Vowel duration and tongue root advancement in Italian and Polish

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1 Import data

`tongues` contains splines coordinates at maximum displacement, `tongues_clos` has splines coordinates at acoustic closure, and `vowels` has durational data.

```
languages <- read_csv("data/languages.csv")
```

```
## Parsed with column specification:
## cols(
##   speaker = col_character(),
##   language = col_character()
## )
```

```
words <- read_csv("data/nonce.csv")
```

```
## Parsed with column specification:
## cols(
##   item = col_integer(),
##   word = col_character(),
##   ipa = col_character(),
##   c1 = col_character(),
##   c1phonation = col_character(),
##   vowel = col_character(),
##   anteropost = col_character(),
##   height = col_character(),
##   c2 = col_character(),
##   c2phonation = col_character(),
##   c2place = col_character(),
##   language = col_character()
## )
```

```
columns <- c(
    "speaker",
    "seconds",
    "rec.date",
    "prompt",
    "label",
    "TT.displacement.sm",
    "TT.velocity",
    "TT.velocity.abs",
    "TD.displacement.sm",
    "TD.velocity",
    "TD.velocity.abs"
)

aaa_files <- list.files(
```

```
    path = "./data/tongue",
    pattern = "*-tongue-cart.tsv",
    full.names = TRUE
)

tongues <- read_aaa(
    aaa_files,
    columns,
    na.rm = TRUE
) %>%
    mutate(word = word(prompt, 2)) %>%
    left_join(y = languages) %>%
    left_join(y = words) %>%
    mutate_if(is.character, as.factor) %>%
    group_by(speaker) %>%
    mutate(
        X.re = rescale(X),
        Y.re = rescale(Y)
    ) %>%
    ungroup() %>%
    mutate(
        vowel.ord = ordered(vowel, levels = c("a", "o", "u")),
        c2place.ord = ordered(c2place, levels = c("coronal", "velar")),
        c2phonation.ord = ordered(c2phonation, levels = c("voiceless", "voiced"))
    ) %>%
    filter(label %in% c("max_TT", "max_TD"), vowel != "u") %>%
    arrange(rec.date, fan.line) %>%
    create_event_start("rec.date")
```

```
## Parsed with column specification:
## cols(
##   .default = col_double(),
##   speaker = col_character(),
##   rec.date = col_character(),
##   prompt = col_character(),
##   label = col_character()
## )
```

```
## See spec(...) for full column specifications.
```

```
## Parsed with column specification:
## cols(
##   .default = col_double(),
##   speaker = col_character(),
##   rec.date = col_character(),
##   prompt = col_character(),
##   label = col_character()
## )
```

```
## See spec(...) for full column specifications.
```

```
## Parsed with column specification:
## cols(
##   .default = col_double(),
##   speaker = col_character(),
##   rec.date = col_character(),
```

```
##   prompt = col_character(),
##   label = col_character()
## )
```

```
## See spec(...) for full column specifications.
```

```
## Parsed with column specification:
## cols(
##   .default = col_double(),
##   speaker = col_character(),
##   rec.date = col_character(),
##   prompt = col_character(),
##   label = col_character()
## )
```

```
## See spec(...) for full column specifications.
```

```
## Joining, by = "speaker"
```

```
## Joining, by = c("word", "language")
```

```
aaa_files_clos <- list.files(
    path = "./data/tongue",
    pattern = "*-tongue-clos-cart.tsv",
    full.names = TRUE
)

tongues_clos <- read_aaa(
    aaa_files_clos,
    columns,
    na.rm = TRUE
) %>%
    mutate(word = word(prompt, 2)) %>%
    left_join(y = languages) %>%
    left_join(y = words) %>%
    mutate_if(is.character, as.factor) %>%
    group_by(speaker) %>%
    mutate(
        X.re = rescale(X),
        Y.re = rescale(Y)
    ) %>%
    ungroup() %>%
    mutate(
        vowel.ord = ordered(vowel, levels = c("a", "o", "u")),
        c2place.ord = ordered(c2place, levels = c("coronal", "velar")),
        c2phonation.ord = ordered(c2phonation, levels = c("voiceless", "voiced"))
    ) %>%
    filter(vowel != "u") %>%
    arrange(rec.date, fan.line) %>%
    create_event_start("rec.date")
```

```
## Parsed with column specification:
## cols(
##   .default = col_double(),
##   speaker = col_character(),
##   rec.date = col_character(),
##   prompt = col_character(),
```

```
##   label = col_character(),
##   X_2 = col_character(),
##   Y_2 = col_character(),
##   X_3 = col_character(),
##   Y_3 = col_character(),
##   X_4 = col_character(),
##   Y_4 = col_character(),
##   X_5 = col_character(),
##   Y_5 = col_character(),
##   X_6 = col_character(),
##   Y_6 = col_character()
## )

## See spec(...) for full column specifications.

## Parsed with column specification:
## cols(
##   .default = col_double(),
##   speaker = col_character(),
##   rec.date = col_character(),
##   prompt = col_character(),
##   label = col_character(),
##   X_3 = col_character(),
##   Y_3 = col_character(),
##   X_4 = col_character(),
##   Y_4 = col_character(),
##   X_5 = col_character(),
##   Y_5 = col_character()
## )

## See spec(...) for full column specifications.

## Parsed with column specification:
## cols(
##   .default = col_double(),
##   speaker = col_character(),
##   rec.date = col_character(),
##   prompt = col_character(),
##   label = col_character()
## )

## See spec(...) for full column specifications.

## Parsed with column specification:
## cols(
##   .default = col_double(),
##   speaker = col_character(),
##   rec.date = col_character(),
##   prompt = col_character(),
##   label = col_character()
## )

## See spec(...) for full column specifications.

## Joining, by = "speaker"

## Joining, by = c("word", "language")
```

```
vowels <- list.files(path = "data/durations",
                     pattern = "*-vowel-durations.csv",
                     full.names = TRUE) %>%
    map_df(~read_csv(., na = "--undefined--")) %>%
    left_join(y = languages) %>%
    left_join(y = words) %>%
    mutate_if(is.character, as.factor) %>%
    mutate(
        index = as.factor(index),
        c2phonation = factor(c2phonation, levels = c("voiceless", "voiced"))
    ) %>%
    filter(!(file == "it04-002" | file == "pl03-020")) # filter obvious outliers
```

```
## Parsed with column specification:
## cols(
##   index = col_integer(),
##   speaker = col_character(),
##   file = col_character(),
##   word = col_character(),
##   time = col_double(),
##   word.duration = col_double(),
##   c1.duration = col_double(),
##   vowel.duration = col_double(),
##   closure.duration = col_double(),
##   rvot = col_double(),
##   c2.duration = col_double(),
##   v2.duration = col_double(),
##   sentence.duration = col_double()
## )
```

```
## Parsed with column specification:
## cols(
##   index = col_integer(),
##   speaker = col_character(),
##   file = col_character(),
##   word = col_character(),
##   time = col_double(),
##   word.duration = col_double(),
##   c1.duration = col_double(),
##   vowel.duration = col_double(),
##   closure.duration = col_double(),
##   rvot = col_double(),
##   c2.duration = col_double(),
##   v2.duration = col_double(),
##   sentence.duration = col_double()
## )
## Parsed with column specification:
## cols(
##   index = col_integer(),
##   speaker = col_character(),
##   file = col_character(),
##   word = col_character(),
##   time = col_double(),
##   word.duration = col_double(),
```

```
##   c1.duration = col_double(),
##   vowel.duration = col_double(),
##   closure.duration = col_double(),
##   rvot = col_double(),
##   c2.duration = col_double(),
##   v2.duration = col_double(),
##   sentence.duration = col_double()
## )
## Parsed with column specification:
## cols(
##   index = col_integer(),
##   speaker = col_character(),
##   file = col_character(),
##   word = col_character(),
##   time = col_double(),
##   word.duration = col_double(),
##   c1.duration = col_double(),
##   vowel.duration = col_double(),
##   closure.duration = col_double(),
##   rvot = col_double(),
##   c2.duration = col_double(),
##   v2.duration = col_double(),
##   sentence.duration = col_double()
## )
## Parsed with column specification:
## cols(
##   index = col_integer(),
##   speaker = col_character(),
##   file = col_character(),
##   word = col_character(),
##   time = col_double(),
##   word.duration = col_double(),
##   c1.duration = col_double(),
##   vowel.duration = col_double(),
##   closure.duration = col_double(),
##   rvot = col_double(),
##   c2.duration = col_double(),
##   v2.duration = col_double(),
##   sentence.duration = col_double()
## )
## Parsed with column specification:
## cols(
##   index = col_integer(),
##   speaker = col_character(),
##   file = col_character(),
##   word = col_character(),
##   time = col_double(),
##   word.duration = col_double(),
##   c1.duration = col_double(),
##   vowel.duration = col_double(),
##   closure.duration = col_double(),
##   rvot = col_double(),
##   c2.duration = col_double(),
##   v2.duration = col_double(),
```

```
##   sentence.duration = col_double()
## )
## Parsed with column specification:
## cols(
##   index = col_integer(),
##   speaker = col_character(),
##   file = col_character(),
##   word = col_character(),
##   time = col_double(),
##   word.duration = col_double(),
##   c1.duration = col_double(),
##   vowel.duration = col_double(),
##   closure.duration = col_double(),
##   rvot = col_double(),
##   c2.duration = col_double(),
##   v2.duration = col_double(),
##   sentence.duration = col_double()
## )
## Parsed with column specification:
## cols(
##   index = col_integer(),
##   speaker = col_character(),
##   file = col_character(),
##   word = col_character(),
##   time = col_double(),
##   word.duration = col_double(),
##   c1.duration = col_double(),
##   vowel.duration = col_double(),
##   closure.duration = col_double(),
##   rvot = col_double(),
##   c2.duration = col_double(),
##   v2.duration = col_double(),
##   sentence.duration = col_double()
## )

## Joining, by = "speaker"

## Joining, by = c("word", "language")
```

2 Vowel duration

2.1 Italian

```
it_vow_lm <- lmer(
    vowel.duration ~
        c2phonation +
        c2place +
        vowel +
        c2phonation:vowel +
        sentence.duration +
        (1+c2phonation|speaker) +
        (1|word),
    data = filter(vowels, language == "italian")
```

```
)

summary(it_vow_lm)
```

```
## Linear mixed model fit by REML t-tests use Satterthwaite approximations
##   to degrees of freedom [lmerMod]
## Formula:
## vowel.duration ~ c2phonation + c2place + vowel + c2phonation:vowel +
##     sentence.duration + (1 + c2phonation | speaker) + (1 | word)
##    Data: filter(vowels, language == "italian")
##
## REML criterion at convergence: 3289.4
##
## Scaled residuals:
##     Min      1Q  Median      3Q     Max
## -2.8640 -0.6543 -0.0251  0.5852  3.2478
##
## Random effects:
##  Groups   Name              Variance Std.Dev. Corr
##  word     (Intercept)        34.65    5.887
##  speaker  (Intercept)        56.01    7.484
##           c2phonationvoiced  51.78    7.196   0.53
##  Residual                   191.02   13.821
## Number of obs: 406, groups:  word, 24; speaker, 4
##
## Fixed effects:
##                           Estimate Std. Error      df t value Pr(>|t|)
## (Intercept)                 14.513     12.434 133.600   1.167  0.24520
## c2phonationvoiced           21.841      6.073  12.700   3.596  0.00335 **
## c2placevelar                -8.524      2.803  15.700  -3.041  0.00791 **
## vowelo                      -8.697      4.864  15.800  -1.788  0.09296 .
## vowelu                     -29.686      4.860  15.800  -6.108 1.62e-05 ***
## sentence.duration           77.009      6.662 336.600  11.559  < 2e-16 ***
## c2phonationvoiced:vowelo     2.561      6.869  15.700   0.373  0.71423
## c2phonationvoiced:vowelu   -15.577      6.866  15.700  -2.269  0.03777 *
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Correlation of Fixed Effects:
##                           (Intr) c2phnt c2plcv vowelo vowelu sntnc.
## c2phontnvcd               -0.059
## c2placevelr               -0.112 -0.002
## vowelo                    -0.174  0.401 -0.003
## vowelu                    -0.182  0.402 -0.002  0.502
## sentnc.drtn               -0.905 -0.005  0.000 -0.024 -0.015
## c2phonationvoiced:vowelo   0.126 -0.566  0.002 -0.708 -0.355  0.014
## c2phonationvoiced:vowelu   0.136 -0.566  0.002 -0.355 -0.708  0.003
##                           c2phonationvoiced:vowelo
## c2phontnvcd
## c2placevelr
## vowelo
## vowelu
## sentnc.drtn
## c2phonationvoiced:vowelo
```

```
## c2phonationvoiced:vowelu  0.501
```

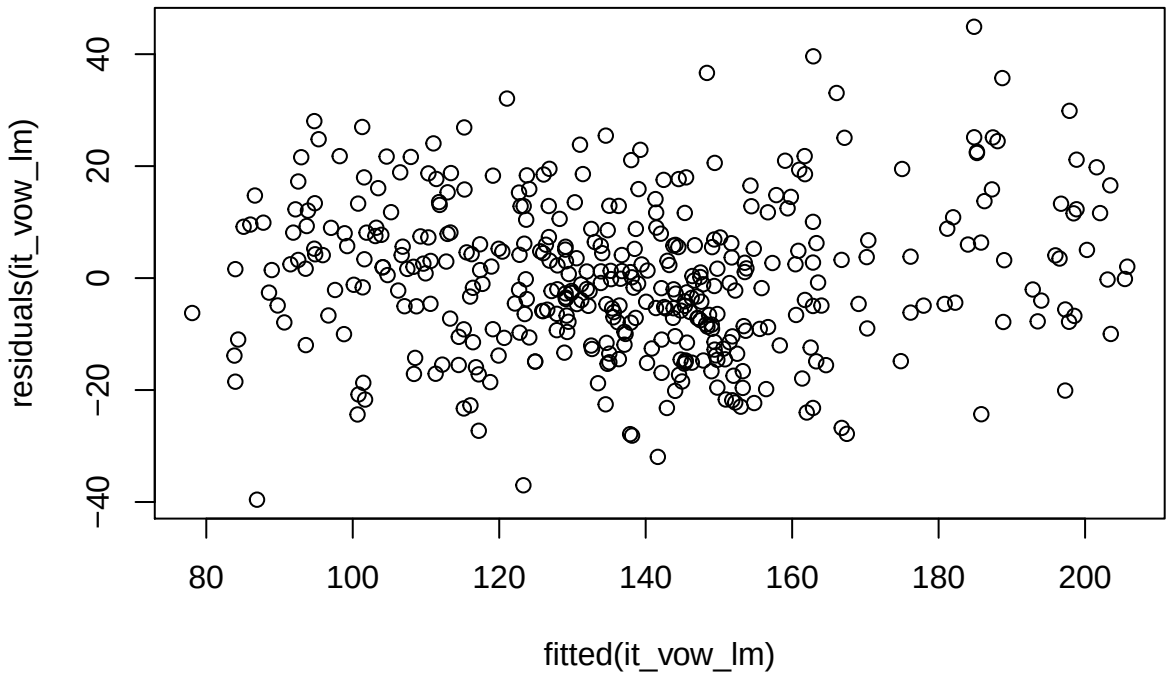
```
it_vow_lm_null <- lmer(
    vowel.duration ~
#         c2phonation +
        c2place +
        vowel +
        sentence.duration +
        (1+c2phonation|speaker) +
        (1|word),
    data = filter(vowels, language == "italian")
)

anova(it_vow_lm_null, it_vow_lm)
```

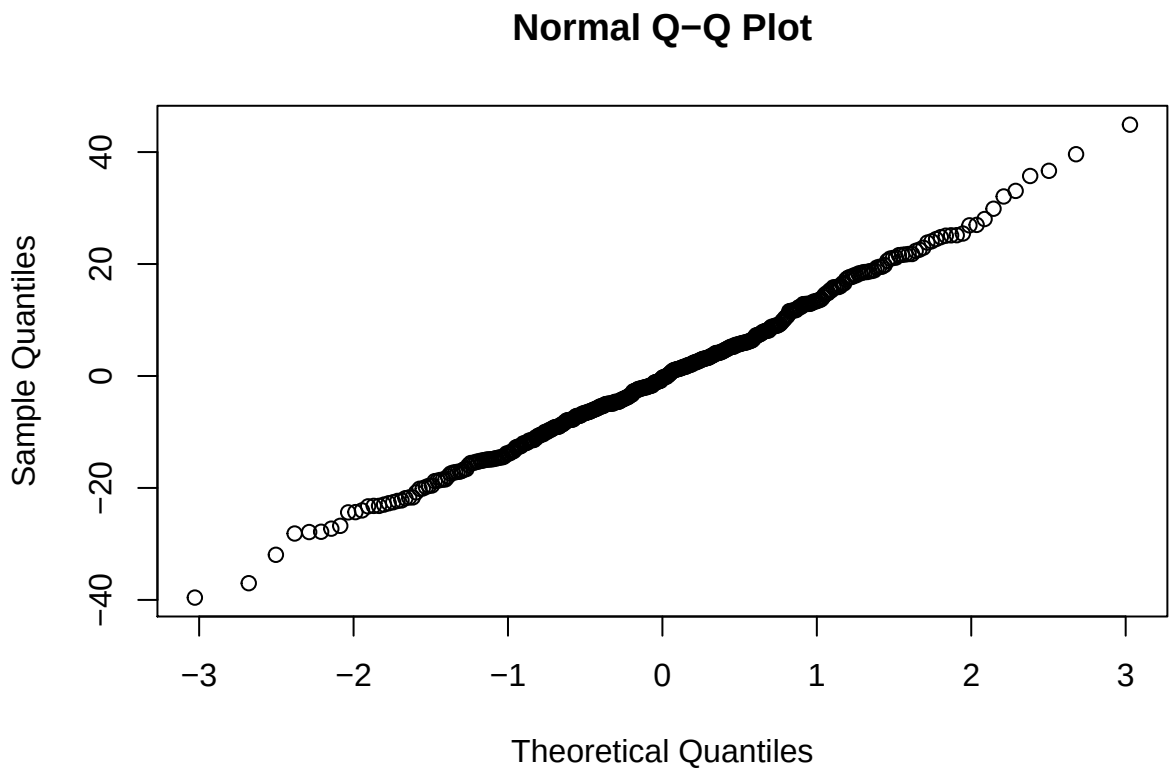
```
## refitting model(s) with ML (instead of REML)
```

```
## Data: filter(vowels, language == "italian")
## Models:
## object: vowel.duration ~ c2place + vowel + sentence.duration + (1 + c2phonation |
## object:     speaker) + (1 | word)
## ..1: vowel.duration ~ c2phonation + c2place + vowel + c2phonation:vowel +
## ..1:     sentence.duration + (1 + c2phonation | speaker) + (1 | word)
##        Df    AIC    BIC  logLik deviance  Chisq Chi Df Pr(>Chisq)
## object 10 3363.5 3403.6 -1671.8   3343.5
## ..1    13 3352.9 3405.0 -1663.4   3326.9 16.609      3  0.0008505 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

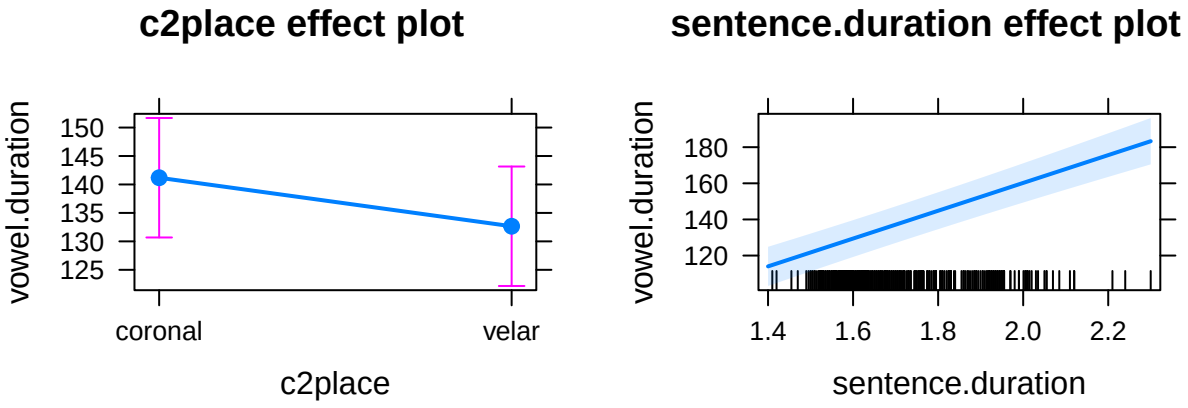
```
plot(fitted(it_vow_lm),residuals(it_vow_lm))
```

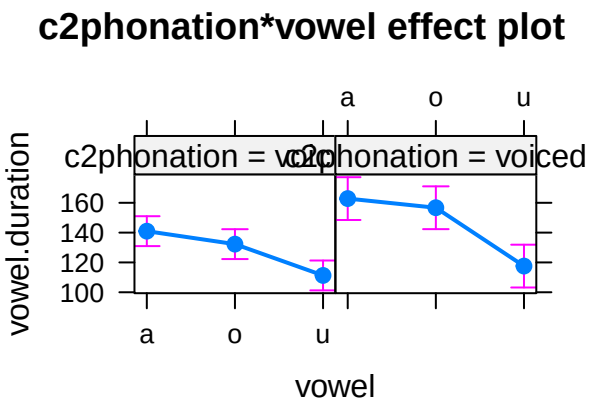


```
qqnorm(resid(it_vow_lm))
```




```
plot(allEffects(it_vow_lm))
```





2.2 Polish

```
pl_vow_lm <- lmer(
    vowel.duration ~
        c2phonation +
        vowel +
        c2place +
        sentence.duration +
        (1+c2phonation|speaker) +
        (1|word),
    data = filter(vowels, language == "polish")
)

summary(pl_vow_lm)
```

```
## Linear mixed model fit by REML t-tests use Satterthwaite approximations
##   to degrees of freedom [lmerMod]
## Formula:
## vowel.duration ~ c2phonation + vowel + c2place + sentence.duration +
##     (1 + c2phonation | speaker) + (1 | word)
##    Data: filter(vowels, language == "polish")
##
## REML criterion at convergence: 2317.9
##
## Scaled residuals:
##      Min       1Q   Median       3Q      Max
## -2.77796 -0.72472  0.00879  0.59730  2.90314
##
## Random effects:
##  Groups   Name              Variance Std.Dev. Corr
##  word     (Intercept)        14.16    3.763
##  speaker  (Intercept)        39.31    6.270
##           c2phonationvoiced  18.37    4.286   1.00
##  Residual                   100.69   10.034
## Number of obs: 311, groups:  word, 12; speaker, 4
##
## Fixed effects:
##                   Estimate Std. Error      df t value Pr(>|t|)
## (Intercept)         22.928     10.437 127.130   2.197  0.02985 *
## c2phonationvoiced    7.881      3.259   6.860   2.418  0.04691 *
## vowelo             -11.795      3.005   7.000  -3.925  0.00571 **
## vowelu             -29.276      3.016   7.100  -9.707 2.37e-05 ***
## c2placevelar        -5.577      2.453   7.000  -2.273  0.05722 .
## sentence.duration   70.813      9.743 261.040   7.268 4.22e-12 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Correlation of Fixed Effects:
##             (Intr) c2phnt vowelo vowelu c2plcv
## c2phontnvcd  0.139
## vowelo      -0.106  0.001
## vowelu      -0.063  0.002  0.501
## c2placevelr -0.098  0.000  0.001  0.003
## sentnc.drtn -0.917 -0.033 -0.041 -0.087 -0.022
```

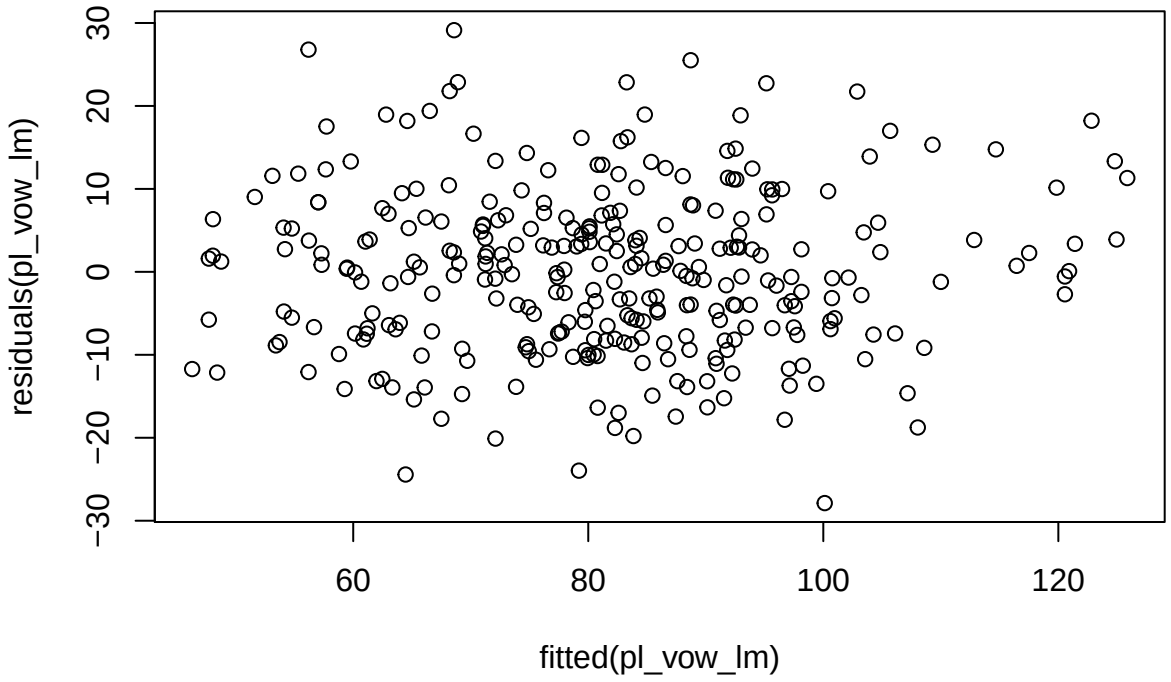
```
pl_vow_lm_null <- lmer(
    vowel.duration ~
#         c2phonation +
        vowel +
        c2place +
        sentence.duration +
        (1+c2phonation|speaker) +
        (1|word),
    data = filter(vowels, language == "polish")
)

anova(pl_vow_lm_null, pl_vow_lm)
```

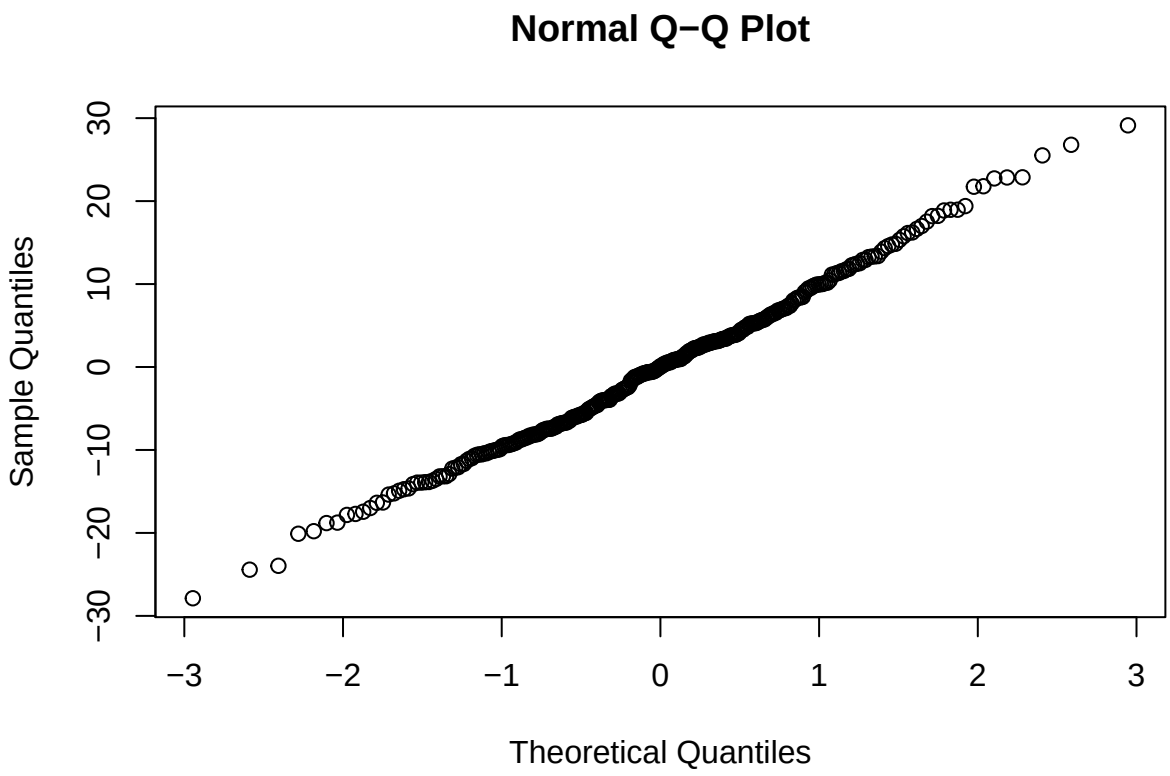
```
## refitting model(s) with ML (instead of REML)
```

```
## Data: filter(vowels, language == "polish")
## Models:
## object: vowel.duration ~ vowel + c2place + sentence.duration + (1 + c2phonation |
## object:     speaker) + (1 | word)
## ..1: vowel.duration ~ c2phonation + vowel + c2place + sentence.duration +
## ..1:     (1 + c2phonation | speaker) + (1 | word)
##        Df    AIC    BIC  logLik deviance  Chisq Chi Df Pr(>Chisq)
## object 10 2368.4 2405.8 -1174.2   2348.4
## ..1    11 2365.0 2406.2 -1171.5   2343.0 5.3949      1     0.0202 *
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

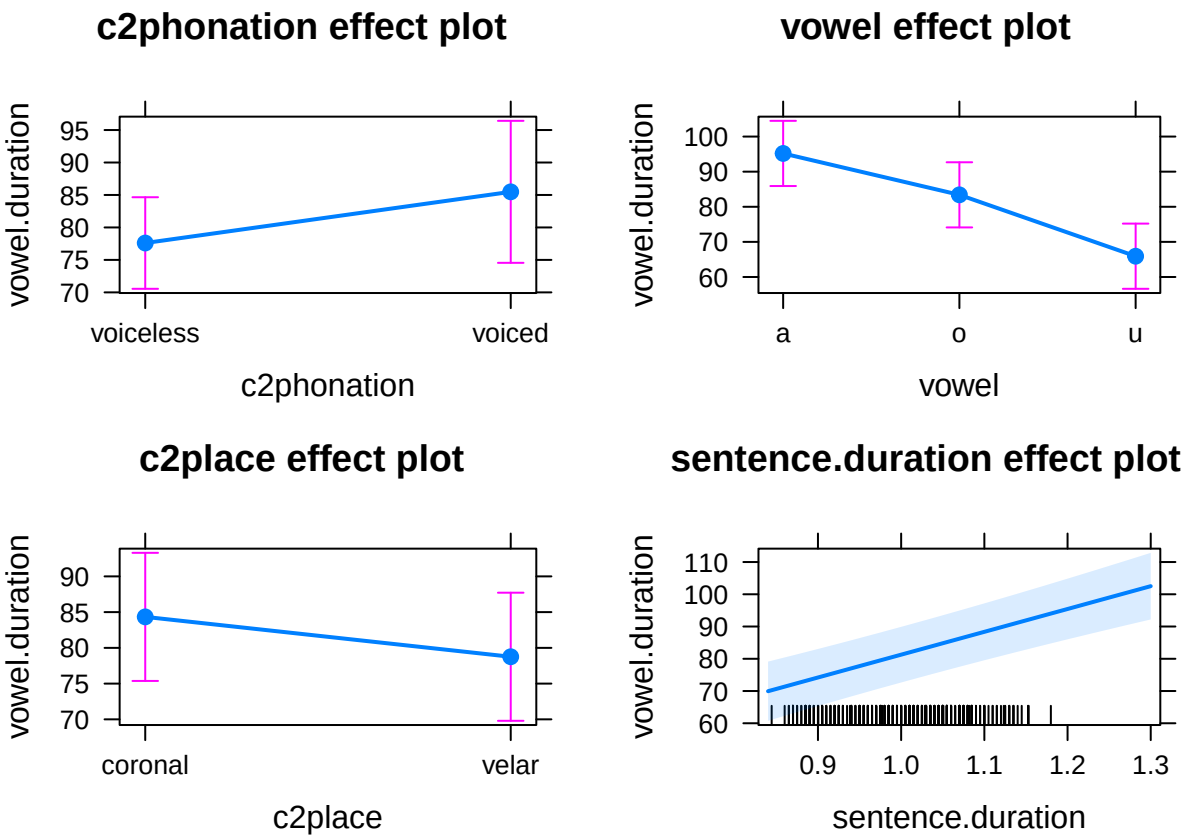
```
plot(fitted(pl_vow_lm),residuals(pl_vow_lm))
```




```
qqnorm(resid(pl_vow_lm))
```




```
plot(allEffects(pl_vow_lm))
```



3 Tongue root advancement at maximum displacement

3.1 Italian

3.1.1 IT01

```
it01_max <- filter(tongues, speaker == "it01")

it01_gamm <- bam(
    Y ~
        X.re +
        s(X, bs = "cr") +
        s(X, by = c2phonation.ord, bs = "cr") +
        s(X, by = c2place.ord, bs = "cr") +
        s(X, by = vowel.ord, bs = "cr") +
        s(X, rec.date, bs = "fs", xt = "cr", m = 1, k = 5),
    data = it01_max,
    method = "fREML"
)
```

```
## Warning in gam.side(sm, X, tol = .Machine$double.eps^0.5): model has
## repeated 1-d smooths of same variable.
```

```
rho <- start_value_rho(it01_gamm)

it01_gamm_ar <- bam(
    Y ~
        X +
        s(X, bs = "cr") +
        s(X, by = c2phonation.ord, bs = "cr") +
        s(X, by = c2place.ord, bs = "cr") +
        s(X, by = vowel.ord, bs = "cr") +
        s(X, rec.date, bs = "fs", xt = "cr", m = 1, k = 5),
    data = it01_max,
    method = "ML",
    rho = rho,
    AR.start = it01_max$start.event
)
```

```
## Warning in gam.side(sm, X, tol = .Machine$double.eps^0.5): model has
## repeated 1-d smooths of same variable.
```

```
summary(it01_gamm_ar)
```

```
##
## Family: gaussian
## Link function: identity
##
## Formula:
## Y ~ X + s(X, bs = "cr") + s(X, by = c2phonation.ord, bs = "cr") +
##     s(X, by = c2place.ord, bs = "cr") + s(X, by = vowel.ord,
##     bs = "cr") + s(X, rec.date, bs = "fs", xt = "cr", m = 1,
##     k = 5)
##
## Parametric coefficients:
```

```
##             Estimate Std. Error t value Pr(>|t|)
## (Intercept) -4.73141    0.30682  -15.42   <2e-16 ***
## X            0.76532    0.02666   28.70   <2e-16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Approximate significance of smooth terms:
##                               edf  Ref.df       F  p-value
## s(X)                        7.764   7.944 181.554  < 2e-16 ***
## s(X):c2phonation.ordvoiced  5.037   6.136   9.480 2.06e-10 ***
## s(X):c2place.ordvelar       8.822   8.979 183.531  < 2e-16 ***
## s(X):vowel.ordo             6.862   7.808  11.566 1.19e-15 ***
## s(X,rec.date)              92.680 225.000   1.976  < 2e-16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Rank: 267/268
## R-sq.(adj) =  0.979   Deviance explained = 91.4%
## -ML = 3488.2  Scale est. = 4.0701    n = 1932
```

```
it01_gamm_ar_null <- bam(
    Y ~
        X +
        s(X, bs = "cr") +
#        s(X, by = c2phonation.ord, bs = "cr") +
        s(X, by = c2place.ord, bs = "cr") +
        s(X, by = vowel.ord, bs = "cr") +
        s(X, rec.date, bs = "fs", xt = "cr", m = 1, k = 5),
    data = it01_max,
    method = "ML",
    rho = rho,
    AR.start = it01_max$start.event
)
```

```
## Warning in gam.side(sm, X, tol = .Machine$double.eps^0.5): model has
## repeated 1-d smooths of same variable.
```

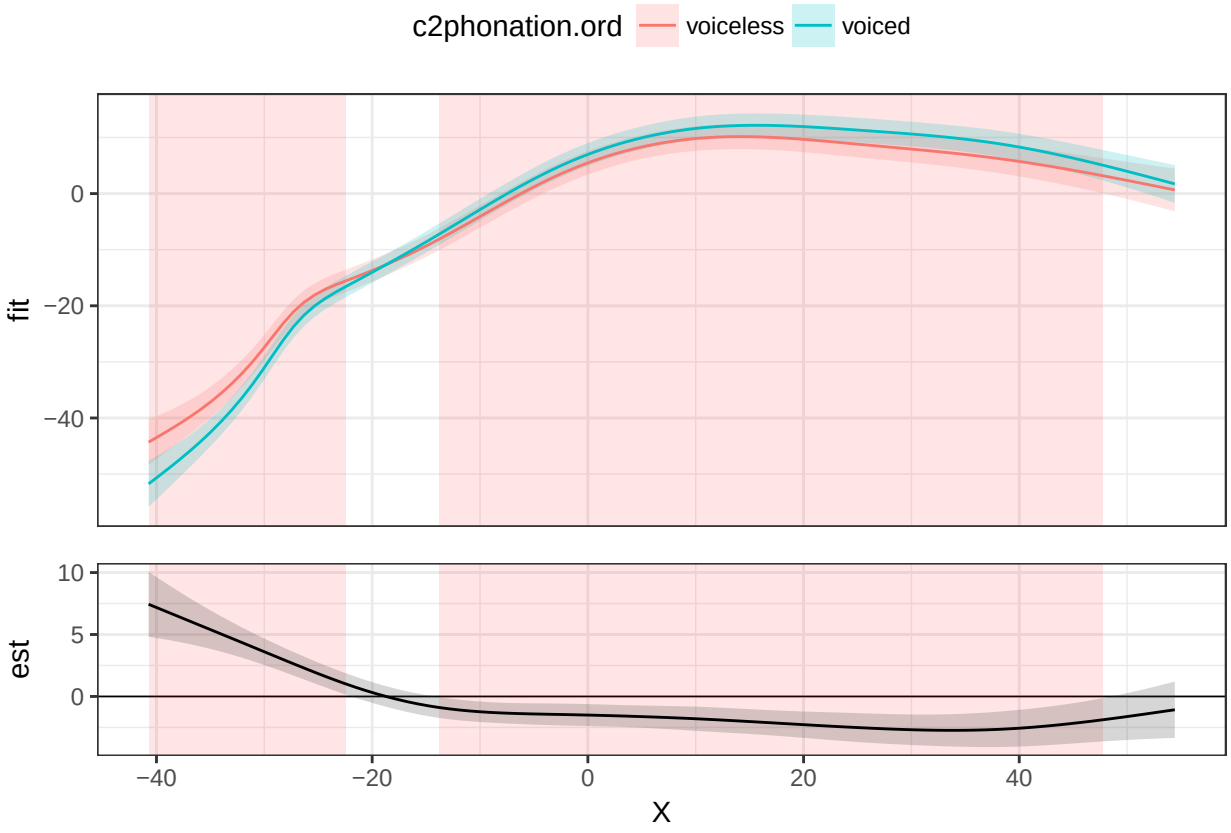
```
compareML(it01_gamm_ar_null, it01_gamm_ar)
```

```
## it01_gamm_ar_null: Y ~ X + s(X, bs = "cr") + s(X, by = c2place.ord, bs = "cr") +
##     s(X, by = vowel.ord, bs = "cr") + s(X, rec.date, bs = "fs",
##     xt = "cr", m = 1, k = 5)
##
## it01_gamm_ar: Y ~ X + s(X, bs = "cr") + s(X, by = c2phonation.ord, bs = "cr") +
##     s(X, by = c2place.ord, bs = "cr") + s(X, by = vowel.ord,
##     bs = "cr") + s(X, rec.date, bs = "fs", xt = "cr", m = 1,
##     k = 5)
##
## Chi-square test of ML scores
## -----
##               Model    Score Edf Difference    Df   p.value Sig.
## 1 it01_gamm_ar_null 3509.547  11
## 2      it01_gamm_ar 3488.231  13     21.316 2.000 5.527e-10  ***
##
## AIC difference: 23.12, model it01_gamm_ar has lower AIC.
```

```
## Warning in compareML(it01_gamm_ar_null, it01_gamm_ar): AIC might not be
## reliable, as an AR1 model is included (rho1 = 0.745137, rho2 = 0.745137).
```

```
plot_gamsd(
    it01_gamm_ar,
    view = "X",
    comparison = list(c2phonation.ord = c("voiceless", "voiced")),
    conditions = list(c2place.ord = "coronal")
)
```

```
## Summary:
##  * X : numeric predictor; with 100 values ranging from -40.731200 to 54.425500.
##  * c2phonation.ord : factor; set to the value(s): voiced, voiceless.
##  * c2place.ord : factor; set to the value(s): coronal.
##  * vowel.ord : factor; set to the value(s): a.
##  * rec.date : factor; set to the value(s): 29/11/2016 15:10:52.
```



3.1.2 IT02

```
it02_max <- filter(tongues, speaker == "it02")

it02_gamm <- bam(
    Y ~
        X.re +
        s(X, bs = "cr") +
        s(X, by = c2phonation.ord, bs = "cr") +
        s(X, by = c2place.ord, bs = "cr") +
```

```
        s(X, by = vowel.ord, bs = "cr") +
        s(X, rec.date, bs = "fs", xt = "cr", m = 1, k = 5),
    data = it02_max,
    method = "fREML"
)
```

```
## Warning in gam.side(sm, X, tol = .Machine$double.eps^0.5): model has
## repeated 1-d smooths of same variable.
```

```
rho <- start_value_rho(it02_gamm)

it02_gamm_ar <- bam(
    Y ~
        X +
        s(X, bs = "cr") +
        s(X, by = c2phonation.ord, bs = "cr") +
        s(X, by = c2place.ord, bs = "cr") +
        s(X, by = vowel.ord, bs = "cr") +
        s(X, rec.date, bs = "fs", xt = "cr", m = 1, k = 5),
    data = it02_max,
    method = "ML",
    rho = rho,
    AR.start = it02_max$start.event
)
```

```
## Warning in gam.side(sm, X, tol = .Machine$double.eps^0.5): model has
## repeated 1-d smooths of same variable.
```

```
summary(it02_gamm_ar)
```

```
##
## Family: gaussian
## Link function: identity
##
## Formula:
## Y ~ X + s(X, bs = "cr") + s(X, by = c2phonation.ord, bs = "cr") +
##     s(X, by = c2place.ord, bs = "cr") + s(X, by = vowel.ord,
##     bs = "cr") + s(X, rec.date, bs = "fs", xt = "cr", m = 1,
##     k = 5)
##
## Parametric coefficients:
##             Estimate Std. Error t value Pr(>|t|)
## (Intercept) -1.67360    0.52437  -3.192  0.00145 **
## X            0.65159    0.03157  20.640  < 2e-16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Approximate significance of smooth terms:
##                               edf  Ref.df      F  p-value
## s(X)                        6.386   7.189 57.403  < 2e-16 ***
## s(X):c2phonation.ordvoiced  6.589   7.613  4.927 9.93e-06 ***
## s(X):c2place.ordvelar       8.630   8.910 52.382  < 2e-16 ***
## s(X):vowel.ordo             5.937   7.020  9.062 6.16e-11 ***
## s(X,rec.date)              72.997 185.000  1.401  < 2e-16 ***
## ---
```

```
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Rank: 227/228
## R-sq.(adj) =  0.916   Deviance explained =   71%
## -ML = 2803.6  Scale est. = 9.778     n = 1233
```

```
it02_gamm_ar_null <- bam(
    Y ~
        X +
        s(X, bs = "cr") +
#        s(X, by = c2phonation.ord, bs = "cr") +
        s(X, by = c2place.ord, bs = "cr") +
        s(X, by = vowel.ord, bs = "cr") +
        s(X, rec.date, bs = "fs", xt = "cr", m = 1, k = 5),
    data = it02_max,
    method = "ML",
    rho = rho,
    AR.start = it02_max$start.event
)
```

```
## Warning in gam.side(sm, X, tol = .Machine$double.eps^0.5): model has
## repeated 1-d smooths of same variable.
```

```
compareML(it02_gamm_ar_null, it02_gamm_ar)
```

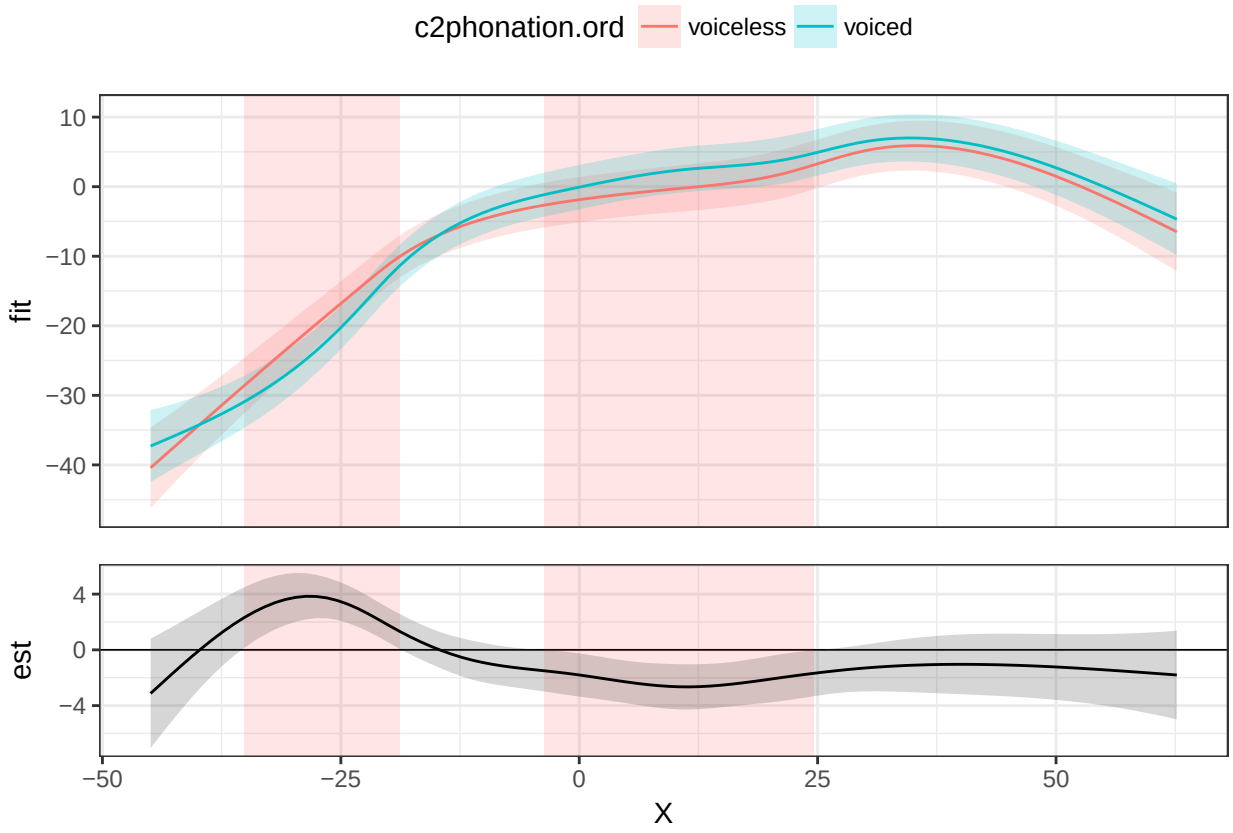
```
## it02_gamm_ar_null: Y ~ X + s(X, bs = "cr") + s(X, by = c2place.ord, bs = "cr") +
##     s(X, by = vowel.ord, bs = "cr") + s(X, rec.date, bs = "fs",
##     xt = "cr", m = 1, k = 5)
##
## it02_gamm_ar: Y ~ X + s(X, bs = "cr") + s(X, by = c2phonation.ord, bs = "cr") +
##     s(X, by = c2place.ord, bs = "cr") + s(X, by = vowel.ord,
##     bs = "cr") + s(X, rec.date, bs = "fs", xt = "cr", m = 1,
##     k = 5)
##
## Chi-square test of ML scores
## -----
##                Model    Score Edf Difference    Df   p.value Sig.
## 1 it02_gamm_ar_null 2813.488  11
## 2      it02_gamm_ar 2803.592  13      9.897 2.000 5.034e-05  ***
##
## AIC difference: 23.42, model it02_gamm_ar has lower AIC.
```

```
## Warning in compareML(it02_gamm_ar_null, it02_gamm_ar): AIC might not be
## reliable, as an AR1 model is included (rho1 = 0.735050, rho2 = 0.735050).
```

```
plot_gamsd(
    it02_gamm_ar,
    view = "X",
    comparison = list(c2phonation.ord = c("voiceless", "voiced")),
    conditions = list(c2place.ord = "coronal")
)
```

```
## Summary:
##  * X : numeric predictor; with 100 values ranging from -44.949000 to 62.666500.
##  * c2phonation.ord : factor; set to the value(s): voiced, voiceless.
##  * c2place.ord : factor; set to the value(s): coronal.
##  * vowel.ord : factor; set to the value(s): a.
```

```
##   * rec.date : factor; set to the value(s): 12/12/2016 14:45:14.
```



3.2 Polish

3.2.1 PL02

```
pl02_max <- filter(tongues, speaker == "pl02", X > -20)

pl02_gamm <- bam(
    Y ~
        X +
        s(X, bs = "cr") +
        s(X, by = c2phonation.ord, bs = "cr") +
        s(X, by = c2place.ord, bs = "cr") +
        s(X, by = vowel.ord, bs = "cr") +
        s(X, rec.date, bs = "fs", xt = "cr", m = 1, k = 5),
    data = pl02_max,
    method = "ML"
)
```

```
## Warning in gam.side(sm, X, tol = .Machine$double.eps^0.5): model has
## repeated 1-d smooths of same variable.
```

```
rho <- start_value_rho(pl02_gamm)

pl02_gamm_ar <- bam(
    Y ~
```

```
        X +
        s(X, bs = "cr") +
        s(X, by = c2phonation.ord, bs = "cr") +
        s(X, by = c2place.ord, bs = "cr") +
        s(X, by = vowel.ord, bs = "cr") +
        s(X, rec.date, bs = "fs", xt = "cr", m = 1, k = 5),
    data = pl02_max,
    method = "ML",
    rho = rho,
    AR.start = pl02_max$start.event
)
```

```
## Warning in gam.side(sm, X, tol = .Machine$double.eps^0.5): model has
## repeated 1-d smooths of same variable.
```

```
summary(pl02_gamm_ar)
```

```
##
## Family: gaussian
## Link function: identity
##
## Formula:
## Y ~ X + s(X, bs = "cr") + s(X, by = c2phonation.ord, bs = "cr") +
##     s(X, by = c2place.ord, bs = "cr") + s(X, by = vowel.ord,
##     bs = "cr") + s(X, rec.date, bs = "fs", xt = "cr", m = 1,
##     k = 5)
##
## Parametric coefficients:
##             Estimate Std. Error t value Pr(>|t|)
## (Intercept)  3.16593    0.50234   6.302 3.52e-10 ***
## X           -0.08800    0.03015  -2.919  0.00355 **
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Approximate significance of smooth terms:
##                                edf  Ref.df       F p-value
## s(X)                         7.112   7.721  53.045 < 2e-16 ***
## s(X):c2phonation.ordvoiced   7.570   8.492   4.417 0.00067 ***
## s(X):c2place.ordvelar        8.821   8.976 209.352 < 2e-16 ***
## s(X):vowel.ordo              7.675   8.550  12.914 < 2e-16 ***
## s(X,rec.date)              135.219 300.000   2.126 < 2e-16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Rank: 342/343
## R-sq.(adj) =  0.936   Deviance explained =   75%
## -ML =   4239  Scale est. = 3.4834    n = 2391
```

```
pl02_gamm_ar_null <- bam(
    Y ~
        X +
        s(X, bs = "cr") +
        s(X, by = c2place.ord, bs = "cr") +
        s(X, by = vowel.ord, bs = "cr") +
        s(X, rec.date, bs = "fs", xt = "cr", m = 1, k = 5),
```

```
    data = pl02_max,
    method = "ML"
)
```

```
## Warning in gam.side(sm, X, tol = .Machine$double.eps^0.5): model has
## repeated 1-d smooths of same variable.
```

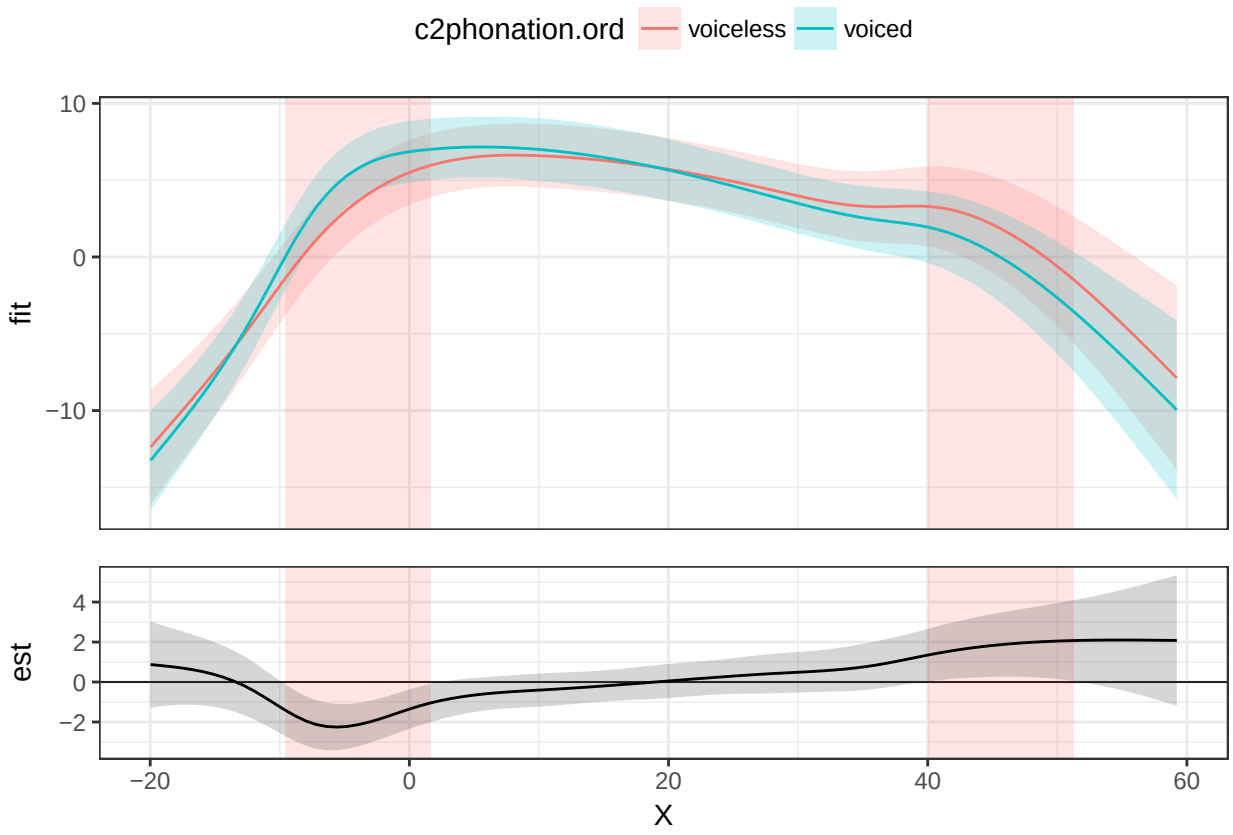
```
compareML(pl02_gamm_ar_null, pl02_gamm_ar)
```

```
## pl02_gamm_ar_null: Y ~ X + s(X, bs = "cr") + s(X, by = c2place.ord, bs = "cr") +
##     s(X, by = vowel.ord, bs = "cr") + s(X, rec.date, bs = "fs",
##     xt = "cr", m = 1, k = 5)
##
## pl02_gamm_ar: Y ~ X + s(X, bs = "cr") + s(X, by = c2phonation.ord, bs = "cr") +
##     s(X, by = c2place.ord, bs = "cr") + s(X, by = vowel.ord,
##     bs = "cr") + s(X, rec.date, bs = "fs", xt = "cr", m = 1,
##     k = 5)
##
## Chi-square test of ML scores
## -----
##               Model    Score Edf Difference    Df  p.value Sig.
## 1 pl02_gamm_ar_null 5557.001  11
## 2      pl02_gamm_ar 4238.954  13   1318.048 2.000  < 2e-16  ***
##
## AIC difference: 2368.80, model pl02_gamm_ar has lower AIC.
```

```
## Warning in compareML(pl02_gamm_ar_null, pl02_gamm_ar): AIC might not be
## reliable, as an AR1 model is included (rho1 = 0.000000, rho2 = 0.717567).
```

```
plot_gamsd(
    pl02_gamm_ar,
    view = "X",
    comparison = list(c2phonation.ord = c("voiceless", "voiced")),
    conditions = list(c2place.ord = "coronal")
)
```

```
## Summary:
##  * X : numeric predictor; with 100 values ranging from -19.967800 to 59.219800.
##  * c2phonation.ord : factor; set to the value(s): voiced, voiceless.
##  * c2place.ord : factor; set to the value(s): coronal.
##  * vowel.ord : factor; set to the value(s): a.
##  * rec.date : factor; set to the value(s): 07/02/2017 16:29:14.
```



3.2.2 PL04

```
pl04_max <- filter(tongues, speaker == "pl04", X > -25)

pl04_gamm <- bam(
    Y ~
        X +
        s(X, bs = "cr") +
        s(X, by = c2phonation.ord, bs = "cr") +
        s(X, by = c2place.ord, bs = "cr") +
        s(X, by = vowel.ord, bs = "cr") +
        s(X, rec.date, bs = "fs", xt = "cr", m = 1, k = 5),
    data = pl04_max,
    method = "ML"
)
```

```
## Warning in gam.side(sm, X, tol = .Machine$double.eps^0.5): model has
## repeated 1-d smooths of same variable.
```

```
rho <- start_value_rho(pl04_gamm)

pl04_gamm_ar <- bam(
    Y ~
        X +
        s(X, bs = "cr") +
        s(X, by = c2phonation.ord, bs = "cr") +
        s(X, by = c2place.ord, bs = "cr") +
```

```
        s(X, by = vowel.ord, bs = "cr") +
        s(X, rec.date, bs = "fs", xt = "cr", m = 1, k = 5),
    data = pl04_max,
    method = "ML",
    rho = rho,
    AR.start = pl04_max$start.event
)
```

```
## Warning in gam.side(sm, X, tol = .Machine$double.eps^0.5): model has
## repeated 1-d smooths of same variable.
```

```
summary(pl04_gamm_ar)
```

```
##
## Family: gaussian
## Link function: identity
##
## Formula:
## Y ~ X + s(X, bs = "cr") + s(X, by = c2phonation.ord, bs = "cr") +
##     s(X, by = c2place.ord, bs = "cr") + s(X, by = vowel.ord,
##     bs = "cr") + s(X, rec.date, bs = "fs", xt = "cr", m = 1,
##     k = 5)
##
## Parametric coefficients:
##             Estimate Std. Error t value Pr(>|t|)
## (Intercept)  3.80103    0.38089   9.979   <2e-16 ***
## X           -0.04730    0.03513  -1.347    0.178
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Approximate significance of smooth terms:
##                                edf  Ref.df      F  p-value
## s(X)                         7.436   7.785 21.721  < 2e-16 ***
## s(X):c2phonation.ordvoiced   4.455   5.521  0.650    0.716
## s(X):c2place.ordvelar        8.454   8.853 29.487  < 2e-16 ***
## s(X):vowel.ordo              8.061   8.670  9.105 1.49e-12 ***
## s(X,rec.date)              196.514 230.000 27.988  < 2e-16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Rank: 272/273
## R-sq.(adj) =  0.977   Deviance explained = 96.6%
## -ML = 1671.6  Scale est. = 0.65314   n = 1165
```

```
pl04_gamm_ar_null <- bam(
    Y ~
        X +
        s(X, bs = "cr") +
        s(X, by = c2place.ord, bs = "cr") +
        s(X, by = vowel.ord, bs = "cr") +
        s(X, rec.date, bs = "fs", xt = "cr", m = 1, k = 5),
    data = pl04_max,
    method = "ML"
)
```

```
## Warning in gam.side(sm, X, tol = .Machine$double.eps^0.5): model has
## repeated 1-d smooths of same variable.
```

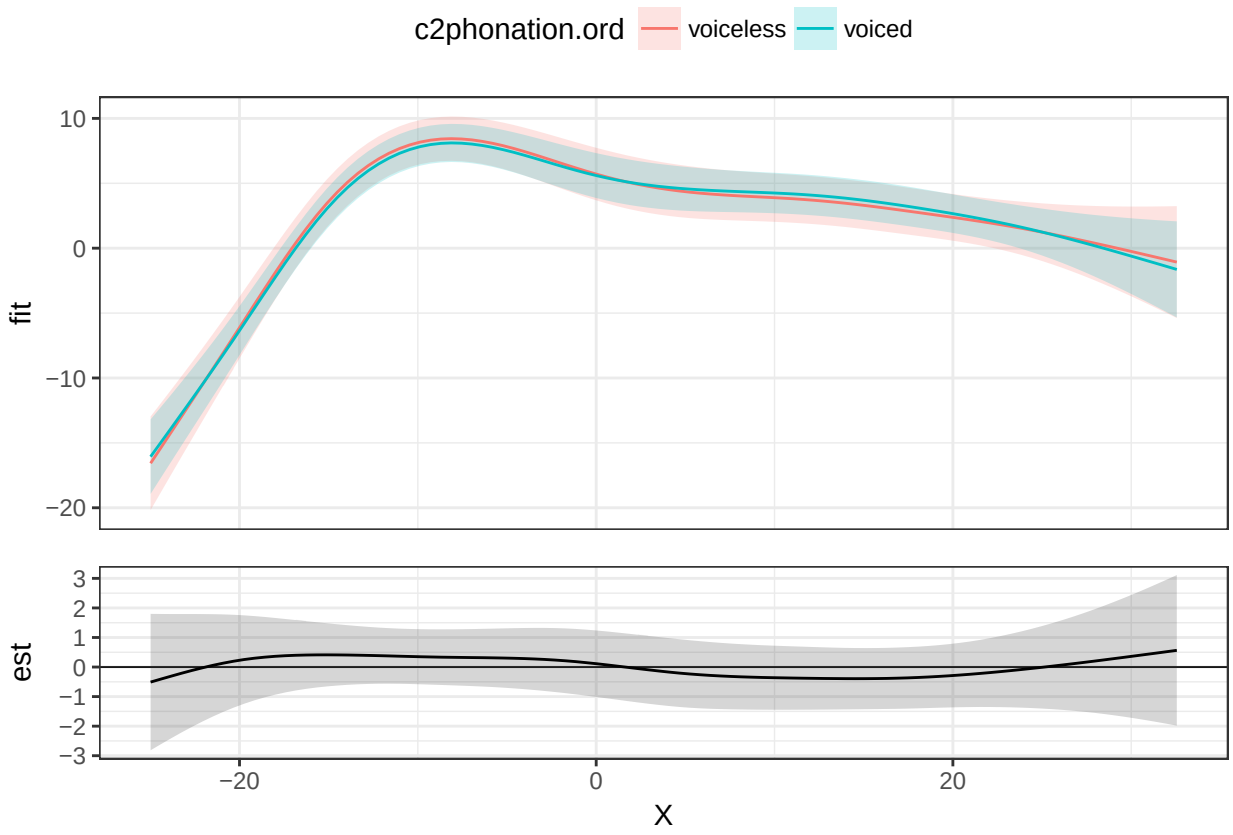
```
compareML(pl04_gamm_ar_null, pl04_gamm_ar)
```

```
## pl04_gamm_ar_null: Y ~ X + s(X, bs = "cr") + s(X, by = c2place.ord, bs = "cr") +
##     s(X, by = vowel.ord, bs = "cr") + s(X, rec.date, bs = "fs",
##     xt = "cr", m = 1, k = 5)
##
## pl04_gamm_ar: Y ~ X + s(X, bs = "cr") + s(X, by = c2phonation.ord, bs = "cr") +
##     s(X, by = c2place.ord, bs = "cr") + s(X, by = vowel.ord,
##     bs = "cr") + s(X, rec.date, bs = "fs", xt = "cr", m = 1,
##     k = 5)
##
## Chi-square test of ML scores
## -----
##               Model    Score Edf Difference    Df  p.value Sig.
## 1 pl04_gamm_ar_null 1937.166  11
## 2      pl04_gamm_ar 1671.593  13    265.573 2.000  < 2e-16  ***
##
## AIC difference: 352.64, model pl04_gamm_ar has lower AIC.
```

```
## Warning in compareML(pl04_gamm_ar_null, pl04_gamm_ar): AIC might not be
## reliable, as an AR1 model is included (rho1 = 0.000000, rho2 = 0.468632).
```

```
plot_gamsd(
    pl04_gamm_ar,
    view = "X",
    comparison = list(c2phonation.ord = c("voiceless", "voiced")),
    conditions = list(c2place.ord = "coronal")
)
```

```
## Summary:
##  * X : numeric predictor; with 100 values ranging from -24.985100 to 32.556800.
##  * c2phonation.ord : factor; set to the value(s): voiced, voiceless.
##  * c2place.ord : factor; set to the value(s): coronal.
##  * vowel.ord : factor; set to the value(s): a.
##  * rec.date : factor; set to the value(s): 26/05/2017 17:58:11.
```



4 Tongue root advancement at closure

4.1 Italian

4.1.1 IT01

```
it01_clos <- filter(tongues_clos, speaker == "it01")

it01_gamm <- bam(
    Y ~
        X.re +
        s(X, bs = "cr") +
        s(X, by = c2phonation.ord, bs = "cr") +
        s(X, by = c2place.ord, bs = "cr") +
        s(X, by = vowel.ord, bs = "cr") +
        s(X, rec.date, bs = "fs", xt = "cr", m = 1, k = 5),
    data = it01_clos,
    method = "fREML"
)
```

```
## Warning in gam.side(sm, X, tol = .Machine$double.eps^0.5): model has
## repeated 1-d smooths of same variable.
```

```
rho <- start_value_rho(it01_gamm)
```

```r
it01_gamm_ar <- bam(
    Y ~
        X +
        s(X, bs = "cr") +
        s(X, by = c2phonation.ord, bs = "cr") +
        s(X, by = c2place.ord, bs = "cr") +
        s(X, by = vowel.ord, bs = "cr") +
        s(X, rec.date, bs = "fs", xt = "cr", m = 1, k = 5),
    data = it01_clos,
    method = "ML",
    rho = rho,
    AR.start = it01_clos$start.event
)
```

```
## Warning in gam.side(sm, X, tol = .Machine$double.eps^0.5): model has
## repeated 1-d smooths of same variable.
```

```r
summary(it01_gamm_ar)
```

```
##
## Family: gaussian
## Link function: identity
##
## Formula:
## Y ~ X + s(X, bs = "cr") + s(X, by = c2phonation.ord, bs = "cr") +
##     s(X, by = c2place.ord, bs = "cr") + s(X, by = vowel.ord,
##     bs = "cr") + s(X, rec.date, bs = "fs", xt = "cr", m = 1,
##     k = 5)
##
## Parametric coefficients:
##             Estimate Std. Error t value Pr(>|t|)
## (Intercept)  0.61066    0.39198   1.558    0.119
## X            0.84888    0.02509  33.831   <2e-16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Approximate significance of smooth terms:
##                               edf  Ref.df       F  p-value
## s(X)                        7.549   7.867 198.722  < 2e-16 ***
## s(X):c2phonation.ordvoiced  4.683   5.594  13.824 3.56e-14 ***
## s(X):c2place.ordvelar       8.641   8.924 174.974  < 2e-16 ***
## s(X):vowel.ordo             6.049   6.977  14.770  < 2e-16 ***
## s(X,rec.date)              96.251 230.000   1.789  < 2e-16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Rank: 272/273
## R-sq.(adj) =  0.981   Deviance explained = 93.6%
## -ML = 2983.9  Scale est. = 3.7241    n = 1648
```

```r
it01_gamm_ar_null <- bam(
    Y ~
        X +
        s(X, bs = "cr") +
#        s(X, by = c2phonation.ord, bs = "cr") +
```

```
        s(X, by = c2place.ord, bs = "cr") +
        s(X, by = vowel.ord, bs = "cr") +
        s(X, rec.date, bs = "fs", xt = "cr", m = 1, k = 5),
    data = it01_clos,
    method = "ML",
    rho = rho,
    AR.start = it01_clos$start.event
)
```

```
## Warning in gam.side(sm, X, tol = .Machine$double.eps^0.5): model has
## repeated 1-d smooths of same variable.
```

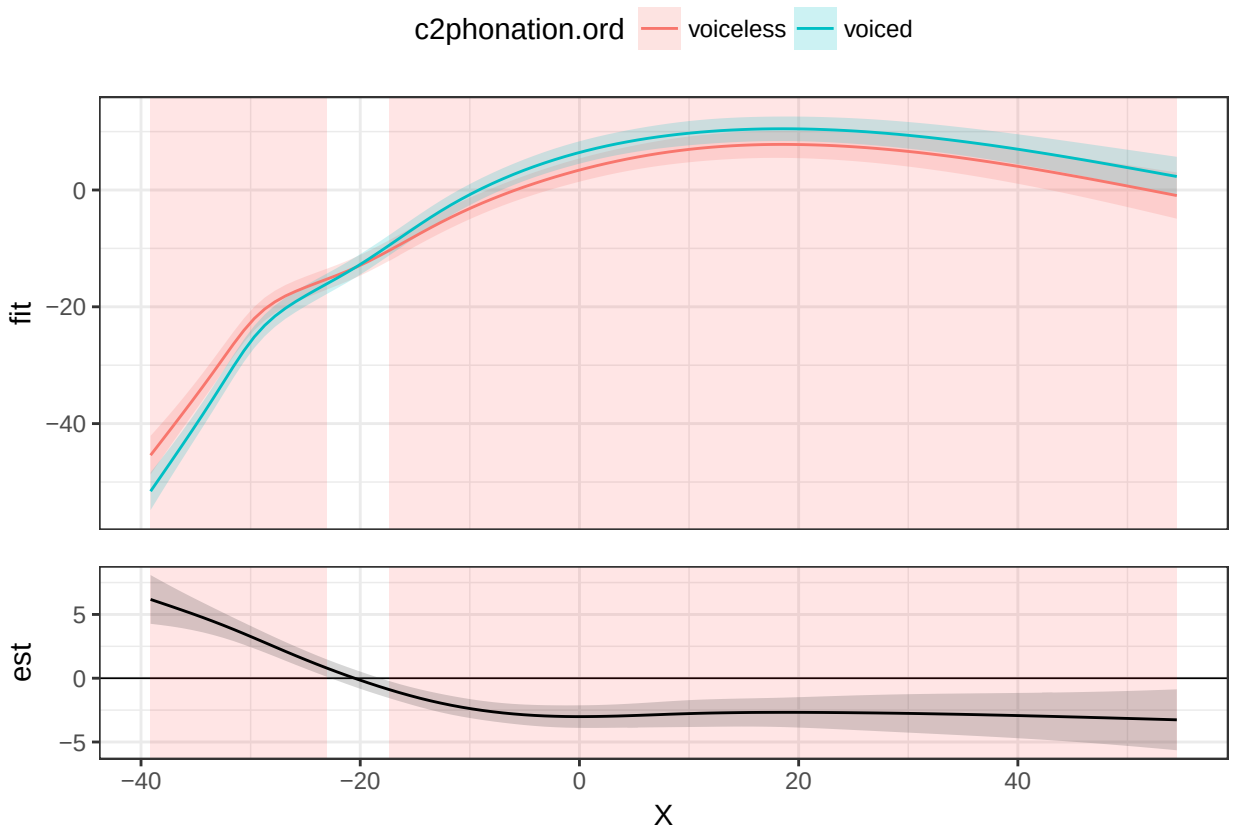
```
compareML(it01_gamm_ar_null, it01_gamm_ar)
```

```
## it01_gamm_ar_null: Y ~ X + s(X, bs = "cr") + s(X, by = c2place.ord, bs = "cr") +
##     s(X, by = vowel.ord, bs = "cr") + s(X, rec.date, bs = "fs",
##     xt = "cr", m = 1, k = 5)
##
## it01_gamm_ar: Y ~ X + s(X, bs = "cr") + s(X, by = c2phonation.ord, bs = "cr") +
##     s(X, by = c2place.ord, bs = "cr") + s(X, by = vowel.ord,
##     bs = "cr") + s(X, rec.date, bs = "fs", xt = "cr", m = 1,
##     k = 5)
##
## Chi-square test of ML scores
## -----
##               Model    Score Edf Difference    Df   p.value Sig.
## 1 it01_gamm_ar_null 3014.072  11
## 2      it01_gamm_ar 2983.854  13     30.218 2.000 7.523e-14  ***
##
## AIC difference: 28.11, model it01_gamm_ar has lower AIC.
```

```
## Warning in compareML(it01_gamm_ar_null, it01_gamm_ar): AIC might not be
## reliable, as an AR1 model is included (rho1 = 0.721734, rho2 = 0.721734).
```

```
plot_gamsd(
    it01_gamm_ar,
    view = "X",
    comparison = list(c2phonation.ord = c("voiceless", "voiced")),
    conditions = list(c2place.ord = "coronal")
)
```

```
## Summary:
##  * X : numeric predictor; with 100 values ranging from -39.125800 to 54.502000.
##  * c2phonation.ord : factor; set to the value(s): voiced, voiceless.
##  * c2place.ord : factor; set to the value(s): coronal.
##  * vowel.ord : factor; set to the value(s): a.
##  * rec.date : factor; set to the value(s): 29/11/2016 15:10:52.
```



4.1.2 IT02

```
it02_clos <- filter(tongues_clos, speaker == "it02")

it02_gamm <- bam(
    Y ~
        X.re +
        s(X, bs = "cr") +
        s(X, by = c2phonation.ord, bs = "cr") +
        s(X, by = c2place.ord, bs = "cr") +
        s(X, by = vowel.ord, bs = "cr") +
        s(X, rec.date, bs = "fs", xt = "cr", m = 1, k = 5),
    data = it02_clos,
    method = "fREML"
)
```

```
## Warning in gam.side(sm, X, tol = .Machine$double.eps^0.5): model has
## repeated 1-d smooths of same variable.
```

```
rho <- start_value_rho(it02_gamm)

it02_gamm_ar <- bam(
    Y ~
        X +
        s(X, bs = "cr") +
        s(X, by = c2phonation.ord, bs = "cr") +
        s(X, by = c2place.ord, bs = "cr") +
```

```
        s(X, by = vowel.ord, bs = "cr") +
        s(X, rec.date, bs = "fs", xt = "cr", m = 1, k = 5),
    data = it02_clos,
    method = "ML",
    rho = rho,
    AR.start = it02_clos$start.event
)
```

```
## Warning in gam.side(sm, X, tol = .Machine$double.eps^0.5): model has
## repeated 1-d smooths of same variable.
```

```
summary(it02_gamm_ar)
```

```
##
## Family: gaussian
## Link function: identity
##
## Formula:
## Y ~ X + s(X, bs = "cr") + s(X, by = c2phonation.ord, bs = "cr") +
##     s(X, by = c2place.ord, bs = "cr") + s(X, by = vowel.ord,
##     bs = "cr") + s(X, rec.date, bs = "fs", xt = "cr", m = 1,
##     k = 5)
##
## Parametric coefficients:
##             Estimate Std. Error t value Pr(>|t|)
## (Intercept) -2.56479    0.48605  -5.277 1.57e-07 ***
## X            0.64094    0.04079  15.714  < 2e-16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Approximate significance of smooth terms:
##                                edf  Ref.df      F  p-value
## s(X)                         7.047   7.612 40.215  < 2e-16 ***
## s(X):c2phonation.ordvoiced   7.191   8.131  5.061 2.41e-06 ***
## s(X):c2place.ordvelar        8.088   8.702 29.725  < 2e-16 ***
## s(X):vowel.ordo              8.257   8.776 10.910 2.49e-15 ***
## s(X,rec.date)              115.667 195.000  2.711  < 2e-16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Rank: 237/238
## R-sq.(adj) =   0.92   Deviance explained = 77.4%
## -ML = 2848.9  Scale est. = 6.7751    n = 1319
```

```
it02_gamm_ar_null <- bam(
    Y ~
        X +
        s(X, bs = "cr") +
#        s(X, by = c2phonation.ord, bs = "cr") +
        s(X, by = c2place.ord, bs = "cr") +
        s(X, by = vowel.ord, bs = "cr") +
        s(X, rec.date, bs = "fs", xt = "cr", m = 1, k = 5),
    data = it02_clos,
    method = "ML",
    rho = rho,
```

```
    AR.start = it02_clos$start.event
)
```

```
## Warning in gam.side(sm, X, tol = .Machine$double.eps^0.5): model has
## repeated 1-d smooths of same variable.
```

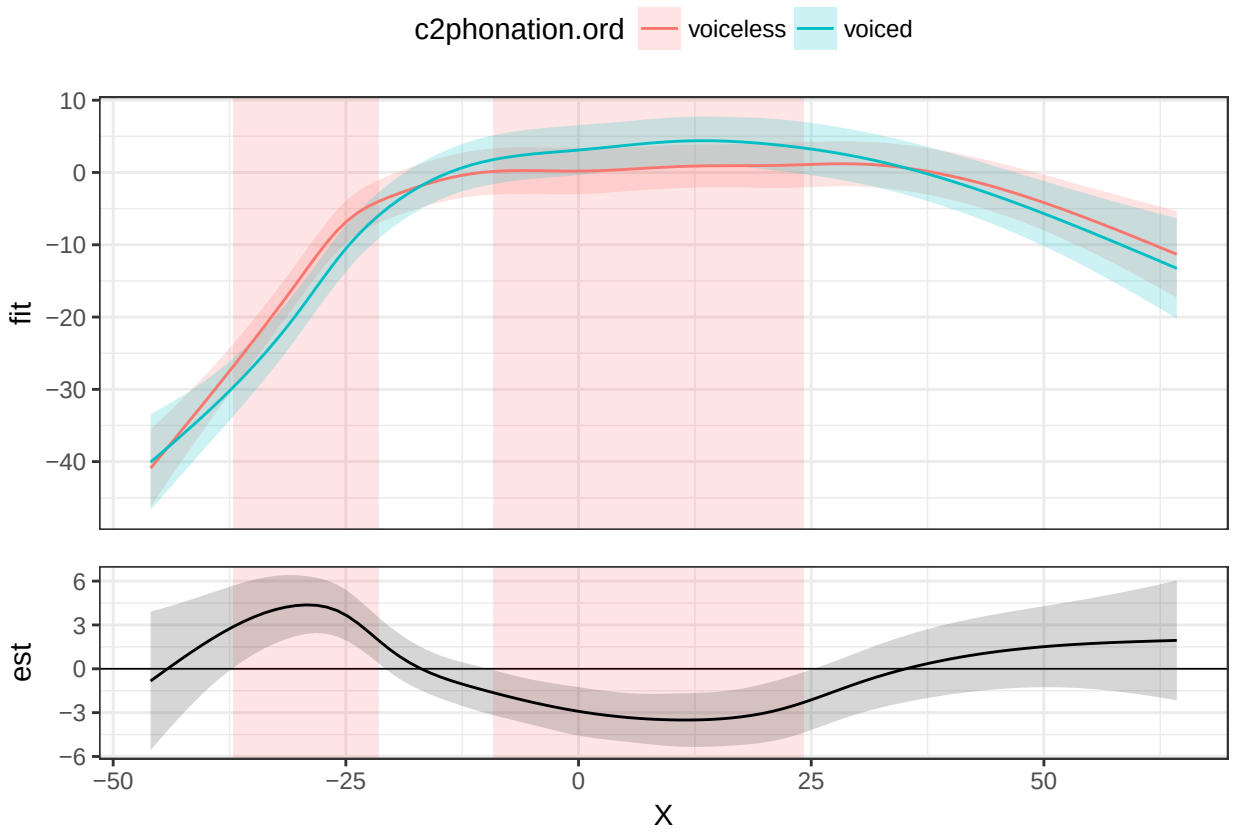
```
compareML(it02_gamm_ar_null, it02_gamm_ar)
```

```
## it02_gamm_ar_null: Y ~ X + s(X, bs = "cr") + s(X, by = c2place.ord, bs = "cr") +
##     s(X, by = vowel.ord, bs = "cr") + s(X, rec.date, bs = "fs",
##     xt = "cr", m = 1, k = 5)
##
## it02_gamm_ar: Y ~ X + s(X, bs = "cr") + s(X, by = c2phonation.ord, bs = "cr") +
##     s(X, by = c2place.ord, bs = "cr") + s(X, by = vowel.ord,
##     bs = "cr") + s(X, rec.date, bs = "fs", xt = "cr", m = 1,
##     k = 5)
##
## Chi-square test of ML scores
## -----
##               Model    Score Edf Difference    Df   p.value Sig.
## 1 it02_gamm_ar_null 2861.022  11
## 2      it02_gamm_ar 2848.944  13     12.078 2.000 5.680e-06  ***
##
## AIC difference: 18.39, model it02_gamm_ar has lower AIC.
```

```
## Warning in compareML(it02_gamm_ar_null, it02_gamm_ar): AIC might not be
## reliable, as an AR1 model is included (rho1 = 0.718876, rho2 = 0.718876).
```

```
plot_gamsd(
    it02_gamm_ar,
    view = "X",
    comparison = list(c2phonation.ord = c("voiceless", "voiced")),
    conditions = list(c2place.ord = "coronal")
)
```

```
## Summary:
##  * X : numeric predictor; with 100 values ranging from -45.980000 to 64.280100.
##  * c2phonation.ord : factor; set to the value(s): voiced, voiceless.
##  * c2place.ord : factor; set to the value(s): coronal.
##  * vowel.ord : factor; set to the value(s): o.
##  * rec.date : factor; set to the value(s): 12/12/2016 14:44:52.
```



4.2 Polish

4.2.1 PL02

```
pl02_clos <- filter(tongues_clos, speaker == "pl02", X > -20)

pl02_gamm <- bam(
    Y ~
        X +
        s(X, bs = "cr") +
        s(X, by = c2phonation.ord, bs = "cr") +
        s(X, by = c2place.ord, bs = "cr") +
        s(X, by = vowel.ord, bs = "cr") +
        s(X, rec.date, bs = "fs", xt = "cr", m = 1, k = 5),
    data = pl02_clos,
    method = "ML"
)
```

```
## Warning in gam.side(sm, X, tol = .Machine$double.eps^0.5): model has
## repeated 1-d smooths of same variable.
```

```
rho <- start_value_rho(pl02_gamm)

pl02_gamm_ar <- bam(
    Y ~
        X +
```

```
        s(X, bs = "cr") +
        s(X, by = c2phonation.ord, bs = "cr") +
        s(X, by = c2place.ord, bs = "cr") +
        s(X, by = vowel.ord, bs = "cr") +
        s(X, rec.date, bs = "fs", xt = "cr", m = 1, k = 5),
    data = pl02_clos,
    method = "ML",
    rho = rho,
    AR.start = pl02_clos$start.event
)
```

```
## Warning in gam.side(sm, X, tol = .Machine$double.eps^0.5): model has
## repeated 1-d smooths of same variable.
```

```
summary(pl02_gamm_ar)
```

```
##
## Family: gaussian
## Link function: identity
##
## Formula:
## Y ~ X + s(X, bs = "cr") + s(X, by = c2phonation.ord, bs = "cr") +
##     s(X, by = c2place.ord, bs = "cr") + s(X, by = vowel.ord,
##     bs = "cr") + s(X, rec.date, bs = "fs", xt = "cr", m = 1,
##     k = 5)
##
## Parametric coefficients:
##             Estimate Std. Error t value Pr(>|t|)
## (Intercept)  5.32290    0.39224  13.570   <2e-16 ***
## X           -0.04301    0.03666  -1.173    0.241
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Approximate significance of smooth terms:
##                                edf  Ref.df       F  p-value
## s(X)                         6.573   7.431  15.117  < 2e-16 ***
## s(X):c2phonation.ordvoiced   1.006   1.009   0.372 0.544001
## s(X):c2place.ordvelar        8.705   8.935 122.916  < 2e-16 ***
## s(X):vowel.ordo              4.822   5.916   4.676 0.000103 ***
## s(X,rec.date)              173.512 315.000   5.860  < 2e-16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Rank: 357/358
## R-sq.(adj) =  0.913   Deviance explained = 85.6%
## -ML =   3918  Scale est. = 3.9958    n = 1844
```

```
pl02_gamm_ar_null <- bam(
    Y ~
        X +
        s(X, bs = "cr") +
        s(X, by = c2place.ord, bs = "cr") +
        s(X, by = vowel.ord, bs = "cr") +
        s(X, rec.date, bs = "fs", xt = "cr", m = 1, k = 5),
    data = pl02_clos,
```

```
    method = "ML",
    rho = rho,
    AR.start = pl02_clos$start.event
)
```

```
## Warning in gam.side(sm, X, tol = .Machine$double.eps^0.5): model has
## repeated 1-d smooths of same variable.
```

```
compareML(pl02_gamm_ar_null, pl02_gamm_ar)
```

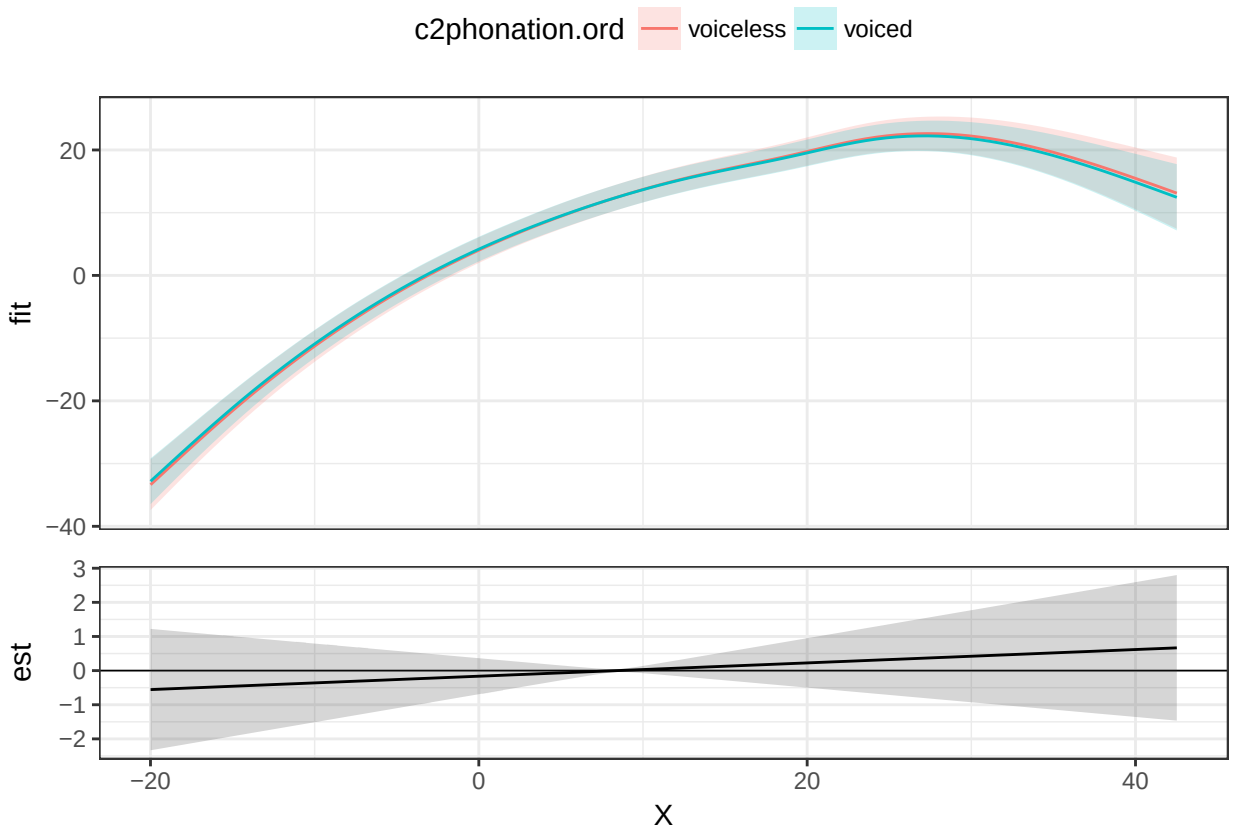
```
## pl02_gamm_ar_null: Y ~ X + s(X, bs = "cr") + s(X, by = c2place.ord, bs = "cr") +
##     s(X, by = vowel.ord, bs = "cr") + s(X, rec.date, bs = "fs",
##     xt = "cr", m = 1, k = 5)
##
## pl02_gamm_ar: Y ~ X + s(X, bs = "cr") + s(X, by = c2phonation.ord, bs = "cr") +
##     s(X, by = c2place.ord, bs = "cr") + s(X, by = vowel.ord,
##     bs = "cr") + s(X, rec.date, bs = "fs", xt = "cr", m = 1,
##     k = 5)
##
## Chi-square test of ML scores
## -----
##               Model    Score Edf Difference    Df p.value Sig.
## 1 pl02_gamm_ar_null 3918.139  11
## 2      pl02_gamm_ar 3917.953  13      0.186 2.000   0.830
##
## AIC difference: 0.01, model pl02_gamm_ar has lower AIC.
```

```
## Warning in compareML(pl02_gamm_ar_null, pl02_gamm_ar): AIC might not be
## reliable, as an AR1 model is included (rho1 = 0.460962, rho2 = 0.460962).
```

```
## Warning in compareML(pl02_gamm_ar_null, pl02_gamm_ar): Only small difference in ML...
```

```
plot_gamsd(
    pl02_gamm_ar,
    view = "X",
    comparison = list(c2phonation.ord = c("voiceless", "voiced")),
    conditions = list(c2place.ord = "coronal")
)
```

```
## Summary:
##  * X : numeric predictor; with 100 values ranging from -19.993600 to 42.515500.
##  * c2phonation.ord : factor; set to the value(s): voiced, voiceless.
##  * c2place.ord : factor; set to the value(s): coronal.
##  * vowel.ord : factor; set to the value(s): a.
##  * rec.date : factor; set to the value(s): 07/02/2017 16:21:39.
```



4.2.2 PL04

```
pl04_clos <- filter(tongues_clos, speaker == "pl04", X > -25)

pl04_gamm <- bam(
    Y ~
        X +
        s(X, bs = "cr") +
        s(X, by = c2phonation.ord, bs = "cr") +
        s(X, by = c2place.ord, bs = "cr") +
        s(X, by = vowel.ord, bs = "cr") +
        s(X, rec.date, bs = "fs", xt = "cr", m = 1, k = 5),
    data = pl04_clos,
    method = "ML"
)
```

```
## Warning in gam.side(sm, X, tol = .Machine$double.eps^0.5): model has
## repeated 1-d smooths of same variable.
```

```
rho <- start_value_rho(pl04_gamm)

pl04_gamm_ar <- bam(
    Y ~
        X +
        s(X, bs = "cr") +
        s(X, by = c2phonation.ord, bs = "cr") +
        s(X, by = c2place.ord, bs = "cr") +
```

```
        s(X, by = vowel.ord, bs = "cr") +
        s(X, rec.date, bs = "fs", xt = "cr", m = 1, k = 5),
    data = pl04_clos,
    method = "ML",
    rho = rho,
    AR.start = pl04_clos$start.event
)
```

```
## Warning in gam.side(sm, X, tol = .Machine$double.eps^0.5): model has
## repeated 1-d smooths of same variable.
```

```
summary(pl04_gamm_ar)
```

```
##
## Family: gaussian
## Link function: identity
##
## Formula:
## Y ~ X + s(X, bs = "cr") + s(X, by = c2phonation.ord, bs = "cr") +
##     s(X, by = c2place.ord, bs = "cr") + s(X, by = vowel.ord,
##     bs = "cr") + s(X, rec.date, bs = "fs", xt = "cr", m = 1,
##     k = 5)
##
## Parametric coefficients:
##             Estimate Std. Error t value Pr(>|t|)
## (Intercept)  0.82123    0.12145   6.762 2.28e-11 ***
## X           -0.14649    0.01221 -11.995  < 2e-16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Approximate significance of smooth terms:
##                                edf  Ref.df       F  p-value
## s(X)                         7.910   7.978 231.653  < 2e-16 ***
## s(X):c2phonation.ordvoiced   4.587   5.667   1.006    0.355
## s(X):c2place.ordvelar        6.586   7.722   6.921 1.44e-08 ***
## s(X):vowel.ordo              8.638   8.943  61.281  < 2e-16 ***
## s(X,rec.date)              177.603 235.000  16.079  < 2e-16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Rank: 277/278
## R-sq.(adj) =   0.99   Deviance explained = 98.2%
## -ML = 924.74  Scale est. = 0.20121   n = 1237
```

```
pl04_gamm_ar_null <- bam(
    Y ~
        X +
        s(X, bs = "cr") +
        s(X, by = c2place.ord, bs = "cr") +
        s(X, by = vowel.ord, bs = "cr") +
        s(X, rec.date, bs = "fs", xt = "cr", m = 1, k = 5),
    data = pl04_clos,
    method = "ML",
    rho = rho,
    AR.start = pl04_clos$start.event
```

```
)
```

```
## Warning in gam.side(sm, X, tol = .Machine$double.eps^0.5): model has
## repeated 1-d smooths of same variable.
```

```
compareML(pl04_gamm_ar_null, pl04_gamm_ar)
```

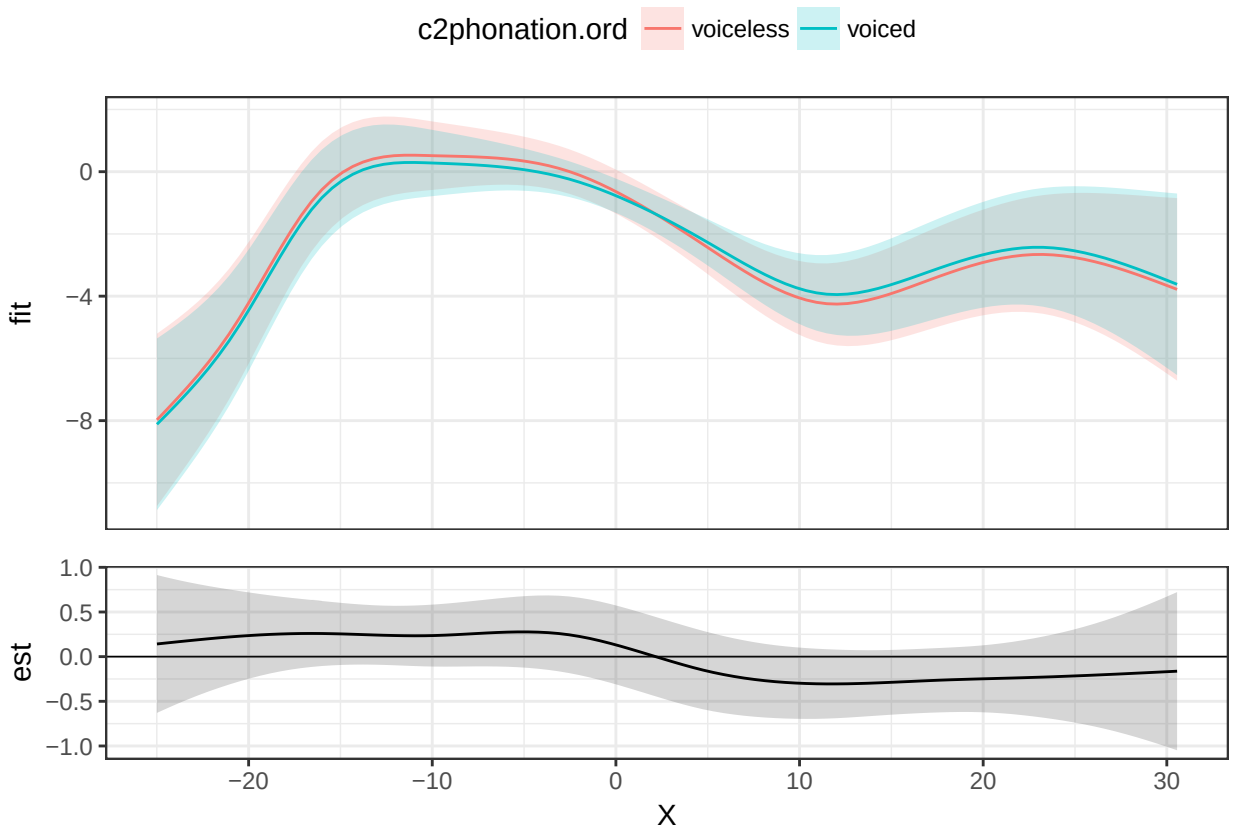
```
## pl04_gamm_ar_null: Y ~ X + s(X, bs = "cr") + s(X, by = c2place.ord, bs = "cr") +
##     s(X, by = vowel.ord, bs = "cr") + s(X, rec.date, bs = "fs",
##     xt = "cr", m = 1, k = 5)
##
## pl04_gamm_ar: Y ~ X + s(X, bs = "cr") + s(X, by = c2phonation.ord, bs = "cr") +
##     s(X, by = c2place.ord, bs = "cr") + s(X, by = vowel.ord,
##     bs = "cr") + s(X, rec.date, bs = "fs", xt = "cr", m = 1,
##     k = 5)
##
## Chi-square test of ML scores
## -----
##                Model    Score Edf Difference    Df p.value Sig.
## 1 pl04_gamm_ar_null 926.0129  11
## 2      pl04_gamm_ar 924.7407  13      1.272 2.000   0.280
##
## AIC difference: 3.22, model pl04_gamm_ar has lower AIC.
```

```
## Warning in compareML(pl04_gamm_ar_null, pl04_gamm_ar): AIC might not be
## reliable, as an AR1 model is included (rho1 = 0.472434, rho2 = 0.472434).
```

```
## Warning in compareML(pl04_gamm_ar_null, pl04_gamm_ar): Only small difference in ML...
```

```
plot_gamsd(
    pl04_gamm_ar,
    view = "X",
    comparison = list(c2phonation.ord = c("voiceless", "voiced")),
    conditions = list(c2place.ord = "coronal")
)
```

```
## Summary:
##  * X : numeric predictor; with 100 values ranging from -24.991700 to 30.560600.
##  * c2phonation.ord : factor; set to the value(s): voiced, voiceless.
##  * c2place.ord : factor; set to the value(s): coronal.
##  * vowel.ord : factor; set to the value(s): a.
##  * rec.date : factor; set to the value(s): 26/05/2017 18:00:08.
```



5 Comparison tongue at closure and maximum displacement in Italian

5.1 IT01

```
it01_voiced <- rbind(it01_max, it01_clos) %>%
    filter(c2phonation == "voiced") %>%
    mutate(
        position = ifelse(label %in% c("max_TT", "max_TD"), "maximum", "closure"),
        position_ord = ordered(position, levels = c("maximum", "closure"))
    ) %>%
    unite(item_no, seconds:rec.date) %>%
    mutate_if(is.character, as.factor)
```

```
it01_voiced_gamm <- bam(
    Y ~
        X.re +
        s(X, bs = "cr") +
        s(X, by = position_ord, bs = "cr") +
        s(X, by = c2place.ord, bs = "cr") +
        s(X, by = vowel.ord, bs = "cr") +
        s(X, item_no, bs = "fs", xt = "cr", m = 1, k = 5),
    data = it01_voiced,
    method = "fREML"
```

```
)
```

```
## Warning in gam.side(sm, X, tol = .Machine$double.eps^0.5): model has
## repeated 1-d smooths of same variable.
```

```
rho <- start_value_rho(it01_voiced_gamm)

it01_voiced_gamm_ar <- bam(
    Y ~
        X +
        s(X, bs = "cr") +
        s(X, by = position_ord, bs = "cr") +
        s(X, by = c2place.ord, bs = "cr") +
        s(X, by = vowel.ord, bs = "cr") +
        s(X, item_no, bs = "fs", xt = "cr", m = 1, k = 5),
    data = it01_voiced,
    method = "ML",
    rho = rho,
    AR.start = it01_voiced$start.event
)
```

```
## Warning in gam.side(sm, X, tol = .Machine$double.eps^0.5): model has
## repeated 1-d smooths of same variable.
```

```
summary(it01_voiced_gamm_ar)
```

```
##
## Family: gaussian
## Link function: identity
##
## Formula:
## Y ~ X + s(X, bs = "cr") + s(X, by = position_ord, bs = "cr") +
##     s(X, by = c2place.ord, bs = "cr") + s(X, by = vowel.ord,
##     bs = "cr") + s(X, item_no, bs = "fs", xt = "cr", m = 1, k = 5)
##
## Parametric coefficients:
##             Estimate Std. Error t value Pr(>|t|)
## (Intercept) -2.06151    0.32749  -6.295 3.92e-10 ***
## X            0.96067    0.02656  36.166  < 2e-16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Approximate significance of smooth terms:
##                               edf  Ref.df       F  p-value
## s(X)                        7.594   7.881 313.331  < 2e-16 ***
## s(X):position_ordclosure    3.981   4.904  11.740 6.68e-11 ***
## s(X):c2place.ordvelar       8.186   8.585 219.239  < 2e-16 ***
## s(X):vowel.ordo             6.676   7.561  16.233  < 2e-16 ***
## s(X,item_no)               79.093 225.000   1.544  < 2e-16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Rank: 267/268
## R-sq.(adj) =   0.98   Deviance explained = 92.5%
## -ML = 3204.3  Scale est. = 3.8788    n = 1776
```

```
it01_voiced_gamm_ar_null <- bam(
    Y ~
        X +
        s(X, bs = "cr") +
#        s(X, by = c2phonation.ord, bs = "cr") +
        s(X, by = c2place.ord, bs = "cr") +
        s(X, by = vowel.ord, bs = "cr") +
        s(X, item_no, bs = "fs", xt = "cr", m = 1, k = 5),
    data = it01_voiced,
    method = "ML",
    rho = rho,
    AR.start = it01_voiced$start.event
)
```

```
## Warning in gam.side(sm, X, tol = .Machine$double.eps^0.5): model has
## repeated 1-d smooths of same variable.
```

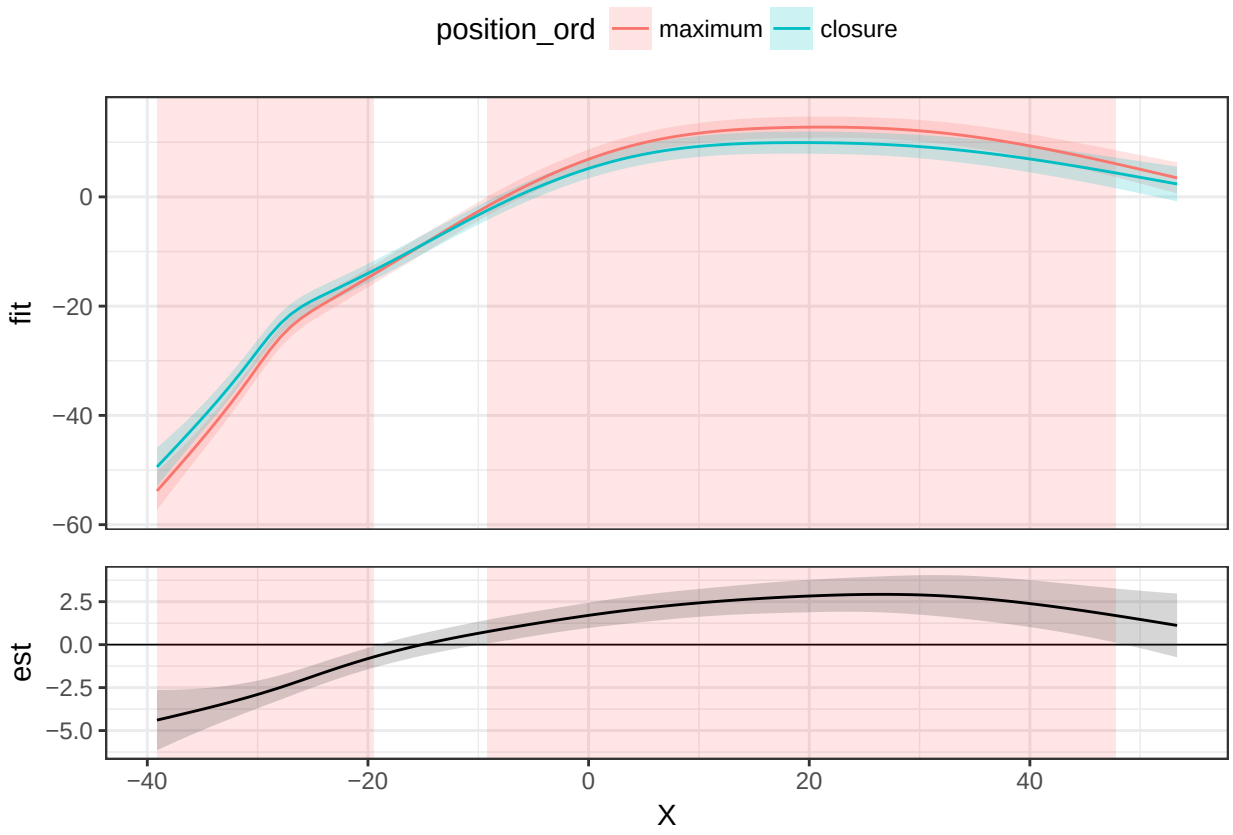
```
compareML(it01_voiced_gamm_ar_null, it01_voiced_gamm_ar)
```

```
## it01_voiced_gamm_ar_null: Y ~ X + s(X, bs = "cr") + s(X, by = c2place.ord, bs = "cr") +
##     s(X, by = vowel.ord, bs = "cr") + s(X, item_no, bs = "fs",
##     xt = "cr", m = 1, k = 5)
##
## it01_voiced_gamm_ar: Y ~ X + s(X, bs = "cr") + s(X, by = position_ord, bs = "cr") +
##     s(X, by = c2place.ord, bs = "cr") + s(X, by = vowel.ord,
##     bs = "cr") + s(X, item_no, bs = "fs", xt = "cr", m = 1, k = 5)
##
## Chi-square test of ML scores
## -----
##                       Model    Score Edf Difference    Df   p.value Sig.
## 1 it01_voiced_gamm_ar_null 3224.556  11
## 2      it01_voiced_gamm_ar 3204.308  13     20.248 2.000 1.608e-09  ***
##
## AIC difference: 8.12, model it01_voiced_gamm_ar has lower AIC.
```

```
## Warning in compareML(it01_voiced_gamm_ar_null, it01_voiced_gamm_ar): AIC
## might not be reliable, as an AR1 model is included (rho1 = 0.727873, rho2 =
## 0.727873).
```

```
plot_gamsd(
    it01_voiced_gamm_ar,
    view = "X",
    comparison = list(position_ord = c("maximum", "closure")),
    conditions = list(c2place.ord = "coronal")
)
```

```
## Summary:
##  * X : numeric predictor; with 100 values ranging from -39.125800 to 53.346500.
##  * position_ord : factor; set to the value(s): closure, maximum.
##  * c2place.ord : factor; set to the value(s): coronal.
##  * vowel.ord : factor; set to the value(s): a.
##  * item_no : factor; set to the value(s): 1.0035_29/11/2016 15:16:05.
```



5.2 IT02

```
it02_voiced <- rbind(it02_max, it02_clos) %>%
    filter(c2phonation == "voiced") %>%
    mutate(
        position = ifelse(label %in% c("max_TT", "max_TD"), "maximum", "closure"),
        position_ord = ordered(position, levels = c("maximum", "closure"))
    ) %>%
    unite(item_no, seconds:rec.date) %>%
    mutate_if(is.character, as.factor)
```

```
it02_voiced_gamm <- bam(
    Y ~
        X.re +
        s(X, bs = "cr") +
        s(X, by = position_ord, bs = "cr") +
        s(X, by = c2place.ord, bs = "cr") +
        s(X, by = vowel.ord, bs = "cr") +
        s(X, item_no, bs = "fs", xt = "cr", m = 1, k = 5),
    data = it02_voiced,
    method = "fREML"
)
```

```
## Warning in gam.side(sm, X, tol = .Machine$double.eps^0.5): model has
## repeated 1-d smooths of same variable.
```

```r
rho <- start_value_rho(it02_voiced_gamm)

it02_voiced_gamm_ar <- bam(
    Y ~
        X +
        s(X, bs = "cr") +
        s(X, by = position_ord, bs = "cr") +
        s(X, by = c2place.ord, bs = "cr") +
        s(X, by = vowel.ord, bs = "cr") +
        s(X, item_no, bs = "fs", xt = "cr", m = 1, k = 5),
    data = it02_voiced,
    method = "ML",
    rho = rho,
    AR.start = it02_voiced$start.event
)
```

```
## Warning in gam.side(sm, X, tol = .Machine$double.eps^0.5): model has
## repeated 1-d smooths of same variable.
```

```r
summary(it02_voiced_gamm_ar)
```

```
##
## Family: gaussian
## Link function: identity
##
## Formula:
## Y ~ X + s(X, bs = "cr") + s(X, by = position_ord, bs = "cr") +
##     s(X, by = c2place.ord, bs = "cr") + s(X, by = vowel.ord,
##     bs = "cr") + s(X, item_no, bs = "fs", xt = "cr", m = 1, k = 5)
##
## Parametric coefficients:
##             Estimate Std. Error t value Pr(>|t|)
## (Intercept) -2.97114    0.44076  -6.741 2.46e-11 ***
## X            0.57698    0.03402  16.962  < 2e-16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Approximate significance of smooth terms:
##                              edf  Ref.df      F  p-value
## s(X)                       7.127   7.649 62.981  < 2e-16 ***
## s(X):position_ordclosure   6.504   7.557  5.531 1.85e-06 ***
## s(X):c2place.ordvelar      8.345   8.814 51.634  < 2e-16 ***
## s(X):vowel.ordo            6.660   7.696 13.608  < 2e-16 ***
## s(X,item_no)              82.051 190.000  1.387  < 2e-16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Rank: 232/233
## R-sq.(adj) =  0.911   Deviance explained = 69.8%
## -ML = 2913.1  Scale est. = 9.7551    n = 1286
```

```r
it02_voiced_gamm_ar_null <- bam(
    Y ~
        X +
        s(X, bs = "cr") +
```

```
#         s(X, by = c2phonation.ord, bs = "cr") +
        s(X, by = c2place.ord, bs = "cr") +
        s(X, by = vowel.ord, bs = "cr") +
        s(X, item_no, bs = "fs", xt = "cr", m = 1, k = 5),
    data = it02_voiced,
    method = "ML",
    rho = rho,
    AR.start = it02_voiced$start.event
)
```

```
## Warning in gam.side(sm, X, tol = .Machine$double.eps^0.5): model has
## repeated 1-d smooths of same variable.
```

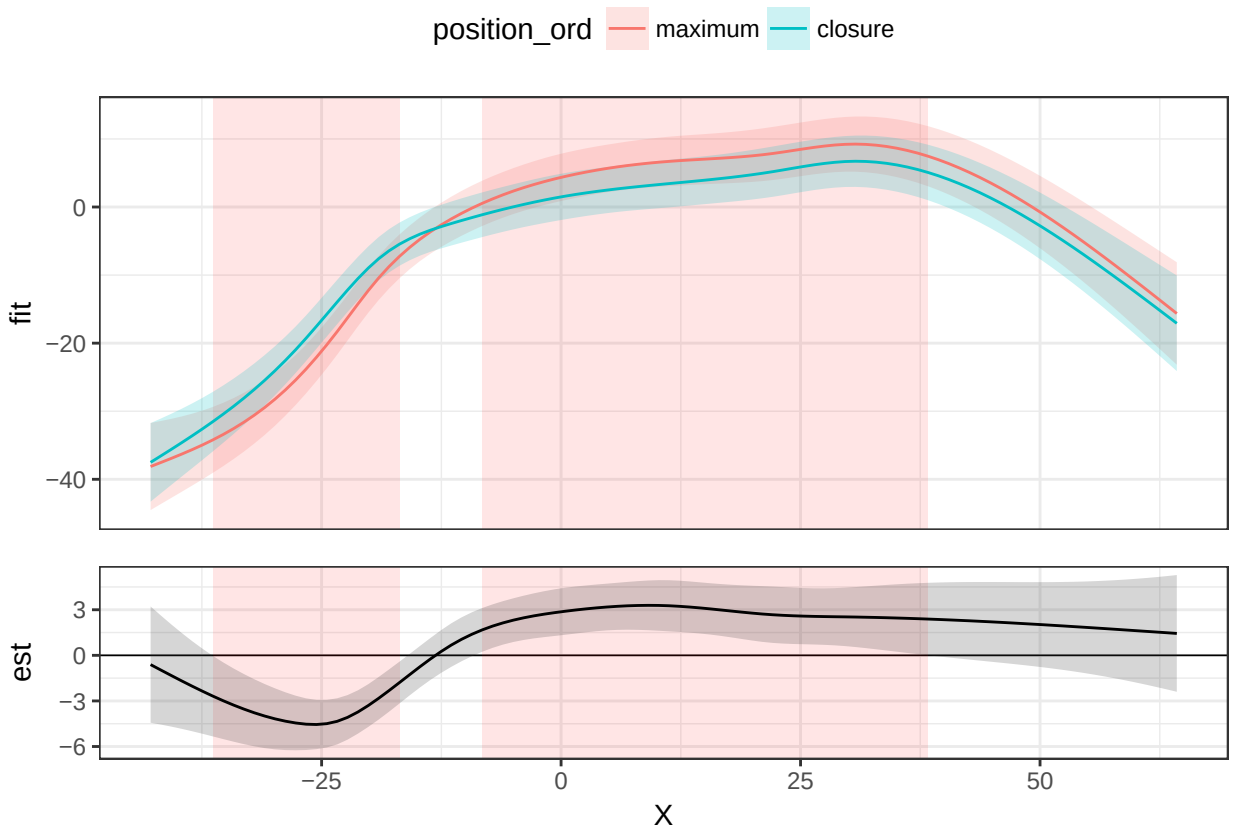
```
compareML(it02_voiced_gamm_ar_null, it02_voiced_gamm_ar)
```

```
## it02_voiced_gamm_ar_null: Y ~ X + s(X, bs = "cr") + s(X, by = c2place.ord, bs = "cr") +
##     s(X, by = vowel.ord, bs = "cr") + s(X, item_no, bs = "fs",
##     xt = "cr", m = 1, k = 5)
##
## it02_voiced_gamm_ar: Y ~ X + s(X, bs = "cr") + s(X, by = position_ord, bs = "cr") +
##     s(X, by = c2place.ord, bs = "cr") + s(X, by = vowel.ord,
##     bs = "cr") + s(X, item_no, bs = "fs", xt = "cr", m = 1, k = 5)
##
## Chi-square test of ML scores
## -----
##                       Model   Score Edf Difference    Df   p.value Sig.
## 1 it02_voiced_gamm_ar_null 2925.68  11
## 2      it02_voiced_gamm_ar 2913.15  13     12.531 2.000 3.614e-06  ***
##
## AIC difference: 20.47, model it02_voiced_gamm_ar has lower AIC.
```

```
## Warning in compareML(it02_voiced_gamm_ar_null, it02_voiced_gamm_ar): AIC
## might not be reliable, as an AR1 model is included (rho1 = 0.741853, rho2 =
## 0.741853).
```

```
plot_gamsd(
    it02_voiced_gamm_ar,
    view = "X",
    comparison = list(position_ord = c("maximum", "closure")),
    conditions = list(c2place.ord = "coronal")
)
```

```
## Summary:
##  * X : numeric predictor; with 100 values ranging from -42.852800 to 64.280100.
##  * position_ord : factor; set to the value(s): closure, maximum.
##  * c2place.ord : factor; set to the value(s): coronal.
##  * vowel.ord : factor; set to the value(s): a.
##  * item_no : factor; set to the value(s): 1.2585_12/12/2016 14:42:43.
```



6 Summary

Italian has TRA at closure and maximum displacement. Polish does not have TRA. Italian TR at closure is less advanced than at maximum displacement.

Italian vowels are 22 msec longer if followed by voiced stops. Polish vowels are 8 msec longer if followed by voiced stops.