Compensatory aspects of the effect of voicing on vowel duration in English

Stefano Coretta

1   Introduction

Consonants and vowels are known to excise a reciprocal influence in a variety of ways. One such way is the well-established tendency for vowels to have shorter durations when followed by voiceless stops and longer durations when followed by voiced stops. This so-called 'voicing effect' has been long recognised in a plethora of languages across different linguistic families. English is possibly by far the most investigated language in relation to the voicing effect. Several hypotheses have been proposed as to the origin of this phenomenon, however no one particular hypothesis has gained unequivocal consensus.

Coretta (2018) proposes to seek the source of the voicing effect in a compensatory mechanism between vowel and consonant closure duration. In an exploratory study of acoustic durations in 17 Italian and Polish speakers, Coretta finds that the duration of the interval between two consecutive consonant releases is not affected by the voicing status of the second consonants. In particular, Coretta investigated disyllabic words of the form CV́CV (with lexical stress on the first syllable), where the second consonant was either voiceless or voiced. The results of that study suggest that, for example, the duration of the release-to-release interval in a word like /pata/ is non-significantly different from that in /pada/.

Coretta (2018) argues that the temporal stability of the release-to-release interval is compatible with a compensatory temporal adjustment account of the voicing effect, which states that vowels are shorter when followed by voiceless stops because the latter have long closure durations, and vice versa with voiced stops, which have shorter closure durations (Lindblom 1967; Slis & Cohen 1969b,a; Lehiste 1970b,a). Coretta also reviews some of the shortcomings of the compensatory account and concludes that the release-to-release invariance offers a resolution to those. In particular, previous versions of the account are not clear on within which speech interval the compensation is implemented. Both the syllable (Lindblom 1967; Farnetani & Kori 1986) and the word (Slis & Cohen 1969b,a; Lehiste 1970b,a) have been proposed but subsequently criticised on empirical grounds (Chen 1970; Jacewicz et al. 2009; Maddieson & Gandour 1976).

Given the temporal stability of the release-to-release interval and the differential closure duration in voiceless vs. voiced stops (Lisker 1957; Van Summers 1987; Davis & Van Summers 1989; de Jong 1991), it follows that the timing of the consonant closure onset within that interval will decide on the respective durations of vowel and consonant closure. Coretta (2018) thus proposes that the source of the voicing effect can be seen in the temporal stability of the release-to-release interval in relation to the voicing of the second consonant and the effect of voicing on closure duration. Other properties of speech production and perception can of course further contribute to the emergence and enhancement of the voicing effect (see Beguš 2017 for an overview).

English is generally the language given as an example in which the voicing effect has a big magnitude. This fact is normally attributed to phonologisation of the voicing effect in this language Sharf (1964); de Jong (2004). Indeed, previous studies on English report a difference in vowel duration before voiceless vs. voiced stops which ranges between 20 and 150 ms. A Bayesian meta-analysis of the English voicing effect (See Supplemental materials) indicates that 95% credible interval for the effect of voicing

in monosyllabic words is between 55 and 95 ms. This means that, based on the data, the true effect lies within that interval at a probability of 95%, on in other words we can be 95% sure that the effect is between 55-95 ms.

1.1 Research hypotheses

The principal aim 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 be observed in English. Jacewicz et al. (2009) report that monosyllabic words in American English are longer when the second consonant is voiced. Based on this finding, it is expected that the duration of the release-to-release interval will differ in monosyllabic words depending on C2 voicing. More specifically, the release-to-release duration should be longer when C2 is voiced. Jacewicz et al. (2009) attribute the difference in 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 to be close to the difference in vowel duration.

The data in Coretta (2018) suggest 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 in Coretta (2018). This is not surprising, given that a well known cross-linguistic tendency is that high vowels are shorter than low vowels (Hertrich & Ackermann 1997; Esposito 2002; Mortensen & Tøndering 2013; Toivonen et al. 2015; Kawahara et al. 2017). As for the consonant place of articulation, the interval is shorter in Italian and Polish if the second consonant is velar compared to when it is coronal. The closure of velar stops is shorter than that of other stops (see for example Sharf 1962). It can thus be expected that intervals with a velar stop in English will be shorter than intervals with consonants of other places of articulation.

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

- Q1: 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.

- Q2: 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 shorter when C2 is velar.

- Q3: 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.

2 Methods

The research design and data analyses of this study has been pre-registered at the Open Science Framework.

2.1 Participants

The participants of this study were 15 native speakers of British English, who were born and brought up in the Greater Manchester area. All the speakers were undergraduate 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.

Sample size and stopping rule were determined prior to data collection by the Region Of Practical Equivalence (ROPE) method (Kruschke 2015; Vasishth et al. 2018b). A 'no-effect' region of values around 0 is first identified. The null region (the ROPE) can be thought of as the Bayesian 95% credible interval from a distribution, the values within which can be interpreted as a 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).

Once a ROPE width is set, the goal is to collect data until the width of the 95% credible interval of the tested effect is equal to or less than the ROPE width (in this study, 20 ms). 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 April 5th 2019, independent of the the ROPE condition.

2.2 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 cloths, about 20 cm under their mouth, displaced a few centimetres on one side.

2.3 Materials

The test words were $C_1V_1C_2$(VC) words, where C_1 = /t/, V_1 = /iː, əː, ɑː/, C_2 = /p, b, k, g/, and (VC) = /əs/. This structure specification generates 24 test words, shown in **??**. 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 Friday, They'll say X this Tuesday*. Each word + frame combination was included once in the stimuli list, so that each speaker would read 120 sentence stimuli (24 words × 5 frames).

2.4 Procedure

The participants were first debriefed on the experimental procedure. Prior to recording, the participants familiarised themselves with the materials by reading them aloud and were instructed not to insert pauses anywhere within the sentence stimuli and to try and keep a similar intonation contour for the total duration of the experiment. They were also given the change to take any number of breaks at any point during recording. Misreadings or speech errors were corrected by letting the participant repeat the stimulus. The reading task took around 6 to 10 minutes.

2.5 Data processing and measurements

The audio recordings were downsampled to 22050 Hz for analysis. 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). A custom Praat script was written to automatically detect the burst onset 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.

The following measures were obtained:

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

2.6 Statistical analysis

All statistical analyses were performed in R v3.5.2 (R Core Team 2018). Bayesian regression models were fit with brms (Bürkner 2017, 2018). A Gaussian (normal) distribution was used in all the models as the response distribution. All factors were coded using treatment contrasts with the first level as the reference level: number of syllables (disyllabic, monosyllabic), vowel (/ɑː/, /ɜː/, /iː/), C2 voicing (voiceless, voiced), C2 place of articulation (velar, labial).[1] Speech rate has been centred when included in the models so that the intercept could be interpreted as the intercept at mean speech rate.

The choice of Bayesian over frequentist statistics stems from the misplaced reliance on *p*-values in a context of commonly low-powered studies (Munafò et al. 2017; Roettger 2019). For an introduction to Bayesian statistics in phonetics, see Vasishth et al. (2018a); Nicenboim et al. (2018), while for a general introduction see Etz et al. (2018); McElreath (2015); Kruschke (2015), and reference therein. While a thorough discussion of Bayesian methods would be beyond the scope of this paper, it is relevant to give the less familiar reader the tools for interpreting analyses and results.

More weight will be given here on the estimated distributions of the sought effects, rather than on point estimates (as in frequentist regression models). 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, i.e. the theoretical probability of the parameter as known or derived by the researcher. This characteristics is at the heart of Bayesian modelling, which includes prior knowledge into 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). A 95% CI can be interpreted as the 95% probability that a parameter lies within the interval range. For example, 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.

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[1]Note that the order of the levels in the vowel factor are reversed compared to that in the pre-registration, and this was done to match the height order in Coretta (2018), from low to high. Changing the order of the levels of course does not affect the results.

In each model, a prior is specified for each of the parameters to be estimated. The priors are in the form of particular distributions, like the normal or the Cauchy distributions. 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).

3 Results

3.1 Release-to-release duration

A Bayesian regression model was fit to model the duration of the release-to-release interval. 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 have been used. Two weakly informative priors based on the results from Coretta (2018) were chosen for the intercept and the effect of C2 voicing. The former prior was a normal distribution with mean 200 ms and SD = 50, while the latter a normal distribution with mean 0 ms and SD = 25. The same prior was specified for the effect of number of syllables and the interaction between C2 voicing and number of syllables. This weakly informative prior was a normal distribution with mean 50 ms and SD = 25, and it is based on differences in vowel duration in mono- vs. disyllabic words and in monosyllabic words before voiceless vs. voiced stops, which range in both cases between 30 and 100 ms (see Sharf 1962 and Klatt 1973 for the difference in vowel duration in mono- vs. disyllabic words). The prior for the effect of centred speech rate was a normal distribution with mean -25 ms and SD = 10, and was based again on results from Coretta (2018). For the random effects, a half Cauchy distribution (location = 0, scale = 25) was used for the standard deviation (also used for the residual standard deviation) and a LKJ(2) distribution for the correlation.

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, estimated error = 10.03). The 95% CI of the estimated interaction between C2 voicing and number of syllables is between -8.41 and 41.41 ms (the mean is 16.53 ms, est.e. = 12.72). The difference in duration of the release-to-release interval between monosyllabic and disyllabic words is between -1.58 and 36.53 ms (95% CI, with a mean of 17.34, est.e. 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 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 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 was 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 Sharf (1962), which range between 10 and 30 ms.

The random effects structure was the same as with the first model. The posterior distribution of the effect of the vowel /ɜː/ shows that this vowel tends to a somewhat negative effect, with a 95% CI between −21.90 and 4.87 ms (mean = −8.58 ms, est.e. = 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 (mean = −36.94 ms, est.e. = 6.96). Less clear is the effect of C2 place of articulation (labial stop): the mean of the posterior is 2.46 ms (est.e. = 5.68), and the 95% CI is [−9.15, 13.28].

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 large credible intervals indicate that the estimated posterior distributions of the effects have a somewhat high degree of uncertainty with them. The uncertainty has been possibly brought about by not controlling for vowel and number of syllables in respectively the first and second model. An exploratory model was thus fitted to the data, in which all the terms from the two models above were included together. 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) has indeed reduced the credible intervals substantially. Note that inferences from this model should be treated with caution, since the model was not pre-registered. Figure 1 shows a variety of crebile intervals for the model terms. 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]) while the mean (−2.43 ms, est.e. = 4.06) is virtually unchanged (−4.43 ms, only a 2 ms difference). The estimated effect of syllable number is now more robustly positive (95% CI = [9.17, 22.48]), with a mean (16.03 ms, est.e. = 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]) suggests a positive and medium-sized coefficient (mean = 11.67 ms, est.e. = 4.71). This result indicates that the duration of the release-to-release is greater in monosyllabic words with voiced C2 than in monosyllabic words with voiceless C2. The effects of vowel and place or articulation have similar means, but the credible intervals are smaller. The release-to-release is on average 10.05 ms (est.e. = 2.95, 95% CI = [−15.92, −4.24]) shorter if the vowel is /ɜː/ and 39.3 ms (est.e. = 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, est.e. = 2.39, 95% CI = [−2.29, 7.28]).

3.2 Vowel duration

A Bayesian regression model was fitted to test vowel duration (the outcome variable in the model). The following terms were entered: C2 voicing (voiceless vs. 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 we used a normal distribution with mean 145 ms and standard deviation 30 (Heffner 1937; House & Fairbanks 1953; Peterson & Lehiste 1960; Sharf 1962; Chen 1970; Klatt 1973; Davis & Van 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, a normal distribution with mean 0 and standard deviation 30, based on differences reported in the previous studies. 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 model were included for the random structure.

The 95% CI of the posterior distribution of the duration of /ɑː/ is included in the range 113.15–137.06
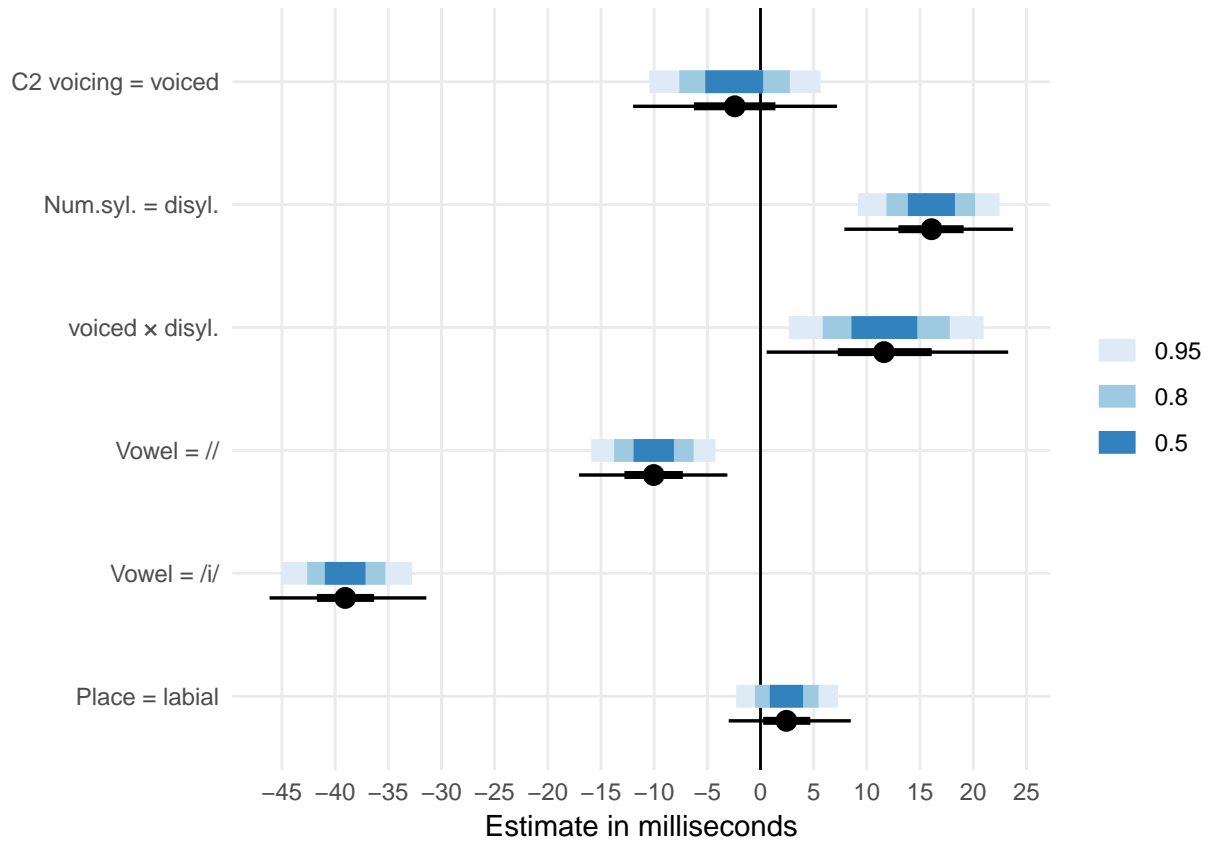
Figure 1: Bayesian credible intervals of the effects on release-to-release duration (model 3). For each effect, the thick blue-coloured bars indicate (from darker to lighter) the 50%, 80%, and 95% CI. The black point with bars are the posterior median (the point), the 98% (thin bar) and 66% (thicker bar) CI

ms (mean = 125.16 ms, est.e. = 6.02). The vowel /ɜː/ is 9.19 ms shorter (est.e. = 5.29) with CI = [−19.24, 1.49], while /iː/ is 36.97 ms shorter (est.e. = 5.14, 95% CI = [−46.99, −26.76]). C2 voicing as a smaller but robust positive effect on vowel duration in disyllabic words. The posterior distribution of the effect of voicing on /ɑː/ has mean 13.47 ms (est.e. = 5.14) and 95% CI = [3.80, 24.36]. The posterior of the interaction of voicing with vowel when the vowel is /ɜː/ is quite spread out, with 95% CI between −13.77 and 13.40 ms. This can indicate that /ɑː/ and /ɜː/ behave similarly for what concern voicing-driven difference in duration, or that, if non-null, the interaction coefficient is very small. On the other hand, the effect of voicing is on average 6.75 ms greater (est.e. = 6.76, 95% CI = [−7.45, 19.55]) with the vowel /iː/. 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 4.07 ms (est.e. = 6.6) and 95% CI [−8.94, 17.30], indicating the possibility for a very small increase of the effect from disyllabic to monosyllabic /ɑː/-words. The three-way interaction C2 voicing/vowel/number of syllables indicates that the effect of voicing with monosyllabic /ɜː/-words is very similar to that of monosyllabic /ɑː/-words (mean = −2.66, est.e. = 9,44, 95% CI = [−21.57, 16.23]), while in monosyllabic /iː/-words it increases by 14.5 ms (est.e. = 9.43, CI = [−4.27, 33.41]). Note that the credible intervals of some of the effect are quite large, so that a large range of values are possible. The posterior means of such effects should be treated with more caution.

3.3 Consonant closure duration

To test various effects on C2 closure duration, a model 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 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 Sharf (1962) and Luce & Charles-Luce (1985) 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 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 posterior distribution of the intercept for closure duration (corresponding to the duration of voiceless velar stops in disyllabic words) has mean 74.62 ms (est.e. = 2.85) and 95% CI = [69.17, 80.42]. The effect of C2 voicing on closure duration is estimated to be between −26.76 and −14.57 ms (95% CI). The posterior mean of this effect is −20.83 ms (est.e. = 3.09). A very small positive effect of place of articulation (labial) is suggested by the 95% CI from −0.30 to 10.63 ms (mean = 5.1 ms, est.e. = 2.73). A possibly even smaller effect of number of syllables or no effect at all can be inferred from the posterior distribution which has mean 2.81 ms and estimated error 2.84 (95% CI = [−2.70, 8.19]).

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