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1 Stimuli for English experiment

labial		velar	
teep	teepus	teek	teekus
teeb	teebus	teeg	teegus
turp	turpus	turk	turkus
turb	turbus	turg	turgus
tarp	tarpus	tark	tarkus
tarb	tarbus	targ	targus

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

1.1 Check nonce words

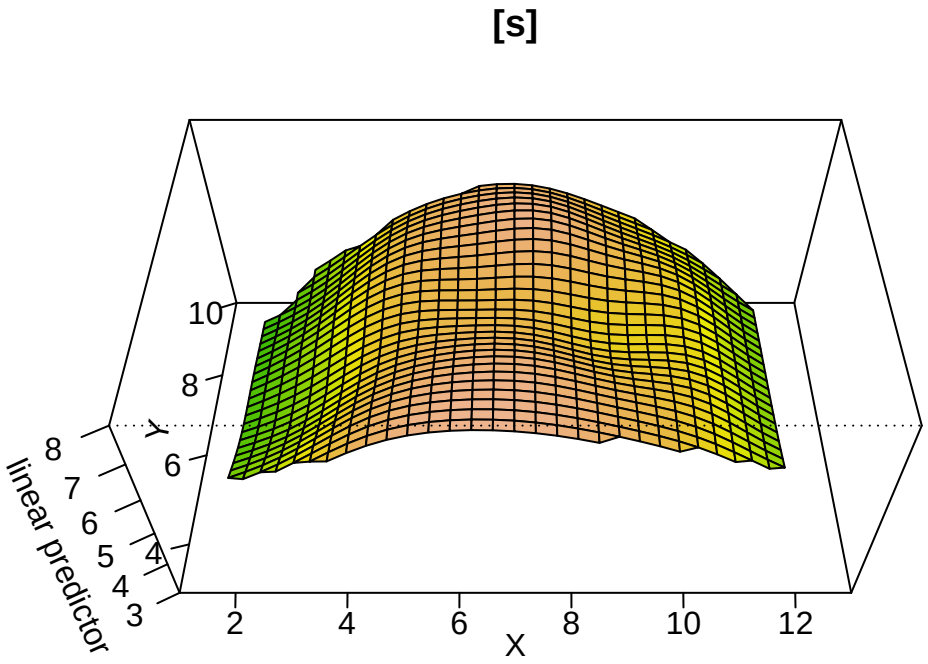
```
## # A tibble: 10 x 4
##    Spelling FreqCount `LogFreq(Zipf)` `LogFreqBNC(Zipf)`
##    <chr>        <dbl>           <dbl>              <dbl>
##  1 turk           162            2.91               3.23
##  2 teak           114            2.76               3.05
##  3 tarp            33            2.23               1.3
##  4 teek             5            1.47               1
##  5 tark             4            1.39               1.3
##  6 turb             4            1.39               1
##  7 terp             3            1.3                1
##  8 targ             2            1.17               1.47
##  9 teeg             2            1.17               1
## 10 teep             2            1.17               1.3
```

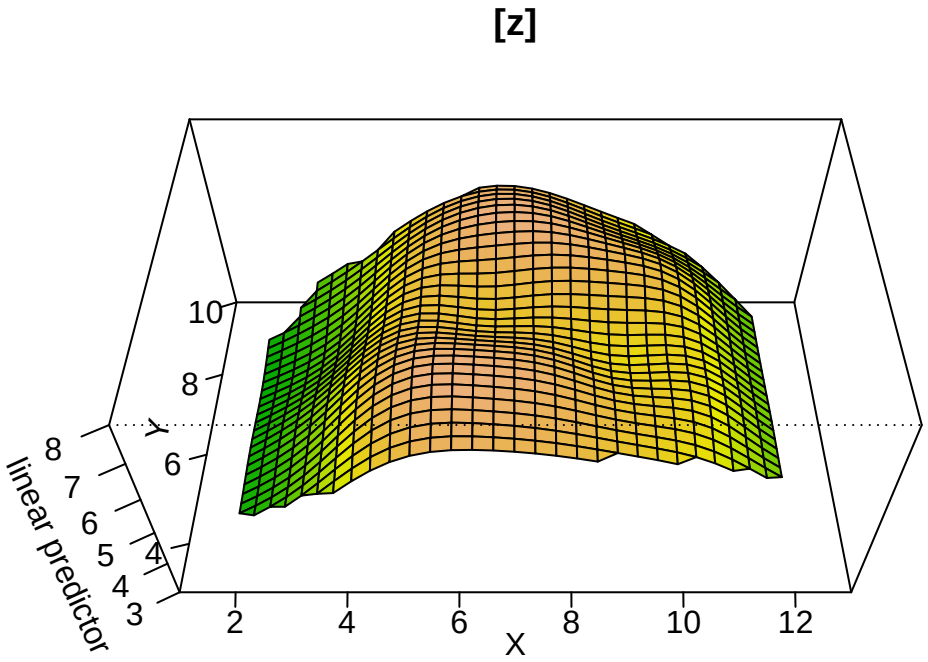
Out of 24 words stimuli, 10 appear in SUBTLEX-UK (either they are phonological matches or full

matches). Two of these 10 have a log frequency > 2.5 (*Turk*, *teak*). Note that the spelling for these words would be *turk* and *teek* in the experiment.

2 3D tongue surface of [s] and [z]

I recorded myself in Bloomington with the 3D ultrasound machine while uttering five tokens of sustained [s] and five tokens of sustained [z]. A single 3D frame has been extracted from each token. The following plots show the output of a 3D GAM fitted to the tongue surfaces of [s] and [z] (tip on the right).





There is a shallower grove in [z] compared to [s], and some lowering/advancing of the tongue root. Note that the tongue data have not been rotated.

2.1 Volume increase

The volume increase of [z] relative to [s] is 12.08 cm^3. This estimate is based on the predicted GAM data on a surface which corresponds to the actual imaged surface. If I remember correctly, Steven Lulich estimated that a volume increase of 20 cm^3 is ideal for maintainance of voicing in a voiced fricative.

3 A Bayesian analysis of the voicing effect in pre-stress vowels (/əˈCV/)

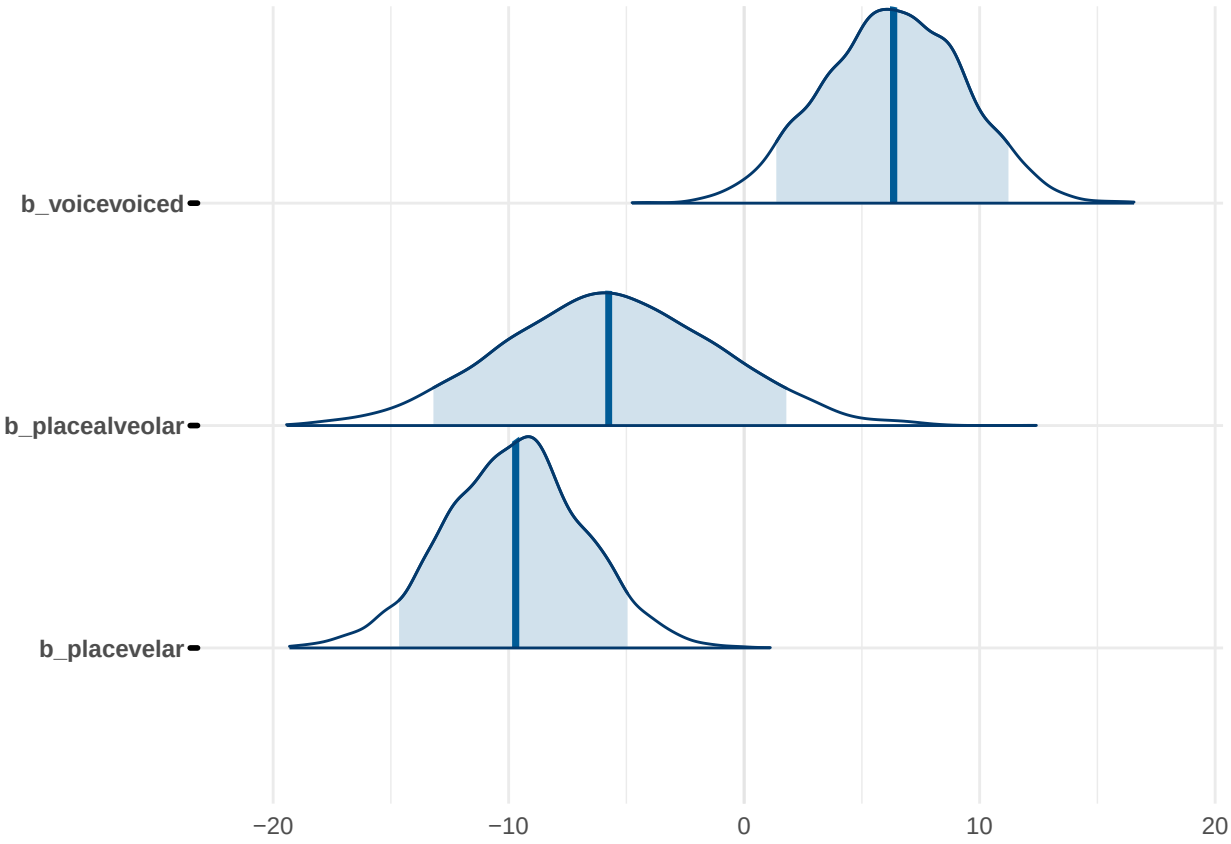
```
## Compiling the C++ model

## Start sampling
```

Davis & Van Summers (1989) report means and standard deviations of the duration of reduced unstressed vowels followed by a voiceless or a voiced stop (*atop*/*adopt*). We can use a Bayesian measurement error model which takes into account the standard deviation of the vowel durations (since we don't have the individual data points that make up the means). The data is based on three speakers, the consonant following the reduced vowel can be labial, alveolar, or velar. A model was fitted to vowel duration (and standard deviation) with the following predictors: C2 voicing (voiceless vs. voiced), C2 place of articulation (labial vs. alveolar vs. velar), and a by-speaker random intercept. The following weakly informative priors have been used: a normal distribution

for the intercept with mean 50 and SD = 25, a normal distribution with mean 0 and SD = 20 for the estimates of C2 voicing and C2 place, and a normal distribution with mean 0 and SD = 25 for the by-speaker random intercept.

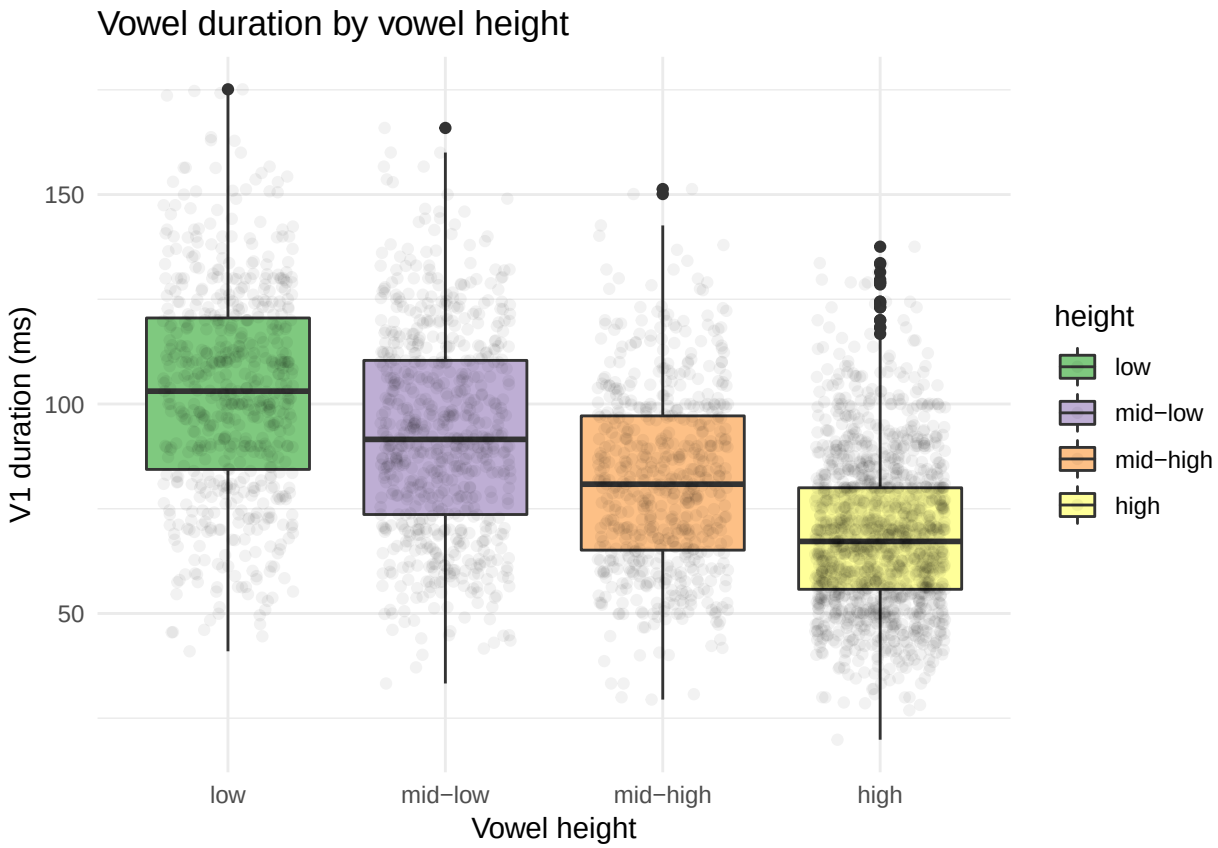
```
##  Family: gaussian
##   Links: mu = identity; sigma = identity
## Formula: v_duration | se(sd) ~ voice + place + (1 | speaker)
##    Data: davis1989 (Number of observations: 18)
## Samples: 4 chains, each with iter = 2000; warmup = 1000; thin = 1;
##          total post-warmup samples = 4000
##
## Group-Level Effects:
## ~speaker (Number of levels: 3)
##               Estimate Est.Error l-90% CI u-90% CI Eff.Sample Rhat
## sd(Intercept)    22.17     10.04    10.41    42.27       1884 1.00
##
## Population-Level Effects:
##               Estimate Est.Error l-90% CI u-90% CI Eff.Sample Rhat
## Intercept        47.65     11.44    29.27    65.91       1446 1.00
## voicevoiced       6.32      3.01     1.37    11.22       3233 1.00
## placealveolar    -5.71      4.55   -13.19     1.79       2789 1.00
## placevelar       -9.76      2.95   -14.65    -4.95       3368 1.00
##
## Samples were drawn using sampling(NUTS). For each parameter, Eff.Sample
## is a crude measure of effective sample size, and Rhat is the potential
## scale reduction factor on split chains (at convergence, Rhat = 1).
```

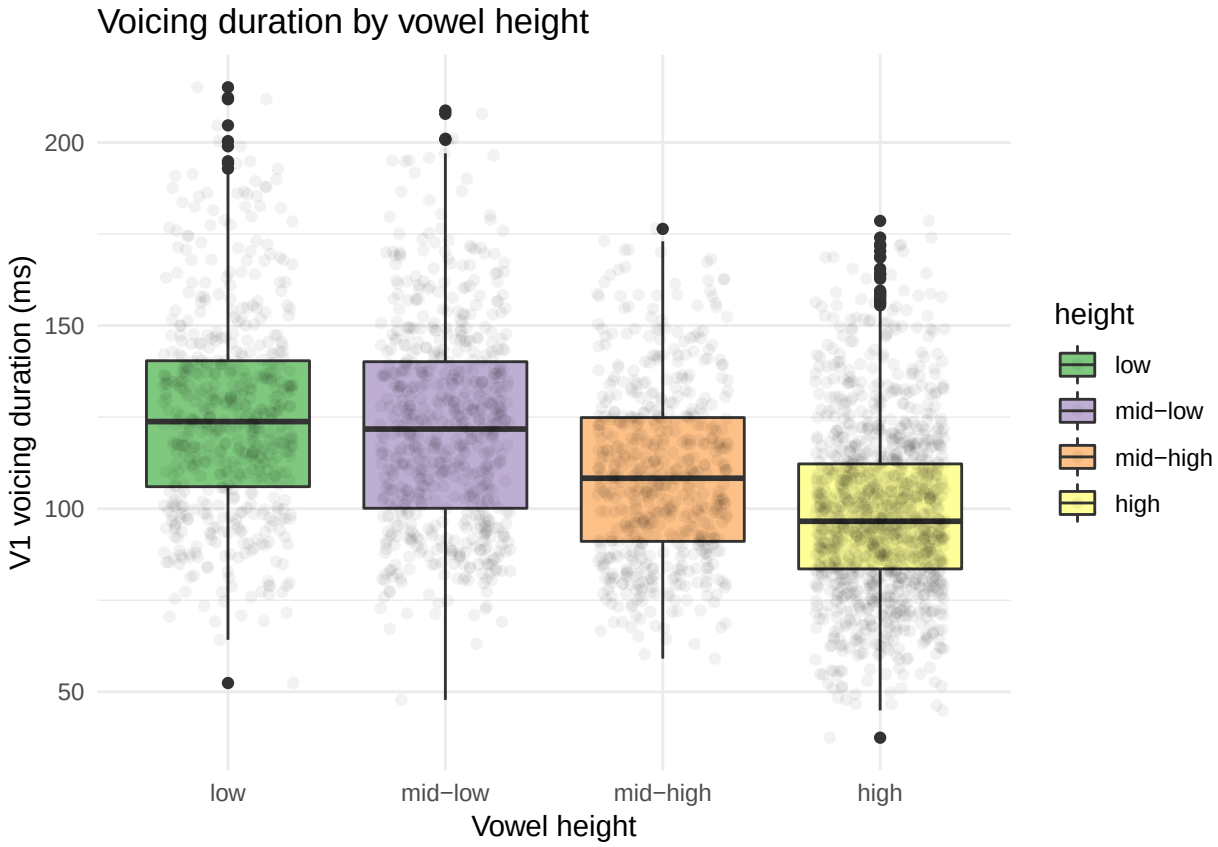
The estimated effect of voicing is 6.32 ms with a 90% credible interval 1.37-11.22 ms. A credible interval idicates the range of values within which there is a given probability of finding the true estimate (a 90% credible interval says in which range there is a 90% probabilty that the true effect is contained within that interval). The following plot shows the posterior distributions of C2 voicing and place (the shaded areas are 90% credible intervals). The posterior distribution of the predictor C2 voicing suggest a small positive effect of voicing on unstressed vowel duration.



4 Italian EGG: vowel and voicing duration

This section briefly reports the results from the EGG study on voicing duration and vowel height in Italian. The following figures show the duration of vowels by vowel height, and the duration of voicing coresponding to the vowel by vowel height. The stimuli (/'CVCo/) contained only voiceless stops, and voicing refers to the voicing of the vowel flanked by singleton voiceless stops. Vowel durations decrease with vowel height. The vowels are: low /a/, mid-low /ɔ/, mid-high /e/, high /u, i/. Voicing durations also decrease with vowel height, possibly with the exeption of the mid-low vowel (/ɔ/), which has a voicing duration similar to the low vowel (/a/). Two linear-mixed models have been fitted to vowel duration and voicing duration. The general pattern is that voicing duration decreases by a smaller degree than vowel duration with increasing vowel height. Also, non-low vowels have longer voicing during the closure of the consonant following the vowel, compared to the low vowel /a/.


Vowel duration by vowel height
V1 duration (ms)
150
100
50
low
mid−low
mid−high
high
Vowel height
height
low
mid−low
mid−high
high


Voicing duration by vowel height
V1 voicing duration (ms)
200
150
100
50
low
mid−low
mid−high
high
Vowel height
height
low
mid−low
mid−high
high

```
## Linear mixed model fit by REML. t-tests use Satterthwaite's method [
## lmerModLmerTest]
## Formula:
## v1_duration ~ height + c2_place + height:c2_place + speech_rate_c +
##     (1 | speaker) + (1 | word)
##    Data: ita_egg
## Control: lmerControl(optimizer = "Nelder_Mead")
##
## REML criterion at convergence: 26199.8
##
## Scaled residuals:
##     Min      1Q  Median      3Q     Max
## -6.8899 -0.6542 -0.0449  0.6013  4.1760
##
## Random effects:
##  Groups   Name        Variance Std.Dev.
##  word     (Intercept)  27.04    5.20
##  speaker  (Intercept) 115.03   10.73
##  Residual             176.93   13.30
## Number of obs: 3253, groups:  word, 43; speaker, 19
##
## Fixed effects:
##                                 Estimate Std. Error        df t value
## (Intercept)                      98.2018     3.9809   48.2609  24.668
## heightmid-low                   -13.0657     4.4253   30.9825  -2.953
## heightmid-high                  -18.5312     4.4257   30.9951  -4.187
## heighthigh                      -31.8662     3.8330   31.0005  -8.314
## c2_placecoronal                   9.9362     4.4257   30.9943   2.245
## c2_placevelar                     4.7546     4.9475   30.9802   0.961
## speech_rate_c                   -12.8447     0.6791 3093.5464 -18.915
## heightmid-low:c2_placecoronal     5.8422     6.2583   30.9833   0.934
## heightmid-high:c2_placecoronal   -5.5431     6.6387   30.9968  -0.835
## heighthigh:c2_placecoronal       -4.2523     5.4208   31.0040  -0.784
## heightmid-low:c2_placevelar       2.5631     6.6377   30.9780   0.386
## heightmid-high:c2_placevelar     -2.5813     6.6379   30.9815  -0.389
## heighthigh:c2_placevelar         -2.8746     5.8543   30.9855  -0.491
##                                Pr(>|t|)
## (Intercept)                     < 2e-16 ***
## heightmid-low                  0.005965 **
## heightmid-high                 0.000217 ***
## heighthigh                     2.17e-09 ***
## c2_placecoronal                0.032038 *
## c2_placevelar                  0.343992
## speech_rate_c                   < 2e-16 ***
## heightmid-low:c2_placecoronal  0.357774
```

```
## heightmid-high:c2_placecoronal 0.410123
## heighthigh:c2_placecoronal     0.438737
## heightmid-low:c2_placevelar    0.702029
## heightmid-high:c2_placevelar   0.700028
## heighthigh:c2_placevelar       0.626873
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

```
##
## Correlation matrix not shown by default, as p = 13 > 12.
## Use print(x, correlation=TRUE)  or
##     vcov(x)        if you need it
```

```
voice_lm_1 <- lmer(
  voice_duration ~
    height +
    c2_place +
    height:c2_place +
    speech_rate_c +
    (1+height|speaker) +
    (1|word),
  data = ita_egg,
  REML = FALSE
)
summary(voice_lm_1)
```

```
## Linear mixed model fit by maximum likelihood . t-tests use
##   Satterthwaite's method [lmerModLmerTest]
## Formula:
## voice_duration ~ height + c2_place + height:c2_place + speech_rate_c +
##     (1 + height | speaker) + (1 | word)
##    Data: ita_egg
##
##      AIC      BIC   logLik deviance df.resid
##  23995.1  24144.4 -11972.5  23945.1     2873
##
## Scaled residuals:
##     Min      1Q  Median      3Q     Max
## -5.0557 -0.6324 -0.0455  0.5932  4.0413
##
## Random effects:
##  Groups   Name           Variance Std.Dev. Corr
##  word     (Intercept)     17.00    4.123
##  speaker  (Intercept)    331.40   18.204
##           heightmid-low   13.75    3.708   -0.30
##           heightmid-high  54.59    7.389   -0.77  0.44
```

```
##           heighthigh      68.37    8.269   -0.71  0.01  0.59
##  Residual                208.88   14.453
## Number of obs: 2898, groups:  word, 43; speaker, 18
##
## Fixed effects:
##                                 Estimate Std. Error         df t value
## (Intercept)                    124.48559    5.01065   30.31622  24.844
## heightmid-low                   -4.82679    3.75949   44.80670  -1.284
## heightmid-high                 -13.62001    4.05136   52.25330  -3.362
## heighthigh                     -24.94753    3.72296   54.80420  -6.701
## c2_placecoronal                  2.30641    3.66162   41.56815   0.630
## c2_placevelar                    2.27648    4.09534   41.62924   0.556
## speech_rate_c                  -12.83599    0.80254 2607.56721 -15.994
## heightmid-low:c2_placecoronal    2.72970    5.17487   41.45696   0.527
## heightmid-high:c2_placecoronal  -2.89677    5.48999   41.49424  -0.528
## heighthigh:c2_placecoronal       0.04385    4.48594   41.61930   0.010
## heightmid-low:c2_placevelar     -0.04639    5.48957   41.48065  -0.008
## heightmid-high:c2_placevelar    -7.07893    5.48825   41.44124  -1.290
## heighthigh:c2_placevelar        -7.87100    4.84632   41.65160  -1.624
##                                Pr(>|t|)
## (Intercept)                     < 2e-16 ***
## heightmid-low                   0.20578
## heightmid-high                  0.00145 **
## heighthigh                     1.18e-08 ***
## c2_placecoronal                 0.53221
## c2_placevelar                   0.58128
## speech_rate_c                   < 2e-16 ***
## heightmid-low:c2_placecoronal   0.60066
## heightmid-high:c2_placecoronal  0.60056
## heighthigh:c2_placecoronal      0.99225
## heightmid-low:c2_placevelar     0.99330
## heightmid-high:c2_placevelar    0.20426
## heighthigh:c2_placevelar        0.11190
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Correlation matrix not shown by default, as p = 13 > 12.
## Use print(x, correlation=TRUE)  or
##     vcov(x)        if you need it
```

References

Davis, Stuart & W. Van Summers. 1989. Vowel length and closure duration in word-medial VC sequences. *Journal of Phonetics* 17. 339–353.