Effects of spatial separation on vowel discrimination in noise, and it's dependence on Auditory Cortex

Version History:

- Created: 2021-09-09 Stephen Town
- Ported to notebook: 2022-05-19

```
rm(list = ls())
suppressPackageStartupMessages( library(dplyr))
suppressPackageStartupMessages( library(tidyverse))
suppressPackageStartupMessages( library(lme4))
suppressPackageStartupMessages( library(DHARMa))
suppressPackageStartupMessages( library(scales))
```

1. Load Data

From animals with functional cooling loops (F1311 and F1509) and animals tested with behavior only (F1201, F1203, F1216, F1217).

```
data_path = '/home/stephen/Github/Vowel_Discrimination_In_Noise/Results/Vowels_Unmasking/data/analysis'

floz = read_csv( file.path( data_path, 'F1201.csv'), show_col_types = FALSE)
virg = read_csv( file.path( data_path, 'F1203.csv'), show_col_types = FALSE)
mini = read_csv( file.path( data_path, 'F1216.csv'), show_col_types = FALSE)
clio = read_csv( file.path( data_path, 'F1217.csv'), show_col_types = FALSE)
magnum = read_csv( file.path( data_path, 'F1311.csv'), show_col_types = FALSE)
robin  = read_csv( file.path( data_path, 'F1509.csv'), show_col_types = FALSE)

cols = c('fNum','treatment',"VowelLocation","SpatialCondition","Atten","F1","Correct")
df = rbind(magnum[cols], robin[cols], floz[cols], virg[cols], mini[cols], clio[cols])

rm(list = c("clio", "floz", "virg", "mini", "robin", "magnum"))
head(df)
```

```
## # A tibble: 6 x 7
##    fNum treatment VowelLocation SpatialCondition Atten    F1 Correct
##   <dbl> <lgl>     <chr>         <chr>            <dbl> <dbl>   <dbl>
## 1  1311 FALSE     left          separated           -6   936       1
## 2  1311 FALSE     right         separated           -6   437       0
## 3  1311 FALSE     left          separated          -12   437       0
## 4  1311 FALSE     left          colocated          -12   437       1
## 5  1311 FALSE     left          colocated           -9   936       1
## 6  1311 FALSE     left          separated          -15   936       1
```

2. Transform data

Format subject number as factor and convert binary data to counts.

```
df$fNum <- as.factor(df$fNum)
df$F1 <- as.factor(df$F1)    # First formant = vowel identity

df$vowel_level_orig = 57 - df$Atten
df$vowel_level <- rescale(df$vowel_level_orig)

counts = df %>%
  group_by(fNum, treatment, VowelLocation, SpatialCondition, F1, vowel_level) %>%
  summarise(
    nCorrect = sum(Correct),
    nTotal = n(),
    .groups = 'keep'
    ) %>%
  mutate( pCorrect = nCorrect / nTotal * 100)

head(counts)
```

```
## # A tibble: 6 x 9
## # Groups:   fNum, treatment, VowelLocation, SpatialCondition, F1, vowel_level
## #   [6]
##   fNum  treatment VowelLocation SpatialCondition F1    vowel_level nCorrect
##   <fct> <lgl>     <chr>         <chr>            <fct>       <dbl>    <dbl>
## 1 1201  FALSE     left          colocated        460           0         91
## 2 1201  FALSE     left          colocated        460           0.4       15
## 3 1201  FALSE     left          colocated        460           0.6       80
## 4 1201  FALSE     left          colocated        730           0         49
## 5 1201  FALSE     left          colocated        730           0.4        8
## 6 1201  FALSE     left          colocated        730           0.6       68
## # ... with 2 more variables: nTotal <int>, pCorrect <dbl>
```

7. All In One Model

What if we just included everything in the dataset, rather than doing four separate modelling analyses?

```
ACS_counts = subset(counts, SpatialCondition %in% c("colocated", "separated"))

clean_counts = subset(counts, SpatialCondition %in% c("single_speaker"))
clean_counts = rename(clean_counts, clean_pCorrect=pCorrect)
clean_counts = clean_counts %>%
    select(fNum, SpatialCondition, treatment, vowel_level, VowelLocation, F1, clean_pCorrect)

ACS_extended <- merge(
  x = ACS_counts,
  y = clean_counts,
  by = c("fNum", "treatment", "VowelLocation", "F1", "vowel_level"),
  all.x = TRUE,
  all.y = FALSE)
```

7.1. Model Fitting

Start with just the main effects

```
ACS_mdl_1 <- glmer(
  cbind(nCorrect, nTotal - nCorrect) ~ SpatialCondition.x + treatment + vowel_level + VowelLocation + (
  data = ACS_extended,
```

```
  family = binomial)

summary(ACS_mdl_1)
```

```
## Generalized linear mixed model fit by maximum likelihood (Laplace
##   Approximation) [glmerMod]
##  Family: binomial  ( logit )
## Formula: cbind(nCorrect, nTotal - nCorrect) ~ SpatialCondition.x + treatment +
##     vowel_level + VowelLocation + (1 | fNum) + (0 + clean_pCorrect |      fNum)
##    Data: ACS_extended
##
##      AIC      BIC   logLik deviance df.resid
##   1717.3   1743.7   -851.7   1703.3      313
##
## Scaled residuals:
##     Min      1Q  Median      3Q     Max
## -5.1272 -0.9766  0.0810  0.9806  3.6507
##
## Random effects:
##  Groups Name           Variance Std.Dev.
##  fNum   (Intercept)    3.016416 1.73678
##  fNum.1 clean_pCorrect 0.001208 0.03476
## Number of obs: 320, groups:  fNum, 6
##
## Fixed effects:
##                             Estimate Std. Error z value Pr(>|z|)
## (Intercept)                 -1.65258    0.72548  -2.278 0.022731 *
## SpatialCondition.xseparated  0.14226    0.04321   3.292 0.000995 ***
## treatmentTRUE               -0.25715    0.10320  -2.492 0.012711 *
## vowel_level                  0.19638    0.08794   2.233 0.025538 *
## VowelLocationright          -0.06120    0.04391  -1.394 0.163407
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Correlation of Fixed Effects:
##             (Intr) SptlC. trTRUE vwl_lv
## SptlCndtn.x -0.032
## tretmntTRUE -0.022 -0.007
## vowel_level -0.029 -0.003  0.008
## VwlLctnrght -0.039  0.001  0.010 -0.009
```

Next, add an interaction between spatial condition and treatment

```
ACS_mdl_2 <- glmer(
  cbind(nCorrect, nTotal - nCorrect) ~ SpatialCondition.x*treatment + vowel_level + VowelLocation + (1|
  data = ACS_extended,
  family = binomial)

summary(ACS_mdl_2)
```

```
## Generalized linear mixed model fit by maximum likelihood (Laplace
##   Approximation) [glmerMod]
##  Family: binomial  ( logit )
## Formula: cbind(nCorrect, nTotal - nCorrect) ~ SpatialCondition.x * treatment +
##     vowel_level + VowelLocation + (1 | fNum) + (0 + clean_pCorrect |      fNum)
```

```
##    Data: ACS_extended
##
##      AIC      BIC   logLik deviance df.resid
##   1716.9   1747.1   -850.5   1700.9      312
##
## Scaled residuals:
##     Min      1Q  Median      3Q     Max
## -4.8272 -0.8993  0.0856  0.9953  3.6070
##
## Random effects:
##  Groups Name           Variance Std.Dev.
##  fNum   (Intercept)    3.025164 1.73930
##  fNum.1 clean_pCorrect 0.001209 0.03477
## Number of obs: 320, groups:  fNum, 6
##
## Fixed effects:
##                                          Estimate Std. Error z value Pr(>|z|)
## (Intercept)                              -1.64228    0.72652  -2.260  0.02379
## SpatialCondition.xseparated               0.12413    0.04477   2.773  0.00556
## treatmentTRUE                            -0.38603    0.13213  -2.922  0.00348
## vowel_level                               0.19628    0.08795   2.232  0.02562
## VowelLocationright                       -0.06127    0.04392  -1.395  0.16302
## SpatialCondition.xseparated:treatmentTRUE  0.26522    0.17166   1.545  0.12233
##
## (Intercept)                              *
## SpatialCondition.xseparated              **
## treatmentTRUE                            **
## vowel_level                              *
## VowelLocationright
## SpatialCondition.xseparated:treatmentTRUE
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Correlation of Fixed Effects:
##             (Intr) SptlC. trTRUE vwl_lv VwlLct
## SptlCndtn.x -0.033
## tretmntTRUE -0.023  0.162
## vowel_level -0.029 -0.003  0.007
## VwlLctnrght -0.039  0.001  0.008 -0.009
## SptlC.:TRUE  0.009 -0.261 -0.622 -0.001 -0.001
```

Add in the interaction between treatment and Attenuation that might capture greater effects of cooling for quieter sounds

```
ACS_mdl_3 <- glmer(
  cbind(nCorrect, nTotal - nCorrect) ~ SpatialCondition.x*treatment + treatment*vowel_level + VowelLoca
  data = ACS_extended,
  family = binomial)

summary(ACS_mdl_3)
```

```
## Generalized linear mixed model fit by maximum likelihood (Laplace
##   Approximation) [glmerMod]
##  Family: binomial  ( logit )
## Formula: cbind(nCorrect, nTotal - nCorrect) ~ SpatialCondition.x * treatment +
```

```
##     treatment * vowel_level + VowelLocation + (1 | fNum) + (0 +
##     clean_pCorrect | fNum)
##    Data: ACS_extended
##
##      AIC      BIC   logLik deviance df.resid
##   1718.9   1752.8   -850.5   1700.9      311
##
## Scaled residuals:
##     Min      1Q  Median      3Q     Max
## -4.8458 -0.9006  0.0836  0.9947  3.6036
##
## Random effects:
##  Groups Name           Variance Std.Dev.
##  fNum   (Intercept)    3.030129 1.74073
##  fNum.1 clean_pCorrect 0.001209 0.03477
## Number of obs: 320, groups:  fNum, 6
##
## Fixed effects:
##                                          Estimate Std. Error z value Pr(>|z|)
## (Intercept)                              -1.64148    0.72713  -2.257  0.02398
## SpatialCondition.xseparated               0.12415    0.04477   2.773  0.00555
## treatmentTRUE                            -0.40961    0.25287  -1.620  0.10527
## vowel_level                               0.19446    0.08953   2.172  0.02986
## VowelLocationright                       -0.06126    0.04392  -1.395  0.16308
## SpatialCondition.xseparated:treatmentTRUE  0.26506    0.17170   1.544  0.12265
## treatmentTRUE:vowel_level                 0.03676    0.33600   0.109  0.91289
##
## (Intercept)                              *
## SpatialCondition.xseparated              **
## treatmentTRUE
## vowel_level                              *
## VowelLocationright
## SpatialCondition.xseparated:treatmentTRUE
## treatmentTRUE:vowel_level
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Correlation of Fixed Effects:
##             (Intr) SptlC. trTRUE vwl_lv VwlLct SC.:TR
## SptlCndtn.x -0.033
## tretmntTRUE -0.021  0.083
## vowel_level -0.030 -0.003  0.163
## VwlLctnrght -0.039  0.001  0.003 -0.010
## SptlC.:TRUE  0.009 -0.261 -0.318  0.001 -0.001
## trtmnTRUE:_  0.010  0.002 -0.853 -0.187  0.001 -0.008
```

Finally, consider a three-way interaction between cooling, spatial separation and sound level

```
ACS_mdl_4 <- glmer(
  cbind(nCorrect, nTotal - nCorrect) ~ SpatialCondition.x*treatment*vowel_level + VowelLocation + (1|fNu
  data = ACS_extended,
  family = binomial)

summary(ACS_mdl_4)
```

```
## Generalized linear mixed model fit by maximum likelihood (Laplace
##   Approximation) [glmerMod]
##  Family: binomial  ( logit )
## Formula: cbind(nCorrect, nTotal - nCorrect) ~ SpatialCondition.x * treatment *
##     vowel_level + VowelLocation + (1 | fNum) + (0 + clean_pCorrect |      fNum)
##    Data: ACS_extended
##
##      AIC      BIC   logLik deviance df.resid
##   1722.4   1763.9   -850.2   1700.4      309
##
## Scaled residuals:
##     Min      1Q  Median      3Q     Max
## -4.7540 -0.8927  0.0881  0.9980  3.6965
##
## Random effects:
##  Groups Name           Variance Std.Dev.
##  fNum   (Intercept)    3.02876  1.74033
##  fNum.1 clean_pCorrect 0.00121  0.03479
## Number of obs: 320, groups:  fNum, 6
##
## Fixed effects:
##                                                    Estimate Std. Error
## (Intercept)                                        -1.66183    0.72794
## SpatialCondition.xseparated                         0.16253    0.08580
## treatmentTRUE                                      -0.30804    0.31220
## vowel_level                                         0.22564    0.10745
## VowelLocationright                                 -0.06128    0.04392
## SpatialCondition.xseparated:treatmentTRUE           0.05198    0.42020
## SpatialCondition.xseparated:vowel_level            -0.06392    0.12189
## treatmentTRUE:vowel_level                          -0.13203    0.45227
## SpatialCondition.xseparated:treatmentTRUE:vowel_level  0.35315    0.63553
##                                                    z value Pr(>|z|)
## (Intercept)                                         -2.283   0.0224 *
## SpatialCondition.xseparated                          1.894   0.0582 .
## treatmentTRUE                                       -0.987   0.3238
## vowel_level                                          2.100   0.0357 *
## VowelLocationright                                  -1.395   0.1629
## SpatialCondition.xseparated:treatmentTRUE            0.124   0.9016
## SpatialCondition.xseparated:vowel_level             -0.524   0.6000
## treatmentTRUE:vowel_level                           -0.292   0.7703
## SpatialCondition.xseparated:treatmentTRUE:vowel_level   0.556   0.5784
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Correlation of Fixed Effects:
##             (Intr) SptlC. trTRUE vwl_lv VwlLct SpC.:TRUE SpC.:_ tTRUE:
## SptlCndtn.x -0.061
## tretmntTRUE -0.024  0.131
## vowel_level -0.053  0.469  0.172
## VwlLctnrght -0.039  0.001  0.002 -0.008
## SptlC.:TRUE  0.015 -0.204 -0.642 -0.096  0.001
## SptlCndt.:_  0.051 -0.853 -0.112 -0.553  0.000  0.174
## trtmnTRUE:_  0.016 -0.110 -0.906 -0.188  0.002  0.611     0.130
## SpC.:TRUE:_ -0.013  0.164  0.586  0.106 -0.001 -0.913    -0.192 -0.670
```

7.2. Model Selection

AIC values

```
anova(ACS_mdl_1, ACS_mdl_2, ACS_mdl_3, ACS_mdl_4)
```

```
## Data: ACS_extended
## Models:
## ACS_mdl_1: cbind(nCorrect, nTotal - nCorrect) ~ SpatialCondition.x + treatment + vowel_level + Vowel
## ACS_mdl_2: cbind(nCorrect, nTotal - nCorrect) ~ SpatialCondition.x * treatment + vowel_level + Vowel
## ACS_mdl_3: cbind(nCorrect, nTotal - nCorrect) ~ SpatialCondition.x * treatment + treatment * vowel_l
## ACS_mdl_4: cbind(nCorrect, nTotal - nCorrect) ~ SpatialCondition.x * treatment * vowel_level + Vowel
##           npar    AIC    BIC  logLik deviance  Chisq Df Pr(>Chisq)
## ACS_mdl_1    7 1717.3 1743.7 -851.65   1703.3
## ACS_mdl_2    8 1716.9 1747.1 -850.46   1700.9 2.3946  1     0.1218
## ACS_mdl_3    9 1718.9 1752.8 -850.45   1700.9 0.0120  1     0.9129
## ACS_mdl_4   11 1722.4 1763.9 -850.21   1700.4 0.4899  2     0.7827
```

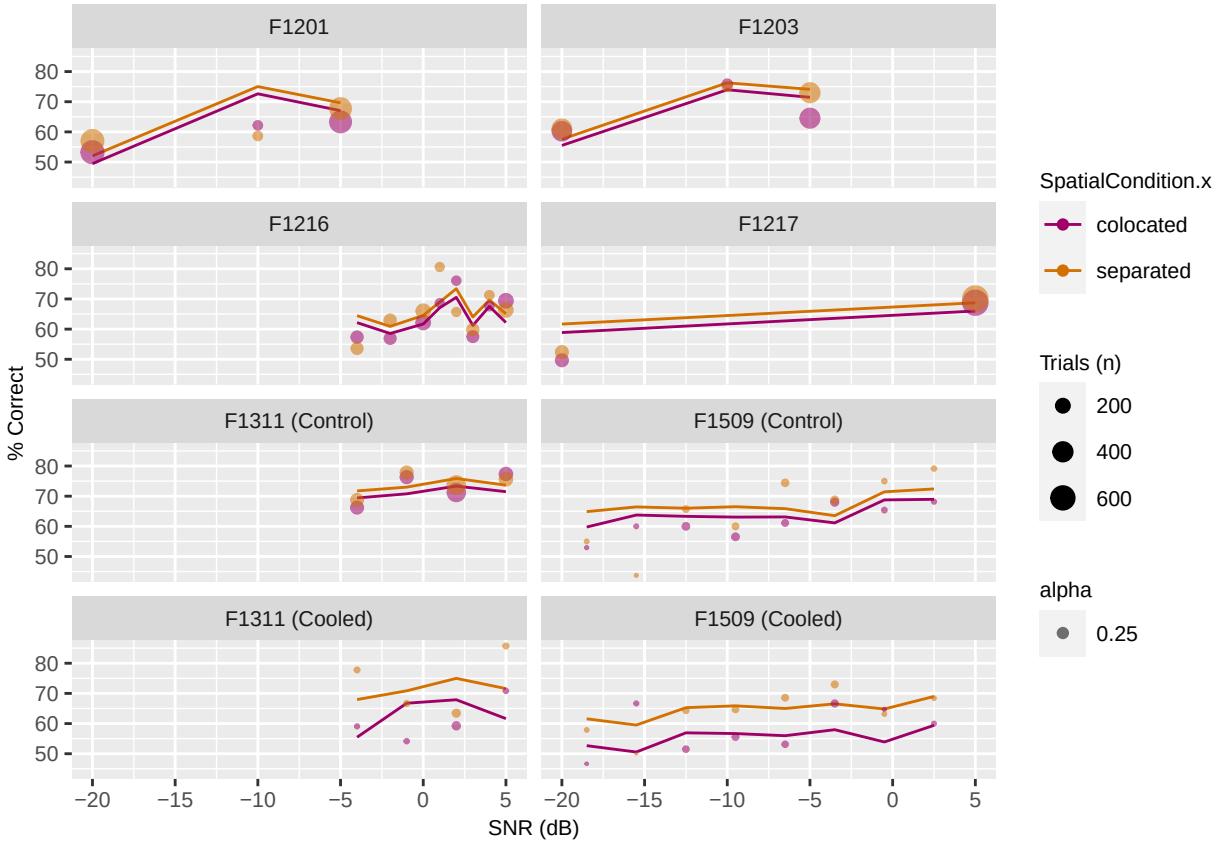
7.3. Model Prediction

```
ACS_extended$fit <- predict(ACS_mdl_2, ACS_extended, type="response")



# Summarize performance for ferret, stimulus condition, treatment, and sound level
ACS_agg_by_level <- ACS_extended %>%
  mutate(
    predicted_correct = fit * nTotal
    ) %>%
  group_by(
    fNum, SpatialCondition.x, treatment, vowel_level,
    ) %>%
  summarise(
    nCorrect = sum(nCorrect),
    nTotal = sum(nTotal),
    predicted_correct = sum(predicted_correct),
    .groups = 'keep'
    ) %>%
  mutate(
    pCorrect = nCorrect / nTotal * 100,
    fit_p = predicted_correct / nTotal * 100,
    group = interaction(fNum, treatment)
  )

# Restore original vowel levels for plotting
ACS_agg_by_level$vowel_level <- rescale(
  ACS_agg_by_level$vowel_level,
  to = c(min(df$vowel_level_orig) , max(df$vowel_level_orig)))

# Calculate SNR
ACS_agg_by_level$SNR = ACS_agg_by_level$vowel_level - 67
```

Plot

```
ggplot(
  ACS_agg_by_level,
```

```
  aes(x = SNR, color = SpatialCondition.x)
  ) +
geom_line(
  aes(y = fit_p)
  ) +
geom_point(
  shape = 19,
  aes(
    y = pCorrect,
    size = nTotal,
    alpha = 0.25
    )
  ) +
scale_size(range = c(0, 4))+
scale_color_manual(values=c('#9e0067','#d37000')) +
labs(
  x = "SNR (dB)",
  y = "% Correct",
  size='Trials (n)') +
theme(
  axis.text = element_text(size = 7.5),
  axis.title = element_text(size = 8),
  strip.text = element_text(size = 8),
  legend.title = element_text(size=8),
  legend.text = element_text(size=7.5)
  #strip.background = element_rect(colour="black", fill="white")
  ) +
facet_wrap(
  . ~ group,
  ncol = 2,
  labeller = labeller(group =
    c("1201.FALSE" = "F1201",
      "1203.FALSE" = "F1203",
      "1216.FALSE" = "F1216",
      "1217.FALSE" = "F1217",
      "1311.FALSE" = "F1311 (Control)",
      "1509.FALSE" = "F1509 (Control)",
      "1311.TRUE" = "F1311 (Cooled)",
      "1509.TRUE" = "F1509 (Cooled)")
  )
)
```

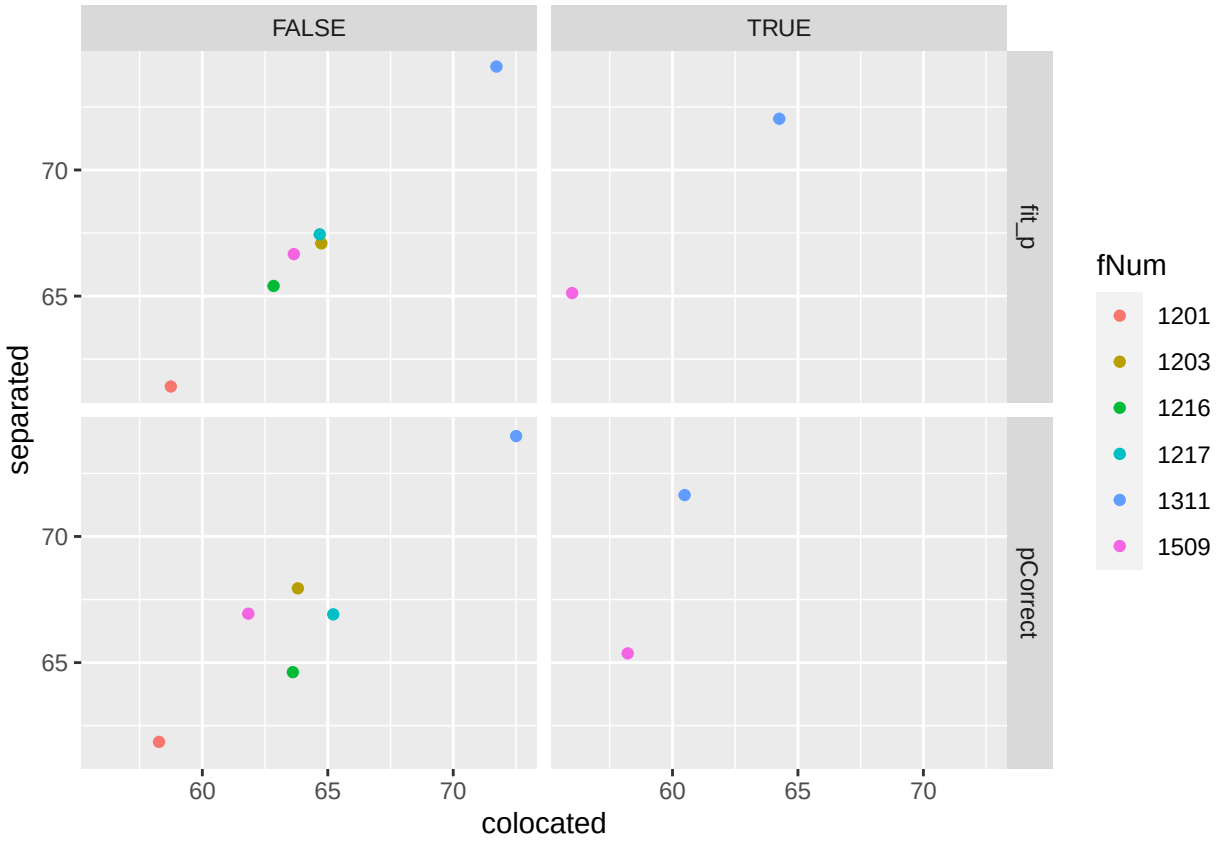



```
#ggsave(filename = "Unmasking_ACS2_predictions.png", width = 12, height = 11.5, units = "cm", dpi=300)
```

```
# Summarize performance for ferret, stimulus condition, treatment
ACS_agg_over_level <- ACS_extended %>%
  mutate(
    predicted_correct = fit * nTotal
    ) %>%
  group_by(
    fNum, SpatialCondition.x, treatment,
    ) %>%
  summarise(
    nCorrect = sum(nCorrect),
    nTotal = sum(nTotal),
    predicted_correct = sum(predicted_correct),
    .groups = 'keep'
    ) %>%
  mutate(
    pCorrect = nCorrect / nTotal * 100,
    fit_p = predicted_correct / nTotal * 100
  )
```

```
pt = pivot_longer(
      ACS_agg_over_level,
      -c(fNum, SpatialCondition.x, treatment, nTotal, nCorrect, predicted_correct),
      names_to='metric',
      values_to = 'values')
```

```
pt = pt %>% select(fNum, SpatialCondition.x, treatment, metric, values)

pt = pivot_wider(pt,
    names_from = SpatialCondition.x,
    values_from = values
  )


ggplot(pt,
    aes(x = colocated, y = separated, color=fNum)
    ) +
geom_point() +
facet_grid(metric ~ treatment)
```

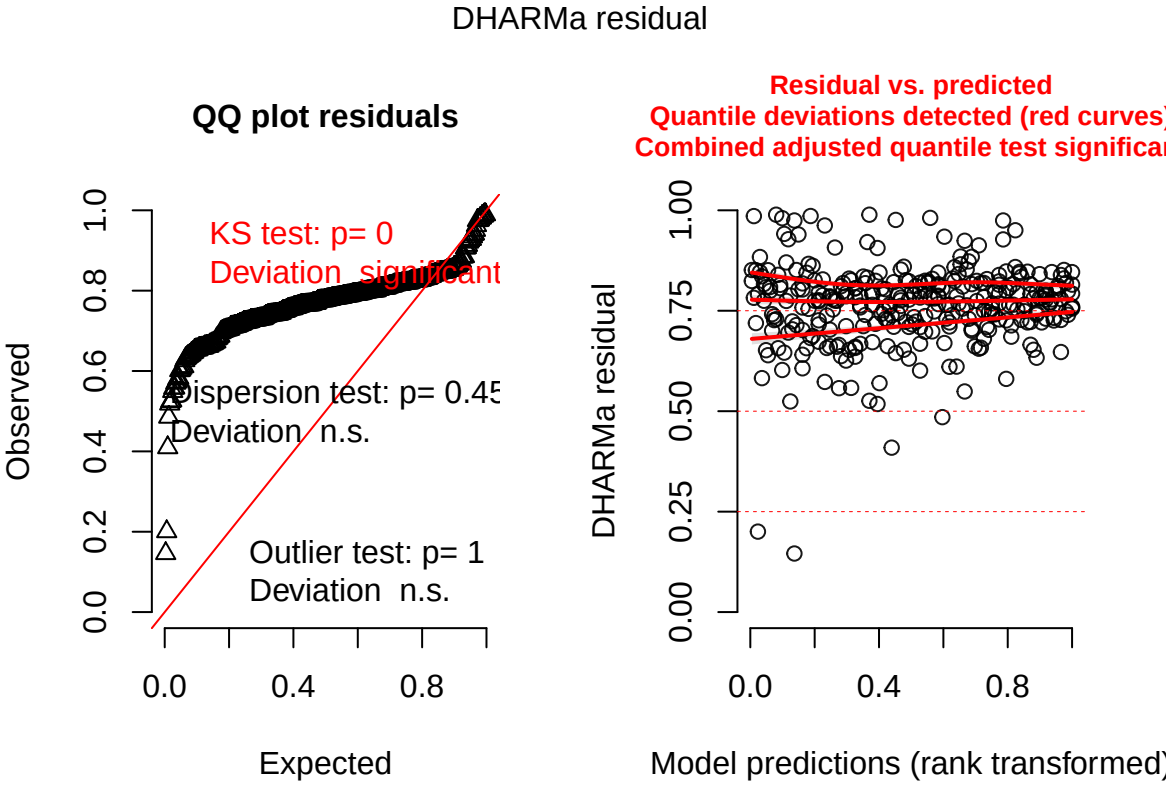


Write tibble to csv file

```
write_csv(pt , file = "/home/stephen/Github/Vowel_Discrimination_In_Noise/Results/Vowels_Unmasking/R_sta
```

7.4. Model Checking

```
simulationOutput <- simulateResiduals(fittedModel = ACS_mdl_2, n=500, plot = T)
```


DHARMa residual
QQ plot residuals
KS test: p= 0
Deviation significant
Dispersion test: p= 0.45
Deviation n.s.
Outlier test: p= 1
Deviation n.s.
Observed
Expected
0.0
0.2
0.4
0.6
0.8
1.0
0.0
0.4
0.8
Residual vs. predicted
Quantile deviations detected (red curves)
Combined adjusted quantile test significa
DHARMa residual
Model predictions (rank transformed)
0.00
0.25
0.50
0.75
1.00
0.0
0.4
0.8