at 95% confidence.

3.3 Consonant closure duration

To test various effects on C2 closure duration, model 5 was fit with closure duration as the outcome variable and the following predictors: C2 voicing (voiceless, voiced), C2 place of articulation (velar, labial), number of syllables (disyllabic, monosyllabic), all interactions between these predictor terms, and centred speech rate. The random effects were again a by-speaker and a by-word random intercept, and a by-speaker random coefficient for C2 voicing.

As priors, a normal distribution with mean 90 ms (SD = 20) was used for the intercept, based on Sharf (1962) and Luce & Charles-Luce (1985). The means reported in these studies also indicate that the closure of the stop in monosyllabic words is 10-30 ms shorter when the stop is voiced. A normal distribution with mean -20 ms (SD = 10) was chosen as the prior of the effect of C2 voicing on closure duration. The same studies indicate that labial stops have a closure which

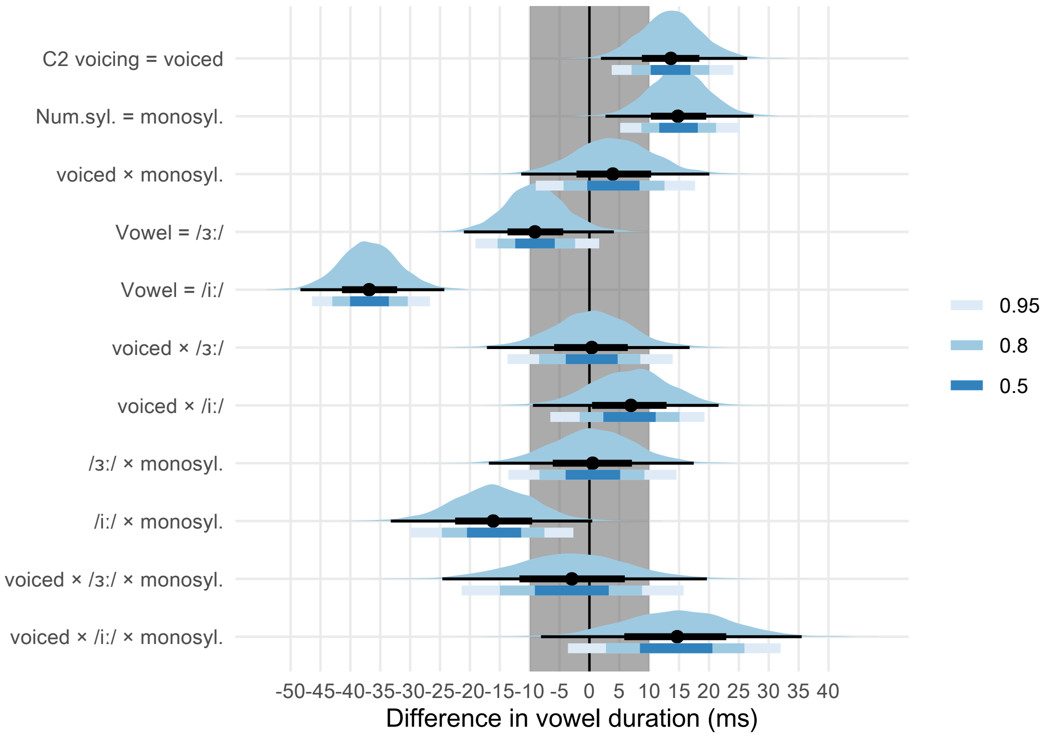

Figure 2: Posterior distributions and Bayesian credible intervals of the effects on vowel duration (model 4). For each effect, the thick blue-coloured bars indicate (from darker to lighter) the 50%, 80%, and 95% CI. The black point with bars are the posterior median (the point), the 98% (thin bar) and 66% (thicker bar) CI. The shaded grey area around 0 is the ROPE.

Table 6: Summary of the Bayesian regression fitted to closure duration (model 5, see Section 3.3)

Predictor	Mean	SD	Q2.5	Q97.5	CI width
Intercept	74.75	2.86	69.07	80.59	11.52
Voicing = voiced	-20.79	3.06	-26.77	-14.74	12.03
C2 place = labial	5.19	2.77	-0.03	10.76	10.79
Num. syll. = monosyllabic	2.98	2.90	-2.80	8.77	11.58
Speech rate (cntr.)	-9.21	1.26	-11.71	-6.74	4.97
voiced × labial	1.37	3.94	-6.79	8.93	15.72
voiced × monosyll.	1.82	4.06	-6.08	9.70	15.78
labial × monosyll.	-0.74	4.02	-8.95	6.88	15.83
voiced × labial × monosyll.	6.41	5.66	-4.72	17.45	22.17

is 10-20 ms longer than the closure of velar stops. For the effect of C2 place, a normal distribution with mean 15 ms (SD = 10) was used.

The summary of model 5 is shown in Table 6. See Figure 3 for the posteriors and credible intervals of the effects. The 96% CI width of all the terms, with the exception of the three-way interaction (voicing/place/number of syllables), is below 20 ms (the precision goal has been reached). The posterior distribution of the intercept for closure duration (corresponding to the duration of voiceless velar stops in disyllabic words) has mean 74.75 ms (SD = 2.86) and 95% CI = [69.07, 80.59]. The effect of C2 voicing on closure duration is robustly negative, between −26.77 and −14.74 ms (95% CI). The posterior mean of this effect is −20.79 ms (SD = 3.06). A very small positive effect of place of articulation (labial) is suggested by the 95% CI from −0.03 to 10.76 ms ($\bar{\theta}$ = 5.19 ms, SD = 2.77). A possibly even smaller effect of number of syllables or no effect at all can be inferred from the posterior distribution which has mean 2.98 ms and SD 2.9 (95% CI = [−2.8, 8.77]). Note that the 95% CIs of the posterior distributions of all the effects, with the exception for the effect of voicing, are within the ROPE around 0, meaning that they can be interpreted as practically null effects.

4 Discussion

This study set out to build on the results discussed in Coretta (2019b) by investigating durational properties of the release-to-release interval in English monosyllabic and disyllabic words. It was expected that the release-to-release interval would not be affected by C2 voicing in disyllabic words but it would in monosyllabic words. Moreover, a conceptual replication of studies on the effect of consonant voicing on vowel and closure durations was sought, with a focus on comparing the effect in mono- vs. disyllabic words. This section discusses in turn the results in relation to the release-to-release interval duration (Section 4.1) and to vowel and closure

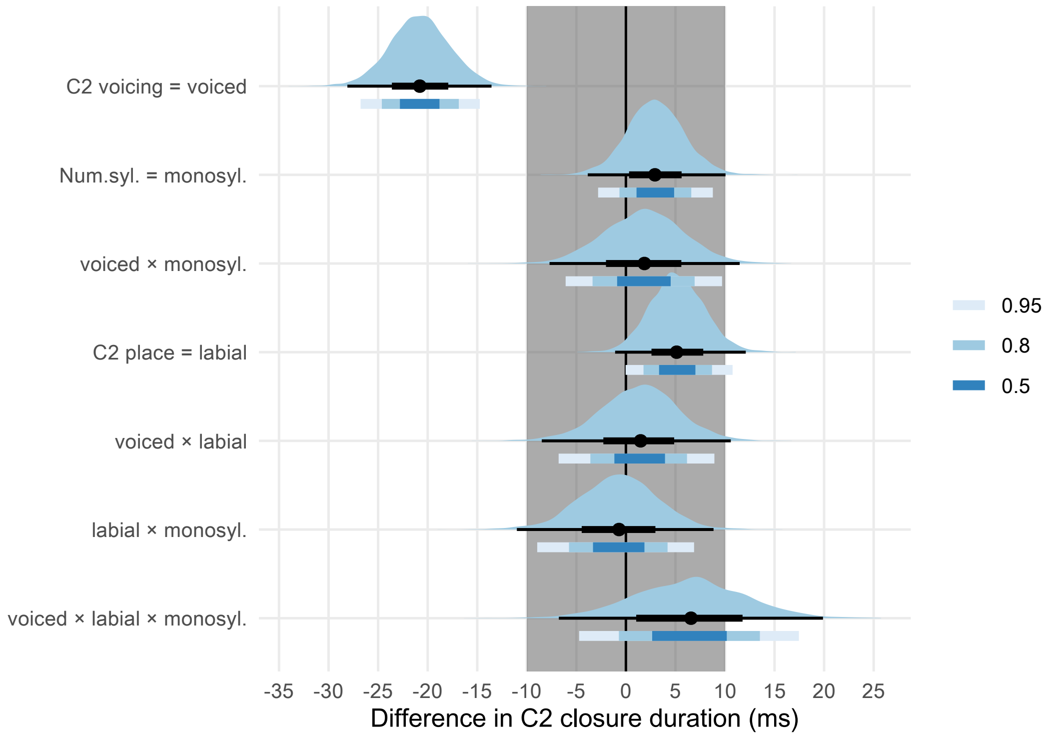

Figure 3: Posterior distributions and Bayesian credible intervals of the effects on closure duration (model 4). For each effect, the thick blue-coloured bars indicate (from darker to lighter) the 50%, 80%, and 95% CI. The black point with bars are the posterior median (the point), the 98% (thin bar) and 66% (thicker bar) CI. The shaded grey area around 0 is the ROPE.

durations (Section 4.2) by comparing them with the hypotheses of this study. Section 4.3 synthesises and links these findings back to the articulatory grounding of the temporal properties of the release-to-release interval in mono- and disyllabic words (Section 1). Limitations and future work are also discussed.

4.1 Release-to-release interval

The first question (see Section 1.3) asked whether the voicing of C2 in disyllabic and monosyllabic words in English influences the duration of the release-to-release interval. Coretta (2019b) showed that the release-to-release interval duration is not affected by C2 voicing in disyllabic words of Italian and Polish. The hypotheses were that, in English, the interval is not affected in disyllabic words, like in Italian and Polish, but that it is in monosyllabic words. In sum, the results of this study indicate that the release-to-release duration of disyllabic words in English is relatively stable independent of whether C2 is voiceless (like in /tɑːpəs/) or voiced C2 (/tɑːbəs/). On the other hand, the release-to-release in monosyllabic words is longer if C2 is voiced (like in /tɑːb/ vs. /tɑːp/).

Two pre-registered Bayesian regression models were fitted to the release-to-release duration (model 1-2). The established ROPE target has not been achieved (see Section 2.1). An exploratory model (model 3) including all predictors from model 1 and 2 resulted in higher estimate precision (CI widths below 20 ms). The results of model 3 suggest a negligible effect of C2 voicing on the interval duration in disyllabic words (hypothesis 1a), with a 95% probability that the true effect is between −10 and +5 ms. At lower levels of probability, the posterior distribution indicates an effect between −6 and 1 ms (60% probability). If the voicing of C2 is conditioning the duration of the release-to-release interval, this effect is very small.

The possible small effect of C2 voicing in disyllabic words could be related to an annotation bias which affects the identification of stop releases. English voiceless stops are generally followed by aspiration, and the glottal friction that makes up aspiration could mask the burst of the release. If the release of the post-vocalic voiceless stops is annotated later than the actual release (by mistaking peaks in the aspiration noise for the release burst), this could lead to longer release-to-release durations when C2 is voiceless compared to when it is voiced. Such annotation bias could explain the quite small negative effect of voicing on the interval duration, and why it is in the opposite direction of the one predicted for monosyllabic words (i.e. *longer* release-to-release when C2 is voiced).

On the other hand, the release-to-release interval in monosyllabic words is longer when C2 is voiced (for example, /tɑːb/) vs. when it is voiceless (/tɑːp/). The interaction term between number of syllables in the word and C2 voicing is positive, between +2.5 and +21 ms (at 95% probability), which means that the effect of C2 voicing increases by 2.5 to 21 ms in monosyllabic words relative to the effect in disyllabic words. This result is compatible with hypothesis 1b that the release-to-release interval is longer in monosyllabic words with a voiced C2 than in monosyllabic words with a voiceless C2. As discussed in Section 1, the absence of release-to-release isochrony in monosyllabic words is possibly due to the absence of a second vowel which would constitute the left articulatory anchor for vowel isochrony, which in turn is argued to be the necessary element for the release-to-release temporal stability (also see Section 4.3).

The second question posed at the beginning of the paper was about other effects on the release-to-release duration. As expected by hypothesis 2a, the release-to-release is longer in monosyllabic than in disyllabic words. At 95% probability, the effect of number of syllables (from di- to monosyllabic) is between 9 and 22.5 ms. As for hypothesis 2b, the results are more robust for /iː/ than for /ɜː/. When the vowel is /iː/, the release-to-release interval is 33 to 45 ms shorter compared with an interval with /ɑː/. The posterior distribution of the effect when the vowel is /ɜː/ substantially overlaps with the ROPE, although it tends towards the negative side. If there is an effect with this vowel compared to /ɑː/, it is negative and possibly around −10 ms. Finally, hypothesis 2c is not unequivocally corroborated. The posterior distribution of the effect of C2 place of articulation (labial) has very high precision (9.5 ms) and it is between 0 and 5 ms (at somewhat less than 80% probability). However, it lies within the ROPE and it is very close to 0.

4.2 Vowel and closure duration

Question 3 addressed the effect of voicing on vowel and closure duration, and the possible differences between disyllabic and monosyllabic words. The results do indicate an effect of voicing on vowel duration (as expected based on previous work on English), but the effect found in this study was estimated to lie between 4 and 25 ms. This range of values is very similar to that reported in Coretta (2019b) for Italian and Polish disyllabic words (the 95% confidence interval for the effect in these languages is [8, 25]), monosyllabic words were not tested). When compared to the values in previous studies that investigated disyllabic words (Sharf 1962; Klatt 1973; Davis & Summers 1989), the effect size found in this study tends towards smaller values. However, note that the posterior distribution of the effect in the current study is entirely contained in the meta-analytical posterior distribution of the effect in the other studies, which roughly ranges between −15 and +65 ms (see Supplement A). Thus, we can assume that the deviation of this study from previous ones is not substantial. As for the effect of number of syllables on vowel duration, a similar effect to that of voicing was found, whereby vowel durations increase by 5 to 25 ms in monosyllabic words compared to disyllabic words. This relation corresponds to what has previously been reported in the literature. Finally, given that the 95% CIs of the effects of voicing and number of syllables overlap with the right side of the ROPE without including 0, the data supports positive effects, but inference on their magnitude should be carefully weighted.

It was expected that the voicing effect on vowels would be stronger in monosyllabic than in disyllabic words (hypothesis 3). The credible intervals of the posterior distributions from model 4, which are larger than the ROPE, make interpretation less straightforward. At 80% probability, the difference in voicing effect between mono- and disyllabic words is between −5 and +12.5 ms. The distribution is skewed towards the positive side, and this is compatible with results from previous studies, although the CI includes 0. The magnitude, however, is considerably lower than what previously reported. However, more data is needed to reach a sensible estimate precision and increase inferential certainty.

The three-way interaction between C2 voicing, vowel, and number of syllables reveals that the effect in monosyllabic words with the vowel /ɜː/ is similar to that with /ɑː/. On the other hand, the effect is larger if the vowel is /iː/. Model 4 estimates an effect increase of about 14.5 ms ([−4.27, 33.41]). Note that the credible interval is very wide (38 ms) and it spans over both negative and positive values, although tends more towards the latter. Moreover, the vowel /iː/ followed by a voiceless stop has, according to the model, the same duration in monosyllabic and disyllabic words. While it is not clear why the vowel should have the same duration in these contexts, this pattern suggest a possible process of /iː/ shortening in monosyllabic words. More research is warranted in relation to the observed patterns.

Turning now to consonants, it was expected for voiced closures to be longer than voiceless closures, but there was no specific hypothesis concerning the effect of number of syllables on the effect of voicing on closure durations. C2 voicing has a robust negative effect on closure duration, so that voiced closures are 14.6-26.8 ms shorter than voiceless closures. The effects of number of syllables, place, and interactions all have credible intervals that are narrower than 20 ms (the ROPE width) but they lie entirely within the ROPE around 0. If these variables do have an effect on closure duration, the present analysis suggests that the means of these effects are between 0 and 5 ms. These values are smaller than those reported in Sharf (1962), which instead indicated a difference of 15 ms between velar and labial closure durations.

As a general trend, although an effect of C2 voicing on vowel and closure duration was found, the voicing-driven differences in vowel and closure duration found here are smaller than those known from the literature, and considerably so in the case of vowels. A possible reason for this discrepancy could be found in problems arising from Type M errors (as briefly discussed in Section 1), and in differences of speech rate, as evidenced by comparing average segment durations. While the model's intercept of vowel duration in this study is approximately 125 ms (SD =

5.89), the mean vowel duration in the studies surveyed in the meta-analysis (Supplement A) is 150 ms (SD = 36). These longer durations may indicate lower speech rates in older studies and so the effect of voicing may have been greater there than at higher speech rates, assuming a linear increase of the effect. However, the ratio between vowel duration and the effect of voicing differs (vowels increase by a third of their total duration in this study vs. half in previous work). Ko's findings 2018 support the idea that the voicing effect (and the vowel-to-consonant ratio) are not stable across speaking rates, with the consequence that differences are enhanced at decreased speaking rates. More studies like Ko (2018) are needed to settle the issue of the diverging results.

4.3 General discussion

Coretta (2019b) proposes that the voicing-related adjustments in the relative timing of the closure onset within an isochronous speech interval (acoustically identified as the release-to-release interval) is the diachronic precursor of the cross-linguistically widespread effect of voicing on vowel duration.[7] Given that the duration of the release-to-release interval in Italian, Polish, and English disyllabic words is arguably not affected by the voicing of the post-vocalic consonant, the relative durations of vowel and closure are thought to depend on the timing of the VC boundary within that interval. A later VC boundary in the context of voiced stops implies a longer vowel and a shorter closure relative to the voiceless context, while, vice versa, an earlier boundary in the context of voiceless stops produces a shorter vowel and a longer closure relative that voiced context. Behind the differential timing of the VC boundary within the release-to-release interval, several other accounts can be envisaged, like accounts relating to laryngeal and supraglottal adjustments (Halle & Stevens 1967; Beguš 2017; Coretta 2019c).

As discussed in Section 1.1, a prerequisite of the articulatory account proposed here for the emergence of the voicing effect is the temporal stability of the acoustic release-to-release interval and of the related articulatory gestures. However, it was expected that English mono-syllabic words do not show such temporal stability, even though the voicing effect is present in this context and allegedly even grater than in disyllabic words (on the latter point, cf. with Supplement A and this study, where a less clear picture emerged).

As mentioned at the end of Section 1.1, the absence of temporal stability and presence of the voicing effect in monosyllabic words can be reconciled by drawing from known mechanisms of perceptual enhancement. Perceptual biases, like the ones proposed by perceptual accounts of the voicing effect (Javkin 1976; Kluender

[7]Note that isochrony here is intended as pertaining the context of voiceless vs. voices stops only.

et al. 1988; Sanker 2019), can contribute to the increase of the effect of voicing, for example as a means to enhance the perceptual difference of voiceless vs. voiced stops (Lisker 1974, 1986; Stevens & Keyser 1989). In particular, vowels can be further lengthened when followed by voiced stops and/or further shortened when followed by voiceless stops, so as to produce a greater and more perceptible difference.

In the case of disyllabic words, movements of the VC boundary within the isochronous interval will logically affect both vowel duration and closure duration, while the release-to-release would not be affected and vowel-to-vowel isochrony would be preserved. On the other hand, the absence of a second vowel acting as temporal articulatory anchor (as per vowel-to-vowel isochrony) in monosyllabic words would allow articulatory stretching or compression to operate independently on the vocalic and the consonantal gestures. In the monosyllabic context, the gestural duration of vowels and following consonants can be modified in such a way that could result in a change in timing of the onset of the consonant closing gesture and in the disruption of the release-to-release isochrony.

The presence of a voicing effect with absence of release-to-release temporal stability could be obtained, for example, by keeping the vocalic gesture when the following stop is voiced active for a longer time relative to when the following stop is voiceless. Although more research is needed in this area, the articulatory studies in Raphael (1972) and de Jong (1991) do suggest that the vocalic gesture in monosyllabic words is executed for a prolonged time when the following consonant is voiced. While differences in magnitude of the voicing effect should be replicated in future studies, the potentially greater effect of voicing in monosyllabic words could be ascribed to the fact that, while vowel-to-vowel isochrony constraints how vowels and consonants can be produced in disyllabic words, mechanisms affecting the VC boundary (articulatory and/or perceptual) in monosyllabic words are less constrained due to the non-application of vowel-to-vowel isochrony.

5 Conclusion

This paper set out to investigate temporal properties of the so-called ‘voicing effect’, by which vowels are shorter when followed by voiceless stops and longer when followed by voiced stops. Coretta (2019b) proposes that the voicing effect emerges via a mechanism of relative timing of the VC boundary within a temporally stable interval. Such interval was argued to be the interval between two consecutive releases, as evidenced by acoustic data from Italian and Polish disyllabic words. The temporal stability of the release-to-release in relation to consonantal voicing is thought to derive from two properties of gestural phasing, namely the isochrony of the distance between the vowels in a VCV sequence, and in-phase alignment of onset consonants and the following vowel. On the other hand, the lack of an articulatory anchor (a second vowel) in monosyllabic words would allow the release-to-release duration to be affected by C2 voicing and differ in the monosyllabic context.

This study adds to the current status of knowledge on temporal aspects of the voicing effect by showing that the release-to-release interval is not affected by C2 voicing in English disyllabic words, as in Italian and Polish, and that, instead, it is longer in monosyllabic words when C2 is voiced. While the timing of the VC boundary within the release-to-release in disyllabic words affects both vowel and closure durations in a logically dependent way, vowel and closure durations can be modulated more independently in monosyllabic words. The less constrained operation of production/perceptual mechanisms affecting the timing of the VC boundary was argued to be the reason for the seemingly greater effect of voicing reported for monosyllabic words. The data in this study, and the cumulative evidence from previous studies as evinced by a Bayesian meta-analysis, however, do not equivocally provide support for a difference in the effect between mono- and disyllabic words, and future work is necessary to shed light on the matter.

To conclude, the results of this study suggest some directions of research. Future studies should further investigate the articulatory temporal patterns of vocalic and consonantal gestures in disyllabic words. In particular, a complete assessment of the isochrony (or lack thereof) of consecutive vocalic gestures should include a variety of oppositions, involving voicing, place of articulation, number of consonants, syllabic affiliation, and prosodic contexts. Moreover, work is needed to shed light on the timing of the consonant closing gesture relative to the articulatory gesture of the preceding vowel in voiceless vs. voiced stops. Finally, the scenario of emergence of the voicing effect offered here should be examined in in relation to other consonantal effects on vowel duration, like other laryngeal effects and effects of manner of articulation.

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