PROST P600 combined groups analysis using lmer

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This script, on the advice of reviewer 1, conducts an ANOVA examining the P600 PROST data with Referentiality, Gender and Anaphor Type as within-subject variables. Gender Identity status will be examined as a post-hoc variable.

Define functions, set parameters and load

Define standard error of mean function

```
sem <- function(x) sd(x)/sqrt(length(x))
```

Before we begin, let's set some general parameters for `ggplot2`. We will set a general theme using the `theme_set()` function. We will use the 'classic' theme which gives us clean white background rather than the default grey with white grid lines. We will position the legend at the top of the graph rather than at the right side which is the default.

```
theme_set(theme_classic()+
            theme(legend.position = "bottom"))
```

```
prost_2022_singular <- read_csv("prost_2022_singular_p600.csv")
prost_2022_plural <- read_csv("prost_2022_plural_p600.csv")
prost_2024_combined <- bind_rows(list(singular = prost_2022_singular,
                                      plural = prost_2022_plural), .id = "Anaphor_Type")
```

Then we re-order factor levels for *Referentiality*

```
prost_2024_combined$Referentiality <- factor(prost_2024_combined$Referentiality,
                                             levels=c('Referential',
                                                      'NonReferential'))
levels(prost_2024_combined$Referentiality)
```

```
## [1] "Referential"    "NonReferential"
```

Check ANOVA assumptions

- *No significant outliers in any cell of the design*. This can be checked by visualizing the data using box plot methods and by using the function `identify_outliers()` in the `rstatix` package.

```
library(rstatix)
kable(identify_outliers(prost_2024_combined, diff_score))
```

Anaphor_Type	SubjID	Referentiality	Gender_Status	Group	Baseline	Critical	diff_score	is.outlier	is.extreme
singular	203	NonReferential	Gendered	Binary	-2.43645	2.24315	4.67960	TRUE	FALSE
singular	207	Referential	Gendered	Binary	3.27080	-0.69125	-3.96205	TRUE	FALSE
singular	216	Referential	Gendered	Binary	3.30220	-1.11125	-4.41345	TRUE	FALSE
singular	221	NonReferential	Gendered	Binary	0.71770	5.81575	5.09805	TRUE	FALSE
singular	305	NonReferential	Gendered	NonBinary	0.12800	6.65140	6.52340	TRUE	FALSE
singular	312	NonReferential	Gendered	NonBinary	-1.43700	3.31660	4.75360	TRUE	FALSE
plural	216	Referential	NonGendered	Binary	2.37845	-1.65425	-4.03270	TRUE	FALSE
plural	222	NonReferential	NonGendered	Binary	2.17760	-2.10860	-4.28620	TRUE	FALSE

- *Normality*: the outcome (or dependent) variable should be approximately normally distributed in each cell of the design. This can be checked using the Shapiro-Wilk normality test `shapiro_test()`in the `rstatix` package.

```
kable(shapiro_test(prost_2024_combined, diff_score))
```

variable	statistic	p
diff_score	0.9918709	0.0938187

- *Assumption of sphericity*: the variance of the differences between groups should be equal. This can be checked using the Mauchly's test of sphericity, which is automatically reported when using the R function `anova_test()` in the `rstatix` package.

Analysis using `rstatix()`

```
res.aov <- anova_test(data = prost_2024_combined,
                      dv = diff_score,
                      wid = SubjID,
                      within = c(Referentiality, Gender_Status, Anaphor_Type))
kable(res.aov)
```

Effect	DFn	DFd	F	p	p<.05	ges
Referentiality	1	37	6.212	1.70e-02	*	0.019000
Gender_Status	1	37	2.094	1.56e-01		0.008000
Anaphor_Type	1	37	0.317	5.77e-01		0.000985
Referentiality:Gender_Status	1	37	0.136	7.15e-01		0.000602
Referentiality:Anaphor_Type	1	37	28.976	4.30e-06	*	0.080000
Gender_Status:Anaphor_Type	1	37	0.410	5.26e-01		0.001000
Referentiality:Gender_Status:Anaphor_Type	1	37	11.701	2.00e-03	*	0.036000

Analysis using EZANOVA

```
library(ez)
fitted.model.1 <- ezANOVA(data = prost_2024_combined
              , dv = diff_score
              , wid = SubjID
              , within = .(Referentiality, Gender_Status, Anaphor_Type)
              , type = 3
              , return_aov = F
              )
pander(fitted.model.1)
```

- **ANOVA**:

Table 4: Table continues below

	Effect	DFn	DFd	F
2	Referentiality	1	37	6.212
3	Gender_Status	1	37	2.094
4	Anaphor_Type	1	37	0.3171
5	Referentiality:Gender_Status	1	37	0.1358
6	Referentiality:Anaphor_Type	1	37	28.98
7	Gender_Status:Anaphor_Type	1	37	0.4098
8	Referentiality:Gender_Status:Anaphor_Type	1	37	11.7

	p	p<.05	ges
2	0.0173	*	0.01894
3	0.1563		0.008441
4	0.5768		0.0009849
5	0.7146		0.0006023
6	4.299e-06	*	0.08024
7	0.526		0.001088
8	0.001537	*	0.03579

Analysis using lmer

```
library(lme4)
library(car)
fitted.model.2 <- lmer(diff_score ~ Referentiality * Gender_Status * Anaphor_Type + (1|SubjID), data=prost_2024_combined)
kable(Anova(fitted.model.2))
```

	Chisq	Df	Pr(>Chisq)
Referentiality	5.7358431	1	0.0166221
Gender_Status	2.5294548	1	0.1117388
Anaphor_Type	0.2929198	1	0.5883555
Referentiality:Gender_Status	0.1790786	1	0.6721663
Referentiality:Anaphor_Type	25.9197219	1	0.0000004
Gender_Status:Anaphor_Type	0.3236341	1	0.5694318
Referentiality:Gender_Status:Anaphor_Type	11.0278606	1	0.0008975

Post-hoc tests

If there is a significant three-way interaction effect, you can decompose it into:

- *Simple two-way interaction*: run two-way interaction at each level of third variable,
- *Simple simple main effect*: run one-way model at each level of second variable, and
- *Simple simple pairwise comparisons*: run pairwise or other post-hoc comparisons if necessary.

Compute simple two-way interaction

You are free to decide which two variables will form the simple two-way interactions and which variable will act as the third (moderator) variable. In the following R code, we have considered the simple two-way interaction of Referentiality*Gender Status at each level of Anaphor Type

It is recommended to adjust the p-value for multiple testing (Bonferroni correction) by dividing the current α-level you declare statistical significance at (i.e., $p < 0.05$) by the number of simple two-way interaction you are computing (i.e., 2). Thus two-way interaction as statistically significant when $p < 0.025$ (i.e., $p < 0.05/2$).

```
prost_2024_combined <- prost_2024_combined |> ungroup() |> group_by(Anaphor_Type)

kable(two.way <- prost_2024_combined |>
  anova_test(dv = diff_score, wid = SubjID, within = c(Referentiality, Gender_Status)))
```

Anaphor_Type	Effect	DFn	DFd	F	p	p<.05	ges
plural	Referentiality	1	37	5.378	2.60e-02	*	0.024
plural	Gender_Status	1	37	0.594	4.46e-01		0.003
plural	Referentiality:Gender_Status	1	37	4.739	3.60e-02	*	0.045
singular	Referentiality	1	37	24.535	1.63e-05	*	0.160
singular	Gender_Status	1	37	2.082	1.57e-01		0.016
singular	Referentiality:Gender_Status	1	37	5.367	2.60e-02	*	0.028

Can aslo compute these using lmer

```
library(lme4)
fitted.model.2a <- lmer(diff_score ~ Referentiality * Gender_Status  + (1|SubjID), data=filter(prost_2024_combined,Anaphor_Type == "singular" ))
kable(Anova(fitted.model.2a))
```

	Chisq	Df	Pr(>Chisq)
Referentiality	28.130117	1	0.0000001
Gender_Status	2.340409	1	0.1260565
Referentiality:Gender_Status	4.214542	1	0.0400789

```
fitted.model.2b <- lmer(diff_score ~ Referentiality * Gender_Status  + (1|SubjID), data=filter(prost_2024_combined,Anaphor_Type == "plural" ))
kable(Anova(fitted.model.2b))
```

	Chisq	Df	Pr(>Chisq)
Referentiality	3.595763	1	0.0579270
Gender_Status	0.516181	1	0.4724753
Referentiality:Gender_Status	6.933698	1	0.0084587

Compute simple simple main effect

A statistically significant simple two-way interaction can be followed up with simple simple main effects.

Group the data by Anaphor_Type and Gender_Status, and analyze the simple main effect of Referentiality. The Bonferroni adjustment will be considered leading to statistical significance being accepted at the $p < 0.025$ level (that is 0.05 divided by the number of tests (here 2).

```
# Effect of Referentiality at each Anaphor_Type X Gender_Status cell
kable(ref.effect <- prost_2024_combined |>
  group_by(Anaphor_Type, Gender_Status) |>
  anova_test(dv = diff_score, wid = SubjID, within = Referentiality) )
```

Anaphor_Type	Gender_Status	Effect	DFn	DFd	F	p	p<.05	ges
plural	Gendered	Referentiality	1	37	11.333	2.00e-03	*	0.143
plural	NonGendered	Referentiality	1	37	0.221	6.41e-01		0.003
singular	Gendered	Referentiality	1	37	23.359	2.36e-05	*	0.233
singular	NonGendered	Referentiality	1	37	6.833	1.30e-02	*	0.082

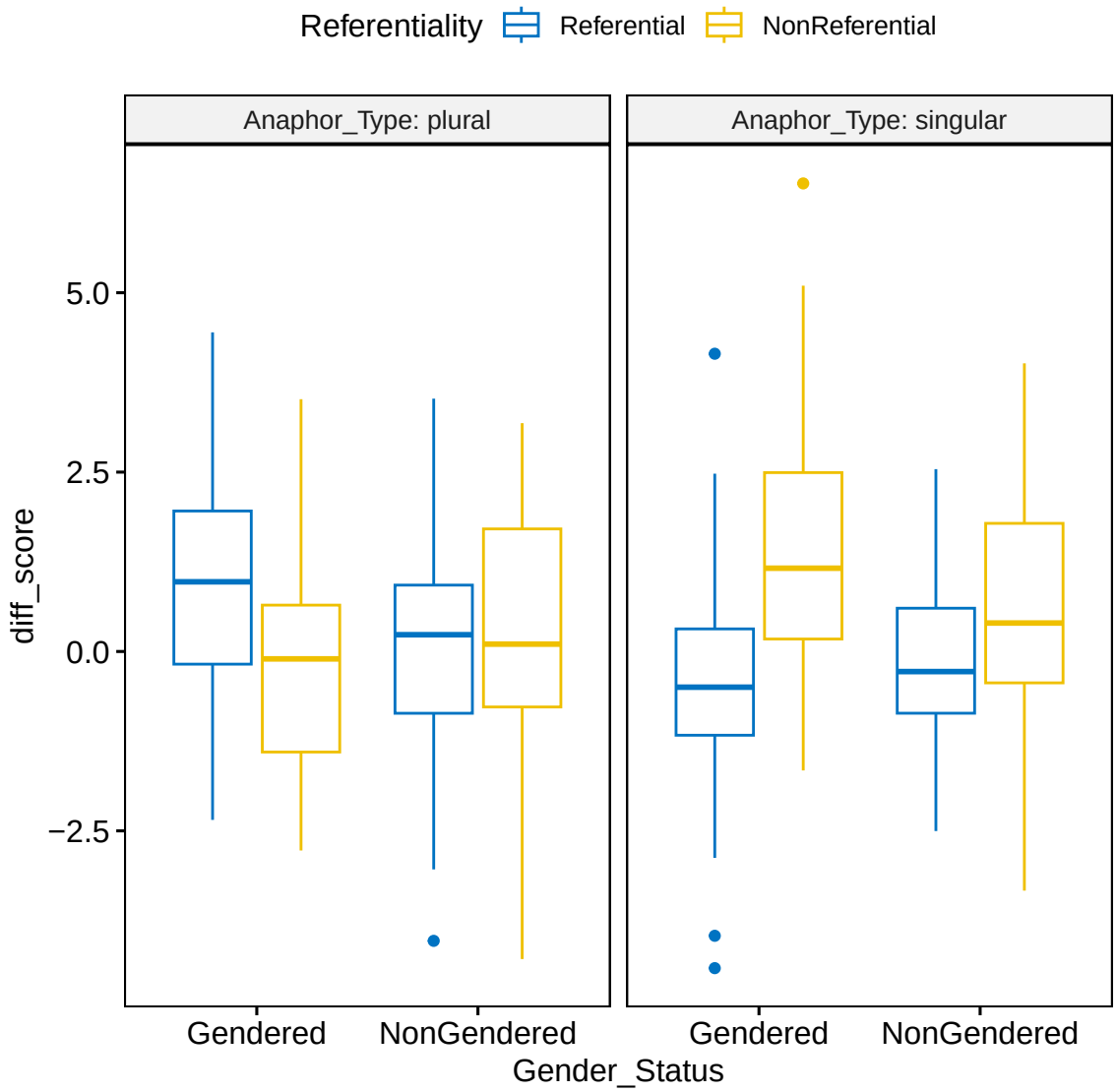
Perform pairwise comparisons between Referentiality levels with Bonferroni adjustment:

```r
# Pairwise comparisons
pwc <- prost_2024_combined |>
  group_by(Anaphor_Type, Gender_Status) |>
  pairwise_t_test(diff_score ~ Referentiality, paired = TRUE, p.adjust.method = "bonferroni") |>
  select(-df, -statistic) # Remove details
kable(pwc)
```

Anaphor_Type	Gender_Status	.y.	group1	group2	n1	n2	p	p.adj	p.adj.signif
plural	Gendered	diff_score	Referential	NonReferential	38	38	2.00e-03	2.00e-03	**
plural	NonGendered	diff_score	Referential	NonReferential	38	38	6.41e-01	6.41e-01	ns
singular	Gendered	diff_score	Referential	NonReferential	38	38	2.36e-05	2.36e-05	****
singular	NonGendered	diff_score	Referential	NonReferential	38	38	1.30e-02	1.30e-02	*

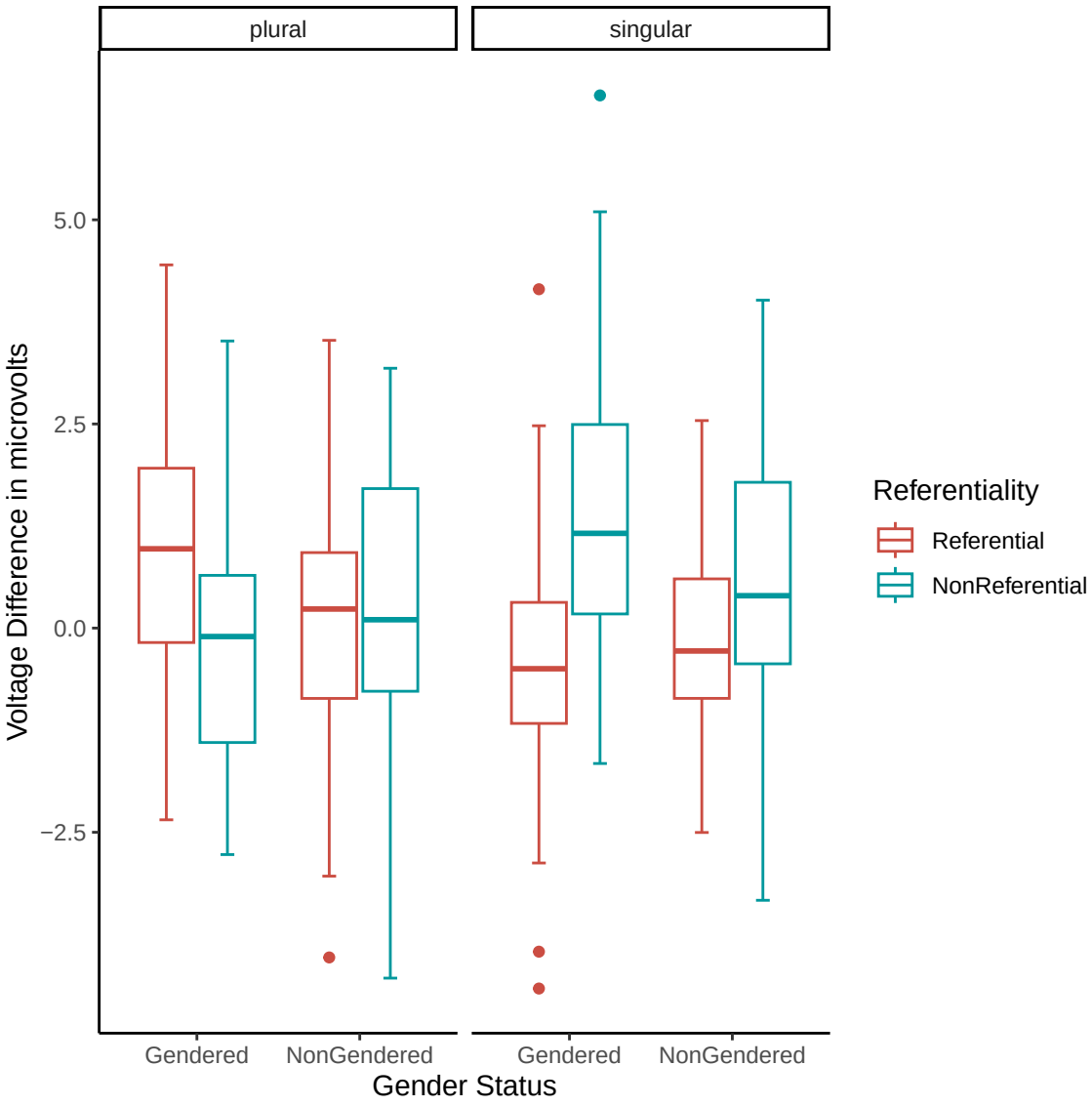
Visualization: box plots

```r
library(ggpubr)
bxp <- ggboxplot(
  prost_2024_combined, x = "Gender_Status", y = "diff_score",
  color = "Referentiality", palette = "jco",
  facet.by = "Anaphor_Type", short.panel.labs = FALSE
  )
bxp
```



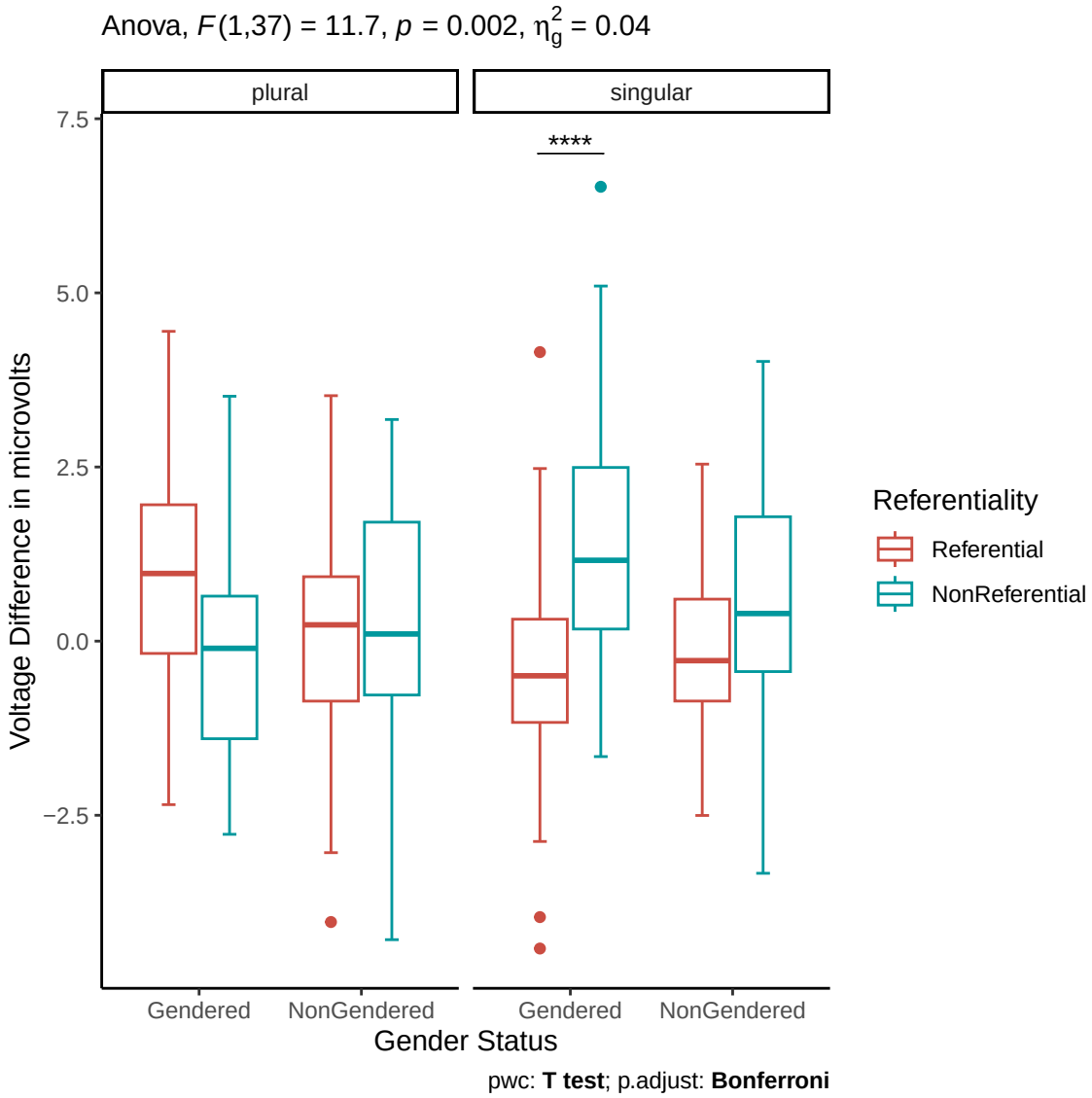
```
prost_2024_combined <- ungroup(prost_2024_combined)
library(ggplot2)
library(ggsci)
bxp2 <- ggplot(data = prost_2024_combined,
       mapping = aes(x = Gender_Status, y = diff_score, colour = Referentiality)) +
  geom_boxplot(staplewidth = .25) +
  facet_wrap(~ Anaphor_Type, ncol = 2) +
  labs(y = "Voltage Difference in microvolts", x = "Gender Status") +
  theme_classic()+
  scale_colour_hue(l=50, c=100)

bxp2
```



Visualization: box plots with p-values

```
pwc <- pwc |> add_xy_position(x = "Gender_Status")
pwc.filtered <- pwc |>
  filter(Anaphor_Type == "singular", Gender_Status == "Gendered")
bxp2 +
  stat_pvalue_manual(pwc.filtered, tip.length = 0, hide.ns = TRUE) +
  labs(
    subtitle = get_test_label(res.aov, detailed = TRUE),
    caption = get_pwc_label(pwc)
  )
```



Condition Means for Analysis 1

Significant Effects: **Referentiality; Referentiality x Anaphor Type; Referentiality X Gender Status X Anaphor Type**

```
kable(singular_means1 <- prost_2024_combined |>
  group_by(Referentiality) |>
  summarise(Mean = mean(diff_score),
            SE = sem(diff_score),
            SD = sd(diff_score),
            Max = max(diff_score),
            Min = min(diff_score)), digits = 2)
```

Referentiality	Mean	SE	SD	Max	Min
Referential	0.08	0.13	1.59	4.45	-4.41
NonReferential	0.51	0.14	1.76	6.52	-4.29

```
kable(singular_means1 <- prost_2024_combined |>
  group_by(Referentiality, Anaphor_Type) |>
  summarise(Mean = mean(diff_score),
            SE = sem(diff_score),
            SD = sd(diff_score),
            Max = max(diff_score),
            Min = min(diff_score)), digits = 2)
```

Referentiality	Anaphor_Type	Mean	SE	SD	Max	Min
Referential	plural	0.49	0.19	1.66	4.45	-4.03
Referential	singular	-0.34	0.16	1.42	4.15	-4.41
NonReferential	plural	0.00	0.18	1.60	3.52	-4.29
NonReferential	singular	1.03	0.20	1.78	6.52	-3.33

```
kable(singular_means2 <- prost_2024_combined |>
  group_by( Anaphor_Type, Referentiality,  Gender_Status) |>
  summarise(Mean = mean(diff_score),
            SE = sem(diff_score),
            SD = sd(diff_score),
            Max = max(diff_score),
            Min = min(diff_score)), digits = 2)
```

Anaphor_Type	Referentiality	Gender_Status	Mean	SE	SD	Max	Min
plural	Referential	Gendered	0.93	0.25	1.52	4.45	-2.35
plural	Referential	NonGendered	0.06	0.28	1.70	3.52	-4.03
plural	NonReferential	Gendered	-0.25	0.23	1.40	3.52	-2.77
plural	NonReferential	NonGendered	0.25	0.29	1.76	3.18	-4.29
singular	Referential	Gendered	-0.40	0.26	1.63	4.15	-4.41
singular	Referential	NonGendered	-0.27	0.19	1.18	2.54	-2.50
singular	NonReferential	Gendered	1.49	0.30	1.84	6.52	-1.66
singular	NonReferential	NonGendered	0.57	0.26	1.62	4.02	-3.33