

M21 LDT ERP HC SEMANTIC SENSITIVITY N250 Family Size

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2025-11-05

Contents

Set parameters	1
1 Load data files	1
2 Format data files	2
3 N250 Word Data	2
3.1 Nested ANOVA Model	2
3.2 Main Effects	3
3.3 Interactions	3
3.3.1 Family Size x Base Frequency Interaction	3
3.3.1.1 family_size x base_freq Simple Contrasts	3
3.3.1.2 family_size x base_freq Interaction Contrasts	4
3.3.1.3 family_size x base_freq Interaction Plots	5
3.3.2 Sensitivity x Family Size x Base Frequency Interaction	5
3.3.2.1 Sensitivity x family_size x base_freq Simple Contrasts	5
3.3.2.2 Sensitivity x family_size x base_freq Interaction Contrasts	6
3.3.2.3 Plots Sensitivity x family_size x base_freq	8
4 N250 Nonword Data	9
4.1 Compute the ANOVA	9
4.2 Main Effects and Interactions	9
4.2.1 Semantic_Sensitivity x family_size x complexity Simple Contrasts	10
4.2.2 Semantic_Sensitivity x family_size x complexity Interaction Contrasts	11
4.2.3 Semantic_Sensitivity x family_size x complexity Plots	12

Set parameters

Set chunk parameters

Load libraries

Set ggplot parameters

Define standard error of the mean function

1 Load data files

```
dir_path <- "CSV files"

erp_2A <- read_csv(file.path(dir_path, "fs_m21_ldt_meas_200300_050050_1_AB.csv"))
erp_2B <- read_csv(file.path(dir_path, "fs_m21_ldt_meas_200300_050050_1_BA.csv"))

dmg_lng_vsl <- read_csv(file.path(dir_path, "demo_lang_vsl_pca_hc.csv"))
```

```

library(dplyr)

erp_2i <- bind_rows(
  erp_2A |> mutate(List = "AB"),
  erp_2B |> mutate(List = "BA")
)

```

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

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

2 Format data files

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 `separate` function from the `stringr` package. Run `vignette("programming", package = "dplyr")` to see more about `tidy-selection` and `tidy-evaluation`.

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 the `mutate` 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.

3 N250 Word Data

Statistical analysis.

Linear mixed-effects models were fit using the `afex::mixed` function (method = "KR") to account for both subject-level and electrode-level variability. Each model included random intercepts for participants (`SubjID`) and electrodes nested within participants (`SubjID:chlabel`), as well as by-subject random slopes for within-subject factors (Family Size, Complexity, or Base Frequency, depending on the analysis). When a significant interaction was obtained, we probed it using estimated marginal means from the fitted model (`emmeans` package) to clarify the source of the effect. Because these follow-up contrasts were intended to interpret a significant higher-order interaction rather than to test independent hypotheses, we reported uncorrected p-values (adjust = "none") for interpretive clarity. The robustness of the overall pattern was verified using a Holm correction, which did not change the substantive conclusions.

3.1 Nested ANOVA Model

```

n250_words_b %>%
  count(family_size, base_freq, Semantic_Sensitivity)

## # A tibble: 8 x 4
##   family_size base_freq Semantic_Sensitivity     n
##   <chr>       <chr>      <chr>             <int>
## 1 Large        High       High Semantic        279
## 2 Large        High       Low Semantic         261
## 3 Large        Low        High Semantic        279
## 4 Large        Low        Low Semantic         261
## 5 Small        High       High Semantic        279
## 6 Small        High       Low Semantic         261
## 7 Small        Low        High Semantic        279
## 8 Small        Low        Low Semantic         261

#Fit ANOVA model
anova_model_n250_words_b <- mixed(
  value ~ Semantic_Sensitivity * family_size * base_freq +
  (1 + family_size + base_freq | SubjID) +      # by-subject intercept + slopes
  (1 | SubjID:chlabel),                          # electrode nested within subject
  data   = n250_words_b,
  method = "KR"
)
anova_model_n250_words_b

## Mixed Model Anova Table (Type 3 tests, KR-method)
##
## Model: value ~ Semantic_Sensitivity * family_size * base_freq + (1 +
## Model:           family_size + base_freq | SubjID) + (1 | SubjID:chlabel)
## Data: n250_words_b
##          Effect      df      F p.value
## 1 Semantic_Sensitivity 1, 58    0.77  .383
## 2 family_size            1, 58    1.49  .228
## 3 base_freq               1, 58    0.55  .459
## 4 Semantic_Sensitivity:family_size 1, 58    0.32  .576
## 5 Semantic_Sensitivity:base_freq   1, 58    0.01  .910
## 6 family_size:base_freq 1, 1498 32.72 ***  <.001
## 7 Semantic_Sensitivity:family_size:base_freq 1, 1498 16.96 ***  <.001
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '+' 0.1 ' ' 1

```

```

m1 <- anova_model_n250_words_b$full_model    # Extract the lmer model
anova(m1) # Run random effects comparison

|| ANOVA-like table for random-effects: Single term deletions
||
|| Model:
|| value ~ Semantic_Sensitivity + family_size + base_freq + (1 + family_size + base_freq | SubjID) + (1 | SubjID:chlabel) + Semantic_Sensitivity:family_size*base_freq
||                                         npar  logLik   AIC      LRT Df Pr(>Chisq)
|| <none>                               16 -4420.1 8872.2
|| family_size in (1 + family_size + base_freq | SubjID)  13 -4731.8 9489.6 623.40  3 < 2.2e-16 ***
|| base_freq in (1 + family_size + base_freq | SubjID)     13 -4639.5 9304.9 438.73  3 < 2.2e-16 ***
|| (1 | SubjID:chlabel)                           15 -4617.1 9264.2 394.07  1 < 2.2e-16 ***
|| ---
|| Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
# Extract effect sizes from your ANOVA model
eta_squared(anova_model_n250_words_b, partial = TRUE)

|| # Effect Size for ANOVA (Type III)
||
|| Parameter                      | Eta2 (partial) |      95% CI
|| -----
|| Semantic_Sensitivity           |      0.01 | [0.00, 1.00]
|| family_size                     |      0.02 | [0.00, 1.00]
|| base_freq                       | 9.47e-03 | [0.00, 1.00]
|| Semantic_Sensitivity:family_size | 5.43e-03 | [0.00, 1.00]
|| Semantic_Sensitivity:base_freq  | 2.22e-04 | [0.00, 1.00]
|| family_size:base_freq          |      0.02 | [0.01, 1.00]
|| Semantic_Sensitivity:family_size:base_freq | 0.01 | [0.00, 1.00]
||
|| - One-sided CIs: upper bound fixed at [1.00].
# Compute Marginal(fixed effects only) and Conditional(fixed + random effects) R^2
r2(anova_model_n250_words_b)

|| # R2 for Mixed Models
||
|| Conditional R2: 0.790
|| Marginal R2: 0.015

```

3.2 Main Effects

No significant main effects

3.3 Interactions

Effect	df	F	p.value
family_size:base_freq	1, 1498	32.72 ***	<.001
Semantic_Sensitivity:family_size:base_freq	1, 1498	16.96 ***	<.001

3.3.1 Family Size x Base Frequency Interaction

```
# Estimated marginal means for the family_size x base frequency interaction
(emm1 <- emmeans(anova_model_n250_words_b, ~ family_size * base_freq))
```

3.3.1.1 family_size x base_freq Simple Contrasts

```

|| family_size base_freq emmean    SE  df lower.CL upper.CL
|| Large       High    -0.851 0.280 59.4  -1.412  -0.290
|| Small       High    -0.823 0.357 58.8  -1.537  -0.110
|| Large       Low     -0.341 0.294 59.2  -0.929  0.247
|| Small       Low     -1.005 0.351 58.9  -1.706  -0.303
||
|| Results are averaged over the levels of: Semantic_Sensitivity
|| Degrees-of-freedom method: kenward-roger
|| Confidence level used: 0.95
# Get all pairwise contrasts
emm1_contrasts <- contrast(emm1, method = "pairwise", by = NULL, adjust = "none")

# Keep only the contrasts you want
# Simple effects of family_size at each level of base_freq
# Simple effects of base_freq at each level of family_size
keep <- c("Large High - Small High",
         "Large Low - Small Low",
         "Large High - Large Low",

```

```

    "Small High - Small Low")
(emmm1_contrasts_filtered <- subset(emmm1_contrasts, contrast %in% keep))

|| contrast      estimate   SE   df t.ratio p.value
|| Large High - Small High -0.0273 0.268 64.4 -0.102 0.9190
|| Large High - Large Low  -0.5095 0.229 67.0 -2.230 0.0291
|| Small High - Small Low  0.1812 0.229 67.0  0.793 0.4305
|| Large Low - Small Low   0.6634 0.268 64.4  2.478 0.0158
||
|| Results are averaged over the levels of: Semantic_Sensitivity
|| Degrees-of-freedom method: kenward-roger
# Get Confidence Intervals
(emmm1_contrasts_filtered_ci <- confint(emmm1_contrasts_filtered))

|| contrast      estimate   SE   df lower.CL upper.CL
|| Large High - Small High -0.0273 0.268 64.4 -0.562 0.5074
|| Large High - Large Low  -0.5095 0.229 67.0 -0.966 -0.0534
|| Small High - Small Low  0.1812 0.229 67.0 -0.275 0.6373
|| Large Low - Small Low   0.6634 0.268 64.4  0.129 1.1981
||
|| Results are averaged over the levels of: Semantic_Sensitivity
|| Degrees-of-freedom method: kenward-roger
|| Confidence level used: 0.95
# Get effect sizes
# Get all pairwise effect sizes
effs1 <- eff_size(emmm1, sigma = sigma(m1), edf = df.residual(m1))

# Remove the two redundant rows (rows 3 and 4)
(emmm1_filtered <- subset(emmm1, !contrast %in% c("Large High - Small Low",
                                                 "Small High - Large Low")))

|| contrast      effect.size   SE   df lower.CL upper.CL
|| Large High - Small High -0.0195 0.191 58.8 -0.4015 0.3625
|| Large High - Large Low  -0.3633 0.163 59.2 -0.6895 -0.0371
|| Small High - Small Low  0.1293 0.163 58.8 -0.1969 0.4554
|| Large Low - Small Low   0.4731 0.191 58.9  0.0908 0.8554
||
|| Results are averaged over the levels of: Semantic_Sensitivity
|| sigma used for effect sizes: 1.402
|| Degrees-of-freedom method: inherited from kenward-roger when re-gridding
|| Confidence level used: 0.95

```

For large-family words, N250 amplitude is more negative when base frequency is high than when it is low. For small-family words, base frequency has little effect. For low-frequency bases, small-family words elicit more negative amplitudes than large-family words.

- At **High Base Frequency**: Large vs. Small family; no difference (-0.0273, $p = 0.9190$). Family size doesn't matter when base frequency is high.
- At **Low Base Frequency**: Large vs. Small family; significant difference (0.6634, $p = 0.0158$). When base frequency is low, small-family words yield more negative amplitudes than large-family words
- Within **Small Family**: High vs. Low base frequency; not significant (0.1812, $p = 0.4305$). Small-family words are unaffected by base frequency.
- Within **Large Family**: High vs. Low base frequency → significant (-0.5095, $p = 0.0291$). Large-family words show more negative amplitudes when their base frequency is high.

```

# Interaction contrasts (difference-of-differences)
# Compare base frequency effect in large vs small family
contrast(emmm1, interaction = "pairwise", by = NULL, adjust = "holm")

```

3.3.1.2 family_size × base_freq Interaction Contrasts

```

|| family_size_pairwise base_freq_pairwise estimate   SE   df t.ratio p.value
|| Large - Small       High - Low          -0.691 0.121 1498 -5.720 <.0001
||
|| Results are averaged over the levels of: Semantic_Sensitivity
|| Degrees-of-freedom method: kenward-roger
# Get confidence intervals, for each base frequency effect for each family size and then for interaction effect
confint(contrast(emmeans(m1, ~ family_size | base_freq), "pairwise"))

|| base_freq = High:
|| contrast      estimate   SE   df lower.CL upper.CL
|| Large - Small -0.0273 0.268 64.4 -0.562 0.507
||
|| base_freq = Low:
|| contrast      estimate   SE   df lower.CL upper.CL
|| Large - Small  0.6634 0.268 64.4  0.129 1.198
||
```

```

|| Results are averaged over the levels of: Semantic_Sensitivity
|| Degrees-of-freedom method: kenward-roger
|| Confidence level used: 0.95
confint(contrast(emm1, interaction = c("pairwise", "pairwise")))

|| family_size_pairwise base_freq_pairwise estimate      SE   df lower.CL upper.CL
|| Large - Small       High - Low            -0.691 0.121 1498  -0.928  -0.454
||

|| Results are averaged over the levels of: Semantic_Sensitivity
|| Degrees-of-freedom method: kenward-roger
|| Confidence level used: 0.95

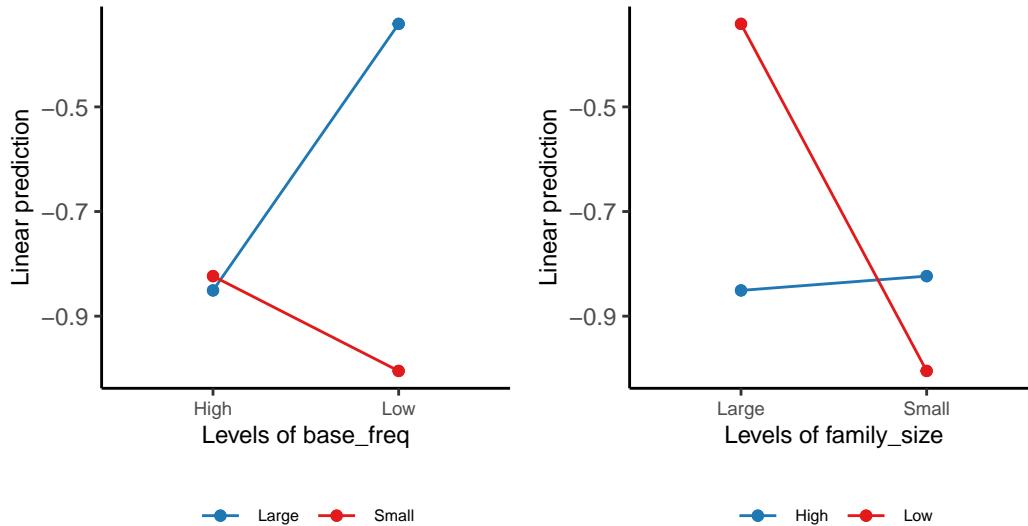
```

3.3.1.3 family_size × base_freq Interaction Plots ...

```

p1 <- emmip(anova_model_n250_words_b, family_size ~ base_freq) + my_style
p2 <- emmip(anova_model_n250_words_b, base_freq ~ family_size) + my_style
plot_grid(p1, p2, ncol = 2)

```



3.3.2 Sensitivity x Family Size x Base Frequency Interaction

```

# Estimated marginal means for the family_size × base_freq interaction
(emm1b <- emmeans(anova_model_n250_words_b, ~ Semantic_Sensitivity * family_size * base_freq))

3.3.2.1 Sensitivity × family_size × base_freq Simple Contrasts

|| Semantic_Sensitivity family_size base_freq emmean      SE   df lower.CL upper.CL
|| High Semantic      Large     High    -1.300 0.390 59.4   -2.08  -0.520
|| Low Semantic       Large     High    -0.402 0.403 59.4   -1.21   0.405
|| High Semantic      Small     High    -0.877 0.496 58.8   -1.87   0.115
|| Low Semantic       Small     High    -0.770 0.513 58.8   -1.80   0.256
|| High Semantic      Large     Low     -0.517 0.409 59.2   -1.33   0.301
|| Low Semantic       Large     Low     -0.166 0.422 59.2   -1.01   0.679
|| High Semantic      Small     Low     -1.282 0.487 58.9   -2.26   -0.307
|| Low Semantic       Small     Low     -0.727 0.504 58.9   -1.74   0.281
||

|| Degrees-of-freedom method: kenward-roger
|| Confidence level used: 0.95
# Get all pairwise contrasts
emm1b_contrasts <- contrast(emm1b, method = "pairwise", by = NULL, adjust = "none")

# Keep only the contrasts you want
# Simple effects of family_size at each level of base_freq
# Simple effects of base_freq at each level of family_size
keep1b <- c("High Semantic Large High - High Semantic Large Low",
           "High Semantic Small High - High Semantic Small Low",
           "Low Semantic Large High - Low Semantic Large Low",
           "Low Semantic Small High - Low Semantic Small Low",
           "High Semantic Large High - High Semantic Small High",
           "High Semantic Large Low - High Semantic Small Low",
           "Low Semantic Large High - Low Semantic Small High",
           "Low Semantic Large Low - Low Semantic Small Low",
           "High Semantic Large High - Low Semantic Large High",
           "High Semantic Small High - Low Semantic Small High",

```

```

    "High Semantic Large Low - Low Semantic Small Low",
    "High Semantic Small Low - Low Semantic Small Low")

(emm1b_contrasts_filtered <- subset(emm1b_contrasts, contrast %in% keep1b))

|| contrast estimate SE df t.ratio p.value
|| High Semantic Large High - Low Semantic Large High -0.8982 0.561 59.4 -1.602 0.1146
|| High Semantic Large High - High Semantic Small High -0.4227 0.372 64.4 -1.136 0.2603
|| High Semantic Large High - High Semantic Large Low -0.7831 0.318 67.0 -2.465 0.0163
|| Low Semantic Large High - Low Semantic Small High 0.3681 0.385 64.4 0.956 0.3424
|| Low Semantic Large High - Low Semantic Large Low -0.2358 0.328 67.0 -0.718 0.4754
|| High Semantic Small High - Low Semantic Small High -0.1074 0.713 58.8 -0.151 0.8809
|| High Semantic Small High - High Semantic Small Low 0.4049 0.318 67.0 1.274 0.2069
|| Low Semantic Small High - Low Semantic Small Low -0.0424 0.328 67.0 -0.129 0.8976
|| High Semantic Large Low - High Semantic Small Low 0.7653 0.372 64.4 2.056 0.0438
|| High Semantic Large Low - Low Semantic Small Low 0.2106 0.649 79.3 0.325 0.7464
|| Low Semantic Large Low - Low Semantic Small Low 0.5614 0.385 64.4 1.459 0.1494
|| High Semantic Small Low - Low Semantic Small Low -0.5547 0.701 58.9 -0.791 0.4319
||
|| Degrees-of-freedom method: kenward-roger
# Get Confidence Intervals
(emm1b_contrasts_filtered_ci <- confint(emm1b_contrasts_filtered))

|| contrast estimate SE df lower.CL upper.CL
|| High Semantic Large High - Low Semantic Large High -0.8982 0.561 59.4 -2.0202 0.224
|| High Semantic Large High - High Semantic Small High -0.4227 0.372 64.4 -1.1662 0.321
|| High Semantic Large High - High Semantic Large Low -0.7831 0.318 67.0 -1.4173 -0.149
|| Low Semantic Large High - Low Semantic Small High 0.3681 0.385 64.4 -0.4006 1.137
|| Low Semantic Large High - Low Semantic Large Low -0.2358 0.328 67.0 -0.8915 0.420
|| High Semantic Small High - Low Semantic Small High -0.1074 0.713 58.8 -1.5348 1.320
|| High Semantic Small High - High Semantic Small Low 0.4049 0.318 67.0 -0.2292 1.039
|| Low Semantic Small High - Low Semantic Small Low -0.0424 0.328 67.0 -0.6981 0.613
|| High Semantic Large Low - High Semantic Small Low 0.7653 0.372 64.4 0.0218 1.509
|| High Semantic Large Low - Low Semantic Small Low 0.2106 0.649 79.3 -1.0806 1.502
|| Low Semantic Large Low - Low Semantic Small Low 0.5614 0.385 64.4 -0.2072 1.330
|| High Semantic Small Low - Low Semantic Small Low -0.5547 0.701 58.9 -1.9576 0.848
||
|| Degrees-of-freedom method: kenward-roger
|| Confidence level used: 0.95
# Get effect sizes
# Get all pairwise effect sizes
effs1b <- eff_size(emm1b, sigma = sigma(m1), edf = df.residual(m1))

# Remove the redundant rows
(effs1b_filtered <- subset(effs1b, contrast %in% keep1b))

|| contrast effect.size SE df lower.CL upper.CL
|| High Semantic Large High - Low Semantic Large High -0.6405 0.400 59.4 -1.4409 0.160
|| High Semantic Large High - High Semantic Small High -0.3015 0.265 58.8 -0.8327 0.230
|| High Semantic Large High - High Semantic Large Low -0.5585 0.227 59.2 -1.0121 -0.105
|| Low Semantic Large High - Low Semantic Small High 0.2625 0.274 58.8 -0.2867 0.812
|| Low Semantic Large High - Low Semantic Large Low -0.1682 0.234 59.2 -0.6369 0.301
|| High Semantic Small High - Low Semantic Small High -0.0766 0.509 58.8 -1.0945 0.941
|| High Semantic Small High - High Semantic Small Low 0.2888 0.227 58.8 -0.1647 0.742
|| Low Semantic Small High - Low Semantic Small Low -0.0303 0.234 58.8 -0.4990 0.439
|| High Semantic Large Low - High Semantic Small Low 0.5458 0.266 58.9 0.0144 1.077
|| High Semantic Large Low - Low Semantic Small Low 0.1502 0.463 58.9 -0.7756 1.076
|| Low Semantic Large Low - Low Semantic Small Low 0.4004 0.274 58.9 -0.1489 0.950
|| High Semantic Small Low - Low Semantic Small Low -0.3956 0.500 58.9 -1.3961 0.605
||
|| sigma used for effect sizes: 1.402
|| Degrees-of-freedom method: inherited from kenward-roger when re-gridding
|| Confidence level used: 0.95

```

3.3.2.2 Sensitivity × family_size × base_freq Interaction Contrasts The interaction contrast tests whether the difference in the *base frequency* effect for large vs small families differs across semantic sensitivity?

```
[(A1 - A2) in B1] - [(A1 - A2) in B2] in Condition C1] - [(A1 - A2) in B1] - [(A1 - A2) in B2] in Condition C2]
```

```

# Interaction contrasts (difference-of-differences)
# Compare base_freq effect in large vs small family
contrast(emm1b, interaction = "pairwise", by = NULL, adjust = "holm")

|| Semantic_Sensitivity_pairwise family_size_pairwise base_freq_pairwise estimate SE df t.ratio p.value
|| High Semantic - Low Semantic Large - Small High - Low -0.995 0.242 1498 -4.119 <.0001
||
|| Degrees-of-freedom method: kenward-roger

```

```

confint(contrast(emm1b, interaction = c("pairwise", "pairwise")))

|| Semantic_Sensitivity_pairwise family_size_pairwise base_freq_pairwise estimate    SE   df lower.CL upper.CL
|| High Semantic - Low Semantic Large - Small           High - Low            -0.995 0.242 1498    -1.47   -0.521
||
|| Degrees-of-freedom method: kenward-roger
|| Confidence level used: 0.95
# Compute the A1 - A2 difference within each combination of B × C
(base_freq_diff <- contrast(emm1b, method = "revpairwise",
                             by = c("Semantic_sensitivity", "family_size"),
                             simple = "base_freq"))

|| Semantic_Sensitivity = High Semantic, family_size = Large:
|| contrast estimate    SE df t.ratio p.value
|| Low - High  0.7831 0.318 67   2.465  0.0163
||
|| Semantic_Sensitivity = Low Semantic, family_size = Large:
|| contrast estimate    SE df t.ratio p.value
|| Low - High  0.2358 0.328 67   0.718  0.4754
||
|| Semantic_Sensitivity = High Semantic, family_size = Small:
|| contrast estimate    SE df t.ratio p.value
|| Low - High -0.4049 0.318 67   -1.274  0.2069
||
|| Semantic_Sensitivity = Low Semantic, family_size = Small:
|| contrast estimate    SE df t.ratio p.value
|| Low - High  0.0424 0.328 67   0.129  0.8976
||
|| Degrees-of-freedom method: kenward-roger
# Compute how that A-effect changes across the levels of B, separately for each level of C
(family_size_base_freq_int_within_sensitivity <- contrast(base_freq_diff,
                                                          method = "revpairwise",
                                                          by = "Semantic_sensitivity", simple = "family_size"))

|| contrast = Low - High, Semantic_Sensitivity = High Semantic:
|| contrast1 estimate    SE df t.ratio p.value
|| Small - Large -1.188 0.168 1498   -7.076 <.0001
||
|| contrast = Low - High, Semantic_Sensitivity = Low Semantic:
|| contrast1 estimate    SE df t.ratio p.value
|| Small - Large -0.193 0.174 1498   -1.114  0.2655
||
|| Degrees-of-freedom method: kenward-roger
# Get confidence intervals
confint(family_size_base_freq_int_within_sensitivity)

|| contrast = Low - High, Semantic_Sensitivity = High Semantic:
|| contrast1 estimate    SE df lower.CL upper.CL
|| Small - Large -1.188 0.168 1498   -1.517   -0.859
||
|| contrast = Low - High, Semantic_Sensitivity = Low Semantic:
|| contrast1 estimate    SE df lower.CL upper.CL
|| Small - Large -0.193 0.174 1498   -0.534   0.147
||
|| Degrees-of-freedom method: kenward-roger
|| Confidence level used: 0.95

```

(a) Base-frequency effect within each Family Size × Sensitivity cell

Semantic Sensitivity	Family Size	Low - High Base Freq	t	p	Interpretation
High Sensitivity	Large Family	0.7831 μ V	2.465	0.0163	
Low Sensitivity	Large Family	0.2358 μ V	0.718	0.4754 (n.s.)	
High Sensitivity	Small Family	-0.4049 μ V	-1.274	0.2069 (n.s.)	
Low Sensitivity	Small Family	0.0424 μ V	1.401	0.1654 (n.s.)	

Pattern: Only high-sensitivity readers show a pronounced base-frequency effect—and only for small-family words, where high-frequency bases elicit larger (more negative) N250s.

(b) Difference of those frequency effects across family size (within each group)

Semantic Sensitivity | (Small – Large Family) | 95% CI | p | Interpretation |
| difference in base-freq effect | | | |

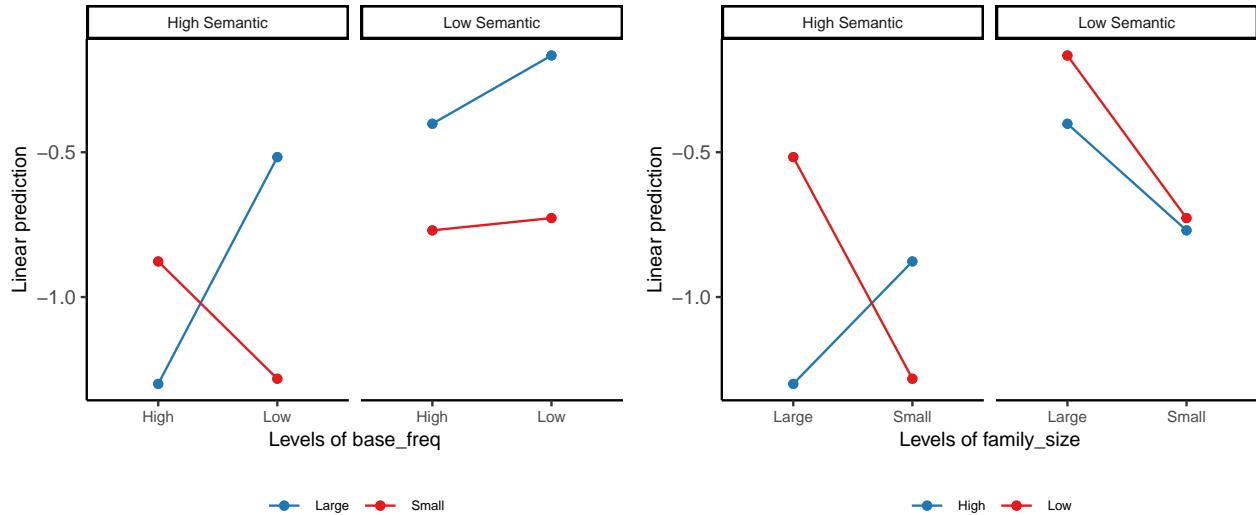
| -0.859 | <0.0001 | the base-freq effect flips between large- and small-family words. | | Low Sensitivity | -0.193 μ V (0.0424 - 0.2358) | [-0.534 0.147] | 0.2655 | No difference in the base frequency effect |

Interpretation:

- High-semantic participants show a large reversal of the frequency effect between large- and small-family words ($\approx 1.2 \mu V$).
- Low-semantic participants show none.

3.3.2.3 Plots Sensitivity \times family_size \times base_freq ...

```
p3 <- emmip(anova_model_n250_words_b, family_size ~ base_freq | Semantic_Sensitivity) + my_style
p4 <- emmip(anova_model_n250_words_b, base_freq ~ family_size | Semantic_Sensitivity) + my_style
plot_grid(p3, p4, ncol = 2)
```



4 N250 Nonword Data

```
n250_nonwords %>%
  count(family_size, complexity, Semantic_Sensitivity)
```

4.1 Compute the ANOVA

```
anova_model_n250_nonwords <- mixed(
  value ~ Semantic_Sensitivity * family_size * complexity +
  (1 + family_size + complexity | SubjID) +      # by-subject intercept + slopes
  (1 | SubjID:chlabel),                          # electrode nested within subject
  data   = n250_nonwords,
  method = "KR"
)
anova_model_n250_nonwords

## Mixed Model Anova Table (Type 3 tests, KR-method)
##
## Model: value ~ Semantic_Sensitivity * family_size * complexity + (1 +
## Model:   family_size + complexity | SubjID) + (1 | SubjID:chlabel)
## Data: n250_nonwords
##          Effect      df     F p.value
## 1           Semantic_Sensitivity 1, 58  0.16  .687
## 2           family_size       1, 58  0.42  .518
## 3           complexity       1, 58  1.78  .187
## 4 Semantic_Sensitivity:family_size 1, 58  0.31  .577
## 5 Semantic_Sensitivity:complexity 1, 58  0.67  .416
## 6 family_size:complexity    1, 1498 0.03  .874
## 7 Semantic_Sensitivity:family_size:complexity 1, 1498 4.71 *  .030
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '+' 0.1 ' ' 1
m2 <- anova_model_n250_nonwords$full_model      # Extract the lmer model
ranova(m2)      # Run random effects comparison

## ANOVA-like table for random-effects: Single term deletions
##
## Model:
## value ~ Semantic_Sensitivity + family_size + complexity + (1 + family_size + complexity | SubjID) + (1 | SubjID:chlabel) + Semantic_Sensitivity
##                                     npar logLik   AIC   LRT Df Pr(>Chisq)
## <none>                           16 -4428.3 8888.6
## family_size in (1 + family_size + complexity | SubjID)  13 -4616.5 9259.0 376.42  3 < 2.2e-16 ***
## complexity in (1 + family_size + complexity | SubjID)  13 -4740.1 9506.3 623.67  3 < 2.2e-16 ***
## (1 | SubjID:chlabel)                                15 -4631.2 9292.3 405.74  1 < 2.2e-16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '+' 0.1 ' ' 1
# Extract effect sizes from your ANOVA model
eta_squared(anova_model_n250_nonwords, partial = TRUE)

## # Effect Size for ANOVA (Type III)
##
## Parameter          | Eta2 (partial) |      95% CI
## -----
## Semantic_Sensitivity | 2.81e-03 | [0.00, 1.00]
## family_size          | 7.26e-03 | [0.00, 1.00]
## complexity           | 0.03 | [0.00, 1.00]
## Semantic_Sensitivity:family_size | 5.39e-03 | [0.00, 1.00]
## Semantic_Sensitivity:complexity | 0.01 | [0.00, 1.00]
## family_size:complexity | 1.69e-05 | [0.00, 1.00]
## Semantic_Sensitivity:family_size:complexity | 3.13e-03 | [0.00, 1.00]
##
## - One-sided CIs: upper bound fixed at [1.00].
# Compute Marginal(fixed effects only) and Conditional(fixed + random effects) R2
r2(anova_model_n250_nonwords)

## # R2 for Mixed Models
##
## Conditional R2: 0.756
## Marginal R2: 0.008
```

4.2 Main Effects and Interactions

Effect	df	F	p.value	eta-sqrdf
Semantic_Sensitivity:family_size:complexity	1, 1498	4.71 *	.030	3.13e-03

4.2.1 Semantic_Sensitivity x family_size x complexity Simple Contrasts

Compare High vs Low Semantic Sensitivity within each combination of Family Size and Complexity

This gives you: 4 contrasts: one for each Family Size \times Complexity combination. Each shows whether High vs Low Semantic Sensitivity differs significantly

If simple effects aren't significant, try looking at interaction contrasts, which test differences in the differences. You're now asking: Does the effect of Sensitivity change more in some complexity/family combinations than others?

Estimated marginal means for the family_size \times complexity interaction

```
(emm2 <- emmeans(anova_model_n250_nonwords, ~ Semantic_Sensitivity * family_size * complexity))
```

```
|| Semantic_Sensitivity family_size complexity emmean    SE   df lower.CL upper.CL
|| High Semantic      Small     Simple    -1.002 0.368 59.6   -1.74  -0.2651
|| Low Semantic       Small     Simple    -0.780 0.381 59.6   -1.54  -0.0182
|| High Semantic      Large     Simple    -0.629 0.392 59.4   -1.41  0.1557
|| Low Semantic       Large     Simple    -0.902 0.405 59.4   -1.71  -0.0915
|| High Semantic      Small     Complex   -0.743 0.413 59.2   -1.57  0.0823
|| Low Semantic       Small     Complex   -0.353 0.427 59.2   -1.21  0.5005
|| High Semantic      Large     Complex   -0.615 0.438 59.1   -1.49  0.2614
|| Low Semantic       Large     Complex   -0.193 0.453 59.1   -1.10  0.7130
||
|| Degrees-of-freedom method: kenward-roger
|| Confidence level used: 0.95
# Get all pairwise contrasts
emm2_contrasts <- contrast(emm2, method = "pairwise", by = NULL, adjust = "none")
# emm2_contrasts

# Keep only the contrasts you want
# Simple effects of family_size at each level of complexity
# Simple effects of complexity at each level of family_size
keep2 <- c("High Semantic Large Simple - High Semantic Large Complex",
          "High Semantic Small Simple - High Semantic Small Complex",
          "Low Semantic Large Simple - Low Semantic Large Complex",
          "Low Semantic Small Simple - Low Semantic Small Complex",
          "High Semantic Small Simple - High Semantic Large Simple",
          "High Semantic Small Complex - High Semantic Large Complex",
          "Low Semantic Small Simple - High Semantic Large Simple",
          "Low Semantic Small Complex - Low Semantic Large Complex",
          "High Semantic Large Simple - Low Semantic Large Simple",
          "High Semantic Large Complex - Low Semantic Large Complex",
          "High Semantic Small Simple - Low Semantic Small Simple",
          "High Semantic Small Complex - Low Semantic Small Complex")

(emm2_contrasts_filtered <- subset(emm2_contrasts, contrast %in% keep2))
```

```
|| contrast                      estimate    SE   df t.ratio p.value
|| High Semantic Small Simple - Low Semantic Small Simple  -0.222 0.529 59.6  -0.419 0.6766
|| High Semantic Small Simple - High Semantic Large Simple -0.373 0.300 68.4  -1.244 0.2179
|| High Semantic Small Simple - High Semantic Small Complex -0.258 0.376 64.3  -0.687 0.4947
|| Low Semantic Small Simple - High Semantic Large Simple -0.151 0.546 78.9  -0.276 0.7830
|| Low Semantic Small Simple - Low Semantic Small Complex -0.427 0.389 64.3  -1.097 0.2768
|| High Semantic Large Simple - Low Semantic Large Simple  0.274 0.564 59.4  0.486 0.6291
|| High Semantic Large Simple - High Semantic Large Complex -0.014 0.376 64.3  -0.037 0.9705
|| Low Semantic Large Simple - Low Semantic Large Complex  -0.710 0.389 64.3  -1.824 0.0727
|| High Semantic Small Complex - Low Semantic Small Complex -0.390 0.594 59.2  -0.657 0.5134
|| High Semantic Small Complex - High Semantic Large Complex -0.129 0.300 68.4  -0.429 0.6694
|| Low Semantic Small Complex - Low Semantic Large Complex  -0.160 0.310 68.4  -0.517 0.6071
|| High Semantic Large Complex - Low Semantic Large Complex -0.422 0.630 59.1  -0.670 0.5056
||
|| Degrees-of-freedom method: kenward-roger
# Get Confidence Intervals
(emm2_contrasts_filtered_ci <- confint(emm2_contrasts_filtered))
```

```
|| contrast                      estimate    SE   df lower.CL upper.CL
|| High Semantic Small Simple - Low Semantic Small Simple  -0.222 0.529 59.6  -1.281 0.8374
|| High Semantic Small Simple - High Semantic Large Simple -0.373 0.300 68.4  -0.971 0.2254
|| High Semantic Small Simple - High Semantic Small Complex -0.258 0.376 64.3  -1.010 0.4931
|| Low Semantic Small Simple - High Semantic Large Simple -0.151 0.546 78.9  -1.239 0.9366
|| Low Semantic Small Simple - Low Semantic Small Complex -0.427 0.389 64.3  -1.204 0.3503
|| High Semantic Large Simple - Low Semantic Large Simple  0.274 0.564 59.4  -0.854 1.4020
|| High Semantic Large Simple - High Semantic Large Complex -0.014 0.376 64.3  -0.765 0.7375
|| Low Semantic Large Simple - Low Semantic Large Complex  -0.710 0.389 64.3  -1.487 0.0673
|| High Semantic Small Complex - Low Semantic Small Complex -0.390 0.594 59.2  -1.578 0.7973
|| High Semantic Small Complex - High Semantic Large Complex -0.129 0.300 68.4  -0.727 0.4698
|| Low Semantic Small Complex - Low Semantic Large Complex  -0.160 0.310 68.4  -0.779 0.4585
|| High Semantic Large Complex - Low Semantic Large Complex -0.422 0.630 59.1  -1.682 0.8384
||
|| Degrees-of-freedom method: kenward-roger
|| Confidence level used: 0.95
```

```

# Get effect sizes
# Get all pairwise effect sizes
effs2 <- eff_size(emm2, sigma = sigma(m2), edf = df.residual(m2))

# Remove the redundant rows
(effs2_filtered <- subset(effs2, contrast %in% keep2))

## contrast                               effect.size    SE   df lower.CL upper.CL
## High Semantic Small Simple - Low Semantic Small Simple -0.15724 0.375 59.6 -0.908 0.5933
## High Semantic Small Simple - High Semantic Large Simple -0.26423 0.213 59.4 -0.689 0.1609
## High Semantic Small Simple - High Semantic Small Complex -0.18302 0.267 59.2 -0.716 0.3503
## Low Semantic Small Simple - High Semantic Large Simple -0.10699 0.387 59.4 -0.881 0.6675
## Low Semantic Small Simple - Low Semantic Small Complex -0.30224 0.276 59.2 -0.854 0.2492
## High Semantic Large Simple - Low Semantic Large Simple 0.19399 0.400 59.4 -0.605 0.9933
## High Semantic Large Simple - High Semantic Large Complex -0.00991 0.267 59.1 -0.543 0.5234
## Low Semantic Large Simple - Low Semantic Large Complex -0.50274 0.276 59.1 -1.054 0.0489
## High Semantic Small Complex - Low Semantic Small Complex -0.27646 0.421 59.2 -1.118 0.5649
## High Semantic Small Complex - High Semantic Large Complex -0.09111 0.212 59.1 -0.516 0.3340
## Low Semantic Small Complex - Low Semantic Large Complex -0.11349 0.220 59.1 -0.553 0.3261
## High Semantic Large Complex - Low Semantic Large Complex -0.29884 0.446 59.1 -1.192 0.5940
##
## sigma used for effect sizes: 1.411
## Degrees-of-freedom method: inherited from kenward-roger when re-gridding
## Confidence level used: 0.95

```

4.2.2 Semantic_Sensitivity x family_size x complexity Interaction Contrasts

The interaction contrast tests whether the difference in the complexity effect for large vs small families differs across sensitivity?

```

[[((A1 - A2) in B1] - [(A1 - A2) in B2] in Condition C1] - [[(A1 - A2) in B1] - [(A1 - A2) in B2] in Condition C2]

# Interaction contrasts (difference-of-differences)
# Compare complexity effect in large vs small family
contrast(emm2, interaction = "pairwise", by = NULL, adjust = "holm")

## Semantic_Sensitivity_pairwise family_size_pairwise complexity_pairwise estimate    SE   df t.ratio p.value
## High Semantic - Low Semantic Small - Large      Simple - Complex      -0.527 0.243 1498 -2.169 0.0302
##
## Degrees-of-freedom method: kenward-roger
confint(contrast(emm2, interaction = c("pairwise", "pairwise")))

## Semantic_Sensitivity_pairwise family_size_pairwise complexity_pairwise estimate    SE   df lower.CL upper.CL
## High Semantic - Low Semantic Small - Large      Simple - Complex      -0.527 0.243 1498      -1 -0.0505
##
## Degrees-of-freedom method: kenward-roger
## Confidence level used: 0.95
# Compute the A1 - A2 difference within each combination of B × C
(complexity_diff <- contrast(emm2, method = "revpairwise",
                             by = c("Semantic_sensitivity", "family_size"),
                             simple = "complexity"))

## Semantic_Sensitivity = High Semantic, family_size = Small:
## contrast          estimate    SE   df t.ratio p.value
## Complex - Simple  0.258 0.376 64.3  0.687 0.4947
##
## Semantic_Sensitivity = Low Semantic, family_size = Small:
## contrast          estimate    SE   df t.ratio p.value
## Complex - Simple  0.427 0.389 64.3  1.097 0.2768
##
## Semantic_Sensitivity = High Semantic, family_size = Large:
## contrast          estimate    SE   df t.ratio p.value
## Complex - Simple  0.014 0.376 64.3  0.037 0.9705
##
## Semantic_Sensitivity = Low Semantic, family_size = Large:
## contrast          estimate    SE   df t.ratio p.value
## Complex - Simple  0.710 0.389 64.3  1.824 0.0727
##
## Degrees-of-freedom method: kenward-roger
# Compute how that A-effect changes across the levels of B, separately for each level of C
(familysize_complexity_int_within_sensitivity <- contrast(complexity_diff,
                           method = "revpairwise",
                           by = "Semantic_sensitivity", simple = "family_size"))

## contrast = Complex - Simple, Semantic_Sensitivity = High Semantic:
## contrast1         estimate    SE   df t.ratio p.value
## Large - Small    -0.244 0.169 1498 -1.446 0.1484
##
```

```

|| contrast = Complex - Simple, Semantic_Sensitivity = Low Semantic:
|| contrast1   estimate    SE   df t.ratio p.value
|| Large - Small     0.283 0.175 1498    1.620  0.1055
||
|| Degrees-of-freedom method: kenward-roger
# Get confidence intervals
confint(familysize_complexity_int_within_sensitivity)

|| contrast = Complex - Simple, Semantic_Sensitivity = High Semantic:
|| contrast1   estimate    SE   df lower.CL upper.CL
|| Large - Small    -0.244 0.169 1498   -0.5758   0.0872
||
|| contrast = Complex - Simple, Semantic_Sensitivity = Low Semantic:
|| contrast1   estimate    SE   df lower.CL upper.CL
|| Large - Small     0.283 0.175 1498   -0.0598   0.6257
||
|| Degrees-of-freedom method: kenward-roger
|| Confidence level used: 0.95

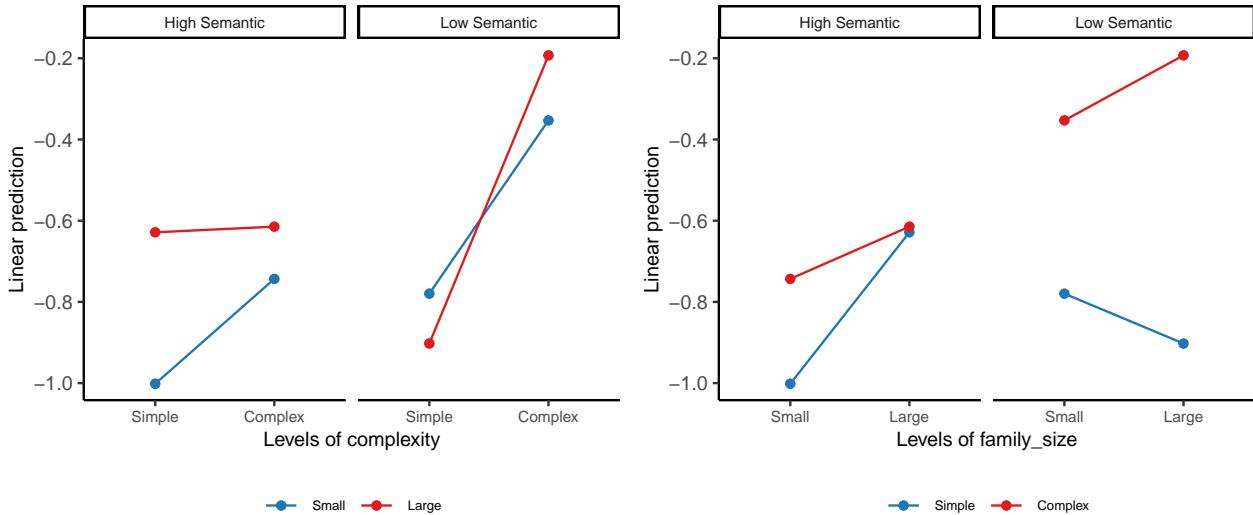
```

4.2.3 Semantic_Sensitivity x family_size x complexity Plots

```

p5 <- emmip(anova_model_n250_nonwords, family_size ~ complexity | Semantic_Sensitivity) + my_style
p6 <- emmip(anova_model_n250_nonwords, complexity ~ family_size | Semantic_Sensitivity) + my_style
plot_grid(p5, p6, ncol = 2)

```



- The interaction arises because for high-semantic participants, there is essentially no difference in N250 amplitude between complex and simple nonwords across either family size.
- For low-semantic participants, however, large-family complex nonwords elicit more negative N250s than simple ones, hinting that increased morphological complexity only affects processing when the participant's semantic sensitivity is low and the item belongs to a large morphological family.

Because these effects were obtained for nonwords in a lexical decision task, we interpret the N250 and N400 modulations as reflecting morpho-orthographic parsing and semantic co-activation from morphemic constituents and morphological families, rather than retrieval of lexical entries. The robust three-way interaction in the N400 indicates that semantic sensitivity alters how family size modulates the semantic co-activation elicited by morphologically complex nonwords—amplifying complexity benefits for low-semantic readers (especially in large families) but attenuating them for high-semantic readers, consistent with differences in reliance on semantic co-activation vs. rapid mismatch detection during nonword rejection.