Acoustics of fricatives in Nendaz Francoprovencal - Main analyses

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April 2022

## Part I: Distinguishing Fricative Category

Spectral Analyses

We first present spectral analyses of fricatives taken from the middle 50% of the fricative segment (segmented in Praat).

LTAS plotting

First, we plot long-term average spectra (LTAS) for each fricative category for only **word-initial** tokens by speaker, then aggregated across speakers. This is the set of tokens submitted to statistical analyses below.
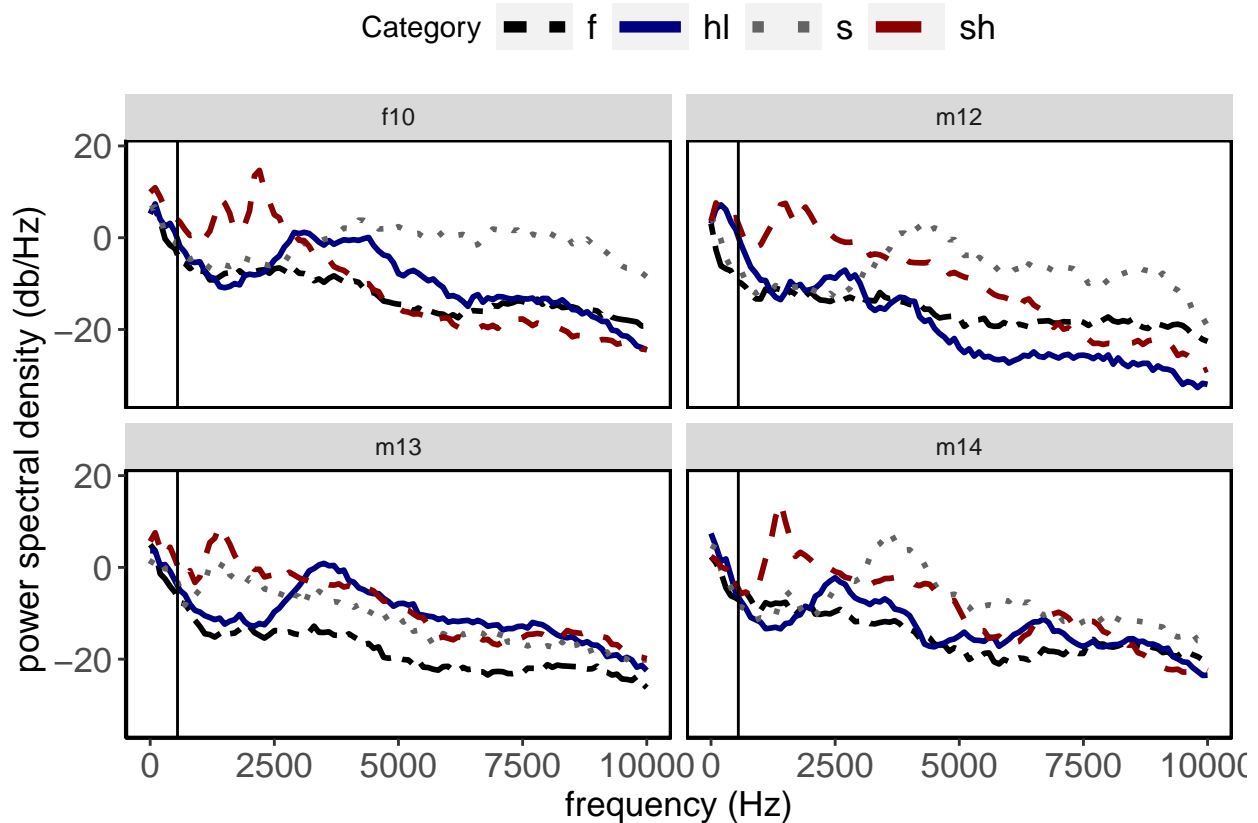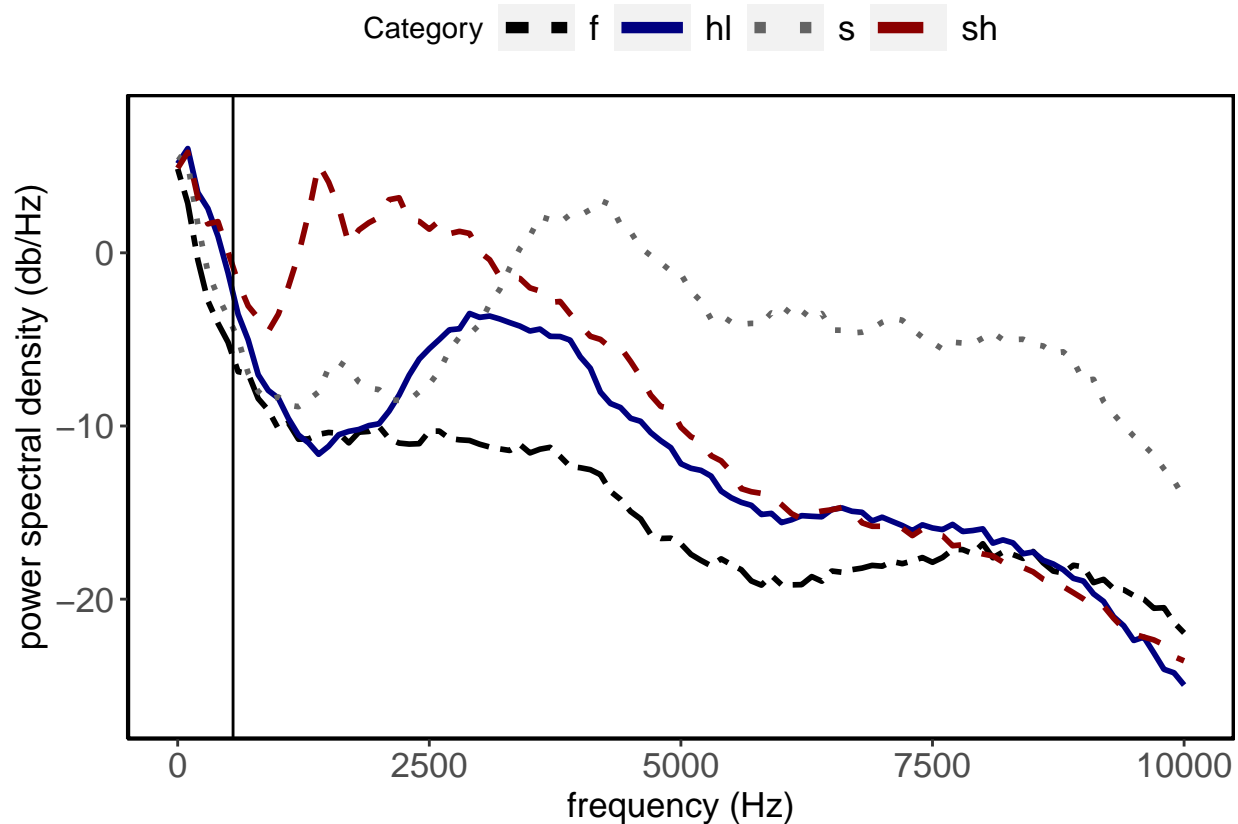
Spectral moments

Next, we examine the degree with fricatives are differentiated by **spectral peak location**, and **spectral moments**:

- **M1: average/center of gravity - COG**
- **M2: variance - standard deviation**
- **L3: skewness**
- **L4: kurtosis**

Spectral peak location and moments were extracted using Multitaper approach using a custom R script from Chodroff & Wilson (2014, 2019). Measurements were extrcated from the middle 50% of the segmented fricative. Sound files were first band-pass filtered with a low cut-off of 550 Hz and a high cut-off of 10,000 Hz.

Spectral Peak location

```
##      foll
## seg   a aa
##   f  24 18
##   h  30  9
##   s   8 19
##   sh 13 29

## , , spk = f10
##
##      foll
## seg   a aa
##   f   9  3
##   h   7  4
```
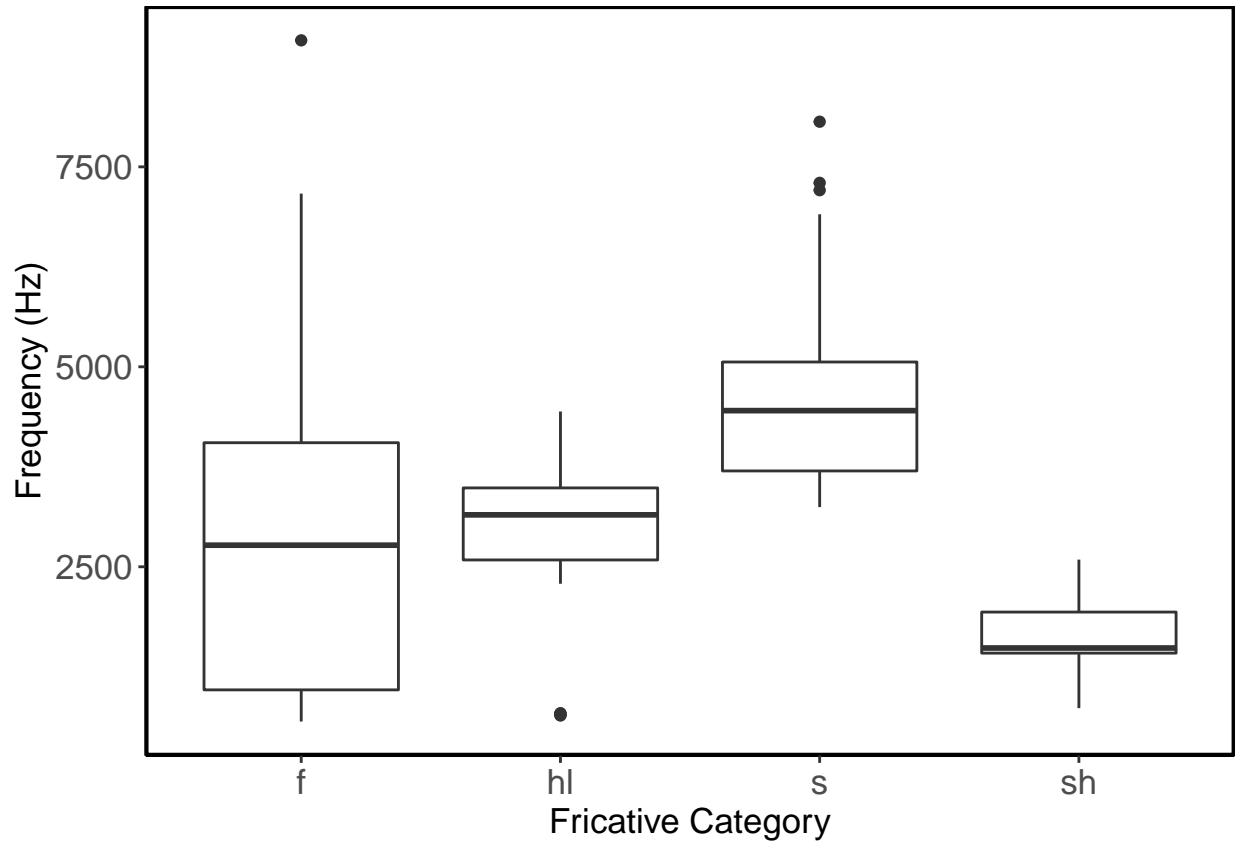
```
##     s   4 7
##    sh  3 6
##
## , , spk = m12
##
##      foll
## seg   a aa
##   f   5  4
##   h   6  0
##   s   4  5
##    sh  4  9
##
## , , spk = m13
##
##      foll
## seg   a aa
##   f   6  8
##   h  11  2
##   s   0  0
##   sh  3  6
##
## , , spk = m14
##
##      foll
## seg   a  aa
##   f   4  3
##   h   6  3
##   s   0  7
##   sh  3  8

## # A tibble: 4 x 4
##   seg    mean    sd       n
##   <fct> <dbl> <dbl> <int>
## 1 f     2818.  431.      4
## 2 h     2655.  391.      4
## 3 s     4591.  723.      3
## 4 sh    1667.  157.      4
```

Peak location measures were submitted to a LME with peak location as the DV and Segment (ref = /f/) as a fixed factor. Random intercepts for speaker and target word were also included. Models with more complex random effect structures did not converge. Significance of Segment was assessed using model comparison, and any post-hoc planned pairwise comparisons were conducted with bonferroni's correction.

```r
#no word intercept - didn't converge
mod_peak <- lmer(peak ~ seg +
                     (1|spk),
                  data = mts2,
                  control=lmerControl(optimizer="bobyqa"))
mod_peakNo <- lmer(peak ~ 1 +
                     (1|spk),
                  data = mts2,
                  control=lmerControl(optimizer="bobyqa"))
anova(mod_peak, mod_peakNo)
```

```
## Data: mts2
## Models:
## mod_peakNo: peak ~ 1 + (1 | spk)
## mod_peak: peak ~ seg + (1 | spk)
##             Df    AIC    BIC  logLik deviance  Chisq Chi Df Pr(>Chisq)
## mod_peakNo   3 2654.2 2663.2 -1324.1   2648.2
## mod_peak     6 2584.1 2602.2 -1286.1   2572.1 76.083      3  < 2.2e-16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

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```
summary(mod_peak)
```

```
## Linear mixed model fit by REML. t-tests use Satterthwaite's method [
## lmerModLmerTest]
## Formula: peak ~ seg + (1 | spk)
##    Data: mts2
## Control: lmerControl(optimizer = "bobyqa")
##
## REML criterion at convergence: 2520.7
##
## Scaled residuals:
##     Min      1Q  Median      3Q     Max
## -1.9411 -0.4980  0.1010  0.3687  4.6487
##
## Random effects:
##  Groups   Name        Variance Std.Dev.
##  spk      (Intercept)  131372   362.5
##  Residual             1624039  1274.4
## Number of obs: 150, groups:  spk, 4
##
## Fixed effects:
##              Estimate Std. Error       df t value Pr(>|t|)
## (Intercept)  2784.870    268.493    7.556  10.372 9.79e-06 ***
## segh           52.139    283.858  143.210   0.184 0.854524
## segs         2054.985    322.618  145.964   6.370 2.32e-09 ***
## segsh       -1121.749    280.410  144.385  -4.000 0.000101 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Correlation of Fixed Effects:
##       (Intr) segh   segs
## segh  -0.509
## segs  -0.461  0.422
## segsh -0.525  0.486  0.448
```

```
emmeans(mod_peak, pairwise ~ seg, adjust = "bonferroni")
```

```
## $emmeans
##  seg emmean  SE    df lower.CL upper.CL
##  f     2785 269  7.86     2163     3407
##  h     2837 275  8.51     2210     3464
##  s     4840 313 13.20     4165     5514
##  sh    1663 268  7.83     1043     2283
##
## Degrees-of-freedom method: kenward-roger
## Confidence level used: 0.95
##
## $contrasts
##  contrast estimate  SE  df t.ratio p.value
##  f - h       -52.1 284 143  -0.184  1.0000
##  f - s     -2055.0 327 146  -6.293  <.0001
##  f - sh     1121.7 282 144   3.985  0.0006
##  h - s     -2002.8 332 146  -6.035  <.0001
##  h - sh     1173.9 287 145   4.086  0.0004
```

```
##  s - sh     3176.7 321 145  9.902  <.0001
##
## Degrees-of-freedom method: kenward-roger
## P value adjustment: bonferroni method for 6 tests
```

M1: Spectral Mean/Center of gravity (COG)

```
## # A tibble: 4 x 4
##   seg    mean    sd     n
##   <fct> <dbl> <dbl> <int>
## 1 f     3995. 145.      4
## 2 h     3274.  65.2     4
## 3 s     4855. 526.      3
## 4 sh    2160.  96.5     4
```
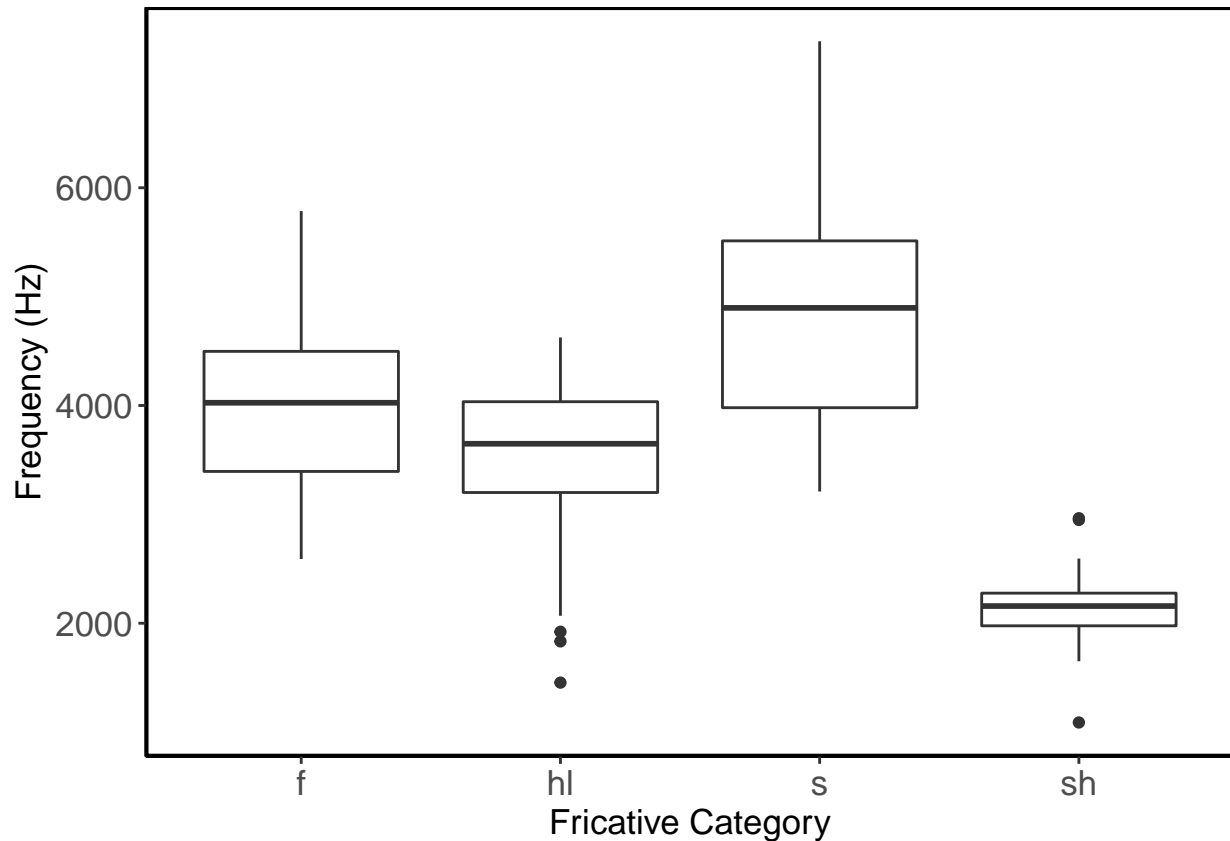

COG measures were submitted to a LME with COG as the DV and Segment (ref = /f/) as a fixed factor. Random intercepts for speaker and target word were also included. Models with more complex random effect structures did not converge. Significance of Segment was assessed using model comparison, and any post-hoc planned pairwise comparisons were conducted with bonferroni's correction.

```r
mod_cog <- lmer(cog ~ seg +
                  (1|spk) + (1|word),
              data = mts2,
            control=lmerControl(optimizer="bobyqa"))


mod_cogNo <- lmer(cog ~ 1 +
                  (1|spk) + (1|word),
              data = mts2,
```

```
                 control=lmerControl(optimizer="bobyqa"))

anova(mod_cog,mod_cogNo)

## Data: mts2
## Models:
## mod_cogNo: cog ~ 1 + (1 | spk) + (1 | word)
## mod_cog: cog ~ seg + (1 | spk) + (1 | word)
##           Df    AIC    BIC  logLik deviance  Chisq Chi Df Pr(>Chisq)
## mod_cogNo  4 2446.0 2458.0 -1219.0   2438.0
## mod_cog    7 2423.3 2444.4 -1204.7   2409.3 28.663      3  2.636e-06 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

summary(mod_cog)

## Linear mixed model fit by REML. t-tests use Satterthwaite's method [
## lmerModLmerTest]
## Formula: cog ~ seg + (1 | spk) + (1 | word)
##    Data: mts2
## Control: lmerControl(optimizer = "bobyqa")
##
## REML criterion at convergence: 2359.1
##
## Scaled residuals:
##      Min       1Q   Median       3Q      Max
## -2.55458 -0.53625  0.03379  0.47495  2.91714
##
## Random effects:
##  Groups   Name        Variance Std.Dev.
##  word     (Intercept) 124021   352.2
##  spk      (Intercept)  63246   251.5
##  Residual             489537   699.7
## Number of obs: 150, groups:  word, 18; spk, 4
##
## Fixed effects:
##             Estimate Std. Error       df t value Pr(>|t|)
## (Intercept)  3860.768    239.945    7.597  16.090 3.83e-07 ***
## segh         -425.423    289.721    5.637  -1.468   0.1955
## segs         1130.869    324.443    6.765   3.486   0.0108 *
## segsh       -1708.308    310.409    4.691  -5.503   0.0033 **
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Correlation of Fixed Effects:
##       (Intr) segh   segs
## segh  -0.598
## segs  -0.536  0.435
## segsh -0.562  0.462  0.416

emmeans(mod_cog, pairwise ~ seg, adjust = "bonferroni")

## $emmeans
##  seg emmean  SE   df lower.CL upper.CL
##  f     3861 244 12.1     3329     4392
```

```
## h      3435 244 11.6      2902      3969
## s      4992 288 15.3      4380      5604
## sh     2152 266  9.9      1560      2745
##
## Degrees-of-freedom method: kenward-roger
## Confidence level used: 0.95
##
## $contrasts
##  contrast estimate  SE    df t.ratio p.value
##  f - h         425 295 11.18  1.444  1.0000
##  f - s       -1131 332 13.31 -3.401  0.0275
##  f - sh       1708 314  9.37  5.439  0.0021
##  h - s       -1556 335 12.90 -4.643  0.0028
##  h - sh       1283 314  9.07  4.086  0.0161
##  s - sh       2839 348 10.66  8.147  <.0001
##
## Degrees-of-freedom method: kenward-roger
## P value adjustment: bonferroni method for 6 tests
```
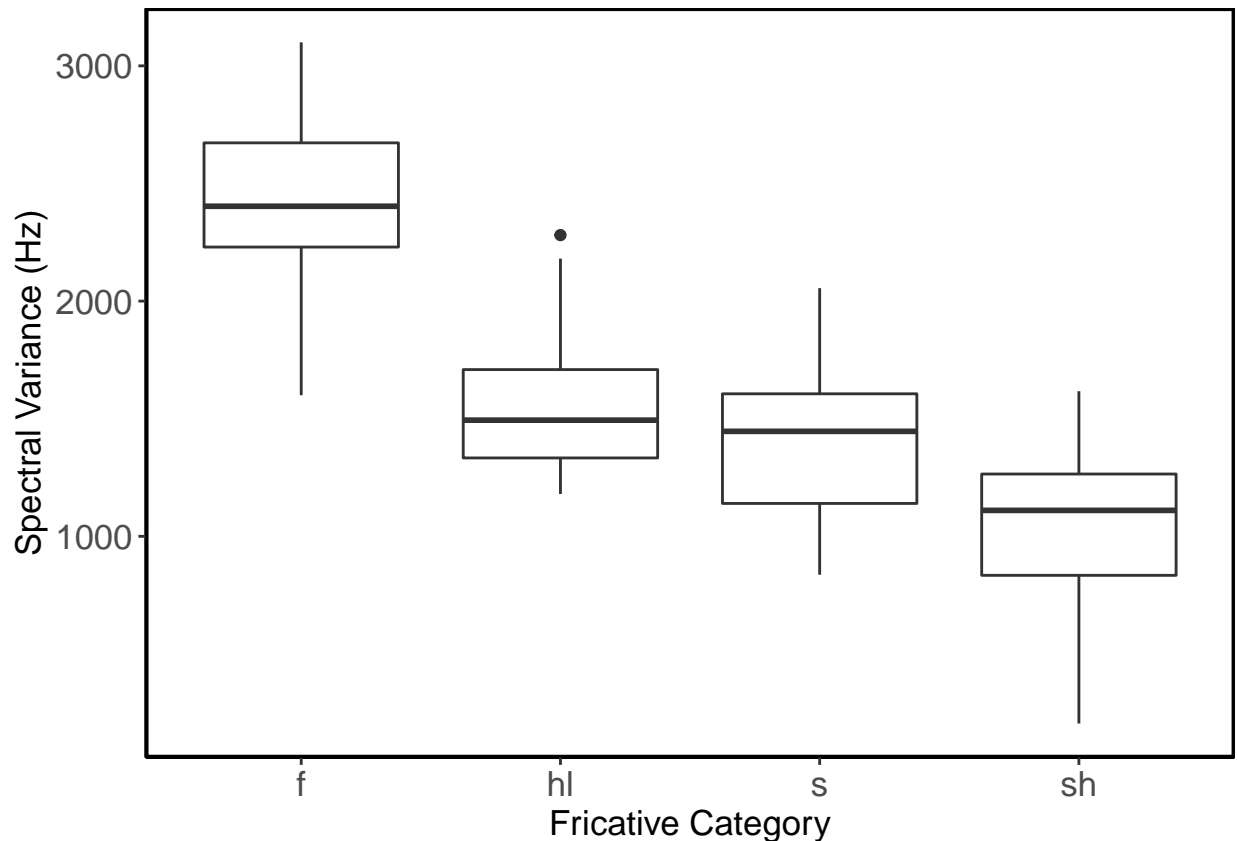
M2: Spectral variance (standard deviation)

```
## # A tibble: 4 x 4
##   seg    mean    sd     n
##   <fct> <dbl> <dbl> <int>
## 1 f     2435.  109.     4
## 2 h     1539.   60.2    4
## 3 s     1354.   71.6    3
## 4 sh    1036.   48.1    4
```

Spectral variance measures were submitted to a LME with spectral variance as the DV and Segment (ref = /f/) as a fixed factor. Random intercepts for speaker and target word were also included. Models with more complex random effect structures did not converge. Significance of Segment was assessed using model comparison, and any post-hoc planned pairwise comparisons were conducted with bonferroni's correction.

```r
##No word intercept - didnt converge
mod_std <- lmer(specSD ~ seg +
                  (1|spk) + (1|word),
               data =mts2,
               control=lmerControl(optimizer="bobyqa"))


mod_stdNoInt <- lmer(specSD ~ 1 +
                  (1|spk) + (1|word),
               data = mts2,
               control=lmerControl(optimizer="bobyqa"))


anova(mod_std,mod_stdNoInt)
```

```
## Data: mts2
## Models:
## mod_stdNoInt: specSD ~ 1 + (1 | spk) + (1 | word)
## mod_std: specSD ~ seg + (1 | spk) + (1 | word)
##               Df    AIC    BIC  logLik deviance  Chisq Chi Df Pr(>Chisq)
## mod_stdNoInt  4 2221.7 2233.7 -1106.8   2213.7
## mod_std       7 2182.8 2203.9 -1084.4   2168.8 44.869      3  9.867e-10
##
## mod_stdNoInt
## mod_std       ***
```

```
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

```
mod_stdNoFoll <- lmer(specSD ~ seg +
                        (1|spk) + (1|word),
                      data = mts2,
                      control=lmerControl(optimizer="bobyqa"))

mod_stdNoSeg <- lmer(specSD ~ foll +
                        (1|spk) + (1|word),
                      data = mts2,
                      control=lmerControl(optimizer="bobyqa"))


anova(mod_stdNoInt,mod_stdNoFoll)
```

```
## Data: mts2
## Models:
## mod_stdNoInt: specSD ~ 1 + (1 | spk) + (1 | word)
## mod_stdNoFoll: specSD ~ seg + (1 | spk) + (1 | word)
##               Df    AIC    BIC  logLik deviance  Chisq Chi Df Pr(>Chisq)
## mod_stdNoInt   4 2221.7 2233.7 -1106.8   2213.7
## mod_stdNoFoll  7 2182.8 2203.9 -1084.4   2168.8 44.869      3  9.867e-10
##
## mod_stdNoInt
## mod_stdNoFoll ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

```
anova(mod_stdNoInt,mod_stdNoSeg)
```

```
## Data: mts2
## Models:
## mod_stdNoInt: specSD ~ 1 + (1 | spk) + (1 | word)
## mod_stdNoSeg: specSD ~ foll + (1 | spk) + (1 | word)
##               Df    AIC    BIC  logLik deviance  Chisq Chi Df Pr(>Chisq)
## mod_stdNoInt   4 2221.7 2233.7 -1106.8   2213.7
## mod_stdNoSeg   5 2223.6 2238.6 -1106.8   2213.6 0.0982      1      0.754
```

```
summary(mod_stdNoFoll)
```

```
## Linear mixed model fit by REML. t-tests use Satterthwaite's method [
## lmerModLmerTest]
## Formula: specSD ~ seg + (1 | spk) + (1 | word)
##    Data: mts2
## Control: lmerControl(optimizer = "bobyqa")
##
## REML criterion at convergence: 2128.6
##
## Scaled residuals:
##      Min       1Q   Median       3Q      Max
## -2.29620 -0.57143 -0.00216  0.64642  2.09191
##
## Random effects:
##  Groups   Name        Variance Std.Dev.
##  word     (Intercept)  2978     54.57
```

```
##   spk        (Intercept)    3375     58.09
##   Residual                110382    332.24
## Number of obs: 150, groups:  word, 18; spk, 4
##
## Fixed effects:
##                Estimate Std. Error        df t value Pr(>|t|)
## (Intercept)   2404.065      65.979     6.331   36.44 1.35e-08 ***
## segh          -854.812      84.336     7.252  -10.14 1.54e-05 ***
## segs         -1018.977      96.189     6.656  -10.59 2.08e-05 ***
## segsh        -1373.754      85.239     5.312  -16.12 1.03e-05 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Correlation of Fixed Effects:
##        (Intr) segh   segs
## segh  -0.627
## segs  -0.557  0.426
## segsh -0.626  0.484  0.434
```

```
emmeans(mod_stdNoFoll, pairwise ~ seg, adjust = "bonferroni")
```

```
## $emmeans
##  seg emmean   SE   df lower.CL upper.CL
##  f     2404 68.3 7.60     2245     2563
##  h     1549 68.6 8.78     1393     1705
##  s     1385 87.7 8.05     1183     1587
##  sh    1030 69.2 5.81      860     1201
##
## Degrees-of-freedom method: kenward-roger
## Confidence level used: 0.95
##
## $contrasts
##  contrast estimate    SE   df t.ratio p.value
##  f - h         855  87.1 8.35   9.816  <.0001
##  f - s        1019 103.7 7.72   9.824  0.0001
##  f - sh       1374  88.4 6.14  15.545  <.0001
##  h - s         164 104.8 8.21   1.567  0.9284
##  h - sh        519  88.7 6.78   5.849  0.0043
##  s - sh        355 103.6 6.31   3.425  0.0779
##
## Degrees-of-freedom method: kenward-roger
## P value adjustment: bonferroni method for 6 tests
```
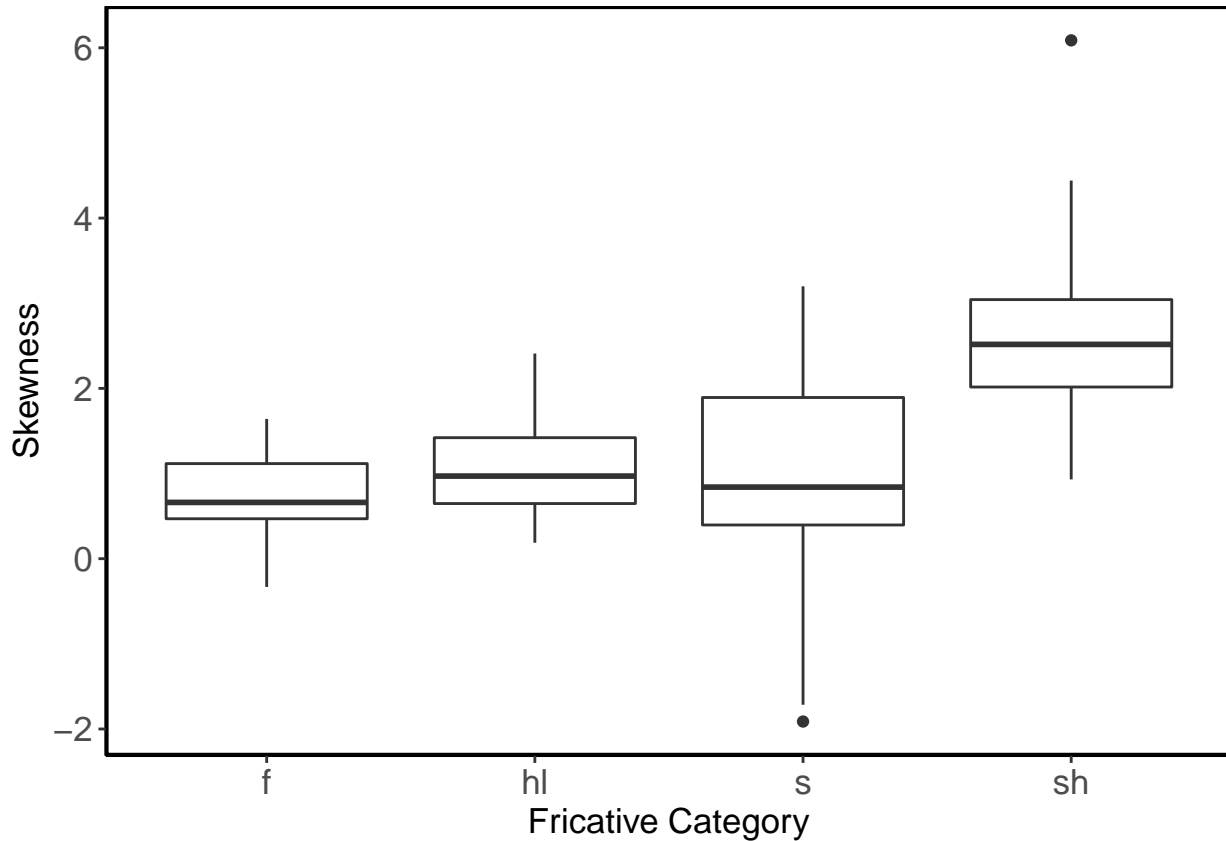
L3: Spectral skewness

```
## # A tibble: 4 x 4
##   seg    mean     sd     n
##   <fct> <dbl>  <dbl> <int>
## 1 f     0.764 0.0579     4
## 2 h     1.09  0.150      4
## 3 s     1.00  0.512      3
## 4 sh    2.60  0.387      4
```

Spectral skewness measures were submitted to a LME with skewness as the DV and Segment (ref = /f/) as a fixed factor. Random intercepts for speaker and target word were also included. Models with more complex random effect structures did not converge. Significance of Segment was assessed using model comparison, and any post-hoc planned pairwise comparisons were conducted with bonferroni's correction.

```
mod_skew <- lmer(skew ~ seg + foll + seg*foll+
                    (1|spk) + (1|word),
                 data = mts2)

mod_skewNoInt <- lmer(skew ~ seg + foll +
                    (1|spk) + (1|word),
                 data = mts2)

anova(mod_skew,mod_skewNoInt)

## Data: mts2
## Models:
## mod_skewNoInt: skew ~ seg + foll + (1 | spk) + (1 | word)
## mod_skew: skew ~ seg + foll + seg * foll + (1 | spk) + (1 | word)
##               Df    AIC    BIC  logLik deviance  Chisq Chi Df Pr(>Chisq)
## mod_skewNoInt  8 390.73 414.82 -187.37   374.73
## mod_skew      11 394.20 427.32 -186.10   372.20 2.5286      3     0.4702

mod_skewNoFoll <- lmer(skew ~ seg +
                    (1|spk) + (1|word),
                 data = mts2)

mod_skewNoSeg <- lmer(skew ~ foll +
```

```
                    (1|spk) + (1|word),
                data = mts2)
```

```
anova(mod_skewNoInt,mod_skewNoFoll)
```

```
## Data: mts2
## Models:
## mod_skewNoFoll: skew ~ seg + (1 | spk) + (1 | word)
## mod_skewNoInt: skew ~ seg + foll + (1 | spk) + (1 | word)
##                Df    AIC    BIC  logLik deviance  Chisq Chi Df Pr(>Chisq)
## mod_skewNoFoll  7 388.77 409.84 -187.38   374.77
## mod_skewNoInt   8 390.73 414.82 -187.37   374.73 0.0361      1     0.8493
```

```
anova(mod_skewNoInt,mod_skewNoSeg)
```

```
## Data: mts2
## Models:
## mod_skewNoSeg: skew ~ foll + (1 | spk) + (1 | word)
## mod_skewNoInt: skew ~ seg + foll + (1 | spk) + (1 | word)
##               Df    AIC    BIC  logLik deviance  Chisq Chi Df Pr(>Chisq)
## mod_skewNoSeg  5 404.92 419.97 -197.46   394.92
## mod_skewNoInt  8 390.73 414.82 -187.37   374.73 20.188      3  0.0001552
##
## mod_skewNoSeg
## mod_skewNoInt ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

```
summary(mod_skewNoFoll)
```

```
## Linear mixed model fit by REML. t-tests use Satterthwaite's method [
## lmerModLmerTest]
## Formula: skew ~ seg + (1 | spk) + (1 | word)
##    Data: mts2
##
## REML criterion at convergence: 379.3
##
## Scaled residuals:
##     Min      1Q  Median      3Q     Max
## -3.2913 -0.4689 -0.0222  0.5015  3.9451
##
## Random effects:
##  Groups   Name        Variance Std.Dev.
##  word     (Intercept) 0.14301  0.3782
##  spk      (Intercept) 0.04649  0.2156
##  Residual             0.64176  0.8011
## Number of obs: 150, groups:  word, 18; spk, 4
##
## Fixed effects:
##             Estimate Std. Error      df t value Pr(>|t|)
## (Intercept)  0.86496    0.24927 8.17999   3.470  0.00816 **
## segh         0.09757    0.31838 6.16496   0.306  0.76935
## segs        -0.08017    0.35739 7.36150  -0.224  0.82861
## segsh        1.79666    0.33980 5.10908   5.287  0.00302 **
## ---
```

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```
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Correlation of Fixed Effects:
##        (Intr) segh   segs
## segh  -0.633
## segs  -0.567  0.436
## segsh -0.597  0.464  0.417
```

```r
emmeans(mod_skewNoFoll, pairwise ~ seg, adjust = "bonferroni")
```

```
## $emmeans
##  seg emmean    SE    df lower.CL upper.CL
##  f    0.865 0.254 12.38    0.313     1.42
##  h    0.963 0.254 11.74    0.408     1.52
##  s    0.785 0.306 15.17    0.133     1.44
##  sh   2.662 0.277  9.27    2.038     3.29
##
## Degrees-of-freedom method: kenward-roger
## Confidence level used: 0.95
##
## $contrasts
##  contrast estimate    SE    df t.ratio p.value
##  f - h     -0.0976 0.324 10.97 -0.301  1.0000
##  f - s      0.0802 0.368 13.01  0.218  1.0000
##  f - sh    -1.7967 0.344  9.14 -5.219  0.0031
##  h - s      0.1777 0.370 12.66  0.480  1.0000
##  h - sh    -1.6991 0.344  8.90 -4.941  0.0050
##  s - sh    -1.8768 0.384 10.45 -4.894  0.0033
##
## Degrees-of-freedom method: kenward-roger
## P value adjustment: bonferroni method for 6 tests
```

L4: Spectral kurtosis
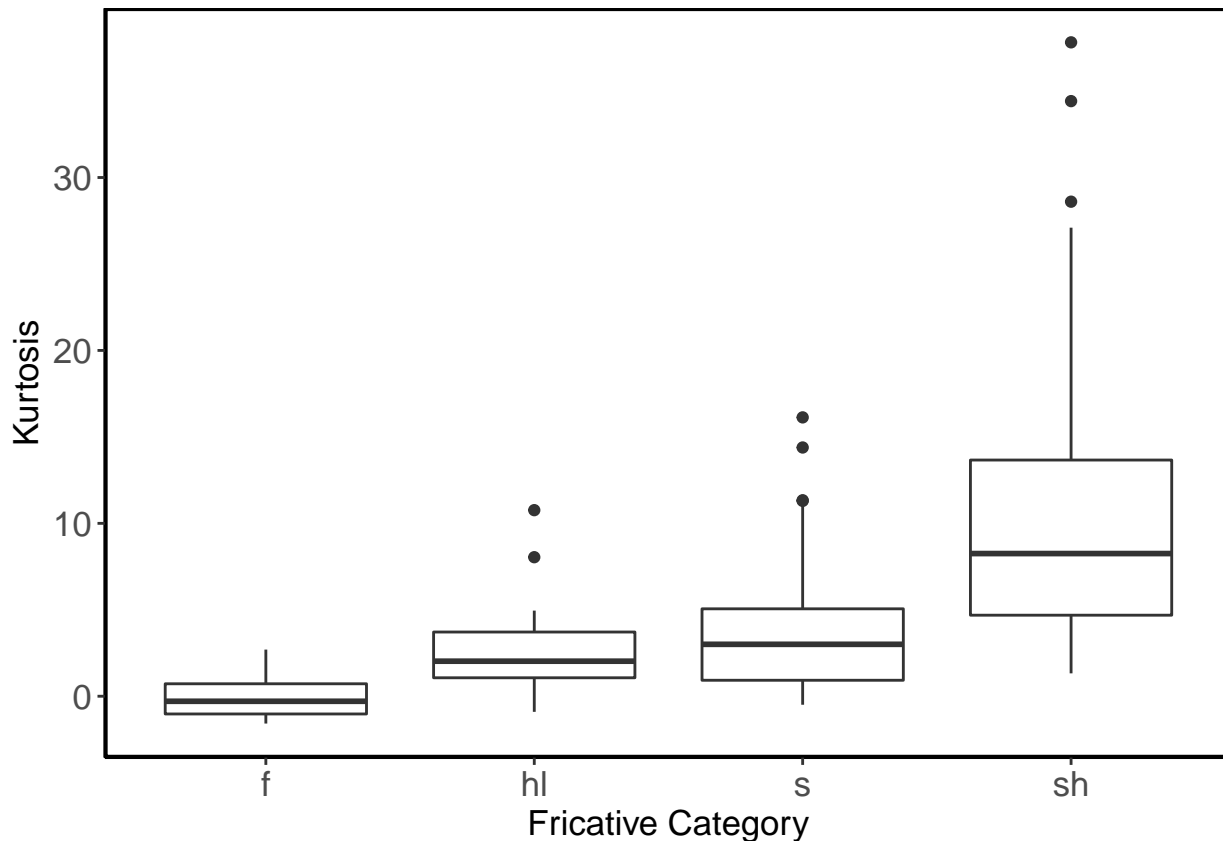
```
## # A tibble: 4 x 4
##   seg     mean     sd     n
##   <fct>  <dbl>  <dbl> <int>
## 1 f    -0.0758  0.458     4
## 2 h     2.73    0.983     4
## 3 s     4.78    2.15      3
## 4 sh   19.5    28.9       4
```

Spectral kurtosis measures were submitted to a LME with kurtosis as the DV and Segment (ref = /f/) as a fixed factor. An initial model with both random intercepts for speaker and target word did not converge. The final model included just a random intercept for speaker. Significance of Segment was assessed using model comparison, and any post-hoc planned pairwise comparisons were conducted with bonferroni's correction.

```r
mod_kurt <- lmer(kurt ~ seg + foll + seg*foll+
                     (1|spk) + (1|word),
                 data = mts2)

mod_kurtNoInt <- lmer(kurt ~ seg + foll +
                     (1|spk) + (1|word),
                 data = mts2)

anova(mod_kurt,mod_kurtNoInt)
```

```
## Data: mts2
## Models:
## mod_kurtNoInt: kurt ~ seg + foll + (1 | spk) + (1 | word)
## mod_kurt: kurt ~ seg + foll + seg * foll + (1 | spk) + (1 | word)
##               Df    AIC    BIC  logLik deviance  Chisq Chi Df Pr(>Chisq)
## mod_kurtNoInt  8 1297.9 1322.0 -640.96   1281.9
## mod_kurt      11 1301.7 1334.8 -639.87   1279.7 2.1904      3     0.5338
```

```r
mod_kurtNoFoll <- lmer(kurt ~ seg +
                     (1|spk) + (1|word),
                 data = mts2)

mod_kurtNoSeg <- lmer(kurt ~ foll +
```

```
                    (1|spk) + (1|word),
                data = mts2)
```

anova(mod_kurtNoInt,mod_kurtNoFoll)

```
## Data: mts2
## Models:
## mod_kurtNoFoll: kurt ~ seg + (1 | spk) + (1 | word)
## mod_kurtNoInt: kurt ~ seg + foll + (1 | spk) + (1 | word)
##                Df    AIC    BIC  logLik deviance  Chisq Chi Df Pr(>Chisq)
## mod_kurtNoFoll  7 1296.6 1317.7 -641.32   1282.6
## mod_kurtNoInt   8 1297.9 1322.0 -640.96   1281.9 0.7077      1     0.4002
```

anova(mod_kurtNoInt,mod_kurtNoSeg)

```
## Data: mts2
## Models:
## mod_kurtNoSeg: kurt ~ foll + (1 | spk) + (1 | word)
## mod_kurtNoInt: kurt ~ seg + foll + (1 | spk) + (1 | word)
##               Df    AIC    BIC  logLik deviance  Chisq Chi Df Pr(>Chisq)
## mod_kurtNoSeg  5 1301.3 1316.3 -645.65   1291.3
## mod_kurtNoInt  8 1297.9 1322.0 -640.96   1281.9 9.3662      3     0.0248 *
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

summary(mod_kurtNoFoll)

```
## Linear mixed model fit by REML. t-tests use Satterthwaite's method [
## lmerModLmerTest]
## Formula: kurt ~ seg + (1 | spk) + (1 | word)
##    Data: mts2
##
## REML criterion at convergence: 1262.2
##
## Scaled residuals:
##     Min      1Q  Median      3Q     Max
## -2.0106 -0.2944  0.0036  0.1323  9.5449
##
## Random effects:
##  Groups   Name        Variance Std.Dev.
##  word     (Intercept) 64.5     8.031
##  spk      (Intercept) 19.0     4.359
##  Residual             270.6    16.449
## Number of obs: 150, groups:  word, 18; spk, 4
##
## Fixed effects:
##             Estimate Std. Error      df t value Pr(>|t|)
## (Intercept)  -0.3157     5.1913 14.8141  -0.061  0.95232
## segh          2.5823     6.6778 13.6952   0.387  0.70492
## segs          2.7469     7.4824 16.1885   0.367  0.71829
## segsh        22.3389     7.1413 11.4810   3.128  0.00916 **
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Correlation of Fixed Effects:
```

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```
##          (Intr) segh    segs
## segh  -0.637
## segs  -0.571  0.436
## segsh -0.600  0.463  0.417
```

```r
emmeans(mod_kurtNoFoll, pairwise ~ seg, adjust = "bonferroni")
```

```
## $emmeans
##  seg emmean   SE    df lower.CL upper.CL
##  f   -0.316 5.30 12.62   -11.79     11.2
##  h    2.267 5.29 11.87    -9.27     13.8
##  s    2.431 6.37 15.34   -11.12     16.0
##  sh  22.023 5.80  9.34     8.98     35.1
##
## Degrees-of-freedom method: kenward-roger
## Confidence level used: 0.95
##
## $contrasts
##  contrast estimate   SE    df t.ratio p.value
##  f - h      -2.582 6.80 11.09 -0.380  1.0000
##  f - s      -2.747 7.69 13.15 -0.357  1.0000
##  f - sh    -22.339 7.23  9.26 -3.089  0.0751
##  h - s      -0.165 7.75 12.76 -0.021  1.0000
##  h - sh    -19.757 7.23  8.99 -2.734  0.1385
##  s - sh    -19.592 8.04 10.56 -2.437  0.2031
##
## Degrees-of-freedom method: kenward-roger
## P value adjustment: bonferroni method for 6 tests
```

By speaker plots for all spectral measures
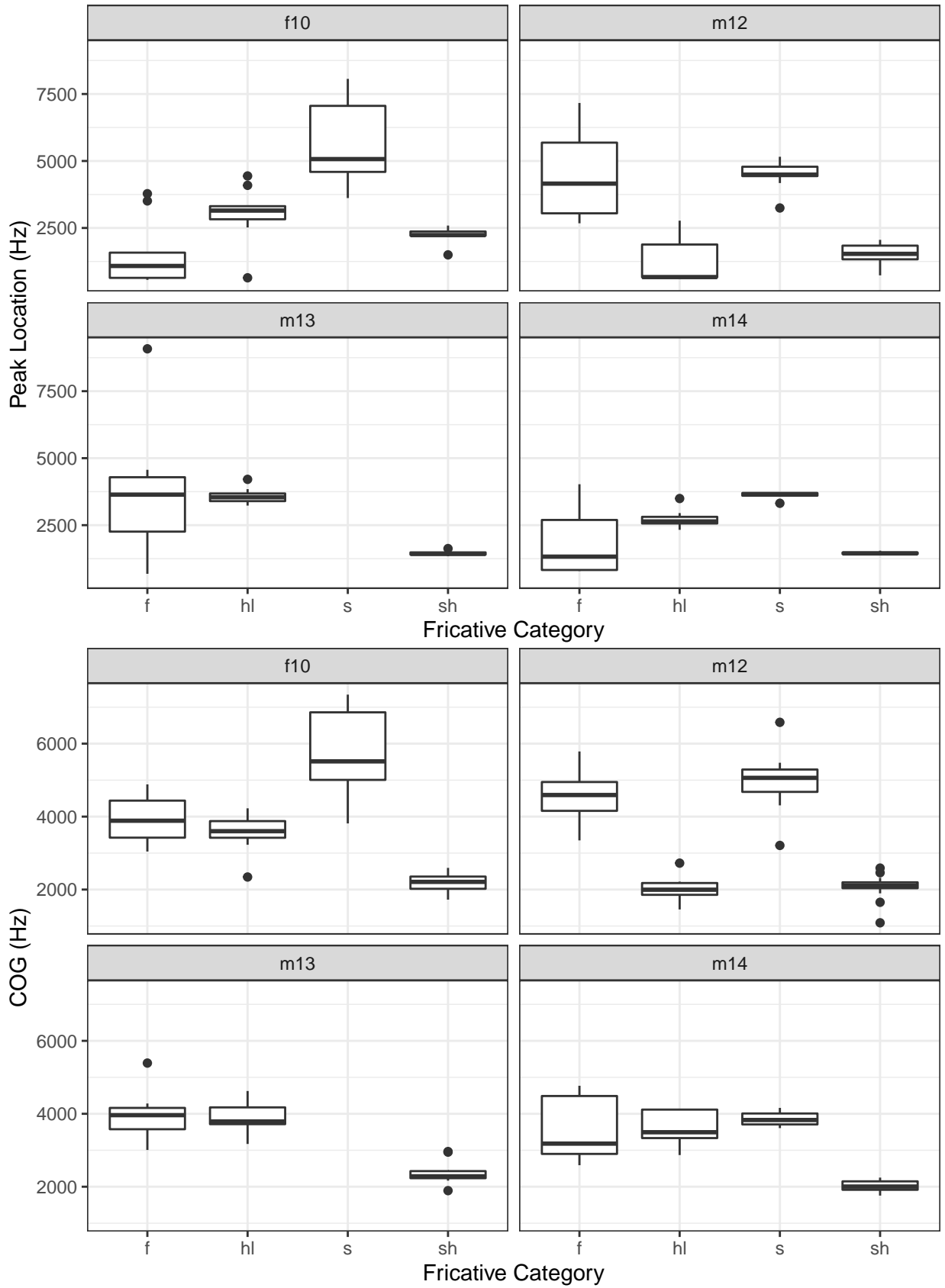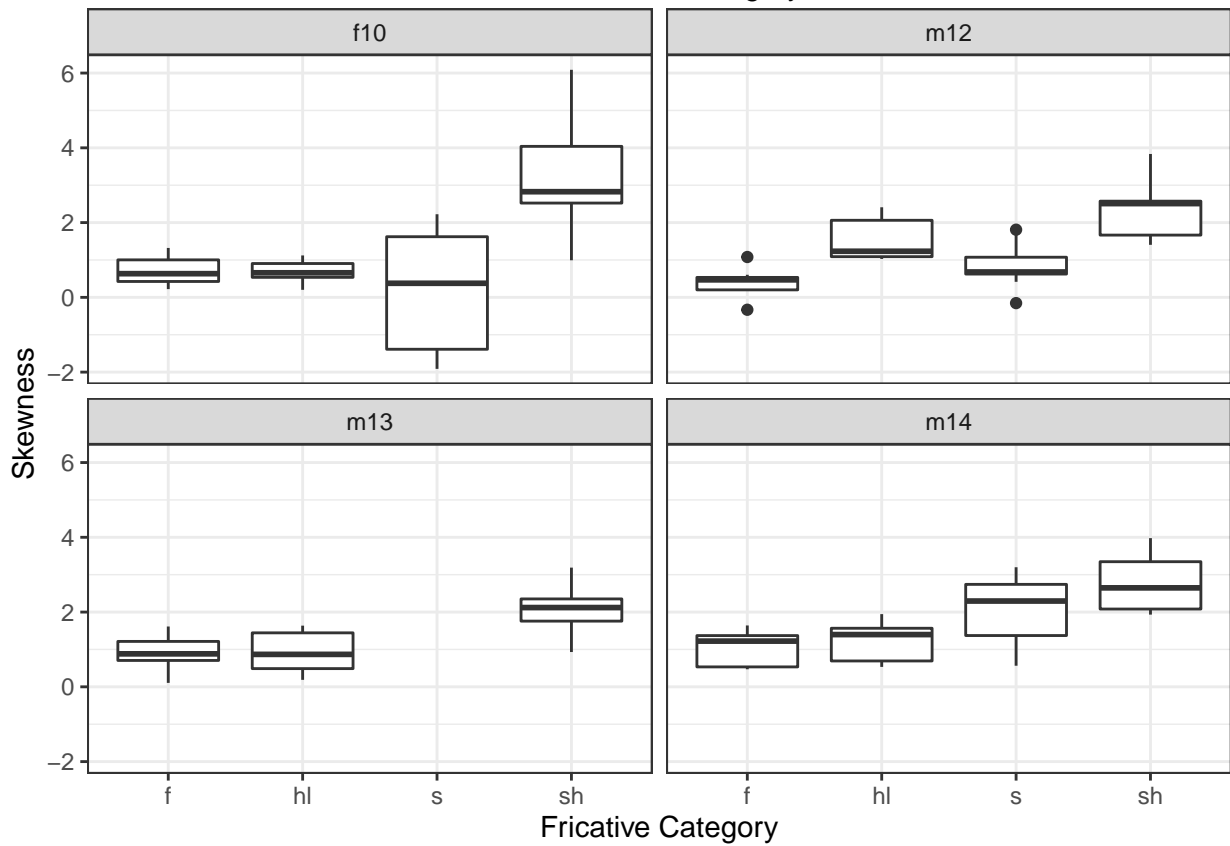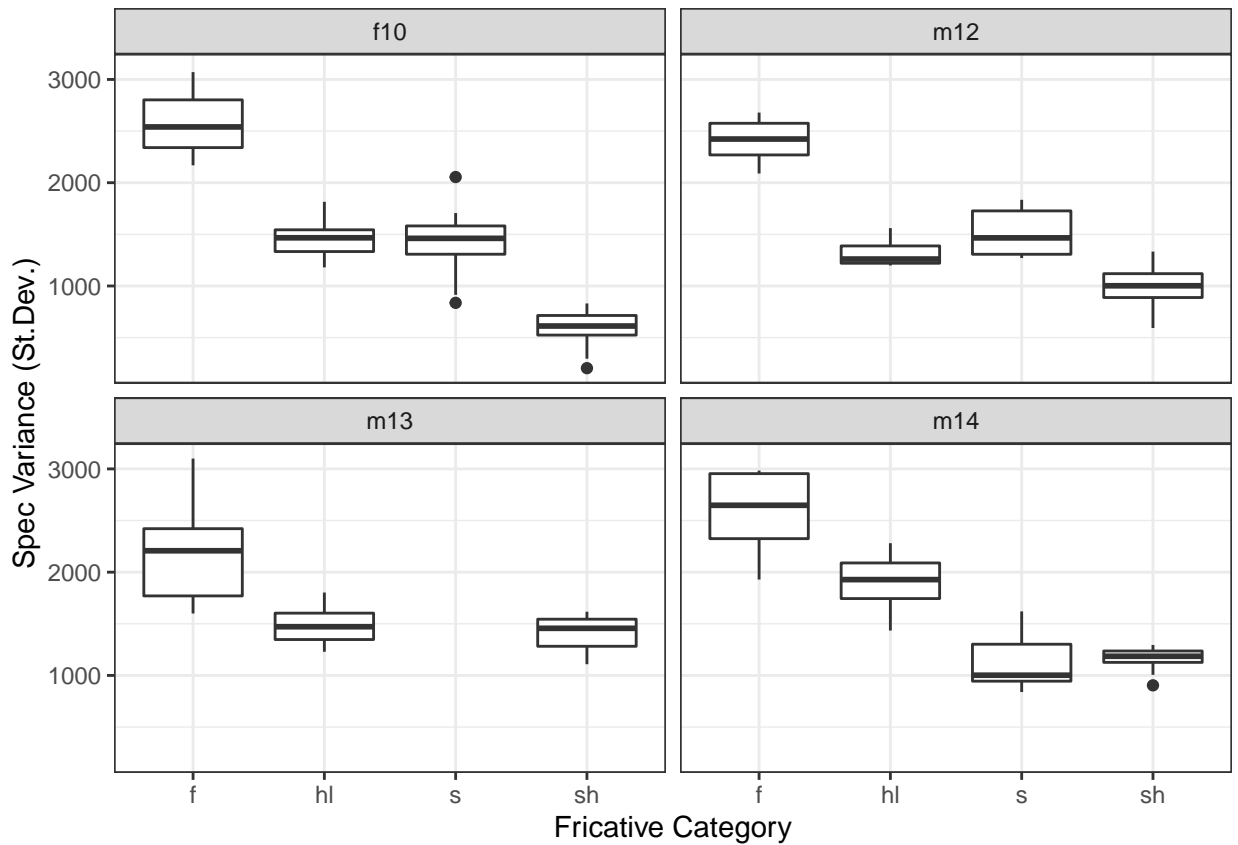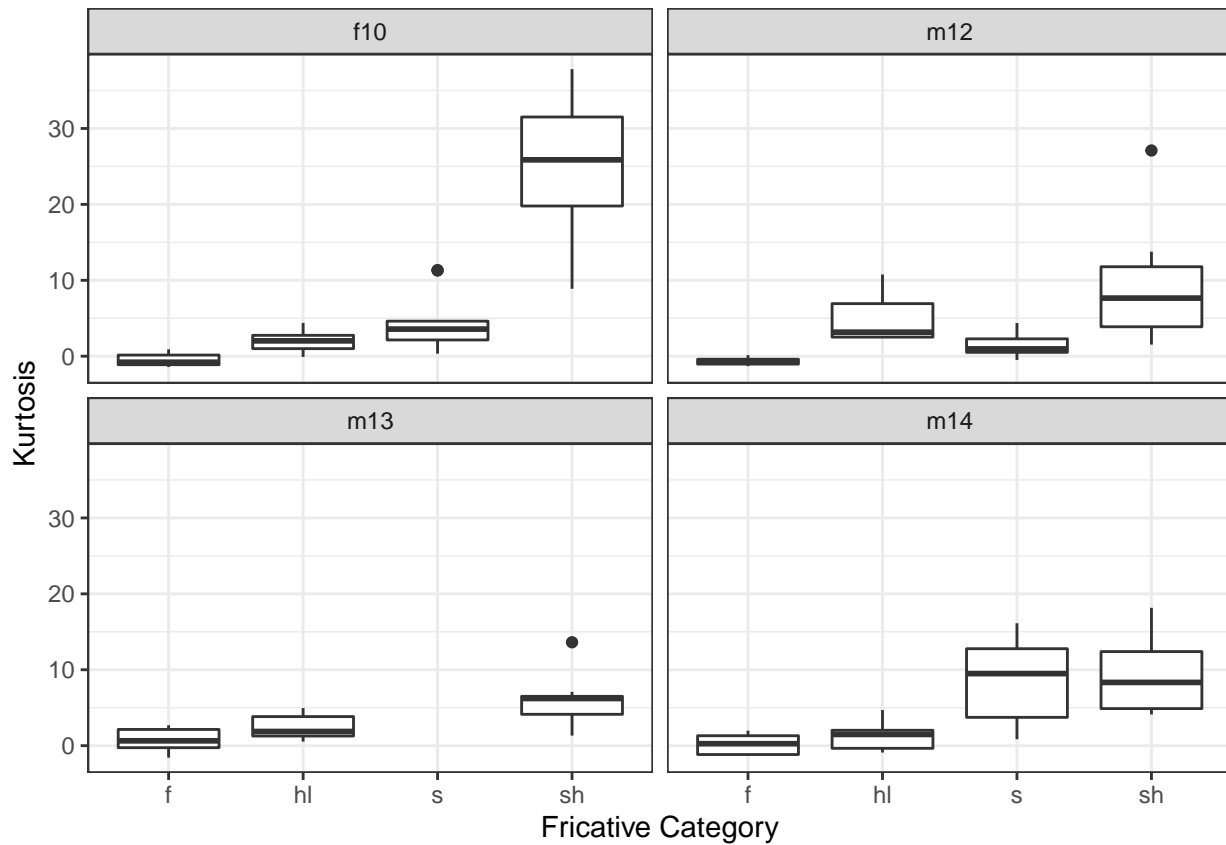
Formants

F1-F3 at onset

```
## # A tibble: 4 x 4
##   seg    mean    sd     n
##   <fct> <dbl> <dbl> <int>
## 1 f      589.  97.5     4
## 2 hl     567.  54.7     4
## 3 s      494.  23.5     3
## 4 sh     540.  28.6     4

## # A tibble: 4 x 4
##   seg    mean    sd     n
##   <fct> <dbl> <dbl> <int>
## 1 f     1190.  88.5     4
## 2 hl    1437. 118.      4
## 3 s     1454.  53.8     3
## 4 sh    1316.  77.4     4

## # A tibble: 4 x 4
##   seg    mean    sd     n
##   <fct> <dbl> <dbl> <int>
## 1 f     2679.  61.2     4
## 2 hl    2699. 135.      4
## 3 s     2893.  30.5     3
## 4 sh    2234.  37.5     4
```

Analysis of formants

```
## Data: dat_all
## Models:
## mod_f1NoInt: f1 ~ seg + foll + (1 | spk)
## mod_f1: f1 ~ seg + foll + seg * foll + (1 | spk)
##             Df    AIC    BIC  logLik deviance  Chisq Chi Df Pr(>Chisq)
## mod_f1NoInt  7 1861.3 1882.4 -923.67   1847.3
## mod_f1      10 1866.0 1896.1 -923.00   1846.0 1.3333      3     0.7212

## Data: dat_all
## Models:
## mod_f1NoFoll: f1 ~ seg + (1 | spk)
## mod_f1NoInt: f1 ~ seg + foll + (1 | spk)
##              Df    AIC    BIC  logLik deviance  Chisq Chi Df Pr(>Chisq)
## mod_f1NoFoll  6 1859.9 1877.9 -923.93   1847.9
## mod_f1NoInt   7 1861.3 1882.4 -923.67   1847.3 0.5362      1      0.464

## Data: dat_all
## Models:
## mod_f1NoSeg: f1 ~ foll + (1 | spk)
## mod_f1NoInt: f1 ~ seg + foll + (1 | spk)
##             Df    AIC    BIC  logLik deviance  Chisq Chi Df Pr(>Chisq)
## mod_f1NoSeg  4 1863.4 1875.5 -927.71   1855.4
## mod_f1NoInt  7 1861.3 1882.4 -923.67   1847.3 8.0926      3    0.04414 *
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

## Linear mixed model fit by REML. t-tests use Satterthwaite's method [
## lmerModLmerTest]
## Formula: f1 ~ seg + (1 | spk)
##    Data: dat_all
##
## REML criterion at convergence: 1814.6
##
## Scaled residuals:
##     Min      1Q  Median      3Q     Max
## -3.8624 -0.5165 -0.1054  0.4482  5.0615
##
## Random effects:
##  Groups   Name        Variance Std.Dev.
##  spk      (Intercept)  4330     65.81
##  Residual             12569    112.11
## Number of obs: 150, groups:  spk, 4
##
## Fixed effects:
##             Estimate Std. Error      df t value Pr(>|t|)
## (Intercept)  587.727     37.249   4.211  15.778 6.63e-05 ***
## seghl        -17.080     24.982 143.096  -0.684  0.49529
## segs         -84.154     28.568 144.362  -2.946  0.00376 **
## segsh        -48.894     24.720 143.476  -1.978  0.04986 *
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Correlation of Fixed Effects:
##       (Intr) seghl  segs
```

```
## seghl -0.323
## segs  -0.293  0.419
## segsh -0.334  0.485  0.450

## $emmeans
##  seg emmean   SE   df lower.CL upper.CL
##  f       588 37.3 4.21      486      689
##  hl      571 37.6 4.35      470      672
##  s       504 39.8 5.43      404      603
##  sh      539 37.2 4.19      437      640
##
## Degrees-of-freedom method: kenward-roger
## Confidence level used: 0.95
##
## $contrasts
##  contrast estimate   SE  df t.ratio p.value
##  f - hl       17.1 25.0 143   0.684  1.0000
##  f - s        84.2 28.7 144   2.935  0.0233
##  f - sh       48.9 24.7 143   1.976  0.3007
##  hl - s       67.1 29.1 144   2.302  0.1367
##  hl - sh      31.8 25.3 144   1.260  1.0000
##  s - sh      -35.3 28.2 144  -1.251  1.0000
##
## Degrees-of-freedom method: kenward-roger
## P value adjustment: bonferroni method for 6 tests
## Data: dat_all
## Models:
## mod_f2NoInt: f2 ~ seg + foll + (1 | spk) + (1 | word)
## mod_f2: f2 ~ seg + foll + seg * foll + (1 | spk) + (1 | word)
##             Df    AIC    BIC  logLik deviance  Chisq Chi Df Pr(>Chisq)
## mod_f2NoInt  8 1999.6 2023.7 -991.78   1983.6
## mod_f2      11 2004.2 2037.3 -991.08   1982.2 1.4077      3     0.7037

## Data: dat_all
## Models:
## mod_f2NoFoll: f2 ~ seg + (1 | spk) + (1 | word)
## mod_f2NoInt: f2 ~ seg + foll + (1 | spk) + (1 | word)
##              Df    AIC    BIC  logLik deviance  Chisq Chi Df Pr(>Chisq)
## mod_f2NoFoll  7 2007.0 2028.0 -996.47   1993.0
## mod_f2NoInt   8 1999.6 2023.7 -991.78   1983.6 9.3863      1   0.002186 **
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

## Data: dat_all
## Models:
## mod_f2NoSeg: f2 ~ foll + (1 | spk) + (1 | word)
## mod_f2NoInt: f2 ~ seg + foll + (1 | spk) + (1 | word)
##             Df    AIC    BIC  logLik deviance  Chisq Chi Df Pr(>Chisq)
## mod_f2NoSeg  5 2021.0 2036.1 -1005.51   2011.0
## mod_f2NoInt  8 1999.6 2023.7  -991.78   1983.6 27.468      3  4.697e-06
##
## mod_f2NoSeg
## mod_f2NoInt ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

```
## Linear mixed model fit by REML. t-tests use Satterthwaite's method [
## lmerModLmerTest]
## Formula: f2 ~ seg + foll + (1 | spk) + (1 | word)
##    Data: dat_all
##
## REML criterion at convergence: 1938
##
## Scaled residuals:
##     Min      1Q  Median      3Q     Max
## -4.7190 -0.4822  0.0506  0.4618  4.6763
##
## Random effects:
##  Groups   Name        Variance Std.Dev.
##  word     (Intercept)     0       0.0
##  spk      (Intercept) 10308     101.5
##  Residual             31306     176.9
## Number of obs: 150, groups:  word, 18; spk, 4
##
## Fixed effects:
##             Estimate Std. Error      df t value Pr(>|t|)
## (Intercept)  1238.57      59.37    4.82  20.863 6.53e-06 ***
## seghl         226.21      39.97  142.21   5.659 8.08e-08 ***
## segs          253.31      45.98  143.45   5.509 1.63e-07 ***
## segsh         144.21      39.87  142.51   3.617 0.000413 ***
## follaa        -97.04      31.65  142.46  -3.066 0.002594 **
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Correlation of Fixed Effects:
##        (Intr) seghl  segs   segsh
## seghl  -0.353
## segs   -0.239  0.372
## segsh  -0.276  0.434  0.472
## follaa -0.231  0.164 -0.197 -0.206
## convergence code: 0
## boundary (singular) fit: see ?isSingular

## $emmeans
##  seg emmean   SE   df lower.CL upper.CL
##  f     1190 58.5 4.10     1029     1351
##  hl    1416 59.5 4.44     1257     1575
##  s     1443 64.6 5.10     1278     1608
##  sh    1334 58.7 4.07     1173     1496
##
## Results are averaged over the levels of: foll
## Degrees-of-freedom method: kenward-roger
## Confidence level used: 0.95
##
## $contrasts
##  contrast estimate   SE   df t.ratio p.value
##  f - hl    -226.2 41.6 6.69 -5.441  0.0067
##  f - s     -253.3 50.5 5.58 -5.013  0.0178
##  f - sh    -144.2 41.9 4.18 -3.443  0.1466
##  hl - s     -27.1 52.6 7.23 -0.515  1.0000
```

```
##  hl - sh      82.0 43.8 5.66  1.872  0.6800
##  s - sh      109.1 48.7 3.88  2.240  0.5443
##
## Results are averaged over the levels of: foll
## Degrees-of-freedom method: kenward-roger
## P value adjustment: bonferroni method for 6 tests

## Data: dat_all
## Models:
## mod_f3NoInt: f3 ~ seg + foll + (1 | spk)
## mod_f3: f3 ~ seg + foll + seg * foll + (1 | spk)
##              Df    AIC    BIC  logLik deviance  Chisq Chi Df Pr(>Chisq)
## mod_f3NoInt  7 2008.0 2029.0 -996.99   1994.0
## mod_f3      10 2006.5 2036.6 -993.23   1986.5 7.5281      3    0.05684 .
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

## Data: dat_all
## Models:
## mod_f3NoFoll: f3 ~ seg + (1 | spk)
## mod_f3NoInt: f3 ~ seg + foll + (1 | spk)
##               Df    AIC    BIC  logLik deviance  Chisq Chi Df Pr(>Chisq)
## mod_f3NoFoll  6 2007.5 2025.5 -997.72   1995.5
## mod_f3NoInt   7 2008.0 2029.0 -996.99   1994.0 1.4678      1     0.2257

## Data: dat_all
## Models:
## mod_f3NoSeg: f3 ~ foll + (1 | spk)
## mod_f3NoInt: f3 ~ seg + foll + (1 | spk)
##              Df    AIC    BIC   logLik deviance  Chisq Chi Df Pr(>Chisq)
## mod_f3NoSeg  4 2144.6 2156.7 -1068.31   2136.6
## mod_f3NoInt  7 2008.0 2029.0  -996.99   1994.0 142.64      3  < 2.2e-16
##
## mod_f3NoSeg
## mod_f3NoInt ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

## Linear mixed model fit by REML. t-tests use Satterthwaite's method [
## lmerModLmerTest]
## Formula: f3 ~ seg + (1 | spk)
##    Data: dat_all
##
## REML criterion at convergence: 1957.5
##
## Scaled residuals:
##     Min      1Q  Median      3Q     Max
## -6.1130 -0.4182  0.0229  0.5036  2.4252
##
## Random effects:
##  Groups   Name        Variance Std.Dev.
##  spk      (Intercept) 28523    168.9
##  Residual             32840    181.2
## Number of obs: 150, groups:  spk, 4
##
## Fixed effects:
```

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```
##              Estimate Std. Error       df t value Pr(>|t|)
## (Intercept) 2675.530      89.040    3.493  30.049 2.42e-05 ***
## seghl         38.205      40.385  143.051   0.946 0.345743
## segs         166.976      46.251  143.624   3.610 0.000422 ***
## segsh       -435.918      39.978  143.213 -10.904  < 2e-16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Correlation of Fixed Effects:
##       (Intr) seghl  segs
## seghl -0.218
## segs  -0.198  0.418
## segsh -0.226  0.485  0.450
##
## $emmeans
##  seg emmean   SE   df lower.CL upper.CL
##  f      2676 89.0 3.48     2413     2938
##  hl     2714 89.4 3.53     2452     2975
##  s      2843 91.9 3.93     2586     3099
##  sh     2240 89.0 3.47     1977     2502
##
## Degrees-of-freedom method: kenward-roger
## Confidence level used: 0.95
##
## $contrasts
##  contrast estimate   SE  df t.ratio p.value
##  f - hl      -38.2 40.4 143  -0.946  1.0000
##  f - s      -167.0 46.3 144  -3.605  0.0026
##  f - sh      435.9 40.0 143  10.899  <.0001
##  hl - s     -128.8 47.1 144  -2.735  0.0421
##  hl - sh     474.1 40.8 143  11.617  <.0001
##  s - sh      602.9 45.6 143  13.235  <.0001
##
## Degrees-of-freedom method: kenward-roger
## P value adjustment: bonferroni method for 6 tests
```
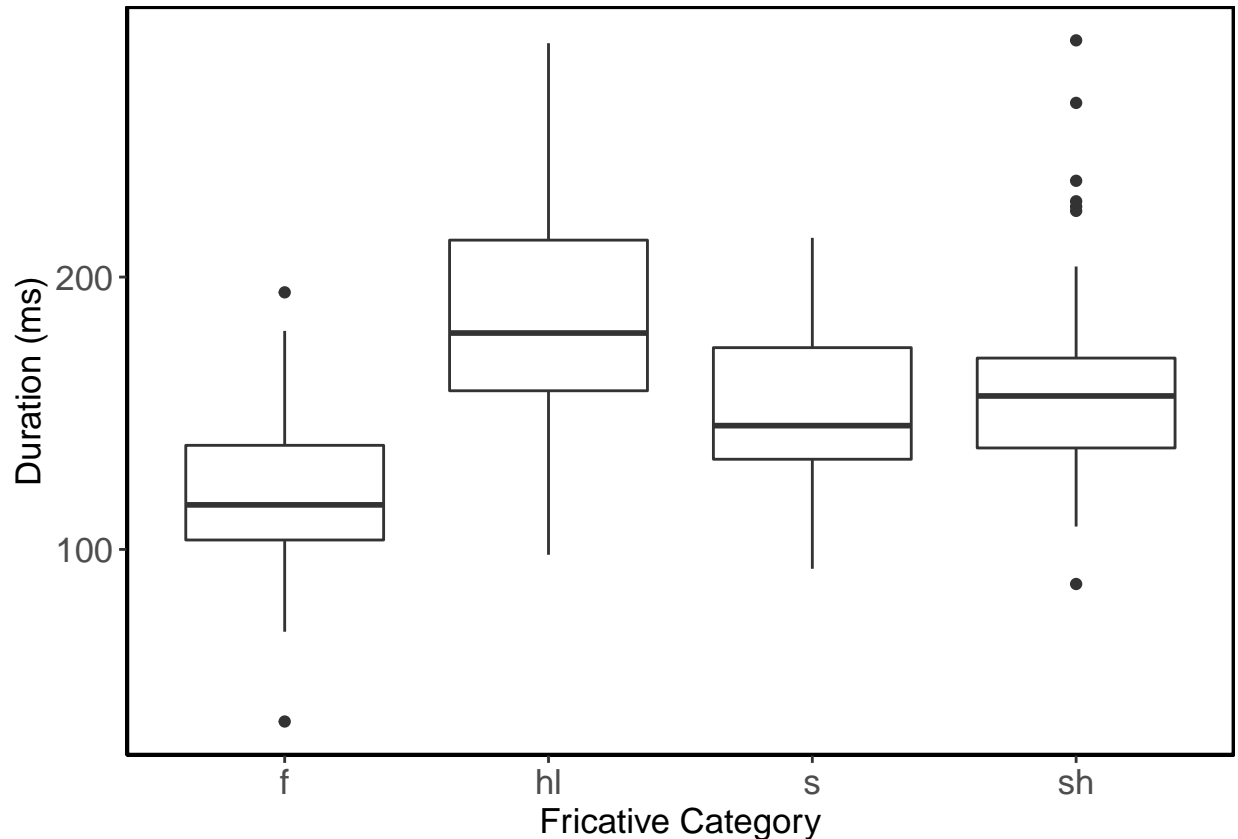
Duration

Next we turn to examine whether duration distinguishes amongst the four fricatives.

```
## # A tibble: 4 x 4
##   seg    mean    sd     n
##   <fct> <dbl> <dbl> <int>
## 1 f      122.  5.69     4
## 2 hl     181. 11.0      4
## 3 s      153.  6.66     3
## 4 sh     163. 15.8      4
```

Duration measures of fricatives were first log-transformed for analysis. These were then submitted to a LME with log-duration as the DV and Segment (ref = /f/) as a fixed factor. The final model included a random intercept for speaker and word. A more complex model did not converge. Significance of Segment was assessed using model comparison, and any post-hoc planned pairwise comparisons were conducted with bonferroni's correction.

```
dat_all$logDur <- log10(dat_all$totalDur)


mod_logDur <- lmer(logDur ~ seg + foll + seg*foll+
                     (1|spk)+(1|word),
                   data = dat_all)

mod_logDurNoInt <- lmer(logDur ~ seg + foll +
                     (1|spk)+(1|word),
                   data = dat_all)

anova(mod_logDur,mod_logDurNoInt)
```

```
## refitting model(s) with ML (instead of REML)

## Data: dat_all
## Models:
## mod_logDurNoInt: logDur ~ seg + foll + (1 | spk) + (1 | word)
## mod_logDur: logDur ~ seg + foll + seg * foll + (1 | spk) + (1 | word)
##                 Df     AIC     BIC logLik deviance  Chisq Chi Df
## mod_logDurNoInt  8 -246.43 -222.35 131.22  -262.43
## mod_logDur      11 -247.28 -214.16 134.64  -269.28 6.8425      3
```

```
##                 Pr(>Chisq)
## mod_logDurNoInt
## mod_logDur        0.07709 .
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

```r
mod_logDurNoFoll <- lmer(logDur ~ seg +
                    (1|spk)+(1|word) ,
                data = dat_all)

mod_logDurNoSeg <- lmer(logDur ~ foll +
                    (1|spk)+(1|word),
                data = dat_all)

anova(mod_logDurNoInt,mod_logDurNoFoll)
```

```
## refitting model(s) with ML (instead of REML)
```

```
## Data: dat_all
## Models:
## mod_logDurNoFoll: logDur ~ seg + (1 | spk) + (1 | word)
## mod_logDurNoInt: logDur ~ seg + foll + (1 | spk) + (1 | word)
##                  Df     AIC     BIC logLik deviance  Chisq Chi Df
## mod_logDurNoFoll  7 -248.31 -227.24 131.16  -262.31
## mod_logDurNoInt   8 -246.43 -222.35 131.22  -262.43 0.1203      1
##                 Pr(>Chisq)
## mod_logDurNoFoll
## mod_logDurNoInt     0.7287
```

```r
anova(mod_logDurNoInt,mod_logDurNoSeg)
```

```
## refitting model(s) with ML (instead of REML)
```

```
## Data: dat_all
## Models:
## mod_logDurNoSeg: logDur ~ foll + (1 | spk) + (1 | word)
## mod_logDurNoInt: logDur ~ seg + foll + (1 | spk) + (1 | word)
##                 Df     AIC     BIC logLik deviance  Chisq Chi Df
## mod_logDurNoSeg  5 -235.48 -220.43 122.74  -245.48
## mod_logDurNoInt  8 -246.43 -222.35 131.22  -262.43 16.956      3
##                 Pr(>Chisq)
## mod_logDurNoSeg
## mod_logDurNoInt  0.0007216 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

```r
summary(mod_logDurNoFoll)
```

```
## Linear mixed model fit by REML. t-tests use Satterthwaite's method [
## lmerModLmerTest]
## Formula: logDur ~ seg + (1 | spk) + (1 | word)
##    Data: dat_all
##
## REML criterion at convergence: -242.4
##
## Scaled residuals:
##      Min       1Q   Median       3Q      Max
```

```
## -3.04442 -0.61414  0.01085   0.62671   3.02273
##
## Random effects:
##  Groups    Name         Variance Std.Dev.
##  word      (Intercept) 0.005644 0.07513
##  spk       (Intercept) 0.004052 0.06365
##  Residual               0.008212 0.09062
## Number of obs: 150, groups:  word, 18; spk, 4
##
## Fixed effects:
##             Estimate Std. Error      df t value Pr(>|t|)
## (Intercept)  2.01882    0.04909 6.19725  41.128 8.62e-09 ***
## seghl        0.21405    0.05366 3.44083   3.989   0.0218 *
## segs         0.18291    0.05857 3.91990   3.123   0.0364 *
## segsh        0.17144    0.05921 2.95528   2.896   0.0639 .
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Correlation of Fixed Effects:
##       (Intr) seghl  segs
## seghl -0.528
## segs  -0.485  0.437
## segsh -0.481  0.438  0.403
```

```r
emmeans(mod_logDurNoFoll, pairwise ~ seg, adjust = "bonferroni")
```

```
## $emmeans
##  seg emmean     SE   df lower.CL upper.CL
##  f     2.02 0.0494 11.1     1.91     2.13
##  hl    2.23 0.0503 11.0     2.12     2.34
##  s     2.20 0.0555 14.0     2.08     2.32
##  sh    2.19 0.0559 11.5     2.07     2.31
##
## Degrees-of-freedom method: kenward-roger
## Confidence level used: 0.95
##
## $contrasts
##  contrast estimate     SE   df t.ratio p.value
##  f - hl    -0.2141 0.0541 12.9  -3.954  0.0101
##  f - s     -0.1829 0.0591 14.5  -3.095  0.0458
##  f - sh    -0.1714 0.0595 11.2  -2.881  0.0885
##  hl - s     0.0311 0.0601 13.8   0.518  1.0000
##  hl - sh    0.0426 0.0602 10.6   0.708  1.0000
##  s - sh     0.0115 0.0646 11.8   0.177  1.0000
##
## Degrees-of-freedom method: kenward-roger
## P value adjustment: bonferroni method for 6 tests
```
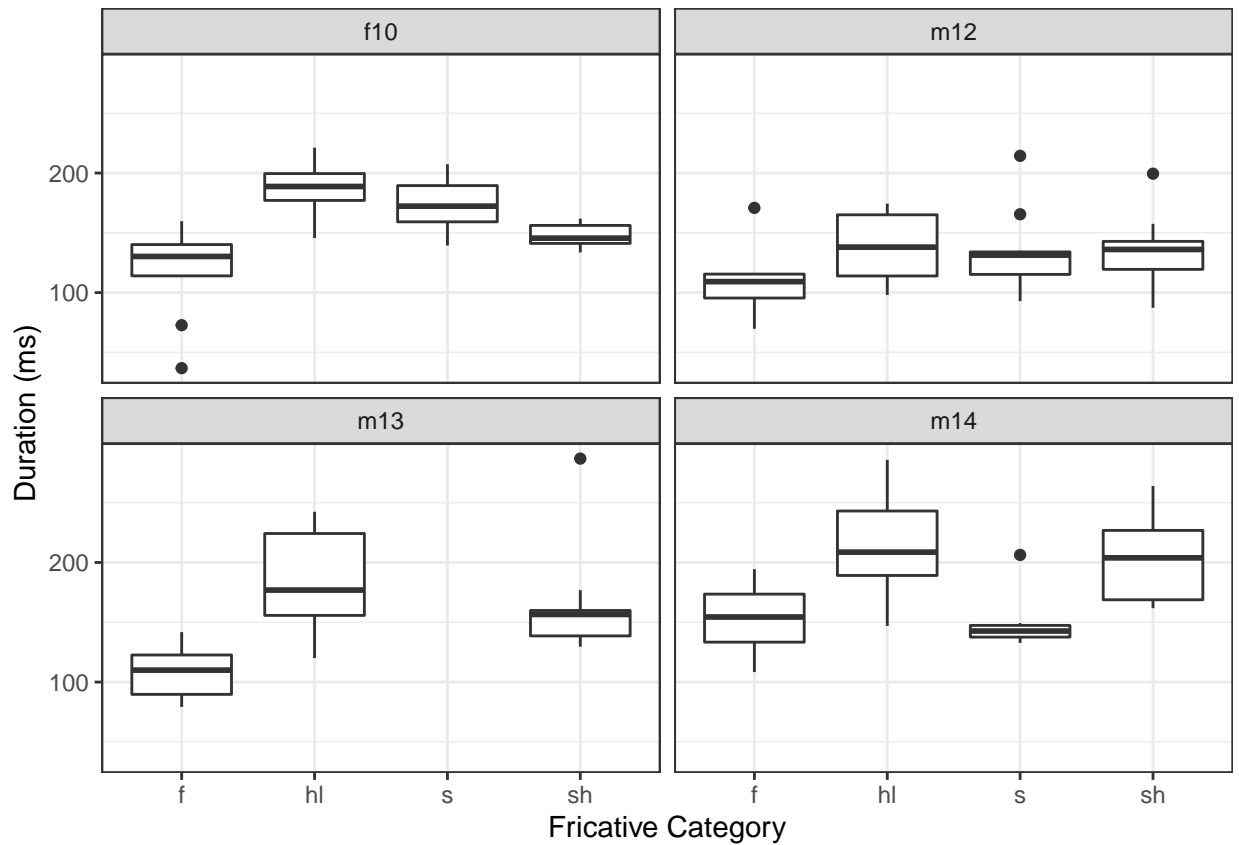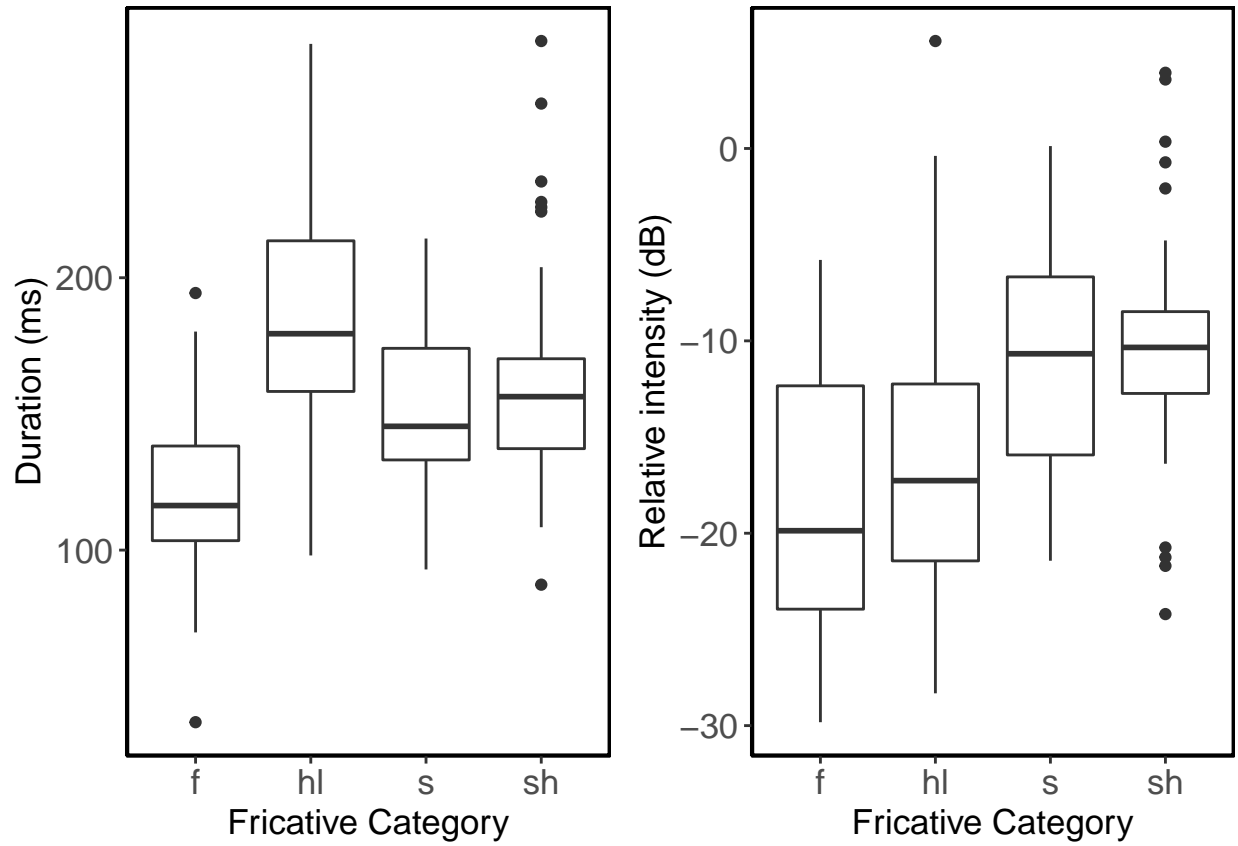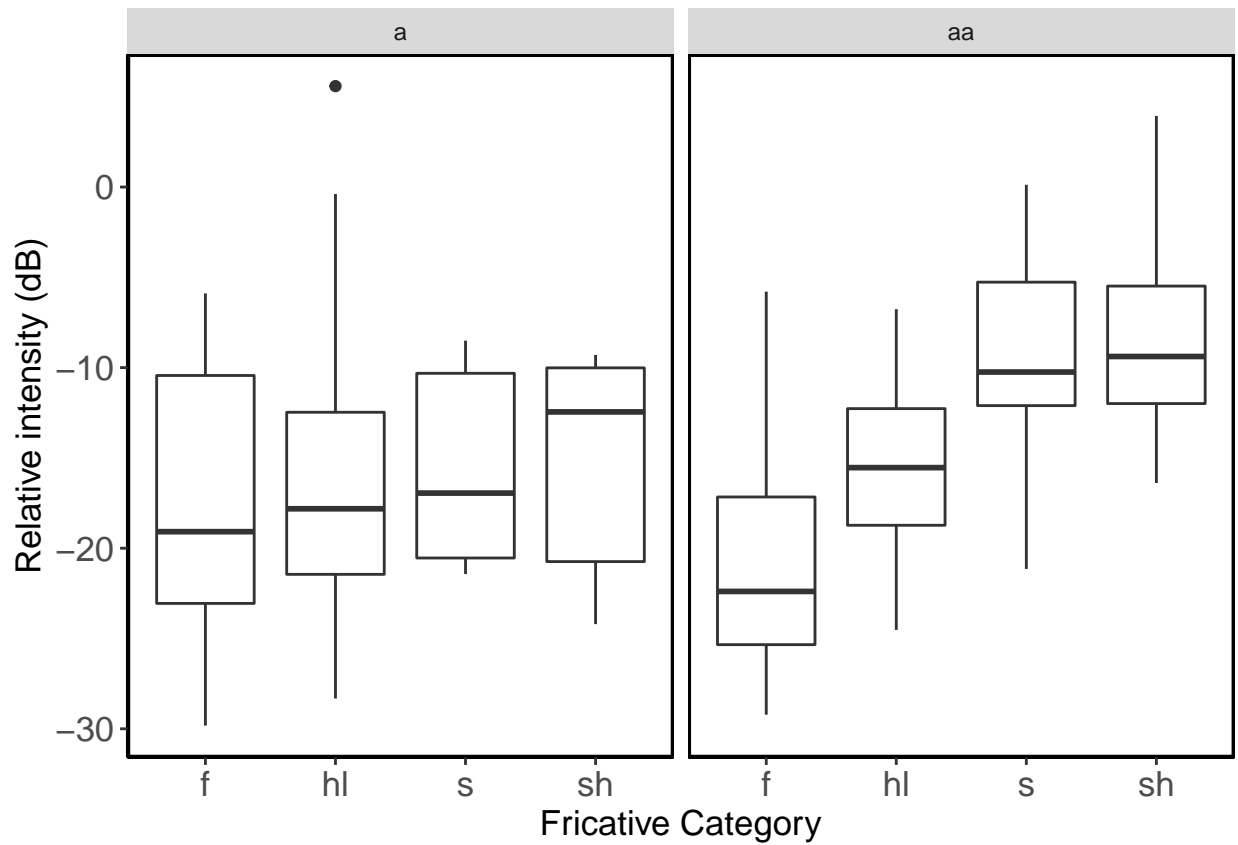
By speaker - plots
```

## Relative intensity

The final measure we examine is relative intensity. Here we measure the difference in intensity measured from the middle 50% of the following vowel and the middle 50% of the fricative (ie. int_Vowel - int_Fric). A larger negative value indicates a larger drop in intensity between vowel and fricative.

```
## # A tibble: 4 x 4
##   seg    mean    sd     n
##   <fct> <dbl> <dbl> <int>
## 1 f     -18.2 0.571     4
## 2 hl    -15.1 2.03      4
## 3 s     -10.9 2.10      3
## 4 sh    -10.4 1.72      4
```

Relative intensity measures were submitted to a LME with relative intensity as the DV and Segment (ref = /f/) as a fixed factor. The final model included a random intercept for speaker and word. A more complex model did not converge. Significance of Segment was assessed using model comparison, and any post-hoc planned pairwise comparisons were conducted with bonferroni's correction.

```
mod_DiffAmp <- lmer(DiffAmp ~ seg + foll + seg*foll+
                    (1|spk)+(1|word),
                data = dat_all)

mod_DiffAmpNoInt <- lmer(DiffAmp ~ seg + foll +
                    (1|spk)+(1|word),
                data = dat_all)

anova(mod_DiffAmp,mod_DiffAmpNoInt)
```

```
## refitting model(s) with ML (instead of REML)

## Data: dat_all
## Models:
## mod_DiffAmpNoInt: DiffAmp ~ seg + foll + (1 | spk) + (1 | word)
## mod_DiffAmp: DiffAmp ~ seg + foll + seg * foll + (1 | spk) + (1 | word)
##                   Df    AIC    BIC  logLik deviance  Chisq Chi Df
## mod_DiffAmpNoInt   8 980.98 1005.1 -482.49   964.98
## mod_DiffAmp       11 974.31 1007.4 -476.16   952.31 12.669      3
##                   Pr(>Chisq)
## mod_DiffAmpNoInt
## mod_DiffAmp         0.005411 **
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

```
summary(mod_DiffAmp)
```

```
## Linear mixed model fit by REML. t-tests use Satterthwaite's method [
## lmerModLmerTest]
## Formula: DiffAmp ~ seg + foll + seg * foll + (1 | spk) + (1 | word)
##    Data: dat_all
##
## REML criterion at convergence: 927.8
##
## Scaled residuals:
##     Min      1Q  Median      3Q     Max
## -2.56824 -0.63318 -0.04749  0.66333  2.96374
##
## Random effects:
##  Groups   Name        Variance Std.Dev.
##  word     (Intercept)  3.535   1.880
##  spk      (Intercept) 12.721   3.567
##  Residual             31.527   5.615
## Number of obs: 150, groups:  word, 18; spk, 4
##
## Fixed effects:
##             Estimate Std. Error      df t value Pr(>|t|)
## (Intercept)  -17.137      2.414   6.974  -7.099 0.000197 ***
## seghl          1.248      2.211   7.039   0.565 0.589851
## segs          -1.452      2.834  16.182  -0.512 0.615249
## segsh          2.347      2.936   5.175   0.799 0.459226
```

```
## follaa           -2.732      2.713    5.513  -1.007 0.356078
## seghl:follaa    3.174      4.112    6.072   0.772 0.469162
## segs:follaa    10.909      4.237    6.614    2.574 0.038609 *
## segsh:follaa    9.277      4.044    4.835    2.294 0.072069 .
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Correlation of Fixed Effects:
##             (Intr) seghl  segs    segsh  follaa sghl:f sgs:fl
## seghl       -0.494
## segs        -0.382  0.408
## segsh       -0.374  0.406  0.317
## follaa      -0.404  0.445  0.337  0.333
## seghl:folla  0.268 -0.544 -0.222 -0.222 -0.667
## segs:follaa  0.255 -0.281 -0.661 -0.212 -0.640  0.430
## segsh:folla  0.271 -0.299 -0.227 -0.726 -0.672  0.449  0.431
```

```r
emmeans(mod_DiffAmp, pairwise ~ seg | foll, adjust = "bonferroni")
```

```
## $emmeans
## foll = a:
##  seg emmean   SE     df lower.CL upper.CL
##  f   -17.14 2.47   6.73    -23.0   -11.26
##  hl  -15.89 2.37   6.08    -21.7   -10.11
##  s   -18.59 2.95  14.27    -24.9   -12.26
##  sh  -14.79 3.02   6.03    -22.2    -7.40
##
## foll = aa:
##  seg emmean   SE     df lower.CL upper.CL
##  f   -19.87 2.91   6.37    -26.9   -12.86
##  hl  -15.45 3.21   7.67    -22.9    -7.98
##  s   -10.41 2.91   5.14    -17.8    -2.99
##  sh   -8.25 2.51   5.84    -14.4    -2.05
##
## Degrees-of-freedom method: kenward-roger
## Confidence level used: 0.95
##
## $contrasts
## foll = a:
##  contrast estimate   SE    df t.ratio p.value
##  f - hl      -1.25 2.30  5.63 -0.542  1.0000
##  f - s        1.45 2.89 13.13  0.502  1.0000
##  f - sh      -2.35 2.98  4.13 -0.788  1.0000
##  hl - s       2.70 2.85 13.23  0.948  1.0000
##  hl - sh     -1.10 2.90  3.93 -0.379  1.0000
##  s - sh      -3.80 3.39  7.07 -1.122  1.0000
##
## foll = aa:
##  contrast estimate   SE    df t.ratio p.value
##  f - hl      -4.42 3.53  4.50 -1.251  1.0000
##  f - s       -9.46 3.27  3.27 -2.894  0.3397
##  f - sh     -11.62 2.90  3.61 -4.006  0.1175
##  hl - s      -5.03 3.52  3.81 -1.432  1.0000
##  hl - sh     -7.20 3.20  4.49 -2.250  0.4823
##  s - sh      -2.17 2.90  2.96 -0.748  1.0000
```

```
##
## Degrees-of-freedom method: kenward-roger
## P value adjustment: bonferroni method for 6 tests
```

By-speaker plots
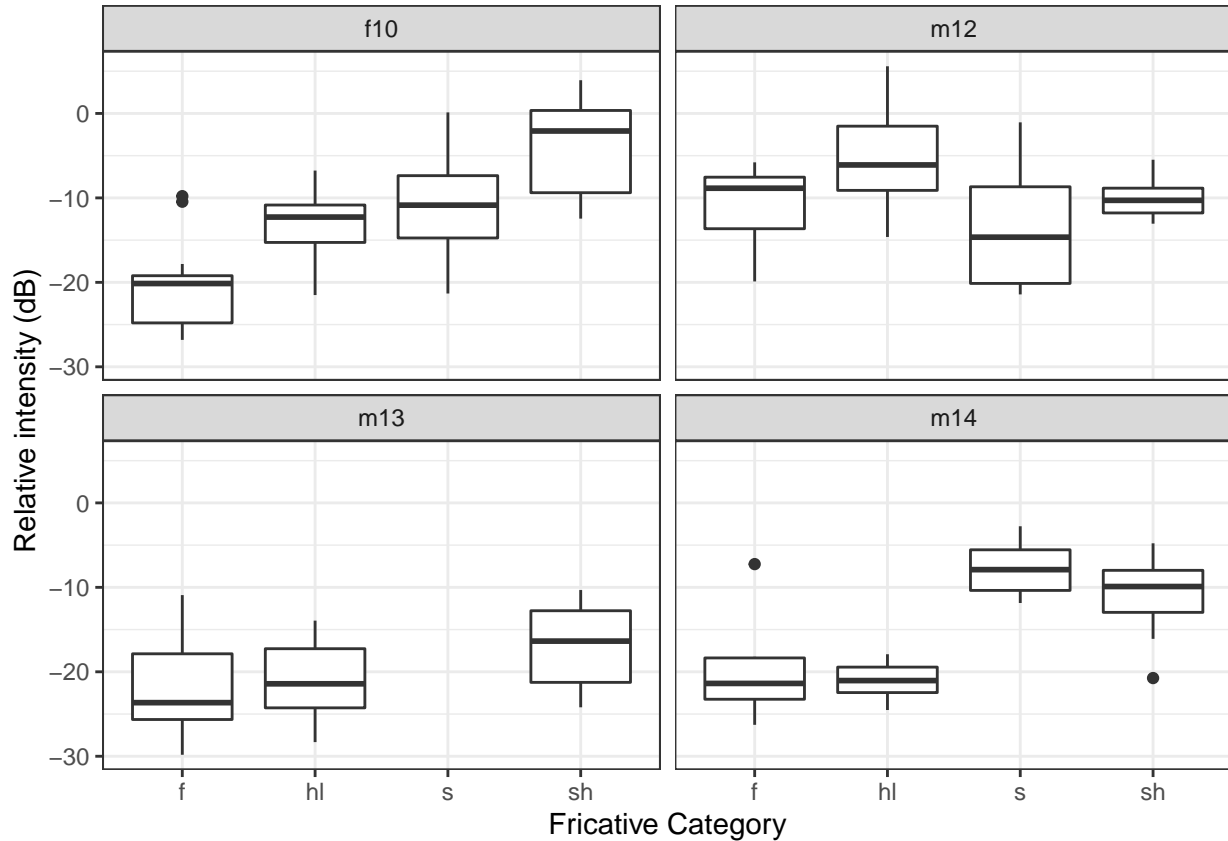
Part II: Exploring lateral fricative in more detail

Duration of lateral fricative vs. other lateral clusters.

```
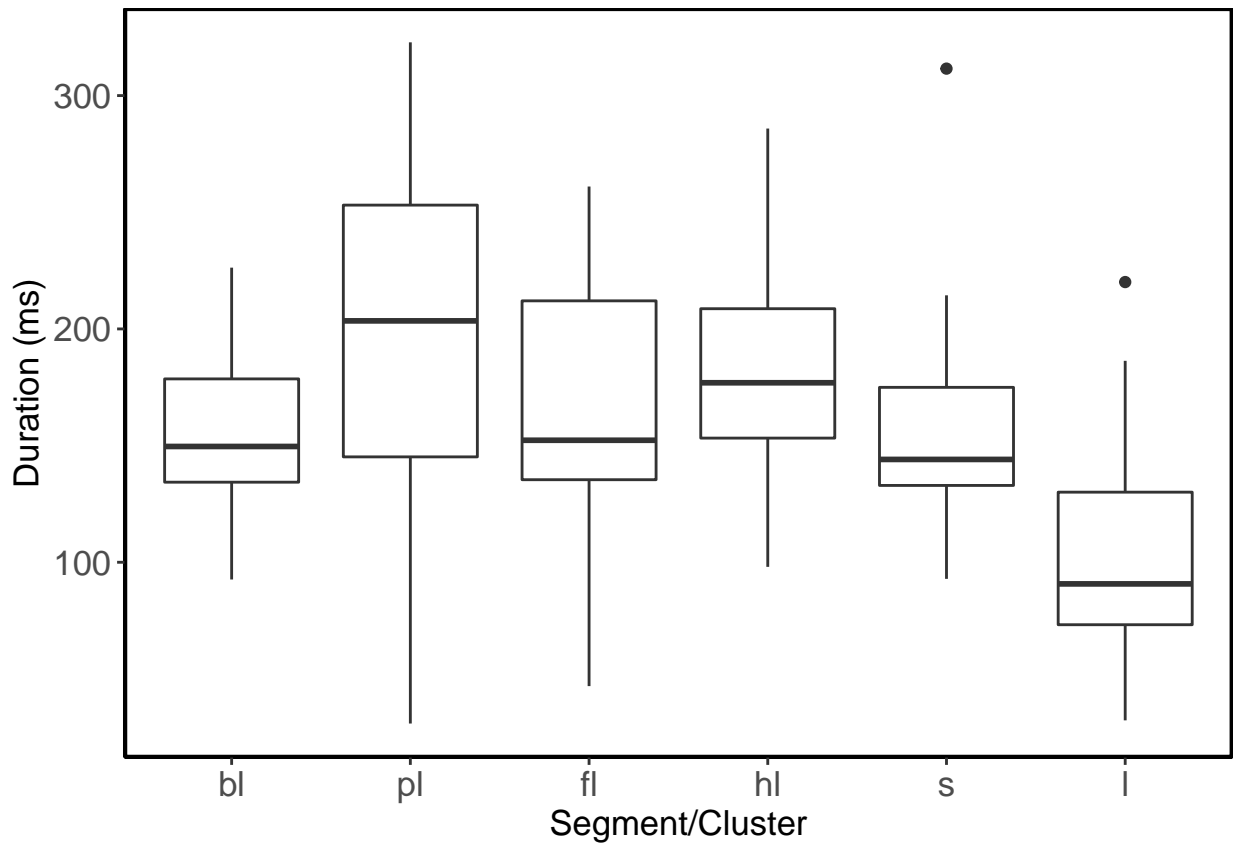##       foll
## target  a aa  e  o
##     bl 14  9  0  0
##     fl 32  0  0  0
##     hl 30  9  4  2
##      l 38  0  0  0
##     pl 21 13  0  0
##      s 11 19  0  0
##
## , , spk = f10
##
##       foll
## target  a aa  e  o
##     bl  5  4  0  0
##     fl 17  0  0  0
##     hl  7  4  0  2
##      l 10  0  0  0
```

```
##     pl 6  2  0  0
##      s 4  7  0  0
##
## , , spk = m12
##
##        foll
## target  a aa  e  o
##     bl 2  5  0  0
##     fl 8  0  0  0
##     hl 6  0  2  0
##      l 8  0  0  0
##     pl 1  6  0  0
##      s 4  5  0  0
##
## , , spk = m13
##
##        foll
## target  a aa  e  o
##     bl 4  0  0  0
##     fl 4  0  0  0
##     hl 11  2  2  0
##      l 8  0  0  0
##     pl 7  2  0  0
##      s 3  0  0  0
##
## , , spk = m14
##
##        foll
## target  a aa  e  o
##     bl 3  0  0  0
##     fl 3  0  0  0
##     hl 6  3  0  0
##      l 12  0  0  0
##     pl 7  3  0  0
##      s 0  7  0  0
```

Histogram of dur_clust_hl$totalDur
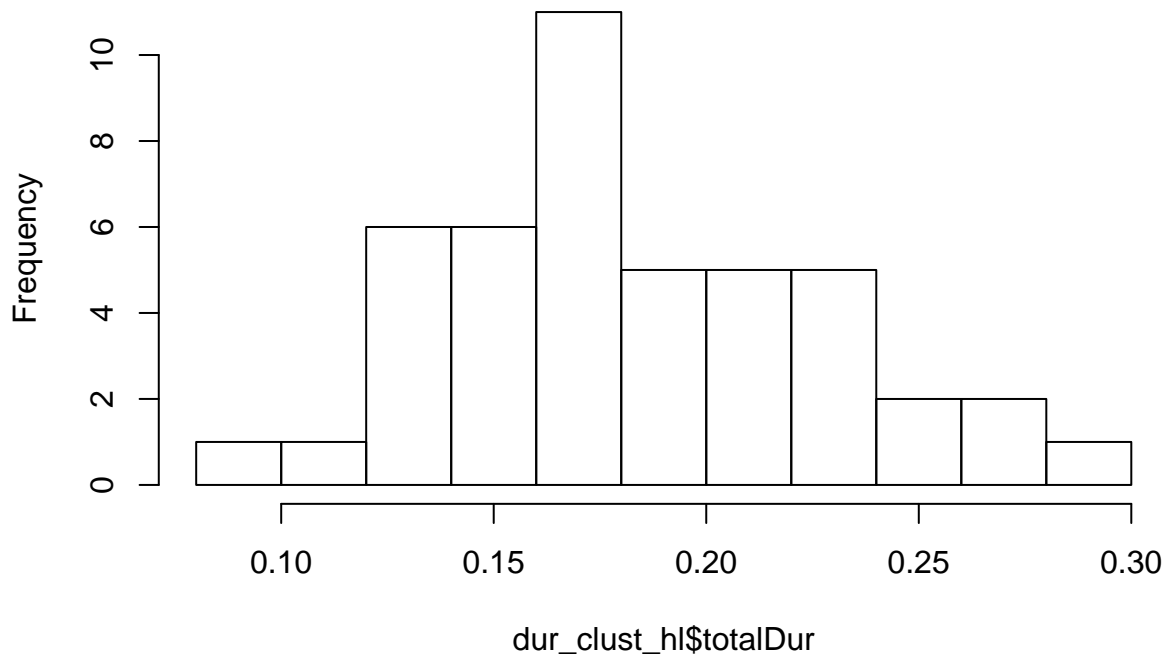
Proportion of pre-voicing

The following plots show the proportion of pre-voicing in lateral clusters and the lateral fricative. We also plot the raw values (duration in ms.) below.

```
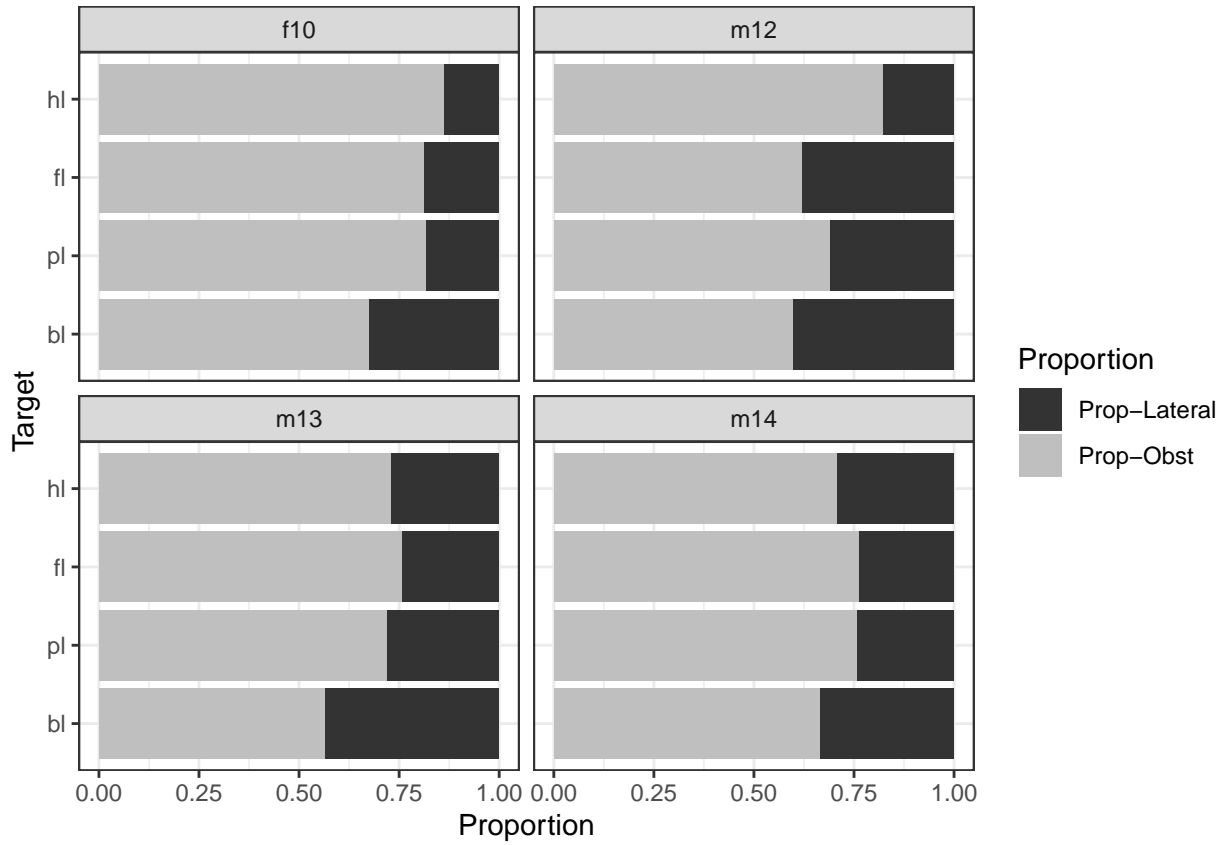## # A tibble: 12 x 5
## # Groups:   target [6]
##    target prop     mean.dur sd.dur n.dur
##    <fct>  <chr>       <dbl>  <dbl> <int>
##  1 bl     propLat      37.0   8.30    23
##  2 bl     propObst     63.0   8.30    23
##  3 fl     propLat      24.8  15.6     32
##  4 fl     propObst     75.2  15.6     32
##  5 hl     propLat      20.0  10.3     63
##  6 hl     propObst     80.0  10.3     63
##  7 l      propLat     100     0       38
##  8 l      propObst      0     0       38
##  9 pl     propLat      25.4  15.5     34
## 10 pl     propObst     74.6  15.5     34
## 11 s      propLat       0     0       47
## 12 s      propObst    100     0       47
```
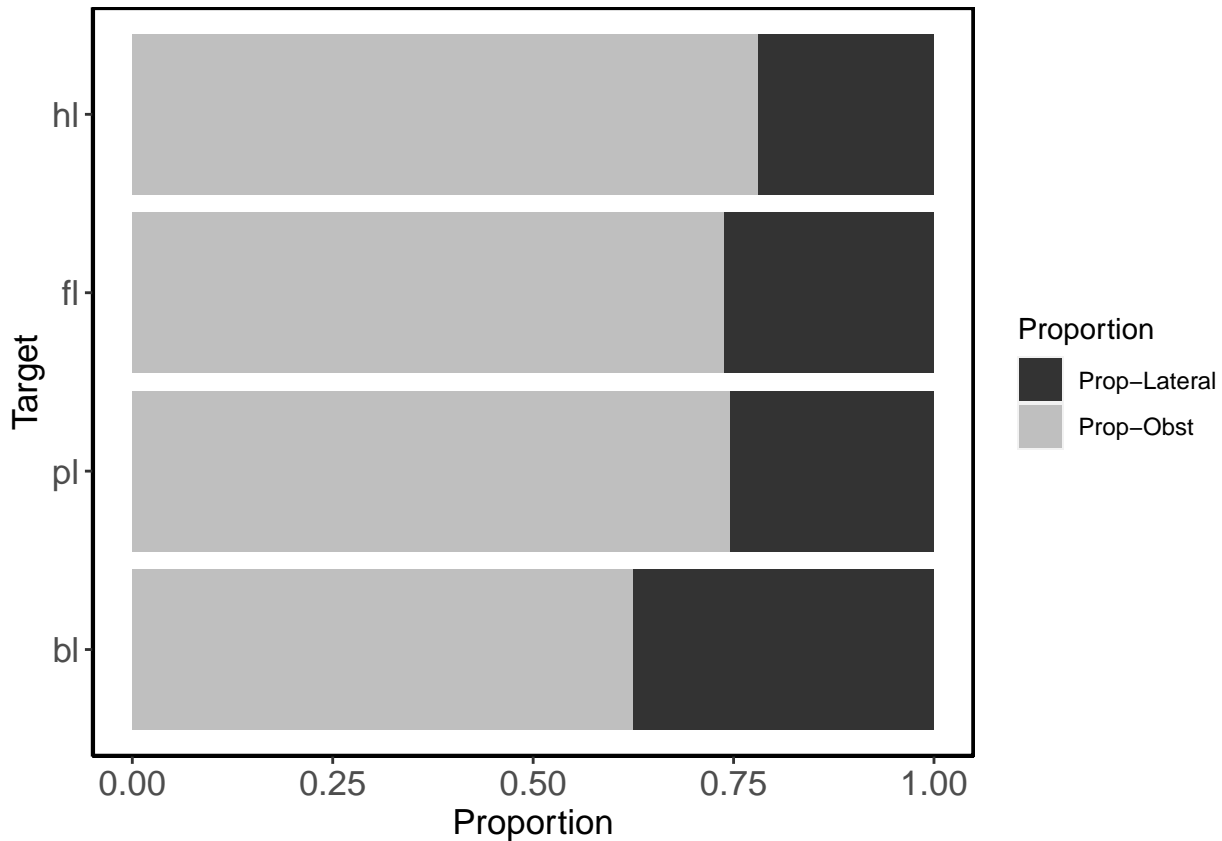
```
## # A tibble: 8 x 5
## # Groups:   target [4]
##   target prop   mean.dur sd.dur n.dur
##   <fct>  <chr>     <dbl>  <dbl> <int>
## 1 bl     latDur   0.0571 0.0143    23
## 2 bl     obstDur  0.0995 0.0287    23
## 3 fl     latDur   0.0385 0.0182    32
## 4 fl     obstDur  0.129  0.0530    32
## 5 hl     latDur   0.0418 0.0222    45
## 6 hl     obstDur  0.141  0.0317    45
## 7 pl     latDur   0.0469 0.0178    34
## 8 pl     obstDur  0.156  0.0591    34
```
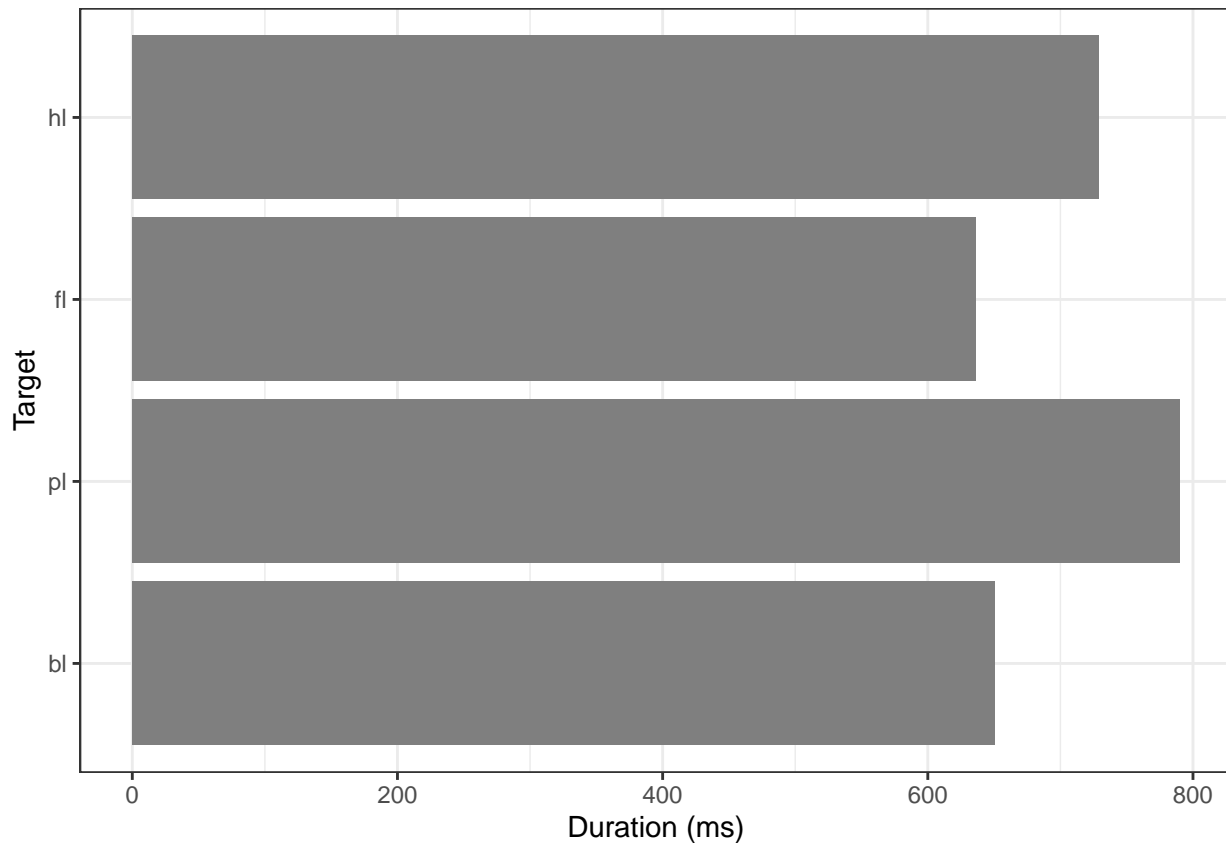
Possible positional effects

We examine whether the rate of pre-voicing and proportion of pre-voicing differ by position for the lateral fricative. Here the number of medial tokens is small, so this represents an exploratory analysis.

```
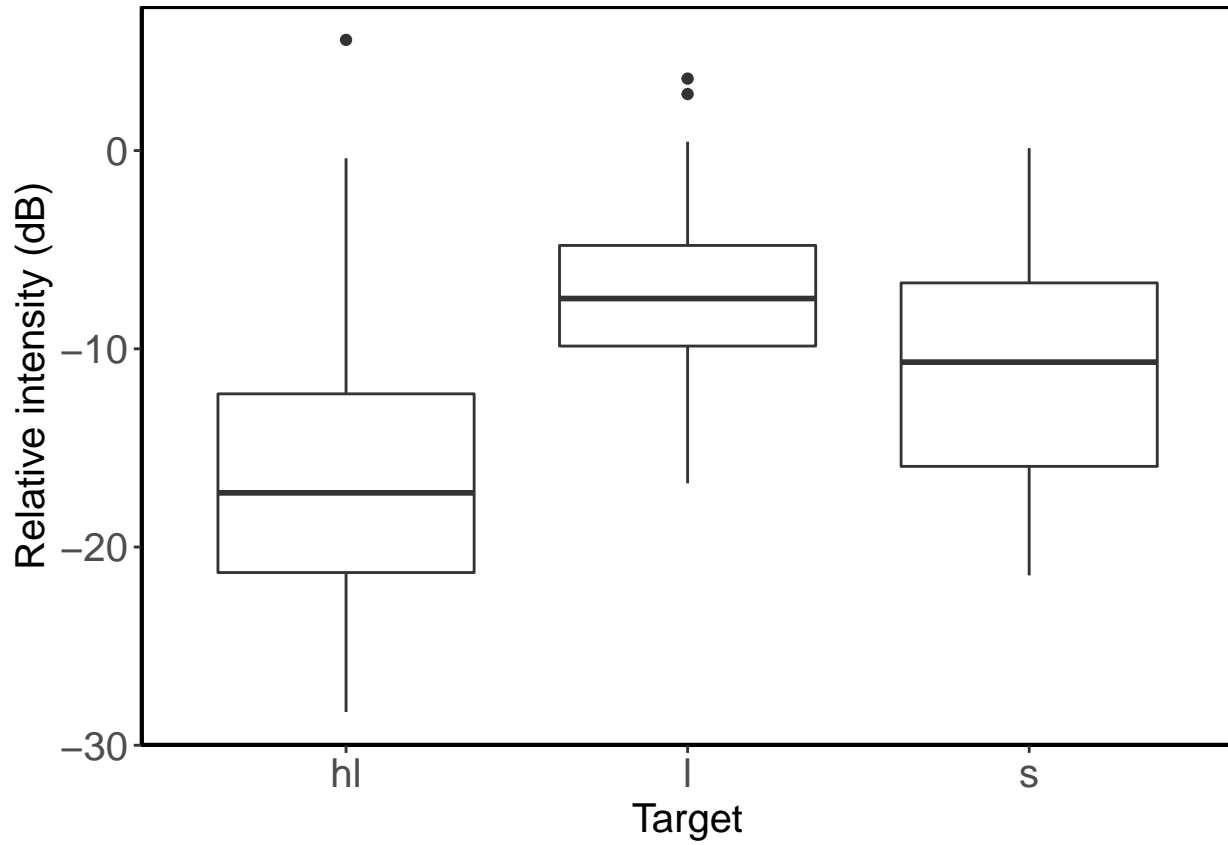##   pos N  Y       prop
## 1  in 2 43 0.9555556
## 2 mid 6 12 0.6666667

## # A tibble: 4 x 5
## # Groups:   pos [2]
##   pos   prop    mean.dur sd.dur n.dur
##   <fct> <chr>      <dbl>  <dbl> <int>
## 1 in    propLat     22.1   8.73    45
## 2 in    propObst    77.9   8.73    45
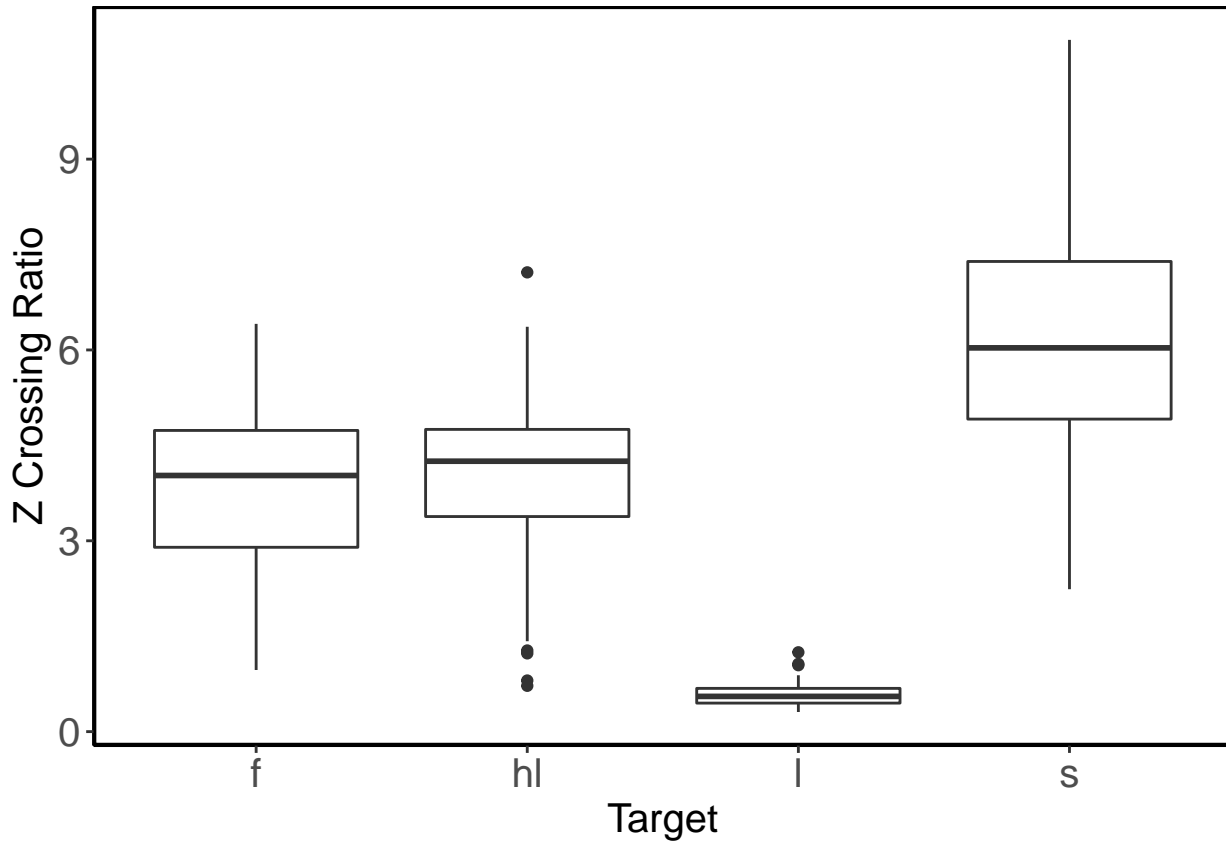## 3 mid   propLat     15.0  12.2     18
## 4 mid   propObst    85.0  12.2     18
```
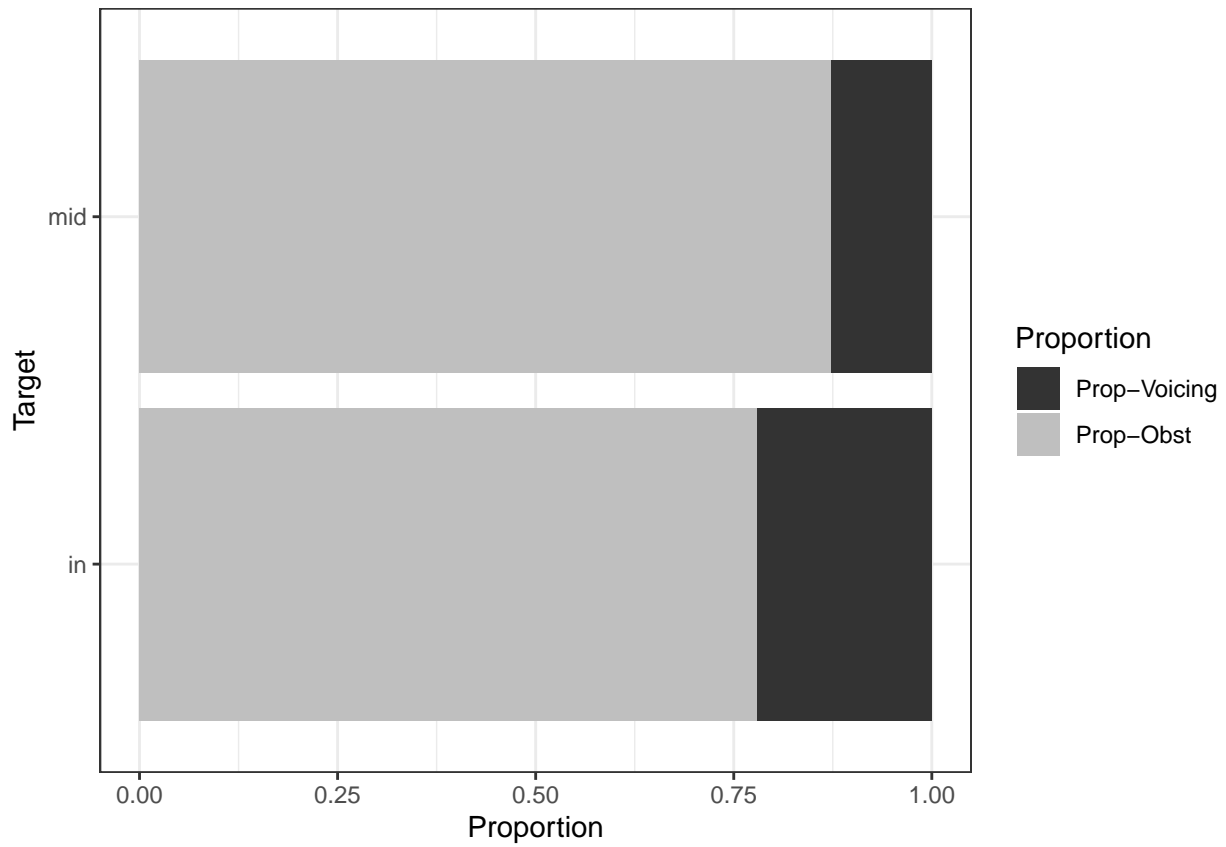
Relative Intensity

Next, we compare the relative intensity of the lateral fricative against /l/ and /s/.

Zero-crossings

Finally, we compare the zero-crossing ratios of the lateral fricative against /l/ and /s/.

```
## Data: z_crs
## Models:
## mod_zC_noT: zRatio ~ 1 + (1 | spk) + (1 | word)
## mod_zC: zRatio ~ target + (1 | spk) + (1 | word)
##             Df    AIC    BIC  logLik deviance  Chisq Chi Df Pr(>Chisq)
## mod_zC_noT  4 553.53 565.80 -272.76   545.53
## mod_zC      7 523.26 544.74 -254.63   509.26 36.265      3  6.582e-08 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

## Linear mixed model fit by REML. t-tests use Satterthwaite's method [
## lmerModLmerTest]
## Formula: zRatio ~ target + (1 | spk) + (1 | word)
##    Data: z_crs
##
## REML criterion at convergence: 508.8
##
## Scaled residuals:
##      Min       1Q   Median       3Q      Max
## -2.27730 -0.56774 -0.02068  0.53228  3.05782
##
## Random effects:
##  Groups   Name        Variance Std.Dev.
##  word     (Intercept) 0.4994   0.7067
##  spk      (Intercept) 0.4845   0.6961
##  Residual             1.1678   1.0807
## Number of obs: 159, groups:  word, 23; spk, 4
```

```
##
## Fixed effects:
##              Estimate Std. Error      df t value Pr(>|t|)
## (Intercept)    3.6948     0.4741  8.0976   7.793 4.93e-05 ***
## targethl       0.2296     0.4618 15.0271   0.497 0.626285
## targetl       -3.1623     0.5193 13.1674  -6.090 3.64e-05 ***
## targets        2.2351     0.5417 15.0951   4.126 0.000887 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Correlation of Fixed Effects:
##          (Intr) trgthl targtl
## targethl -0.469
## targetl  -0.424  0.429
## targets  -0.401  0.407  0.366

## $emmeans
##  target emmean    SE    df lower.CL upper.CL
##  f       3.695 0.476  8.14     2.60     4.79
##  hl      3.924 0.484  8.54     2.82     5.03
##  l       0.533 0.536 10.75    -0.65     1.71
##  s       5.930 0.562 12.62     4.71     7.15
##
## Degrees-of-freedom method: kenward-roger
## Confidence level used: 0.95
##
## $contrasts
##  contrast estimate    SE   df t.ratio p.value
##  f - hl      -0.23 0.465 17.4  -0.493  1.0000
##  f - l        3.16 0.523 15.3   6.050  0.0001
##  f - s       -2.24 0.546 17.5  -4.093  0.0043
##  hl - l       3.39 0.530 15.0   6.405  0.0001
##  hl - s      -2.01 0.555 17.3  -3.615  0.0125
##  l - s       -5.40 0.602 15.5  -8.972  <.0001
##
## Degrees-of-freedom method: kenward-roger
## P value adjustment: bonferroni method for 6 tests
```