M21 LDT ERP N250

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Contents

Set parameters

Set chunk parameters

Load libraries

Set ggplot parameters

Define standard error of the mean function

1 Load and format data files

```
erp_2 <- read_csv("m21_ldt_mea_200300_050050_1.csv")
erp_4 <- read_csv("m21_ldt_mea_300500_050050_1.csv")
dmg_lng_vsl <- read_csv("demo_lang_vsl_pca_hc.csv")
```

Now we extract `SubjID` from the `ERPset` column

```
# Remove '_LDT_diff_waves' from each string in the ERPset column
# This code first renames the column and then applies the `str_replace` function
# to the newly renamed column.
erp_2 <- erp_2 |>
  rename(SubjID = ERPset) |>
  mutate(SubjID = str_replace(SubjID, "_LDT_diff_waves", "")) |>
```

```
  mutate(binlabel = str_replace(binlabel, "Critical_", "")) |>
  mutate(binlabel = str_replace(binlabel, "_family", "")) |>
  select(-mlabel)

erp_4 <- erp_4 |>
  rename(SubjID = ERPset) |>
  mutate(SubjID = str_replace(SubjID, "_LDT_diff_waves", "")) |>
  mutate(binlabel = str_replace(binlabel, "Critical_", "")) |>
  mutate(binlabel = str_replace(binlabel, "_family", "")) |>
  select(-mlabel)
```

We then join the ERP data and language into a single data frame

```
n250 <- erp_2 |>
  left_join(dmg_lng_vsl, by = "SubjID") |>
  select(SubjID, everything())
n400 <- erp_4 |>
  left_join(dmg_lng_vsl, by = "SubjID") |>
  select(SubjID, everything())
```

Divide into word, non-word and difference wave dataframes

Then we do some more formatting and cleanup of the dataframes.We create separate columns, one for each independent variable (anteriority, laterality, morphological family size). To do this we have to use `seperate` function from the `stringr` package. Run `vignette("programming", package = "dplyr")` to see more about `tidy-selection` and `tidy-evaluation`.

```
# Words
n250_words <- n250_words |>
  separate(binlabel, into = c("trial_type","family_size"), sep = "_", remove = TRUE) |>
  select(-trial_type)
n250_words_b <- n250_words_b |>
  separate(binlabel, into = c("trial_type", "family_size","tmp1", "base_freq", "tmp2"), sep = "_", remove = TRUE) |>
  select(-c(trial_type, tmp1, tmp2))

n400_words <- n400_words |>
  separate(binlabel, into = c("trial_type","family_size"), sep = "_", remove = TRUE) |>
  select(-trial_type)
n400_words_b <- n400_words_b |>
  separate(binlabel, into = c("trial_type", "family_size","tmp1", "base_freq", "tmp2"), sep = "_", remove = TRUE) |>
  select(-c(trial_type, tmp1, tmp2))

# Assuming your data frame is named 'df' and the column is named 'your_column'
n250_words_b$Orthographic_Sensitivity[n250_words_b$Orthographic_Sensitivity == "Low"] <- "Low Sensitivity"
n250_words_b$Orthographic_Sensitivity[n250_words_b$Orthographic_Sensitivity == "High"] <- "High Sensitivity"
n250_words_b$base_freq[n250_words_b$base_freq == "Low"] <- "Low Base Frequency"
n250_words_b$base_freq[n250_words_b$base_freq == "High"] <- "High Base Frequency"
n250_words_b$family_size[n250_words_b$family_size == "large"] <- "Large Family"
n250_words_b$family_size[n250_words_b$family_size == "small"] <- "Small Family"

n400_words_b$Orthographic_Sensitivity[n400_words_b$Orthographic_Sensitivity == "Low"] <- "Low Sensitivity"
n400_words_b$Orthographic_Sensitivity[n400_words_b$Orthographic_Sensitivity == "High"] <- "High Sensitivity"
n400_words_b$base_freq[n400_words_b$base_freq == "Low"] <- "Low Base Frequency"
n400_words_b$base_freq[n400_words_b$base_freq == "High"] <- "High Base Frequency"
n400_words_b$family_size[n400_words_b$family_size == "large"] <- "Large Family"
n400_words_b$family_size[n400_words_b$family_size == "small"] <- "Small Family"

# Nonwords
n250_nonwords <- n250_nonwords |>
  separate(binlabel, into = c("trial_type", "family_size", "complexity"), sep = "_", remove = TRUE) |>
  select(-trial_type)

n400_nonwords <- n400_nonwords |>
  separate(binlabel, into = c("trial_type", "family_size", "complexity"), sep = "_", remove = TRUE) |>
  select(-trial_type)

# Assuming your data frame is named 'df' and the column is named 'your_column'
n250_nonwords$Orthographic_Sensitivity[n250_nonwords$Orthographic_Sensitivity == "Low"] <- "Low Sensitivity"
n250_nonwords$Orthographic_Sensitivity[n250_nonwords$Orthographic_Sensitivity == "High"] <- "High Sensitivity"
n250_nonwords$complexity[n250_nonwords$complexity == "complex"] <- "Complex"
n250_nonwords$complexity[n250_nonwords$complexity == "simple"] <- "Simple"
n250_nonwords$family_size[n250_nonwords$family_size == "large"] <- "Large Family"
n250_nonwords$family_size[n250_nonwords$family_size == "small"] <- "Small Family"

n400_nonwords$Orthographic_Sensitivity[n400_nonwords$Orthographic_Sensitivity == "Low"] <- "Low Sensitivity"
n400_nonwords$Orthographic_Sensitivity[n400_nonwords$Orthographic_Sensitivity == "High"] <- "High Sensitivity"
n400_nonwords$complexity[n400_nonwords$complexity == "complex"] <- "Complex"
n400_nonwords$complexity[n400_nonwords$complexity == "simple"] <- "Simple"
n400_nonwords$family_size[n400_nonwords$family_size == "large"] <- "Large Family"
n400_nonwords$family_size[n400_nonwords$family_size == "small"] <- "Small Family"
```

Now we need to extract just the bins and channels that we intend to analyse. For this analysis we will use 9 channels: F3, Fz, F4, C3,

Cz, C4, P3, Pz, P4 . We will use themutate function from the dplyr package along with the case_when function. The case_when function is a sequence of two-sided formulas. The left hand side determines which values match this case. The right hand side provides the replacement value.

```
channels_1 <-  c(3, 2, 25, 7, 20, 21, 12, 11, 16)
channels_2 <-  c(3, 2, 29, 8, 23, 24, 14, 13, 19)

# Words
n250_words <- n250_words |>
  filter(chindex %in% channels_1) |>
  mutate(anteriority = case_when(grepl("F", chlabel) ~ "Frontal",
                                 grepl("C", chlabel) ~ "Central",
                                 grepl("P", chlabel) ~ "Parietal"),
         laterality = case_when(grepl("3", chlabel) ~ "Left",grepl("z", chlabel) ~ "Midline",
                                grepl("Z", chlabel) ~ "Midline",grepl("4", chlabel) ~ "Right"))
n250_words$anteriority <- factor(n250_words$anteriority, levels = c("Frontal",  "Central",  "Parietal"))
n250_words$laterality <- factor(n250_words$laterality, levels = c("Left", "Midline", "Right"))

n250_words_b <- n250_words_b |>
  filter(chindex %in% channels_1) |>
  mutate(anteriority = case_when(grepl("F", chlabel) ~ "Frontal",
                                 grepl("C", chlabel) ~ "Central",
                                 grepl("P", chlabel) ~ "Parietal"),
         laterality = case_when(grepl("3", chlabel) ~ "Left",grepl("z", chlabel) ~ "Midline",
                                grepl("Z", chlabel) ~ "Midline",grepl("4", chlabel) ~ "Right"))
n250_words_b$anteriority <- factor(n250_words_b$anteriority, levels = c("Frontal",  "Central",  "Parietal"))
n250_words_b$laterality <- factor(n250_words_b$laterality, levels = c("Left", "Midline", "Right"))

n400_words <- n400_words |>
  filter(chindex %in% channels_1) |>
  mutate(anteriority = case_when(grepl("F", chlabel) ~ "Frontal",
                                 grepl("C", chlabel) ~ "Central",
                                 grepl("P", chlabel) ~ "Parietal"),
         laterality = case_when(grepl("3", chlabel) ~ "Left",grepl("z", chlabel) ~ "Midline",
                                grepl("Z", chlabel) ~ "Midline",grepl("4", chlabel) ~ "Right"))
n400_words$anteriority <- factor(n400_words$anteriority, levels = c("Frontal",  "Central",  "Parietal"))
n400_words$laterality <- factor(n400_words$laterality, levels = c("Left", "Midline", "Right"))

n400_words_b <- n400_words_b |>
  filter(chindex %in% channels_1) |>
  mutate(anteriority = case_when(grepl("F", chlabel) ~ "Frontal",
                                 grepl("C", chlabel) ~ "Central",
                                 grepl("P", chlabel) ~ "Parietal"),
         laterality = case_when(grepl("3", chlabel) ~ "Left",grepl("z", chlabel) ~ "Midline",
                                grepl("Z", chlabel) ~ "Midline",grepl("4", chlabel) ~ "Right"))
n400_words_b$anteriority <- factor(n400_words_b$anteriority, levels = c("Frontal",  "Central",  "Parietal"))
n400_words_b$laterality <- factor(n400_words_b$laterality, levels = c("Left", "Midline", "Right"))

# Nonwords
n250_nonwords <- n250_nonwords |>
  filter(chindex %in% channels_1) |>
  mutate(anteriority = case_when(grepl("F", chlabel) ~ "Frontal",
                                 grepl("C", chlabel) ~ "Central",
                                 grepl("P", chlabel) ~ "Parietal"),
         laterality = case_when(grepl("3", chlabel) ~ "Left",grepl("z", chlabel) ~ "Midline",
                                grepl("Z", chlabel) ~ "Midline", grepl("4", chlabel) ~ "Right"))
n250_nonwords$anteriority <- factor(n250_nonwords$anteriority, levels = c("Frontal",  "Central","Parietal"))
n250_nonwords$laterality <- factor(n250_nonwords$laterality, levels = c("Left", "Midline", "Right"))

n400_nonwords <- n400_nonwords |>
  filter(chindex %in% channels_1) |>
  mutate(anteriority = case_when(grepl("F", chlabel) ~ "Frontal",
                                 grepl("C", chlabel) ~ "Central",
                                 grepl("P", chlabel) ~ "Parietal"),
         laterality = case_when(grepl("3", chlabel) ~ "Left",grepl("z", chlabel) ~ "Midline",
                                grepl("Z", chlabel) ~ "Midline", grepl("4", chlabel) ~ "Right"))
n400_nonwords$anteriority <- factor(n400_nonwords$anteriority, levels = c("Frontal",  "Central","Parietal"))
n400_nonwords$laterality <- factor(n400_nonwords$laterality, levels = c("Left", "Midline", "Right"))
```

2 N250 Word Data

2.1 Compute the ANOVA

```
anova_model_1a <- mixed(
  value ~ Orthographic_Sensitivity * family_size * base_freq  +
    laterality * anteriority  +  # Nuisance variables
    (1 | SubjID),
  data = n250_words_b,
```

```
  method = "KR")  # Kenward-Roger approximation for accurate F-tests
# Print ANOVA results
anova_model_1a
```

```
|| Mixed Model Anova Table (Type 3 tests, KR-method)
||
|| Model: value ~ Orthographic_Sensitivity * family_size * base_freq +
|| Model:     laterality * anteriority + (1 | SubjID)
|| Data: n250_words_b
||                                          Effect      df         F p.value
|| 1                         Orthographic_Sensitivity   1, 59      0.03    .854
|| 2                                      family_size 1, 2121   8.10 **    .004
|| 3                                        base_freq 1, 2121    6.24 *    .013
|| 4                                       laterality 2, 2121      0.29    .745
|| 5                                      anteriority 2, 2121 18.18 ***   <.001
|| 6            Orthographic_Sensitivity:family_size 1, 2121      0.70    .403
|| 7              Orthographic_Sensitivity:base_freq 1, 2121      0.65    .421
|| 8                          family_size:base_freq 1, 2121 14.43 ***   <.001
|| 9                         laterality:anteriority 4, 2121      0.76    .551
|| 10 Orthographic_Sensitivity:family_size:base_freq 1, 2121      0.01    .925
|| ---
|| Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '+' 0.1 ' ' 1
```

```
# Partial Eta Squared
# Extract effect sizes from your ANOVA model
eta_squared(anova_model_1a , partial = TRUE)
```

```
|| # Effect Size for ANOVA (Type III)
||
|| Parameter                                    | Eta2 (partial) |       95% CI
|| -----------------------------------------------------------------------------
|| Orthographic_Sensitivity                     |       5.82e-04 | [0.00, 1.00]
|| family_size                                  |       3.81e-03 | [0.00, 1.00]
|| base_freq                                    |       2.94e-03 | [0.00, 1.00]
|| laterality                                   |       2.78e-04 | [0.00, 1.00]
|| anteriority                                  |           0.02 | [0.01, 1.00]
|| Orthographic_Sensitivity:family_size         |       3.30e-04 | [0.00, 1.00]
|| Orthographic_Sensitivity:base_freq           |       3.05e-04 | [0.00, 1.00]
|| family_size:base_freq                        |       6.76e-03 | [0.00, 1.00]
|| laterality:anteriority                       |       1.43e-03 | [0.00, 1.00]
|| Orthographic_Sensitivity:family_size:base_freq |       4.14e-06 | [0.00, 1.00]
||
|| - One-sided CIs: upper bound fixed at [1.00].
```

```
# Compute Marginal (fixed effects) and Conditional (fixed + random effects) R²
r2(anova_model_1a)
```

```
|| # R2 for Mixed Models
||
||   Conditional R2: 0.476
||      Marginal R2: 0.017
```

2.2 Significant Effects

Effect	df	F	p.value	
family_size	1, 2121	8.10 **	.003	3.81e-03
base_freq	1, 2121	6.24 *	.010	2.94e-03
family_size:base_freq	1, 2121	14.43 ***	<.001	6.76e-03

Main Effects

```
## `family_size` main effect
pairs <- emmeans(anova_model_1a, pairwise ~ family_size, adjust = "bonferroni", pbkrtest.limit = 6480)
(pairs_df <- as.data.frame(pairs$contrasts))
```

```
||  contrast                    estimate         SE   df t.ratio p.value
||  Large Family - Small Family 0.2675816 0.09401042 2121   2.846  0.0045
||
|| Results are averaged over the levels of: Orthographic_Sensitivity, base_freq, laterality, anteriority
|| Degrees-of-freedom method: kenward-roger
```

```
cohensd <- as.data.frame(cohens_d(value ~ family_size, data = n250_words_b))
(family_size_contrasts_df <- bind_cols(pairs_df,cohensd))
```

```
||  contrast                    estimate         SE   df t.ratio p.value
||  Large Family - Small Family 0.2675816 0.09401042 2121   2.846  0.0045
||    Cohens_d   CI      CI_low   CI_high
||  0.09242177 0.95 0.008717338 0.1761052
```

```
||
|| Results are averaged over the levels of: Orthographic_Sensitivity, base_freq, laterality, anteriority
|| Degrees-of-freedom method: kenward-roger
```

```
(family_size_means <- as.data.frame(pairs$emmeans))
```

```
||  family_size      emmean        SE    df  lower.CL   upper.CL
||  Large Family -0.6228727 0.2722607 62.68 -1.166997 -0.0787487
||  Small Family -0.8904543 0.2722607 62.68 -1.434578 -0.3463303
||
|| Results are averaged over the levels of: Orthographic_Sensitivity, base_freq, laterality, anteriority
|| Degrees-of-freedom method: kenward-roger
|| Confidence level used: 0.95
```

```
## `base_freq` main effect
pairs <- emmeans(anova_model_1a, pairwise ~ base_freq, adjust = "bonferroni", pbkrtest.limit = 6480)
(pairs_df <- as.data.frame(pairs$contrasts))
```

```
||  contrast                                  estimate         SE   df t.ratio
||  High Base Frequency - Low Base Frequency -0.2349092 0.09401042 2121  -2.499
||  p.value
||   0.0125
||
|| Results are averaged over the levels of: Orthographic_Sensitivity, family_size, laterality, anteriority
|| Degrees-of-freedom method: kenward-roger
```

```
cohensd <- as.data.frame(cohens_d(value ~ base_freq, data = n250_words_b))
(base_freq_contrasts_df <- bind_cols(pairs_df,cohensd))
```

```
||  contrast                                  estimate         SE   df t.ratio
||  High Base Frequency - Low Base Frequency -0.2349092 0.09401042 2121  -2.499
||  p.value   Cohens_d   CI     CI_low     CI_high
||   0.0125 -0.0755643 0.95 -0.1592348 0.008123396
||
|| Results are averaged over the levels of: Orthographic_Sensitivity, family_size, laterality, anteriority
|| Degrees-of-freedom method: kenward-roger
```

```
(base_freq_means <- as.data.frame(pairs$emmeans))
```

```
||  base_freq               emmean        SE    df  lower.CL   upper.CL
||  High Base Frequency -0.8741181 0.2722607 62.68 -1.418242 -0.3299941
||  Low Base Frequency  -0.6392089 0.2722607 62.68 -1.183333 -0.0950849
||
|| Results are averaged over the levels of: Orthographic_Sensitivity, family_size, laterality, anteriority
|| Degrees-of-freedom method: kenward-roger
|| Confidence level used: 0.95
```

Interactions

```
# `base_freq` x `family_size` interaction

selected_contrasts_famsize <- c("Large Family High Base Frequency - Small Family High Base Frequency",
                                "Large Family Low Base Frequency - Small Family Low Base Frequency")
selected_contrasts_basefreq <- c("Large Family High Base Frequency - Large Family Low Base Frequency",
                                 "Small Family High Base Frequency - Small Family Low Base Frequency")

emmeans_obj <- emmeans(anova_model_1a, pairwise ~ family_size * base_freq, adjust = "bonferroni", pbkrtest.limit = 6480)

# Get selected contrasts and convert the emmGrid object to a dataframe
(contrasts_df <- as.data.frame(emmeans_obj$contrasts))
```

```
||  contrast                                                              estimate
||  Large Family High Base Frequency - Small Family High Base Frequency -0.0894763
||  Large Family High Base Frequency - Large Family Low Base Frequency  -0.5919671
||  Large Family High Base Frequency - Small Family Low Base Frequency   0.0326724
||  Small Family High Base Frequency - Large Family Low Base Frequency  -0.5024908
||  Small Family High Base Frequency - Small Family Low Base Frequency   0.1221487
||  Large Family Low Base Frequency - Small Family Low Base Frequency    0.6246395
||         SE   df t.ratio p.value
||  0.1329508 2121  -0.673  1.0000
||  0.1329508 2121  -4.453  0.0001
||  0.1329508 2121   0.246  1.0000
||  0.1329508 2121  -3.780  0.0010
||  0.1329508 2121   0.919  1.0000
||  0.1329508 2121   4.698  <.0001
||
|| Results are averaged over the levels of: Orthographic_Sensitivity, laterality, anteriority
|| Degrees-of-freedom method: kenward-roger
|| P value adjustment: bonferroni method for 6 tests
```

```
selected_contrasts_famsize_df <- as.data.frame(emmeans_obj$contrasts[contrasts_df$contrast %in% selected_contrasts_famsize, ])
selected_contrasts_basefrq_df <- as.data.frame(emmeans_obj$contrasts[contrasts_df$contrast %in% selected_contrasts_basefreq,])
```

```
cohensd_hi_basefrq <- as.data.frame(cohens_d(value ~ family_size,
                                    data = subset(n250_words_b, base_freq == "High Base Frequency")))
cohensd_lo_basefrq <- as.data.frame(cohens_d(value ~ family_size,
                                     data = subset(n250_words_b, base_freq == "Low Base Frequency")))
cohensd_lrg_fam <- as.data.frame(cohens_d(value ~ base_freq,
                                    data = subset(n250_words_b, family_size == "Large Family")))
cohensd_sml_fam <- as.data.frame(cohens_d(value ~ base_freq,
                                   data = subset(n250_words_b, family_size == "Small Family")))

cohensd_basefrq <- bind_rows(hi_basefrq = cohensd_hi_basefrq,
                             lo_basefrq = cohensd_lo_basefrq,
                             .id = "base_freq")

cohensd_famsize <- bind_rows(lrg_fam = cohensd_lrg_fam,
                             sml_fam = cohensd_sml_fam,
                             .id = "family_size")

(basefreq_contrasts_df <- bind_cols(selected_contrasts_basefrq_df,cohensd_basefrq))
```

```
||  contrast                                                        estimate
||  Large Family High Base Frequency - Large Family Low Base Frequency -0.5919671
||  Small Family High Base Frequency - Small Family Low Base Frequency  0.1221487
||         SE   df t.ratio p.value base_freq     Cohens_d   CI      CI_low
||  0.1329508 2121  -4.453  <.0001 hi_basefrq -0.02625453 0.95 -0.14455152
||  0.1329508 2121   0.919  0.7167 lo_basefrq  0.21467322 0.95  0.09598588
||    CI_high
||  0.0920544
||  0.3332632
||
|| Results are averaged over the levels of: Orthographic_Sensitivity, laterality, anteriority
|| Degrees-of-freedom method: kenward-roger
|| P value adjustment: bonferroni method for 2 tests
```

```
(sensitivity_contrasts_df <- bind_cols(selected_contrasts_famsize_df,cohensd_famsize))
```

```
||  contrast                                                         estimate
||  Large Family High Base Frequency - Small Family High Base Frequency -0.0894763
||  Large Family Low Base Frequency - Small Family Low Base Frequency    0.6246395
||         SE   df t.ratio p.value family_size    Cohens_d   CI      CI_low
||  0.1329508 2121  -0.673  1.0000 lrg_fam     -0.20058496 0.95 -0.3191349
||  0.1329508 2121   4.698  <.0001 sml_fam      0.04230879 0.95 -0.0760120
||      CI_high
||  -0.08194398
||   0.16061027
||
|| Results are averaged over the levels of: Orthographic_Sensitivity, laterality, anteriority
|| Degrees-of-freedom method: kenward-roger
|| P value adjustment: bonferroni method for 2 tests
```

```
(famsize.basefreq_means <- as.data.frame(emmeans_obj$emmeans))
```

```
||  family_size  base_freq               emmean        SE    df   lower.CL
||  Large Family High Base Frequency -0.9188563 0.2802585 70.36 -1.4777640
||  Small Family High Base Frequency -0.8293799 0.2802585 70.36 -1.3882876
||  Large Family Low Base Frequency  -0.3268891 0.2802585 70.36 -0.8857968
||  Small Family Low Base Frequency  -0.9515286 0.2802585 70.36 -1.5104363
||    upper.CL
||  -0.3599486
||  -0.2704722
||   0.2320186
||  -0.3926209
||
|| Results are averaged over the levels of: Orthographic_Sensitivity, laterality, anteriority
|| Degrees-of-freedom method: kenward-roger
|| Confidence level used: 0.95
```

2.3 Model Comparisons

```
# Family Size
reduced_model <- update(anova_model_1a,
                        . ~ . - family_size - Orthographic_Sensitivity:family_size - family_size:base_freq - Orthographic_Sensitivity:family_size:
anova(anova_model_1a, reduced_model)
```

```
|| Data: data
|| Models:
|| reduced_model: value ~ Orthographic_Sensitivity + base_freq + laterality + anteriority + Orthographic_Sensitivity:base_freq + laterality:anteri
|| anova_model_1a: value ~ Orthographic_Sensitivity * family_size * base_freq + laterality * anteriority + (1 | SubjID)
||                npar    AIC   BIC  logLik deviance Chisq Df Pr(>Chisq)
|| reduced_model    14 9957.5 10037 -4964.7   9929.5
|| anova_model_1a   18 9958.7 10061 -4961.4   9922.7 6.787  4     0.1476
```

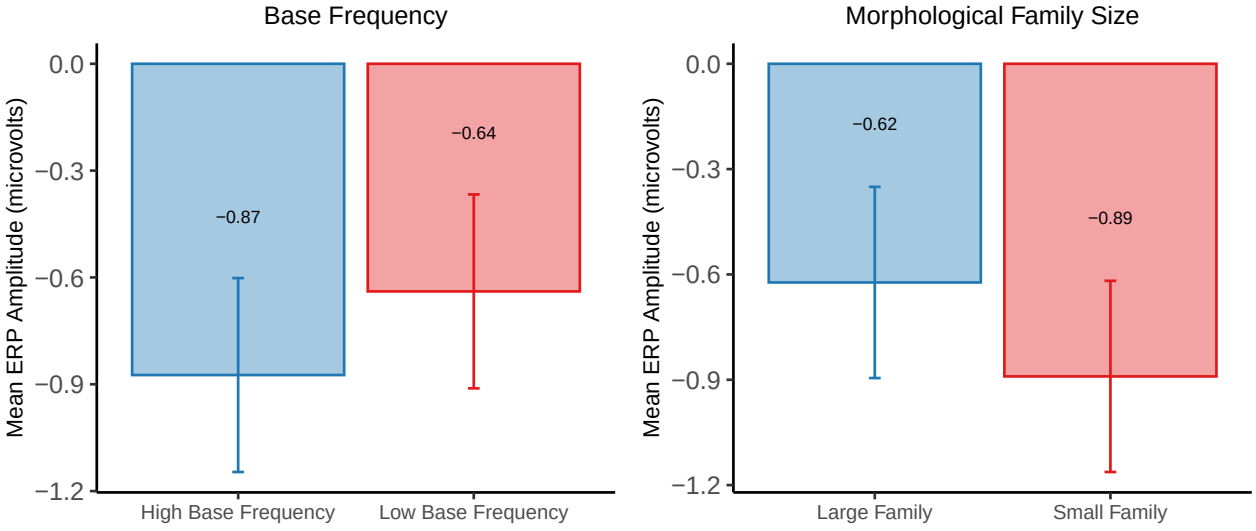
```r
# Base Frequency
reduced_model <- update(anova_model_1a,
                        . ~ . - base_freq - Orthographic_Sensitivity:base_freq - base_freq:family_size - Orthographic_Sensitivity:base_freq:family
anova(anova_model_1a, reduced_model)
```

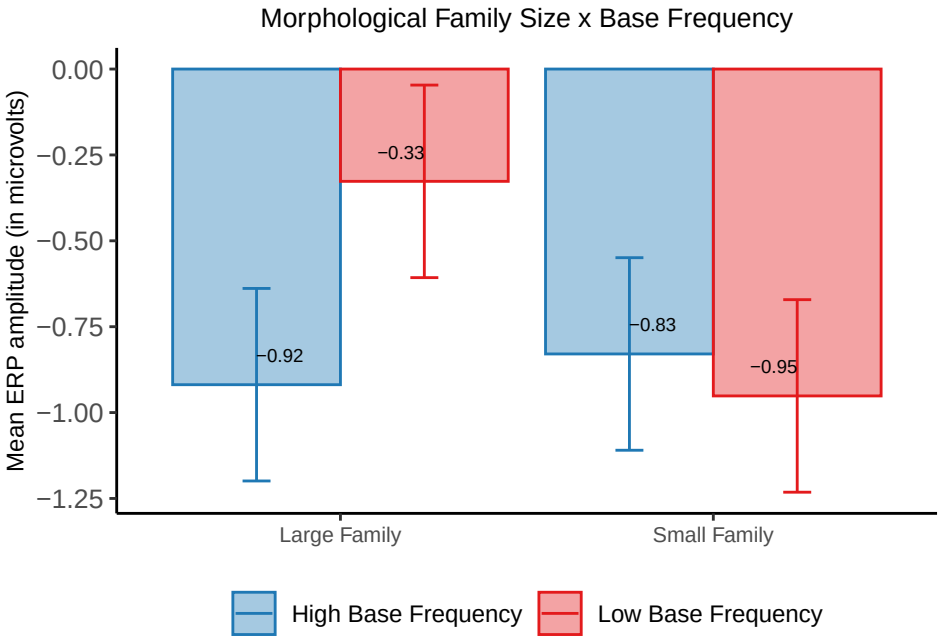
```
|| Data: data
|| Models:
|| reduced_model: value ~ Orthographic_Sensitivity + family_size + laterality + anteriority + Orthographic_Sensitivity:family_size + laterality:an
|| anova_model_1a: value ~ Orthographic_Sensitivity * family_size * base_freq + laterality * anteriority + (1 | SubjID)
||                npar    AIC   BIC  logLik deviance  Chisq Df Pr(>Chisq)
|| reduced_model    14 9954.6 10034 -4963.3   9926.6
|| anova_model_1a   18 9958.7 10061 -4961.4   9922.7 3.8562  4     0.4258
```

```r
# Family Size x Base Frequency
reduced_model_int <- update(anova_model_1a,
  . ~ . - family_size:base_freq - Orthographic_Sensitivity:family_size:base_freq)
anova(anova_model_1a, reduced_model_int)
```

```
|| Data: data
|| Models:
|| reduced_model_int: value ~ Orthographic_Sensitivity + family_size + base_freq + laterality + anteriority + Orthographic_Sensitivity:family_size
|| anova_model_1a: value ~ Orthographic_Sensitivity * family_size * base_freq + laterality * anteriority + (1 | SubjID)
||                    npar    AIC   BIC  logLik deviance  Chisq Df Pr(>Chisq)
|| reduced_model_int   16 9960.7 10052 -4964.3   9928.7
|| anova_model_1a      18 9958.7 10061 -4961.4   9922.7 5.9396  2    0.05131 .
|| ---
|| Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

2.4 Plots





3 N250 Nonword Data

3.1 Compute the ANOVA

```
# Fit the ANOVA/mixed model
anova_model_1b <- mixed(
  value ~ Orthographic_Sensitivity * family_size * complexity +
    laterality * anteriority  +  # Nuisance variables
    (1 | SubjID),
  data = n250_nonwords,
  method = "KR"  # Kenward-Roger approximation for accurate F-tests
)

# Print ANOVA results
anova_model_1b
```

```
|| Mixed Model Anova Table (Type 3 tests, KR-method)
||
|| Model: value ~ Orthographic_Sensitivity * family_size * complexity +
|| Model:     laterality * anteriority + (1 | SubjID)
|| Data: n250_nonwords
||                                           Effect      df         F p.value
|| 1                          Orthographic_Sensitivity   1, 59      0.05    .823
|| 2                                        family_size 1, 2121      0.59    .442
|| 3                                         complexity 1, 2121      0.07    .786
|| 4                                         laterality 2, 2121      0.51    .599
|| 5                                        anteriority 2, 2121 35.56 ***   <.001
|| 6             Orthographic_Sensitivity:family_size 1, 2121      0.00    .976
|| 7              Orthographic_Sensitivity:complexity 1, 2121      1.73    .189
|| 8                           family_size:complexity 1, 2121      0.78    .377
|| 9                           laterality:anteriority 4, 2121      0.81    .520
|| 10 Orthographic_Sensitivity:family_size:complexity 1, 2121      1.86    .173
|| ---
|| Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '+' 0.1 ' ' 1
```

```
# Partial Eta Squared
# Extract effect sizes from your ANOVA model
eta_squared(anova_model_1b , partial = TRUE)
```

```
|| # Effect Size for ANOVA (Type III)
||
|| Parameter                                | Eta2 (partial) |       95% CI
|| -----------------------------------------------------------------------------
|| Orthographic_Sensitivity                 |       8.51e-04 | [0.00, 1.00]
|| family_size                              |       2.79e-04 | [0.00, 1.00]
|| complexity                               |       3.48e-05 | [0.00, 1.00]
|| laterality                               |       4.83e-04 | [0.00, 1.00]
|| anteriority                              |           0.03 | [0.02, 1.00]
```

```
|| Orthographic_Sensitivity:family_size            |       4.33e-07 | [0.00, 1.00]
|| Orthographic_Sensitivity:complexity             |       8.14e-04 | [0.00, 1.00]
|| family_size:complexity                          |       3.69e-04 | [0.00, 1.00]
|| laterality:anteriority                          |       1.52e-03 | [0.00, 1.00]
|| Orthographic_Sensitivity:family_size:complexity |       8.77e-04 | [0.00, 1.00]
||
|| - One-sided CIs: upper bound fixed at [1.00].
```

```
# Compute Marginal (fixed effects) and Conditional (fixed + random effects) R²
r2(anova_model_1b)
```

```
|| # R2 for Mixed Models
||
||   Conditional R2: 0.405
||      Marginal R2: 0.022
```

3.2 Effects

No significant effects

4 N400 Word Data

4.1 Compute the ANOVA

```
anova_model_2a <- mixed(
  value ~ Orthographic_Sensitivity * family_size * base_freq  +
    laterality * anteriority  +  # Nuisance variables
    (1 | SubjID),
  data = n400_words_b,
  method = "KR")  # Kenward-Roger approximation for accurate F-tests
# Print ANOVA results
anova_model_2a
```

```
|| Mixed Model Anova Table (Type 3 tests, KR-method)
||
|| Model: value ~ Orthographic_Sensitivity * family_size * base_freq +
|| Model:     laterality * anteriority + (1 | SubjID)
|| Data: n400_words_b
||                                          Effect      df           F p.value
|| 1                          Orthographic_Sensitivity   1, 59       0.45    .507
|| 2                                      family_size 1, 2121  11.63 ***   <.001
|| 3                                        base_freq 1, 2121       2.30    .129
|| 4                                       laterality 2, 2121    4.76 **    .009
|| 5                                      anteriority 2, 2121 104.58 ***   <.001
|| 6            Orthographic_Sensitivity:family_size 1, 2121       0.30    .586
|| 7              Orthographic_Sensitivity:base_freq 1, 2121     4.36 *    .037
|| 8                          family_size:base_freq 1, 2121  21.94 ***   <.001
|| 9                         laterality:anteriority 4, 2121       0.78    .541
|| 10 Orthographic_Sensitivity:family_size:base_freq 1, 2121       0.96    .328
|| ---
|| Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '+' 0.1 ' ' 1
```

```
# Partial Eta Squared
# Extract effect sizes from your ANOVA model
eta_squared(anova_model_2a , partial = TRUE)
```

```
|| # Effect Size for ANOVA (Type III)
||
|| Parameter                                  | Eta2 (partial) |       95% CI
|| ------------------------------------------------------------------------------
|| Orthographic_Sensitivity                   |       7.51e-03 | [0.00, 1.00]
|| family_size                                |       5.45e-03 | [0.00, 1.00]
|| base_freq                                  |       1.09e-03 | [0.00, 1.00]
|| laterality                                 |       4.47e-03 | [0.00, 1.00]
|| anteriority                                |           0.09 | [0.07, 1.00]
|| Orthographic_Sensitivity:family_size       |       1.40e-04 | [0.00, 1.00]
|| Orthographic_Sensitivity:base_freq         |       2.05e-03 | [0.00, 1.00]
|| family_size:base_freq                      |           0.01 | [0.00, 1.00]
|| laterality:anteriority                     |       1.46e-03 | [0.00, 1.00]
|| Orthographic_Sensitivity:family_size:base_freq |   4.52e-04 | [0.00, 1.00]
||
|| - One-sided CIs: upper bound fixed at [1.00].
```

```
# Compute Marginal (fixed effects) and Conditional (fixed + random effects) R²
r2(anova_model_2a)
```

```
|| # R2 for Mixed Models
||
||   Conditional R2: 0.569
```

```
||      Marginal R2: 0.056
```

4.2 Effects

Effect	df	F	p.value	
family_size	1, 2121	11.63 **	.003	5.45e-03
Orthographic_Sensitivity:base_freq	1, 2121	4.36 *	.037	2.05e-03
family_size:base_freq	1, 2121	21.94 ***	<.001	0.01

Main Effects

```
## `family_size` main effect
pairs <- emmeans(anova_model_2a, pairwise ~ family_size, adjust = "bonferroni", pbkrtest.limit = 6480)
(pairs_df <- as.data.frame(pairs$contrasts))
```

```
||  contrast                    estimate        SE   df t.ratio p.value
||  Large Family - Small Family 0.3647076 0.1069595 2121   3.410  0.0007
||
|| Results are averaged over the levels of: Orthographic_Sensitivity, base_freq, laterality, anteriority
|| Degrees-of-freedom method: kenward-roger
```

```
cohensd <- as.data.frame(cohens_d(value ~ family_size, data = n400_words_b))
(family_size_contrasts_df <- bind_cols(pairs_df,cohensd))
```

```
||  contrast                    estimate        SE   df t.ratio p.value
||  Large Family - Small Family 0.3647076 0.1069595 2121   3.410  0.0007
||    Cohens_d   CI     CI_low  CI_high
||  0.09544102 0.95 0.01173328 0.179127
||
|| Results are averaged over the levels of: Orthographic_Sensitivity, base_freq, laterality, anteriority
|| Degrees-of-freedom method: kenward-roger
```

```
(family_size_means <- as.data.frame(pairs$emmeans))
```

```
||  family_size     emmean       SE    df   lower.CL upper.CL
||  Large Family 0.8184090 0.358128 61.72  0.1024570 1.534361
||  Small Family 0.4537014 0.358128 61.72 -0.2622506 1.169653
||
|| Results are averaged over the levels of: Orthographic_Sensitivity, base_freq, laterality, anteriority
|| Degrees-of-freedom method: kenward-roger
|| Confidence level used: 0.95
```

Interactions

```
# `Orthographic_Sensitivity` x `base_freq`  interaction

selected_contrasts_orthosens <- c("High Orthographic High Base Frequency - Low Orthographic High Base Frequency",
                                  "High Orthographic Low Base Frequency - Low Orthographic Low Base Frequency")
selected_contrasts_basefreq <- c("High Orthographic High Base Frequency - High Orthographic Low Base Frequency",
                                 "Low Orthographic High Base Frequency - Low Orthographic Low Base Frequency")

emmeans_obj <- emmeans(anova_model_2a, pairwise ~ Orthographic_Sensitivity * base_freq, adjust = "bonferroni", pbkrtest.limit = 6480)

# Get selected contrasts and convert the emmGrid object to a dataframe
contrasts_df <- as.data.frame(emmeans_obj$contrasts)
selected_contrasts_orthosens_df <- as.data.frame(emmeans_obj$contrasts[contrasts_df$contrast %in% selected_contrasts_orthosens, ])
selected_contrasts_basefrq_df <- as.data.frame(emmeans_obj$contrasts[contrasts_df$contrast %in% selected_contrasts_basefreq,])


cohensd_hi_basefrq <- as.data.frame(cohens_d(value ~ Orthographic_Sensitivity,
                                             data = subset(n400_words_b, base_freq == "High Base Frequency")))
cohensd_lo_basefrq <- as.data.frame(cohens_d(value ~ Orthographic_Sensitivity,
                                               data = subset(n400_words_b, base_freq == "Low Base Frequency")))
cohensd_hi_orthosens <- as.data.frame(cohens_d(value ~ base_freq,
                                               data = subset(n400_words_b, Orthographic_Sensitivity == "High Orthographic")))
cohensd_lo_orthosens <- as.data.frame(cohens_d(value ~ base_freq,
                                              data = subset(n400_words_b, Orthographic_Sensitivity == "Low Orthographic")))

cohensd_basefrq <- bind_rows(hi_basefrq = cohensd_hi_basefrq,
                             lo_basefrq = cohensd_lo_basefrq,
                             .id = "base_freq")

cohensd_orthosens <- bind_rows(hi_orthosens = cohensd_hi_orthosens,
                             lo_orthosens = cohensd_lo_orthosens,
                             .id = "Orthographic_Sensitivity")

(basefreq_contrasts_df <- bind_cols(selected_contrasts_basefrq_df,cohensd_basefrq))
```

```
||  contrast
```

```
||  High Orthographic High Base Frequency - High Orthographic Low Base Frequency
||  Low Orthographic High Base Frequency - Low Orthographic Low Base Frequency
||    estimate        SE   df t.ratio p.value base_freq    Cohens_d   CI
||   0.3858252 0.1423201 2121   2.711  0.0135 hi_basefrq 0.18383138 0.95
||  -0.0610556 0.1597069 2121  -0.382  1.0000 lo_basefrq 0.06740484 0.95
||       CI_low   CI_high
||   0.06445672 0.3031225
||  -0.05172849 0.1865074
||
|| Results are averaged over the levels of: family_size, laterality, anteriority
|| Degrees-of-freedom method: kenward-roger
|| P value adjustment: bonferroni method for 2 tests
```

```
(orthosens_contrasts_df <- bind_cols(selected_contrasts_orthosens_df,cohensd_orthosens))
```

```
||  contrast
||  High Orthographic High Base Frequency - Low Orthographic High Base Frequency
||  High Orthographic Low Base Frequency - Low Orthographic Low Base Frequency
||   estimate       SE    df t.ratio p.value Orthographic_Sensitivity    Cohens_d
||  0.6965734 0.716256 61.72   0.973  0.6692 hi_orthosens              0.09351089
||  0.2496927 0.716256 61.72   0.349  1.0000 lo_orthosens             -0.01904135
||    CI      CI_low   CI_high
||  0.95 -0.01861321 0.2055967
||  0.95 -0.14477104 0.1066982
||
|| Results are averaged over the levels of: family_size, laterality, anteriority
|| Degrees-of-freedom method: kenward-roger
|| P value adjustment: bonferroni method for 2 tests
```

```
(orthosens.basefreq_means <- as.data.frame(emmeans_obj$emmeans))
```

```
||  Orthographic_Sensitivity base_freq              emmean        SE    df
||  High Orthographic        High Base Frequency 1.0655343 0.4765245 61.72
||  Low Orthographic         High Base Frequency 0.3689609 0.5347402 61.72
||  High Orthographic        Low Base Frequency  0.6797092 0.4765245 61.72
||  Low Orthographic         Low Base Frequency  0.4300165 0.5347402 61.72
||    lower.CL upper.CL
||   0.1128897 2.018179
||  -0.7000656 1.437987
||  -0.2729354 1.632354
||  -0.6390100 1.499043
||
|| Results are averaged over the levels of: family_size, laterality, anteriority
|| Degrees-of-freedom method: kenward-roger
|| Confidence level used: 0.95
```

```
# `base_freq` x `family_size` interaction

selected_contrasts_famsize <- c("Large Family High Base Frequency - Small Family High Base Frequency",
                                "Large Family Low Base Frequency - Small Family Low Base Frequency")
selected_contrasts_basefreq <- c("Large Family High Base Frequency - Large Family Low Base Frequency",
                                 "Small Family High Base Frequency - Small Family Low Base Frequency")

emmeans_obj <- emmeans(anova_model_2a, pairwise ~ family_size * base_freq, adjust = "bonferroni", pbkrtest.limit = 6480)

# Get selected contrasts and convert the emmGrid object to a dataframe
contrasts_df <- as.data.frame(emmeans_obj$contrasts)
selected_contrasts_famsize_df <- as.data.frame(emmeans_obj$contrasts[contrasts_df$contrast %in% selected_contrasts_famsize, ])
selected_contrasts_basefrq_df <- as.data.frame(emmeans_obj$contrasts[contrasts_df$contrast %in% selected_contrasts_basefreq,])


cohensd_hi_basefrq <- as.data.frame(cohens_d(value ~ family_size,
                                             data = subset(n400_words_b, base_freq == "High Base Frequency")))
cohensd_lo_basefrq <- as.data.frame(cohens_d(value ~ family_size,
                                               data = subset(n400_words_b, base_freq == "Low Base Frequency")))
cohensd_lrg_fam <- as.data.frame(cohens_d(value ~ base_freq,
                                            data = subset(n400_words_b, family_size == "Large Family")))
cohensd_sml_fam <- as.data.frame(cohens_d(value ~ base_freq,
                                           data = subset(n400_words_b, family_size == "Small Family")))

cohensd_basefrq <- bind_rows(hi_basefrq = cohensd_hi_basefrq,
                             lo_basefrq = cohensd_lo_basefrq,
                             .id = "base_freq")

cohensd_famsize <- bind_rows(lrg_fam = cohensd_lrg_fam,
                             sml_fam = cohensd_sml_fam,
                             .id = "family_size")

(basefreq_contrasts_df <- bind_cols(selected_contrasts_basefrq_df,cohensd_basefrq))
```

```
||  contrast                                                          estimate
||  Large Family High Base Frequency - Large Family Low Base Frequency -0.3386483
```

```
||  Small Family High Base Frequency - Small Family Low Base Frequency  0.6634179
||         SE   df t.ratio p.value base_freq    Cohens_d   CI     CI_low   CI_high
||  0.1512635 2121  -2.239  0.0505 hi_basefrq -0.0407526 0.95 -0.1590535 0.0775669
||  0.1512635 2121   4.386  <.0001 lo_basefrq  0.2366583 0.95  0.1178928 0.3553166
||
|| Results are averaged over the levels of: Orthographic_Sensitivity, laterality, anteriority
|| Degrees-of-freedom method: kenward-roger
|| P value adjustment: bonferroni method for 2 tests
```

```
(sensitivity_contrasts_df <- bind_cols(selected_contrasts_famsize_df,cohensd_famsize))
```

```
||  contrast                                                          estimate
||  Large Family High Base Frequency - Small Family High Base Frequency -0.1363255
||  Large Family Low Base Frequency - Small Family Low Base Frequency    0.8657407
||         SE   df t.ratio p.value family_size   Cohens_d   CI      CI_low
||  0.1512635 2121  -0.901  0.7351 lrg_fam     -0.0915178 0.95 -0.20985682
||  0.1512635 2121   5.723  <.0001 sml_fam      0.1786143 0.95  0.06003985
||     CI_high
||  0.02686293
||  0.29710762
||
|| Results are averaged over the levels of: Orthographic_Sensitivity, laterality, anteriority
|| Degrees-of-freedom method: kenward-roger
|| P value adjustment: bonferroni method for 2 tests
```

```
(famsize.basefreq_means <- as.data.frame(emmeans_obj$emmeans))
```

```
||  family_size  base_freq             emmean        SE    df   lower.CL
||  Large Family High Base Frequency 0.6490848 0.3660271 67.34 -0.0814402
||  Small Family High Base Frequency 0.7854104 0.3660271 67.34  0.0548853
||  Large Family Low Base Frequency  0.9877332 0.3660271 67.34  0.2572081
||  Small Family Low Base Frequency  0.1219924 0.3660271 67.34 -0.6085326
||   upper.CL
||  1.3796099
||  1.5159354
||  1.7182582
||  0.8525175
||
|| Results are averaged over the levels of: Orthographic_Sensitivity, laterality, anteriority
|| Degrees-of-freedom method: kenward-roger
|| Confidence level used: 0.95
```

4.3 Model Comparisons

```
# Family Size
reduced_model <- update(anova_model_1a,
                        . ~ . - family_size - Orthographic_Sensitivity:family_size - family_size:base_freq - Orthographic_Sensitivity:family_size:
anova(anova_model_1a, reduced_model)
```

```
|| Data: data
|| Models:
|| reduced_model: value ~ Orthographic_Sensitivity + base_freq + laterality + anteriority + Orthographic_Sensitivity:base_freq + laterality:anteri
|| anova_model_1a: value ~ Orthographic_Sensitivity * family_size * base_freq + laterality * anteriority + (1 | SubjID)
||                npar    AIC   BIC  logLik deviance Chisq Df Pr(>Chisq)
|| reduced_model    14 9957.5 10037 -4964.7   9929.5
|| anova_model_1a   18 9958.7 10061 -4961.4   9922.7 6.787  4     0.1476
```

```
# Orthographic Sensitivity x Base Frequency
reduced_model_int <- update(anova_model_1a,
  . ~ . - Orthographic_Sensitivity:base_freq - Orthographic_Sensitivity:family_size:base_freq)
anova(anova_model_1a, reduced_model_int)
```

```
|| Data: data
|| Models:
|| reduced_model_int: value ~ Orthographic_Sensitivity + family_size + base_freq + laterality + anteriority + Orthographic_Sensitivity:family_size
|| anova_model_1a: value ~ Orthographic_Sensitivity * family_size * base_freq + laterality * anteriority + (1 | SubjID)
||                   npar    AIC   BIC  logLik deviance Chisq Df Pr(>Chisq)
|| reduced_model_int   16 9946.8 10038 -4957.4   9914.8
|| anova_model_1a      18 9958.7 10061 -4961.4   9922.7     0  2          1
```

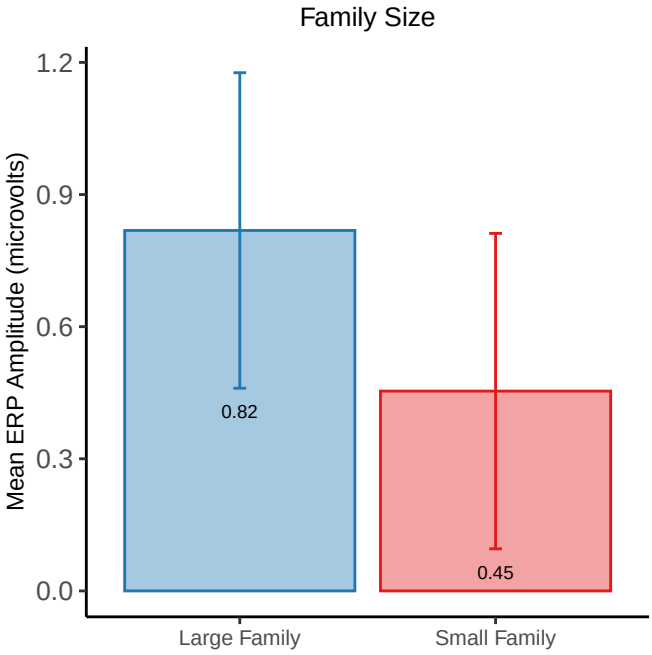
```
# Family Size x Base Frequency
reduced_model_int <- update(anova_model_1a,
  . ~ . - family_size:base_freq - Orthographic_Sensitivity:family_size:base_freq)
anova(anova_model_1a, reduced_model_int)
```

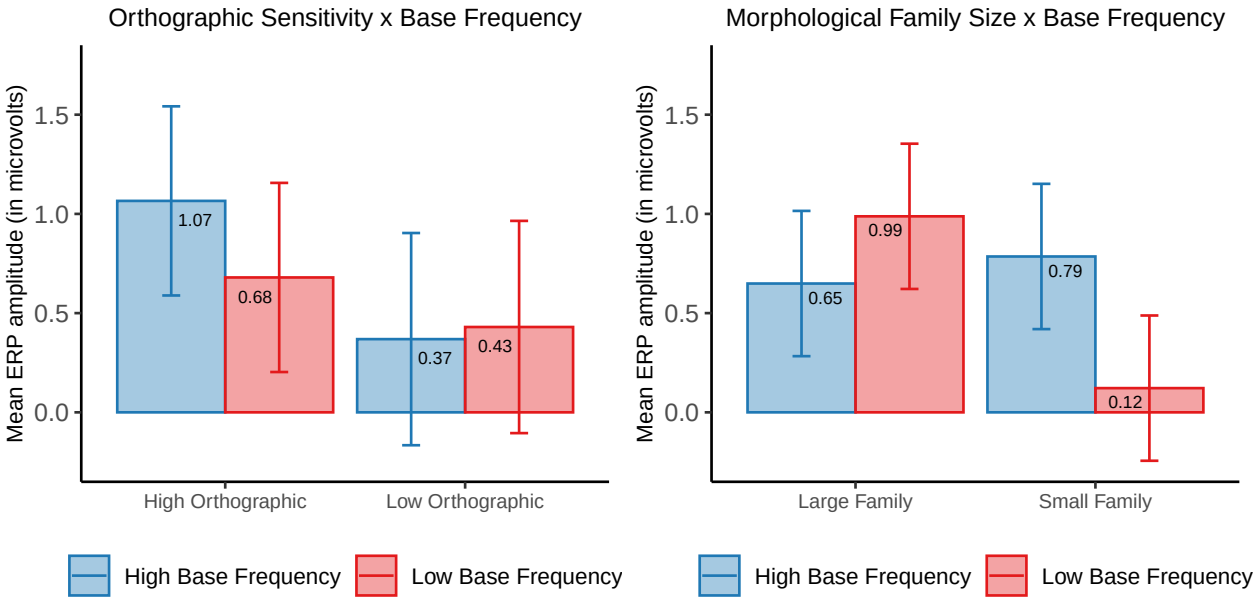
```
|| Data: data
|| Models:
|| reduced_model_int: value ~ Orthographic_Sensitivity + family_size + base_freq + laterality + anteriority + Orthographic_Sensitivity:family_size
|| anova_model_1a: value ~ Orthographic_Sensitivity * family_size * base_freq + laterality * anteriority + (1 | SubjID)
||                   npar    AIC   BIC  logLik deviance  Chisq Df Pr(>Chisq)
|| reduced_model_int   16 9960.7 10052 -4964.3   9928.7
|| anova_model_1a      18 9958.7 10061 -4961.4   9922.7 5.9396  2    0.05131 .
```

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

4.4 Plots

...





5 N400 Nonword Data

5.1 Compute the ANOVA

```
# Fit the ANOVA/mixed model
anova_model_2b <- mixed(
  value ~ Orthographic_Sensitivity * family_size * complexity +
    laterality * anteriority  +  # Nuisance variables
    (1 | SubjID),
  data = n400_nonwords,
  method = "KR"  # Kenward-Roger approximation for accurate F-tests
```

```
)

# Print ANOVA results
anova_model_2b
```

```
|| Mixed Model Anova Table (Type 3 tests, KR-method)
||
|| Model: value ~ Orthographic_Sensitivity * family_size * complexity +
|| Model:     laterality * anteriority + (1 | SubjID)
|| Data: n400_nonwords
||                                          Effect      df          F p.value
|| 1                          Orthographic_Sensitivity   1, 59       0.01    .932
|| 2                                        family_size 1, 2121       0.03    .872
|| 3                                         complexity 1, 2121       0.15    .702
|| 4                                         laterality 2, 2121     4.22 *    .015
|| 5                                        anteriority 2, 2121 140.74 ***   <.001
|| 6             Orthographic_Sensitivity:family_size 1, 2121       0.87    .350
|| 7              Orthographic_Sensitivity:complexity 1, 2121     3.03 +    .082
|| 8                           family_size:complexity 1, 2121       1.82    .177
|| 9                           laterality:anteriority 4, 2121       0.40    .812
|| 10 Orthographic_Sensitivity:family_size:complexity 1, 2121       0.34    .563
|| ---
|| Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '+' 0.1 ' ' 1
```

```
# Partial Eta Squared
# Extract effect sizes from your ANOVA model
eta_squared(anova_model_2b , partial = TRUE)
```

```
|| # Effect Size for ANOVA (Type III)
||
|| Parameter                                   | Eta2 (partial) |       95% CI
|| ------------------------------------------------------------------------------
|| Orthographic_Sensitivity                    |       1.23e-04 | [0.00, 1.00]
|| family_size                                 |       1.22e-05 | [0.00, 1.00]
|| complexity                                  |       6.90e-05 | [0.00, 1.00]
|| laterality                                  |       3.96e-03 | [0.00, 1.00]
|| anteriority                                 |           0.12 | [0.10, 1.00]
|| Orthographic_Sensitivity:family_size        |       4.11e-04 | [0.00, 1.00]
|| Orthographic_Sensitivity:complexity         |       1.43e-03 | [0.00, 1.00]
|| family_size:complexity                      |       8.59e-04 | [0.00, 1.00]
|| laterality:anteriority                      |       7.45e-04 | [0.00, 1.00]
|| Orthographic_Sensitivity:family_size:complexity |       1.58e-04 | [0.00, 1.00]
||
|| - One-sided CIs: upper bound fixed at [1.00].
```

```
# Compute Marginal (fixed effects) and Conditional (fixed + random effects) R²
r2(anova_model_2b)
```

```
|| # R2 for Mixed Models
||
||   Conditional R2: 0.522
||      Marginal R2: 0.065
```

5.2 Effects

No Significant Effects