Modality effects in a signalling game: Efficiency

Contents

Introduction

The main data used in this analysis comes from `../../data/FinalSignalData.csv` (compiled by `analyseData.R`). Each row represents one signal, but this script only keeps one signal per trial, and the rest of the analysis is on the trial-by-trial level. The variables in the data are as follows (some are calculated in the script below):

- X: ID
- filename: Filename of the ELAN file
- dyadNumber: ID of the participant dyad
- condition: Stimuli type (Auditory or Visual)
- game: Game number (0-3)
- trial: Trial number (0-15)
- target: Target stimuli shown to the director
- choice: Meaning chosen by the matcher
- correct: True if the matcher's choice is correct
- trialStart, trialEnd, trialLength: Start, end and length of trial in milliseconds
- trialValue: A unique string that represents data from the trial. Numbers in the curly brackets represent the choices given to the matcher
- startOfNextTrial: Timestamp for next trial, used in processing the data.
- turnStart, turnEnd, turnLength: the start, end and length of the turn in milliseconds.
- signalStart, signalEnd, signalLength: the start, end and length of the signal.
- signalType: Annotation value in ELAN, not meaningful
- tiralString: Unique string to identify trial

- modalityCondition: The condition for the dyad (multi= multimodal, visual=gesture only, vocal=vocal only)
- playerId: Unique ID for the participant producing the signal
- itemId: Unique ID for the target stimulus
- turnString: Unque ID for the turn
- matcherResponds: Does matcher take a turn in this trial?
- matcherResponds.cumulative: The (scaled) number of previous trials that a has responded.
- T1Length, T1Length.log: Length and log length of the director's first turn.
- trialTotal: Number of trials played so far, scaled (and centered) to represent number of games played.
- firstBlock: Block order
- incorrect: Was the matcher's choice incorrect?
- multimodal: Was the director's first turn multimodal?

Load libraries

```
library(lme4)
library(sjPlot)
library(ggplot2)
library(lattice)
#library(influence.ME)
library(dplyr)
```

The sjPlot library was updated during this investigation, removing various functions. They are reinstated here:

```
sjp.lmer = plot_model
```

Load data

```
d = read.csv("../../data/FinalSignalData.csv")
```

Variable for length of first T1

```
T1L = tapply(d[d$turnType=="T1",]$turnLength,
             d[d$turnType=="T1",]$trialString, head, n=1)
d$T1Length = T1L[d$trialString]
d$T1Length[is.na(d$T1Length)] = mean(d$T1Length,na.rm=T)
d$T1Length.log = log(d$T1Length)
d$T1Length.log = d$T1Length.log - mean(d$T1Length.log)
```

We don't need info on every signal in each turn, just the trial time. Keep only 1st signal in each trial.

```
d = d[!duplicated(d$trialString),]
```

Descriptive stats

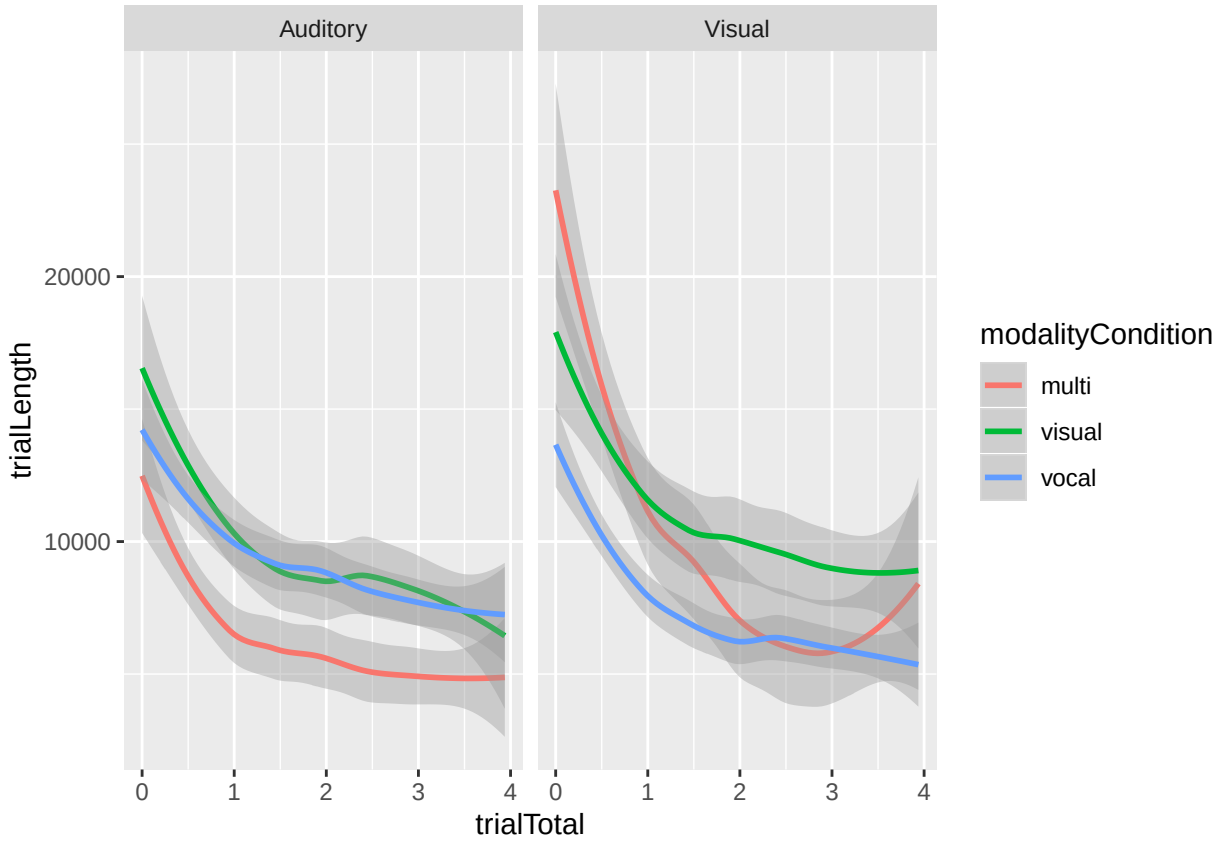
Make a variable to represent proportion of games played:

```
# Make a variable that represents the number of trials played
d$trialTotal = d$trial + (d$game * (max(d$trial)+1))
# Convert to proportion of games played, so that estimates reflect change per game.
d$trialTotal = d$trialTotal / 16
```

Here is a graph showing the distribution of trial lengths by conditions:

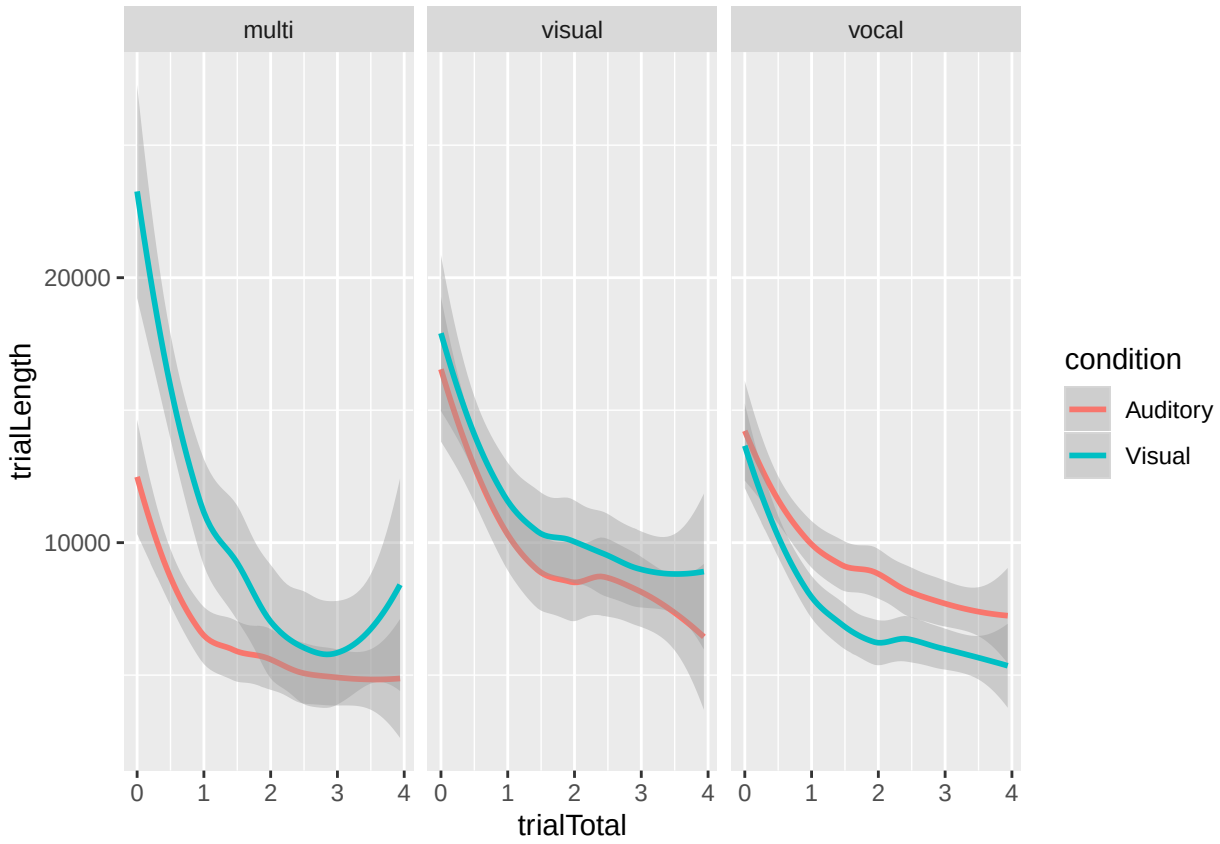
```
summary = d %>%
  group_by(condition, modalityCondition,game) %>%
  summarise(Efficiency=mean(trialLength),
            sd=sd(trialLength),
            ci.w =            qnorm(0.95)*sd/sqrt(length(trialLength)),
            upper=Efficiency+ci.w,
            lower = Efficiency-ci.w)
summary$game = summary$game +1

summary$modalityCondition =
  factor(summary$modalityCondition,
         levels = c("visual",'multi','vocal'),
         labels=c("Gestural","Multimodal","Vocal"))

ggplot(d, aes(x=trialTotal, y=trialLength,colour=modalityCondition)) +
  geom_smooth() + facet_grid(.~condition)
```

```
## `geom_smooth()` using method = 'loess' and formula 'y ~ x'
```

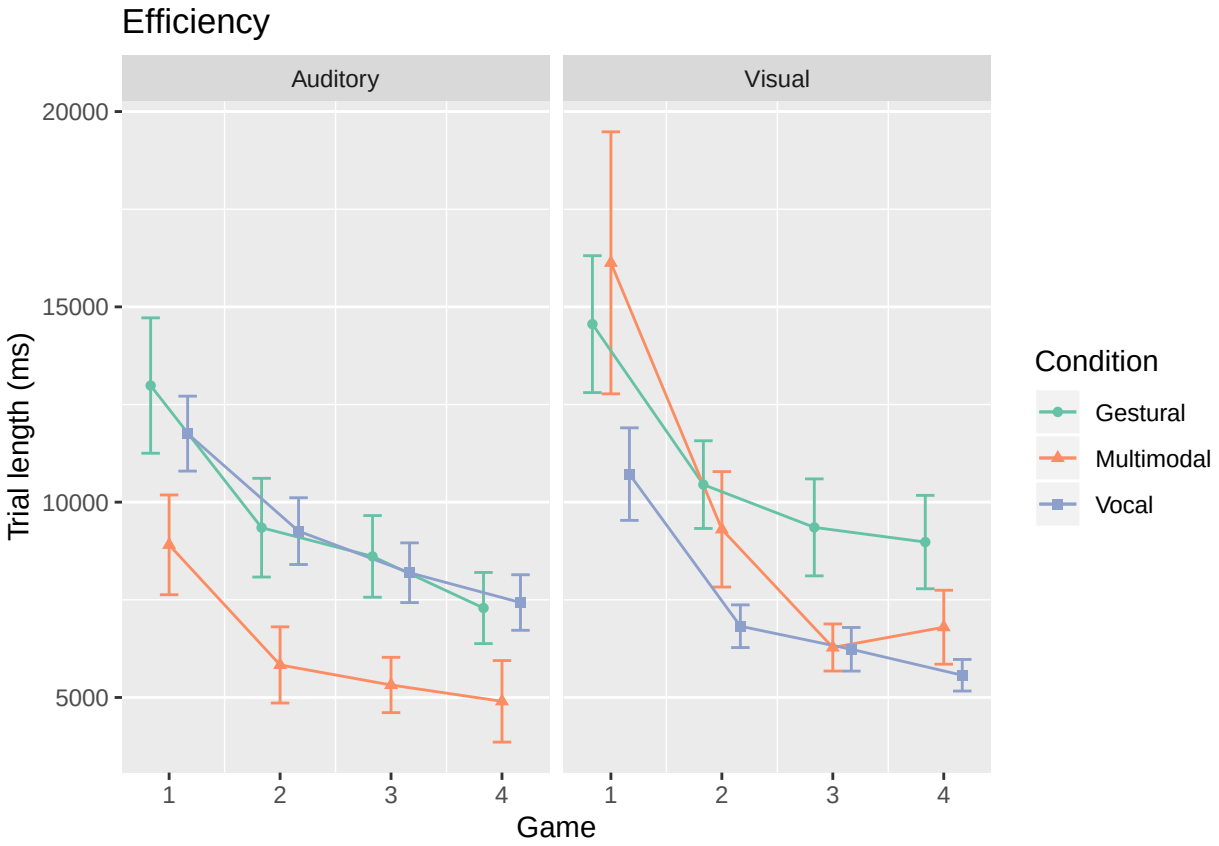



```
ggplot(d, aes(x=trialTotal, y=trialLength,colour=condition)) +
  geom_smooth() + facet_grid(.~modalityCondition)
```

```
## `geom_smooth()` using method = 'loess' and formula 'y ~ x'
```



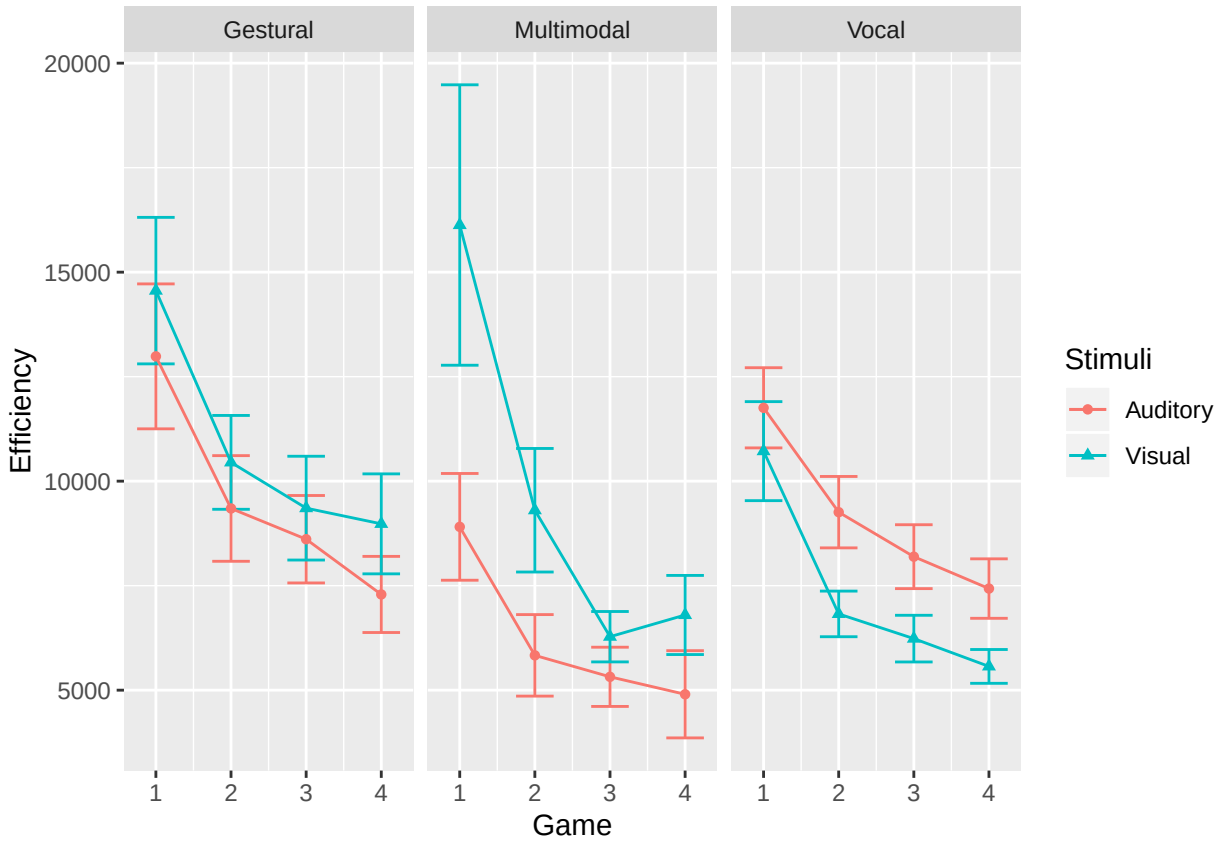

```
pd = position_dodge(width=0.5)
gx1 = ggplot(summary, aes(x=game, y=Efficiency, group=condition, colour=modalityCondition)) +
  geom_errorbar(aes(ymin=lower, ymax=upper,group=modalityCondition), width=0.5,position=pd) +
  facet_grid(. ~ condition) +
  stat_summary(fun.y="mean", geom="line", aes(group=modalityCondition),position=pd) +
    geom_point(aes(group=modalityCondition,shape=modalityCondition),position=pd) +
  scale_colour_brewer(palette="Set2", name="Condition") +
  scale_shape(name="Condition") +
  theme(panel.grid.major.x = element_blank()) +
  ggtitle("Efficiency") +
  xlab("Game") +
  ylab("Trial length (ms)")

gx1
```




```
pdf("../../results/graphs/Efficiency_gg.pdf",
    width = 5, height=3)
gx1
dev.off()
```

```
## pdf
##   2
```

```
gx2 = ggplot(summary, aes(x=game, y=Efficiency, group=condition, colour=condition, shape=condition)) +
  geom_errorbar(aes(ymin=lower, ymax=upper), width=0.5) +
  facet_grid(. ~ modalityCondition) +
  stat_summary(fun.y="mean", geom="line", aes(group=condition)) +
    geom_point() +
  scale_colour_discrete(name="Stimuli") +
  scale_shape_discrete(name="Stimuli") +
  xlab("Game")

gx2
```




```
pdf("../../results/graphs/Efficiency_gg_alt.pdf",
    width = 5, height=3)
gx2
dev.off()
```

```
## pdf
##   2
```

Average trial time for the whole experiment:

```
mean(d$trialLength)
```

```
## [1] 8795.327
```

```
sd(d$trialLength)
```

```
## [1] 7239.617
```

The distribution of trial times is very skewed:

```
hist(d$trialLength)
```

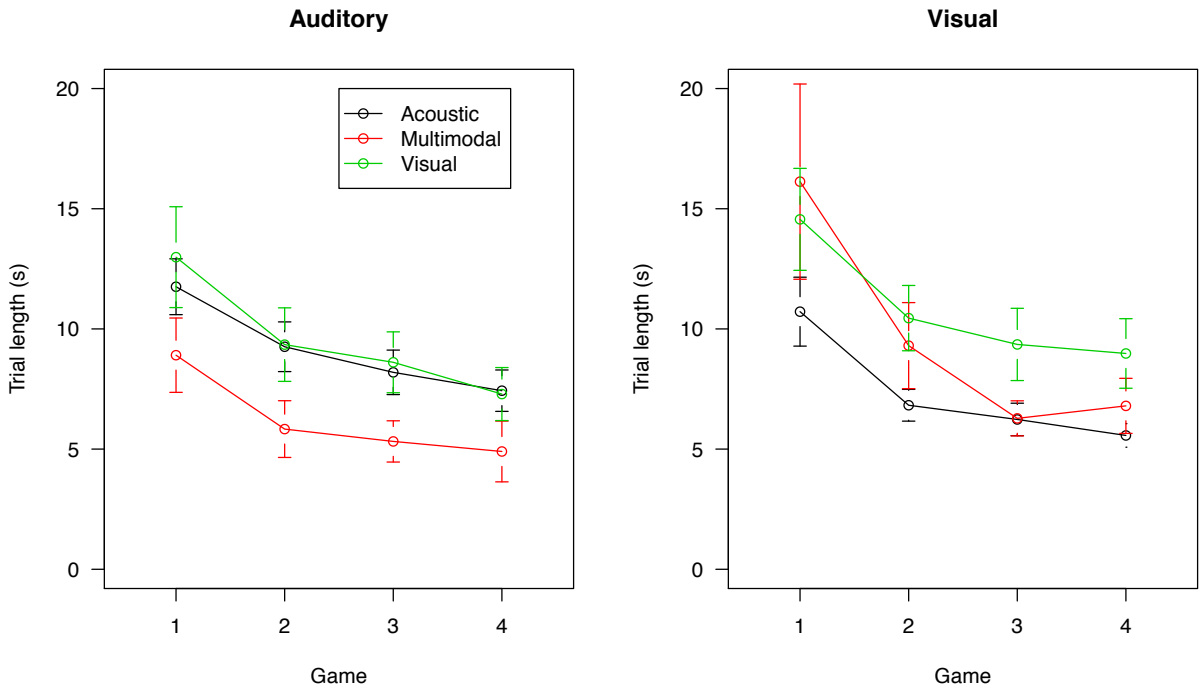
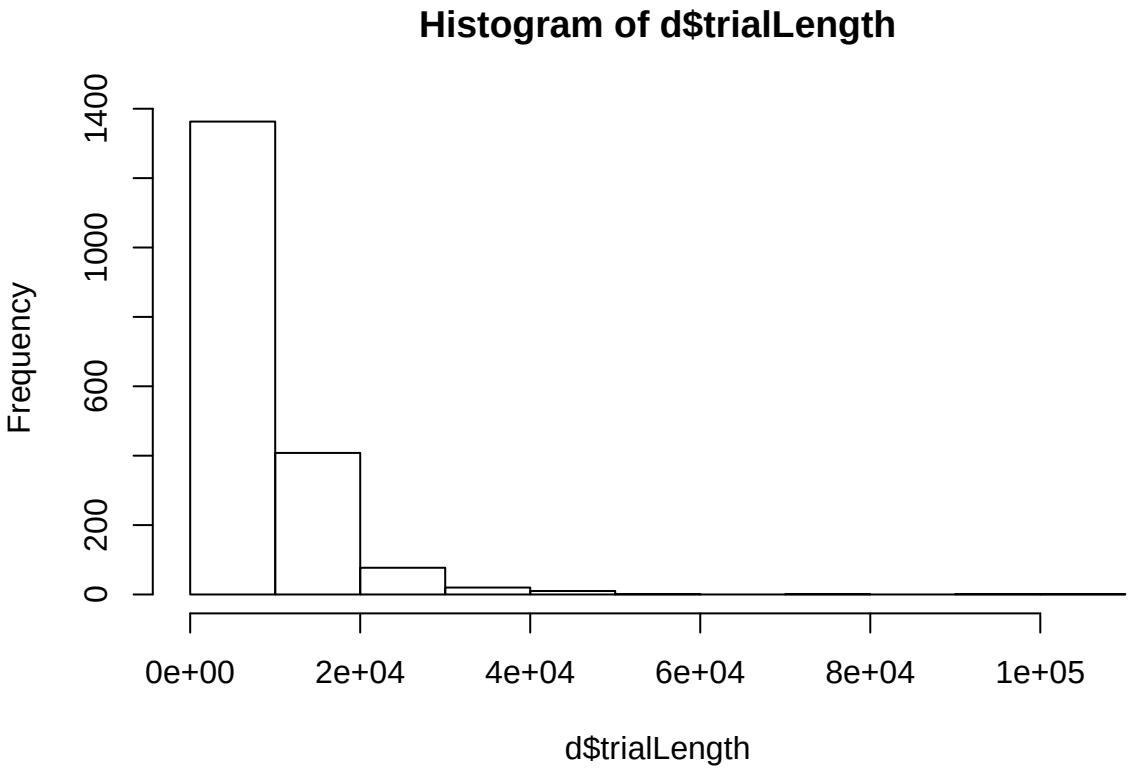
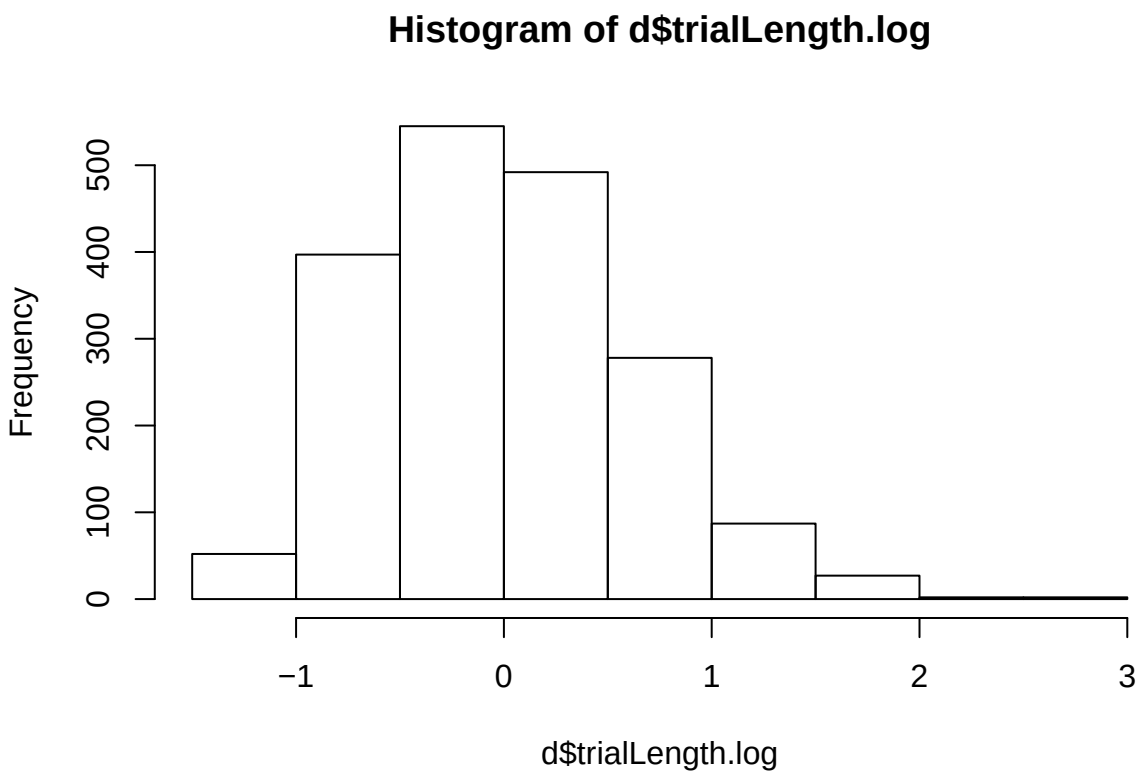


Figure 1: The efficiency of trials in different conditions



So we transform it using a log transform, then center the data.

```
d$trialLength.log = log(d$trialLength)
meanLogTrialLength = mean(d$trialLength.log)
d$trialLength.log = d$trialLength.log - meanLogTrialLength
hist(d$trialLength.log)
```




```
# Center the trialTotal variable so intercept reflects after the first game
d$trialTotal = d$trialTotal - 2

matcherResponds.cumulative.mean = mean(d$matcherResponds.cumulative)

d$matcherResponds.cumulative = d$matcherResponds.cumulative - matcherResponds.cumulative.mean

d$matcherResponds = factor(d$matcherResponds)
```

Make a variable for which stimuli the players experienced first.

```
firstBlock = tapply(as.character(d$condition),d$dyadNumber,head,n=1)
d$firstBlock = as.factor(firstBlock[match(d$dyadNumber,names(firstBlock))])
```

Reorder some levels so that the intercept reflects the most frequent condition.

```
d$incorrect = !d$correct
```

Variable for whether T1 was a multimodal signal.

```
turnD = read.csv("../../data/Final_Turn_data.csv")
turnD = turnD[turnD$turnType=="T1",]
turnD = turnD[turnD$role == "Director",]
d$multimodal = turnD[match(d$trialString, turnD$trialString),]$turnModalityType == "multi"
d$multimodal[is.na(d$multimodal)] = F
```

Mixed models

Make a series of models with random effects for dyad, director (nested within dyad) and item.

Not all random slopes are appropriate. For example, items are used in only one stimulus condition, so a random slope for condition by item is not appropriate. Similarly, each dyad only plays in one modality condition.

It is reasonable to have a random slope for trial by dyad, but this caused unreliable model convergence, so is not included.

The final random slopes were for condition and incorrectness by dyad/player, and modality condition by item.

```
# lme4 version 1.1-21 introduces different default optimisers
# Switch back to original:
ctrl = lmerControl(optimizer = "bobyqa")
# No fixed effects
m0 =  lmer(trialLength.log ~ 1 +
             (1 + condition + incorrect |dyadNumber/playerId) +
             (1 + modalityCondition|itemId),
           data=d, REML = FALSE,control = ctrl)
```

```
## boundary (singular) fit: see ?isSingular
```

Now we add a series of possible confounding factors such as whether the matcher responds. We add the main experimental factors at the end to ensure that they're really contributing to the model over and above the confounds.

```
# Add effect of trial

game = lmer(trialLength.log ~ 1 +
             trialTotal +
             (1 + condition + incorrect |dyadNumber/playerId) +
             (1 + modalityCondition|itemId),
           data=d, REML = FALSE,control = ctrl)

# Add the quadratic effect of trial
gamQuad = lmer(trialLength.log ~ 1 +
             trialTotal + I(trialTotal^2) +
             (1 + condition + incorrect |dyadNumber/playerId) +
             (1 + modalityCondition|itemId),
           data=d, REML = FALSE,control = ctrl)

# Add number of matcher turns
mtchTrn = lmer(trialLength.log ~ 1 +
                 trialTotal + I(trialTotal^2) +
                 matcherResponds +
             (1 + condition + incorrect |dyadNumber/playerId) +
             (1 + modalityCondition|itemId),
           data=d, REML = FALSE,control = ctrl)
```

```
## boundary (singular) fit: see ?isSingular
```

```
tMtchTr = lmer(trialLength.log ~ 1 +
                 trialTotal + I(trialTotal^2) +
                 matcherResponds +
                 matcherResponds.cumulative +
             (1 + condition + incorrect |dyadNumber/playerId) +
```

```
            (1 + modalityCondition|itemId),
          data=d, REML = FALSE,control = ctrl)
```

```
## boundary (singular) fit: see ?isSingular
```

```
# Add whether the response was incorrect
incor = lmer(trialLength.log ~ 1 +
            trialTotal + I(trialTotal^2) +
            matcherResponds +
            matcherResponds.cumulative +
            incorrect +
            (1 + condition + incorrect |dyadNumber/playerId) +
            (1 + modalityCondition|itemId),
          data=d, REML = FALSE,control = ctrl)
```

```
## boundary (singular) fit: see ?isSingular
```

```
# Add multimodal signal

multim = lmer(trialLength.log ~ 1 +
            trialTotal + I(trialTotal^2) +
            matcherResponds +
            matcherResponds.cumulative +
            incorrect +
            multimodal +
            (1 + condition + incorrect |dyadNumber/playerId) +
            (1 + modalityCondition|itemId),
          data=d, REML = FALSE,control = ctrl)
```

```
## boundary (singular) fit: see ?isSingular
```

```
# Add modality condition
modality =  lmer(trialLength.log ~ 1 + modalityCondition +
            trialTotal + I(trialTotal^2) +
            matcherResponds +
            matcherResponds.cumulative +
            incorrect +
            multimodal +
            (1 + condition + incorrect |dyadNumber/playerId) +
            (1 + modalityCondition|itemId),
          data=d, REML = FALSE,control = ctrl)
```

```
## boundary (singular) fit: see ?isSingular
```

```
# Add stimulus condition
cond = lmer(trialLength.log ~ 1 + modalityCondition + condition +
            trialTotal + I(trialTotal^2) +
            matcherResponds +
            matcherResponds.cumulative +
            incorrect +
            multimodal +
            (1 + condition + incorrect |dyadNumber/playerId) +
            (1 + modalityCondition|itemId),
          data=d, REML = FALSE,control = ctrl)
```

```
## boundary (singular) fit: see ?isSingular
```

```
# Add interaction between modality and stimulus condition
modXcond = lmer(trialLength.log ~ 1 + modalityCondition*condition +
           trialTotal + I(trialTotal^2) +
            matcherResponds +
            matcherResponds.cumulative +
            incorrect +
            multimodal +
            (1 + condition + incorrect |dyadNumber/playerId) +
            (1 + modalityCondition|itemId),
          data=d, REML = FALSE,control = ctrl)
```

```
## boundary (singular) fit: see ?isSingular
```

```
# Add interaction between condition and trial
conXgame = lmer(trialLength.log ~ 1 + modalityCondition*condition +
            trialTotal + I(trialTotal^2) +
              condition:trialTotal +
            matcherResponds +
            matcherResponds.cumulative +
            incorrect +
            multimodal +
            (1 + condition + incorrect |dyadNumber/playerId) +
            (1 + modalityCondition|itemId),
          data=d, REML = FALSE,control = ctrl)
```

```
## boundary (singular) fit: see ?isSingular
```

```
# Add interaction between modality and trial
modXgame = lmer(trialLength.log ~ 1 + modalityCondition*condition +
             trialTotal + I(trialTotal^2) +
              condition:trialTotal + modalityCondition:trialTotal +
            matcherResponds +
            matcherResponds.cumulative +
            incorrect +
            multimodal +
            (1 + condition + incorrect |dyadNumber/playerId) +
            (1 + modalityCondition|itemId),
          data=d, REML = FALSE,control = ctrl)
```

```
## boundary (singular) fit: see ?isSingular
```

```
# Add 3-way interaction
moXcoXga =  lmer(trialLength.log ~ 1 + modalityCondition*condition*trialTotal +
             I(trialTotal^2) +
            matcherResponds +
            incorrect +
            multimodal +
            (1 + condition + incorrect |dyadNumber/playerId) +
            (1 + modalityCondition|itemId),
          data=d, REML = FALSE,control = ctrl)
```

```
## boundary (singular) fit: see ?isSingular
```

Interactions

```
# interaction between turns and modality
nTurnXmo = lmer(trialLength.log ~ 1 + modalityCondition*condition*trialTotal +
```

```
             I(trialTotal^2) +
            matcherResponds + matcherResponds:modalityCondition +
            matcherResponds.cumulative +
            incorrect +
            multimodal +
            (1 + condition + incorrect |dyadNumber/playerId) +
            (1 + modalityCondition|itemId),
          data=d, REML = FALSE,control = ctrl)
```

```
## boundary (singular) fit: see ?isSingular
```

```
nTurnXco = lmer(trialLength.log ~ 1 + modalityCondition*condition*trialTotal +
             I(trialTotal^2) +
            matcherResponds + matcherResponds:modalityCondition +
            matcherResponds:condition +
            matcherResponds.cumulative +
            incorrect +
            multimodal +
            (1 + condition + incorrect |dyadNumber/playerId) +
            (1 + modalityCondition|itemId),
          data=d, REML = FALSE,control = ctrl)
```

```
## boundary (singular) fit: see ?isSingular
```

```
# Turn x modality x condtion
# Note that the acousitc modality had hardly any matcher turns,
# so the factor is dropped

tuXmoXco = lmer(trialLength.log ~ 1 + modalityCondition*condition*trialTotal +
             I(trialTotal^2) +
            matcherResponds*modalityCondition*condition +
            matcherResponds.cumulative +
            incorrect +
            multimodal +
            (1 + condition + incorrect |dyadNumber/playerId) +
            (1 + modalityCondition|itemId),
          data=d, REML = FALSE,control = ctrl)
```

```
## fixed-effect model matrix is rank deficient so dropping 1 column / coefficient
## boundary (singular) fit: see ?isSingular
```

```
# Add the interaction between modality and incorrectness
moXincor =   lmer(trialLength.log ~ 1 + modalityCondition*condition*trialTotal +
             I(trialTotal^2) +
            matcherResponds*modalityCondition*condition +
            matcherResponds.cumulative +
            incorrect + incorrect:modalityCondition +
            multimodal +
            (1 + condition + incorrect |dyadNumber/playerId) +
            (1 + modalityCondition|itemId),
          data=d, REML = FALSE,control = ctrl)
```

```
## fixed-effect model matrix is rank deficient so dropping 1 column / coefficient
## boundary (singular) fit: see ?isSingular
```

```
# Add the interaction between condition and incorrectness
coXincor =  lmer(trialLength.log ~ 1 + modalityCondition*condition*trialTotal +
```

```
             I(trialTotal^2) +
            matcherResponds*modalityCondition*condition +
            matcherResponds.cumulative +
            incorrect + incorrect:modalityCondition + incorrect:condition +
            multimodal +
            (1 + condition + incorrect |dyadNumber/playerId) +
            (1 + modalityCondition|itemId),
          data=d, REML = FALSE,control = ctrl)
```

```
## fixed-effect model matrix is rank deficient so dropping 1 column / coefficient
## boundary (singular) fit: see ?isSingular
```

```
# Add the three-way interaction between condition, modality and incorrectness
coXmoXin = lmer(trialLength.log ~ 1 + modalityCondition*condition*trialTotal +
             I(trialTotal^2) +
            matcherResponds*modalityCondition*condition +
            matcherResponds.cumulative +
            incorrect *modalityCondition*condition +
            multimodal +
            (1 + condition + incorrect |dyadNumber/playerId) +
            (1 + modalityCondition|itemId),
          data=d, REML = FALSE,control = ctrl)
```

```
## fixed-effect model matrix is rank deficient so dropping 1 column / coefficient
## boundary (singular) fit: see ?isSingular
```

```
# Interaction between multimodality and condition
multiXco = lmer(trialLength.log ~ 1 + modalityCondition*condition*trialTotal +
             I(trialTotal^2) +
            matcherResponds*modalityCondition*condition +
            matcherResponds.cumulative +
            incorrect *modalityCondition*condition +
            multimodal + multimodal:condition +
            (1 + condition + incorrect |dyadNumber/playerId) +
            (1 + modalityCondition|itemId),
          data=d, REML = FALSE,control = ctrl)
```

```
## fixed-effect model matrix is rank deficient so dropping 1 column / coefficient
```

```
## boundary (singular) fit: see ?isSingular
```

```
# Add interaction between quadratic effect of trial and modality
modXgamQ =  lmer(trialLength.log ~ 1 + modalityCondition*condition*trialTotal +
             I(trialTotal^2) +(modalityCondition:I(trialTotal^2)) +
            matcherResponds*modalityCondition*condition +
            matcherResponds.cumulative +
            incorrect *modalityCondition*condition +
            multimodal + multimodal:condition +
            (1 + condition + incorrect |dyadNumber/playerId) +
            (1 + modalityCondition|itemId),
          data=d, REML = FALSE,control = ctrl)
```

```
## fixed-effect model matrix is rank deficient so dropping 1 column / coefficient
## boundary (singular) fit: see ?isSingular
```

Interactions with matcher turns

```
tMaTxMod = lmer(trialLength.log ~ 1 + modalityCondition*condition*trialTotal +
             I(trialTotal^2) +(modalityCondition:I(trialTotal^2)) +
            matcherResponds*modalityCondition*condition +
            matcherResponds.cumulative +
              matcherResponds.cumulative:modalityCondition +
            incorrect *modalityCondition*condition +
            multimodal + multimodal:condition +
            (1 + condition + incorrect |dyadNumber/playerId) +
            (1 + modalityCondition|itemId),
          data=d, REML = FALSE,control = ctrl)
```

```
## fixed-effect model matrix is rank deficient so dropping 1 column / coefficient
```

```
## boundary (singular) fit: see ?isSingular
```

Check block has no effect

```
# Add block order
block =  lmer(trialLength.log ~ 1 + modalityCondition*condition*trialTotal +
             I(trialTotal^2) +(modalityCondition:I(trialTotal^2)) +
            matcherResponds*modalityCondition*condition +
            matcherResponds.cumulative +
              matcherResponds.cumulative:modalityCondition +
            incorrect *modalityCondition*condition +
            multimodal + multimodal:condition +
            matcherResponds +
            firstBlock +
            (1 + condition + incorrect |dyadNumber/playerId) +
            (1 + modalityCondition|itemId),
          data=d, REML = TRUE, control = ctrl)
```

```
## fixed-effect model matrix is rank deficient so dropping 1 column / coefficient
```

```
## boundary (singular) fit: see ?isSingular
```

```
# Last model is REML to get estimates

# Add interaction between block order and modality
blocXmod = lmer(trialLength.log ~ 1 + modalityCondition*condition*trialTotal +
             I(trialTotal^2) +(modalityCondition:I(trialTotal^2)) +
            matcherResponds*modalityCondition*condition +
            matcherResponds.cumulative +
              matcherResponds.cumulative:modalityCondition +
            incorrect *modalityCondition*condition +
            multimodal + multimodal:condition +
            matcherResponds +
            firstBlock*modalityCondition +
            (1 + condition + incorrect |dyadNumber/playerId) +
            (1 + modalityCondition|itemId),
          data=d, REML = TRUE)
```

```
## fixed-effect model matrix is rank deficient so dropping 1 column / coefficient
## boundary (singular) fit: see ?isSingular
```

Results

Compare the fit of the models:

```
modelComparison = anova(m0,modality,cond,game,modXcond,conXgame, modXgame,
      moXcoXga,mtchTrn,tMtchTr,tMaTxMod,nTurnXmo,nTurnXco,tuXmoXco,
      incor,moXincor,coXincor,coXmoXin,
      multim,multiXco,
      gamQuad,modXgamQ,
      block, blocXmod)
```

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

```
attributes(modelComparison)$heading = ""
modelComparison
```

```
##
##          Df    AIC    BIC   logLik deviance    Chisq Chi Df Pr(>Chisq)
## m0       20 2686.0 2796.8 -1323.01   2646.0
## game     21 2287.7 2404.1 -1122.86   2245.7 400.3001      1  < 2.2e-16 ***
## gamQuad  22 2211.0 2332.9 -1083.51   2167.0  78.7027      1  < 2.2e-16 ***
## mtchTrn  23 1721.6 1849.1  -837.82   1675.6 491.3671      1  < 2.2e-16 ***
## tMtchTr  24 1723.6 1856.5  -837.79   1675.6   0.0676      1  0.7948416
## incor    25 1712.3 1850.8  -831.16   1662.3  13.2481      1  0.0002729 ***
## multim   26 1712.8 1856.9  -830.41   1660.8   1.5030      1  0.2202137
## modality 28 1716.2 1871.3  -830.10   1660.2   0.6327      2  0.7287886
## cond     29 1717.7 1878.3  -829.83   1659.7   0.5376      1  0.4634404
## modXcond 31 1706.2 1877.9  -822.10   1644.2  15.4611      2  0.0004392 ***
## conXgame 32 1708.0 1885.3  -822.00   1644.0   0.1885      1  0.6641504
## modXgame 34 1701.5 1889.9  -816.75   1633.5  10.5073      2  0.0052284 **
## moXcoXga 35 1702.9 1896.8  -816.44   1632.9   0.6220      1  0.4303010
## nTurnXmo 38 1706.0 1916.5  -814.98   1630.0   2.9249      3  0.4033423
## nTurnXco 39 1707.8 1923.9  -814.90   1629.8   0.1425      1  0.7058457
## tuXmoXco 40 1709.0 1930.6  -814.48   1629.0   0.8569      1  0.3545994
## moXincor 42 1707.8 1940.5  -811.89   1623.8   5.1708      2  0.0753659 .
## coXincor 43 1709.7 1947.9  -811.86   1623.7   0.0630      1  0.8017564
## coXmoXin 45 1711.5 1960.8  -810.77   1621.5   2.1705      2  0.3378165
## multiXco 46 1713.2 1968.0  -810.58   1621.2   0.3966      1  0.5288414
## modXgamQ 48 1710.3 1976.3  -807.17   1614.3   6.8134      2  0.0331502 *
## tMaTxMod 50 1712.5 1989.5  -806.24   1612.5   1.8515      2  0.3962261
## block    51 1714.1 1996.6  -806.03   1612.1   0.4164      1  0.5187396
## blocXmod 53 1718.4 2012.0  -806.18   1612.4   0.0000      2  1.0000000
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

Pick final model for estimates:

```
finalModel = block
```

Final model estimates:

```
summary(finalModel)
```

```
## Linear mixed model fit by REML ['lmerMod']
## Formula:
## trialLength.log ~ 1 + modalityCondition * condition * trialTotal +
##     I(trialTotal^2) + (modalityCondition:I(trialTotal^2)) + matcherResponds *
```

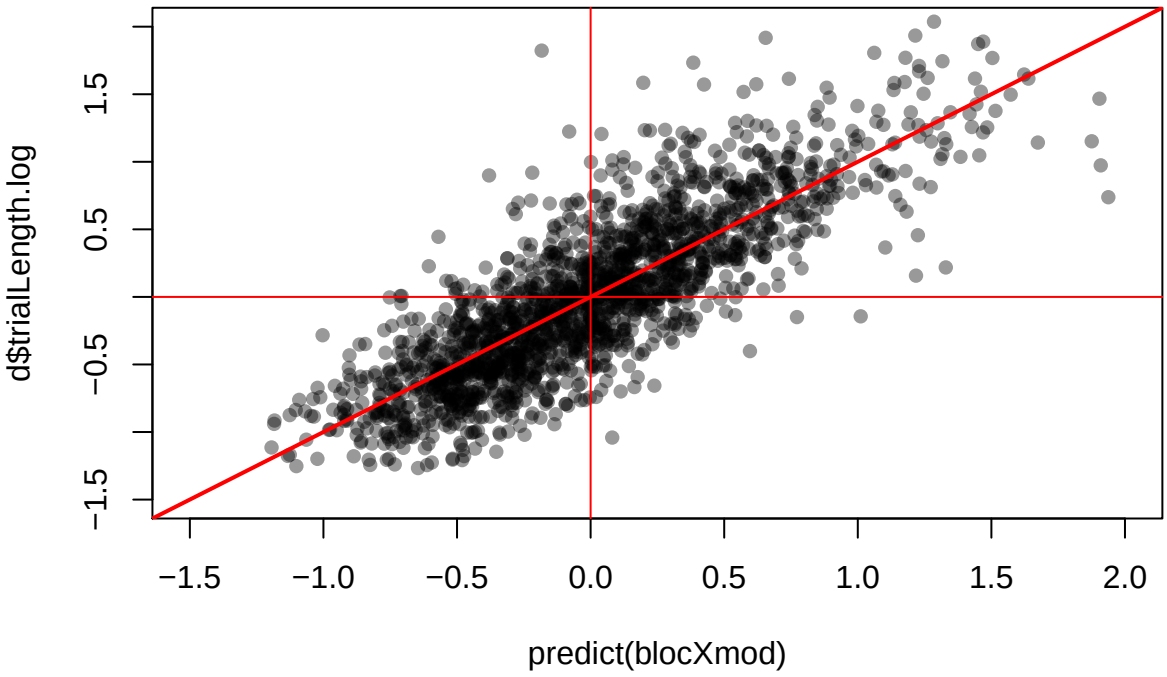
```
##     modalityCondition * condition + matcherResponds.cumulative +
##     matcherResponds.cumulative:modalityCondition + incorrect *
##     modalityCondition * condition + multimodal + multimodal:condition +
##     matcherResponds + firstBlock + (1 + condition + incorrect |
##     dyadNumber/playerId) + (1 + modalityCondition | itemId)
##    Data: d
## Control: ctrl
##
## REML criterion at convergence: 1744.1
##
## Scaled residuals:
##     Min      1Q  Median      3Q     Max
## -3.4137 -0.6137 -0.0552  0.5712  5.7083
##
## Random effects:
##  Groups              Name                    Variance Std.Dev. Corr
##  playerId:dyadNumber (Intercept)             0.043220 0.20790
##                      conditionVisual         0.028599 0.16911  -0.58
##                      incorrectTRUE           0.015801 0.12570  -0.72  0.16
##  itemId              (Intercept)             0.025369 0.15928
##                      modalityConditionvisual 0.002625 0.05123   0.80
##                      modalityConditionvocal  0.012299 0.11090  -0.09  0.52
##  dyadNumber          (Intercept)             0.066131 0.25716
##                      conditionVisual         0.023988 0.15488  -0.13
##                      incorrectTRUE           0.001567 0.03959  -0.46 -0.82
##  Residual                                    0.123399 0.35128
## Number of obs: 1882, groups:
## playerId:dyadNumber, 30; itemId, 16; dyadNumber, 15
##
## Fixed effects:
##                                                          Estimate
## (Intercept)                                             -0.530835
## modalityConditionvisual                                  0.498797
## modalityConditionvocal                                   0.378782
## conditionVisual                                          0.409872
## trialTotal                                              -0.157898
## I(trialTotal^2)                                          0.061550
## matcherRespondsTRUE                                      0.907786
## matcherResponds.cumulative                              -0.019613
## incorrectTRUE                                            0.268012
## multimodalTRUE                                           0.115162
## firstBlockVisual                                        -0.079581
## modalityConditionvisual:conditionVisual                 -0.247559
## modalityConditionvocal:conditionVisual                  -0.690612
## modalityConditionvisual:trialTotal                       0.018677
## modalityConditionvocal:trialTotal                        0.008403
## conditionVisual:trialTotal                              -0.001521
## modalityConditionvisual:I(trialTotal^2)                 -0.036022
## modalityConditionvocal:I(trialTotal^2)                  -0.002917
## modalityConditionvisual:matcherRespondsTRUE             -0.008214
## modalityConditionvocal:matcherRespondsTRUE              -0.105875
## conditionVisual:matcherRespondsTRUE                      0.088654
## modalityConditionvisual:matcherResponds.cumulative       0.021201
## modalityConditionvocal:matcherResponds.cumulative       -0.090406
```

```
## modalityConditionvisual:incorrectTRUE                       -0.077329
## modalityConditionvocal:incorrectTRUE                        -0.228144
## conditionVisual:incorrectTRUE                                0.027018
## conditionVisual:multimodalTRUE                              -0.064590
## modalityConditionvisual:conditionVisual:trialTotal           0.014131
## modalityConditionvocal:conditionVisual:trialTotal           -0.016712
## modalityConditionvisual:conditionVisual:matcherRespondsTRUE -0.104292
## modalityConditionvisual:conditionVisual:incorrectTRUE       -0.129780
## modalityConditionvocal:conditionVisual:incorrectTRUE         0.064822
##                                                            Std. Error
## (Intercept)                                                  0.173737
## modalityConditionvisual                                      0.197178
## modalityConditionvocal                                       0.498299
## conditionVisual                                              0.132324
## trialTotal                                                   0.019476
## I(trialTotal^2)                                              0.012668
## matcherRespondsTRUE                                          0.092247
## matcherResponds.cumulative                                   0.012612
## incorrectTRUE                                                0.091586
## multimodalTRUE                                               0.058240
## firstBlockVisual                                             0.139013
## modalityConditionvisual:conditionVisual                      0.143128
## modalityConditionvocal:conditionVisual                       0.157212
## modalityConditionvisual:trialTotal                           0.028170
## modalityConditionvocal:trialTotal                            0.026254
## conditionVisual:trialTotal                                   0.025965
## modalityConditionvisual:I(trialTotal^2)                      0.017465
## modalityConditionvocal:I(trialTotal^2)                       0.017385
## modalityConditionvisual:matcherRespondsTRUE                  0.120640
## modalityConditionvocal:matcherRespondsTRUE                   0.374660
## conditionVisual:matcherRespondsTRUE                          0.116446
## modalityConditionvisual:matcherResponds.cumulative           0.016084
## modalityConditionvocal:matcherResponds.cumulative            0.212914
## modalityConditionvisual:incorrectTRUE                        0.121223
## modalityConditionvocal:incorrectTRUE                         0.125045
## conditionVisual:incorrectTRUE                                0.101040
## conditionVisual:multimodalTRUE                               0.107341
## modalityConditionvisual:conditionVisual:trialTotal           0.036040
## modalityConditionvocal:conditionVisual:trialTotal            0.035938
## modalityConditionvisual:conditionVisual:matcherRespondsTRUE  0.156611
## modalityConditionvisual:conditionVisual:incorrectTRUE        0.137872
## modalityConditionvocal:conditionVisual:incorrectTRUE         0.133813
##                                                            t value
## (Intercept)                                                 -3.055
## modalityConditionvisual                                      2.530
## modalityConditionvocal                                       0.760
## conditionVisual                                              3.097
## trialTotal                                                  -8.107
## I(trialTotal^2)                                              4.859
## matcherRespondsTRUE                                          9.841
## matcherResponds.cumulative                                  -1.555
## incorrectTRUE                                                2.926
## multimodalTRUE                                               1.977
## firstBlockVisual                                            -0.572
```

```
## modalityConditionvisual:conditionVisual                      -1.730
## modalityConditionvocal:conditionVisual                       -4.393
## modalityConditionvisual:trialTotal                            0.663
## modalityConditionvocal:trialTotal                             0.320
## conditionVisual:trialTotal                                   -0.059
## modalityConditionvisual:I(trialTotal^2)                      -2.063
## modalityConditionvocal:I(trialTotal^2)                       -0.168
## modalityConditionvisual:matcherRespondsTRUE                  -0.068
## modalityConditionvocal:matcherRespondsTRUE                   -0.283
## conditionVisual:matcherRespondsTRUE                           0.761
## modalityConditionvisual:matcherResponds.cumulative            1.318
## modalityConditionvocal:matcherResponds.cumulative            -0.425
## modalityConditionvisual:incorrectTRUE                        -0.638
## modalityConditionvocal:incorrectTRUE                         -1.825
## conditionVisual:incorrectTRUE                                 0.267
## conditionVisual:multimodalTRUE                               -0.602
## modalityConditionvisual:conditionVisual:trialTotal            0.392
## modalityConditionvocal:conditionVisual:trialTotal            -0.465
## modalityConditionvisual:conditionVisual:matcherRespondsTRUE  -0.666
## modalityConditionvisual:conditionVisual:incorrectTRUE        -0.941
## modalityConditionvocal:conditionVisual:incorrectTRUE          0.484

##
## Correlation matrix not shown by default, as p = 32 > 12.
## Use print(x, correlation=TRUE)  or
##     vcov(x)        if you need it

## fit warnings:
## fixed-effect model matrix is rank deficient so dropping 1 column / coefficient
## convergence code: 0
## boundary (singular) fit: see ?isSingular
```

Check model predictions. The model predictions are in the right range and direction, fitting linear quite well:

```
plot(predict(blocXmod),d$trialLength.log, pch=16, col=rgb(0,0,0,0.4),
     ylim=c(-1.5,2),xlim=c(-1.5,2))
abline(a=0,b=1, col=2, lwd=2)
abline(h=0, col=2)
abline(v=0, col=2)
```

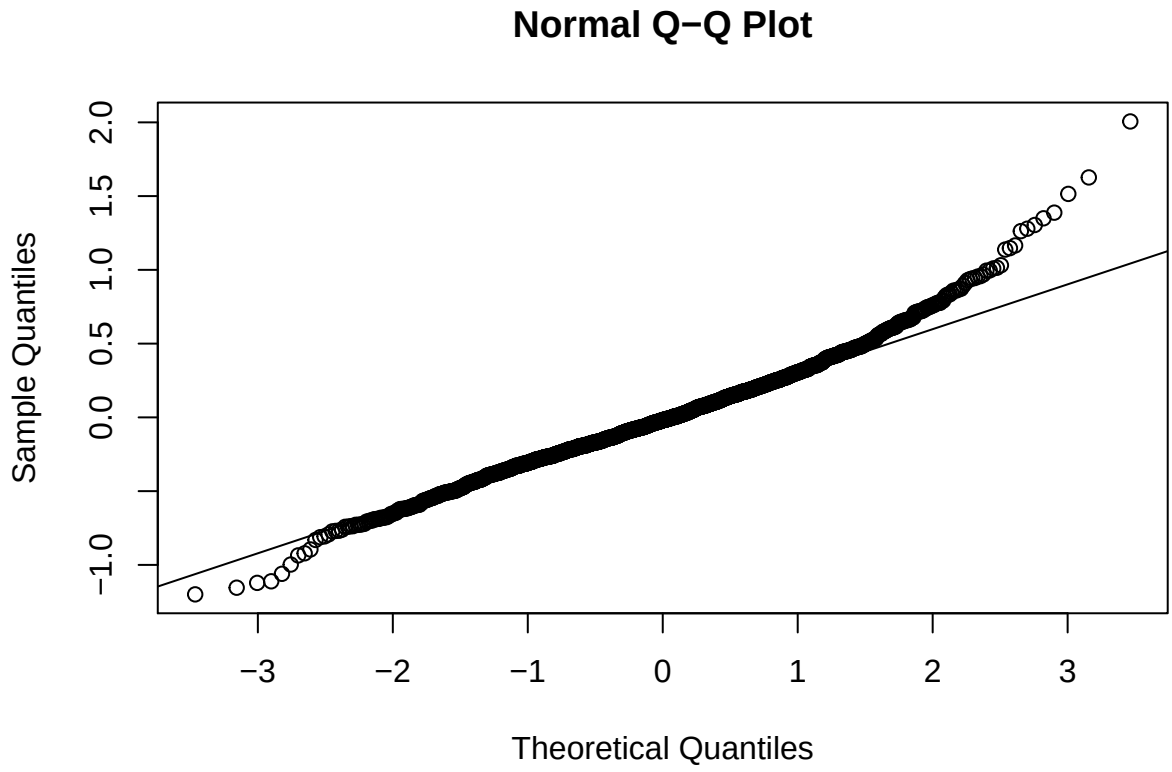



```
cor(predict(finalModel), d$trialLength.log)
```

```
## [1] 0.8336072
```

The residuals are ok, though it tends to do worse at higher values. This is expected from using the log scale.

```
qqnorm(resid(blocXmod))
qqline(resid(blocXmod))
```



Plot the fixed effects

Relabel the effects:

```
feLabels = matrix(c(
"(Intercept)"              ,"Intercept"      , NA,
"modalityConditionvisual" ,"Visual modality", "modality",
"modalityConditionvocal"  , "Acoustic modality", "modality",
"conditionVisual" , "Visual stimuli","cond",
"trialTotal"              , "Game","game",
"modalityConditionvisual:conditionVisual"  , "Visual modality:Visual stimuli", "modXcond",
"modalityConditionvocal:conditionVisual" , "Acoustic modality:Visual stimuli","modXcond",
"modalityConditionvisual:trialTotal"    , "Visual modality:Game","modXgame",
"modalityConditionvocal:trialTotal"     , "Acoustic modality:Game", "modXgame",
"conditionVisual:trialTotal"             , "Visual stimuli:Game","conXgame",
"modalityConditionvisual:conditionVisual:trialTotal", "Visual modality:Visual stimuli:Game", "moXcoXga"
"modalityConditionvocal:conditionVisual:trialTotal", "Acoustic modality:Visual stimuli:Game", "moXcoXga
"incorrectTRUE","Incorrect","incor",
"modalityConditionvisual:incorrectTRUE","Visual modality:Incorrect","moXincor",
"modalityConditionvocal:incorrectTRUE","Acoustic modality:Incorrect","moXincor",
"modalityConditionvisual:I(trialTotal^2)", "Visual modality:Game^2","modXgamQ",
"modalityConditionvocal:I(trialTotal^2)", "Acoustic modality:Game^2","modXgamQ",
"I(trialTotal^2)","Game^2","gamQuad",
"firstBlockVisual","Visual stims first","block",
"modalityConditionvisual:firstBlockVisual","Visual modality:Visual stim first","blocXmod",
"modalityConditionvocal:firstBlockVisual","Acoustic modality:Visual stim first","blocXmod",
"conditionVisual:incorrectTRUE","Visual stimuli:incorrect","coXincor",
"modalityConditionvisual:conditionVisual:incorrectTRUE","Visual modality:Visual stimuli:incorrect","coX
"modalityConditionvocal:conditionVisual:incorrectTRUE","Acoustic modality:Visual stimuli:incorrect","co

"modalityConditionvisual:conditionVisual:numberOfTurns","VisualModality:Visual stim:NumTurns","tuXmoXco
"modalityConditionvisual:conditionVisual:matcherRespondsTRUE","VisualModality:Visual stim:Matcher Respo
"modalityConditionvocal:conditionVisual:numberOfTurns","Vocal Modality:Visual stim:NumTurns","tuXmoXco"
"modalityConditionvocal:conditionVisual:matcherRespondsTRUE","Vocal Modality:Visual stim:Matcher Respon
"conditionVisual:numberOfTurns","Visual stim:NumTurns","nTurnXco",
"conditionVisual:matcherRespondsTRUE","Visual stim:Matcher Responds","nTurnXco",
"modalityConditionvisual:numberOfTurns","VisualModality:NumTurns","nTurnXmo",
"modalityConditionvisual:matcherRespondsTRUE","VisualModality:Matcher Responds","nTurnXmo",
"modalityConditionvocal:numberOfTurns","Vocal Modality:NumTurns","nTurnXmo",
"modalityConditionvocal:matcherRespondsTRUE","Vocal Modality:Matcher Responds","nTurnXmo",
"numberOfTurns","Number of turns","nTurns",
"multimodalTRUE","Multimodal T1","multim",
"conditionVisual:multimodalTRUE","VisualStim:MultimodalT1","multiXco",
"matcherRespondsTRUE","Matcher Responds",'mtchTrn',
"matcherResponds.cumulative","Total interaction","tMtchTr",
"modalityConditionvisual:matcherResponds.cumulative","Total interaction:Visual Modality","tMaTxMod",
"modalityConditionvocal:matcherResponds.cumulative","Total interaction:Vocal Modality","tMaTxMod"
), ncol=3, byrow = T)

feLabels2 = as.vector(feLabels[match(names(fixef(finalModel)),feLabels[,1]),2])
feModel = as.vector(feLabels[match(names(fixef(finalModel)),feLabels[,1]),3])

sig = modelComparison$`Pr(>Chisq)`
names(sig) = rownames(modelComparison)
```

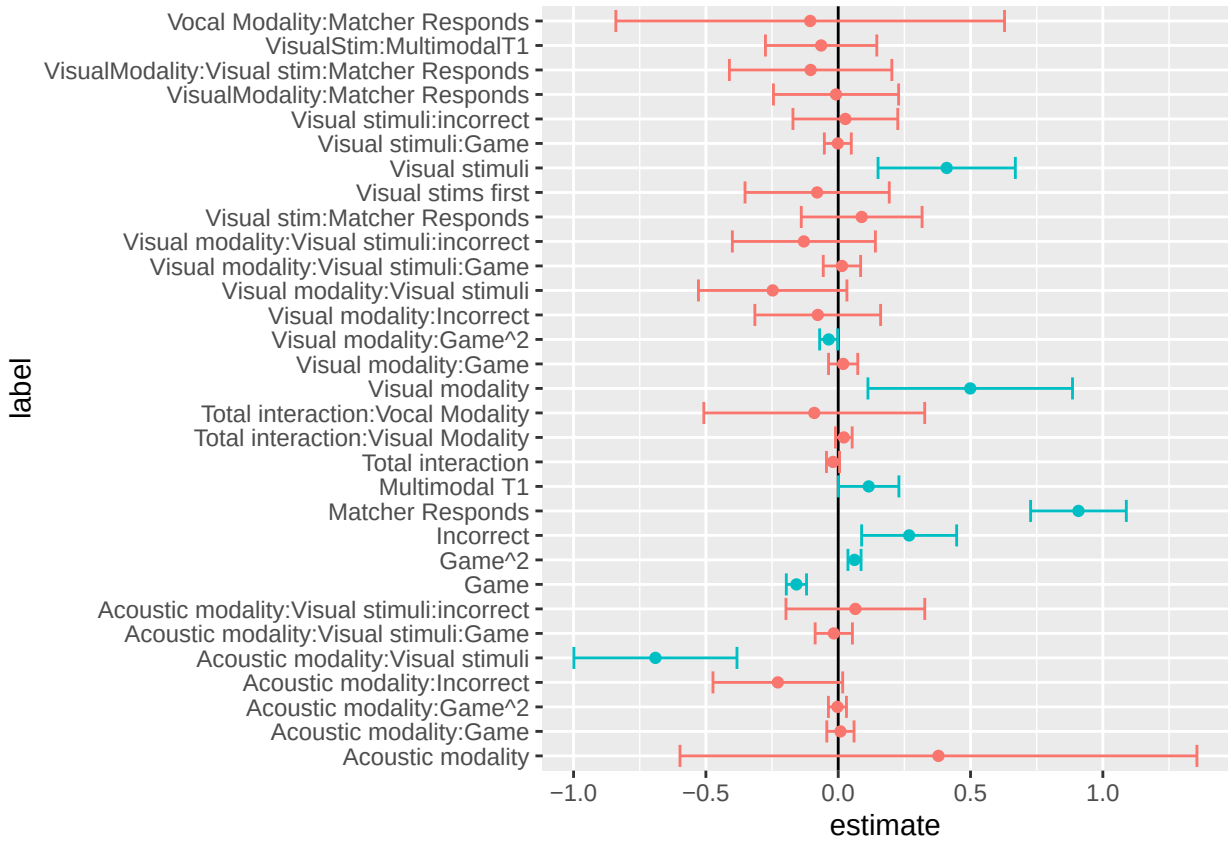
```
sig.data = data.frame(estimate = fixef(finalModel),
                      y=1:length(fixef(finalModel)),
                      sig=sig[feModel])

cols= c("black",'red')
sig.data$pointCol = cols[1]
sig.data$pointCol[!is.na(sig.data$sig)] =
  cols[1 + (sig.data$sig[!is.na(sig.data$sig)] < 0.05)]
# Mark marginal effects
#sig.data$pointCol[!is.na(sig.data$sig) &
#                    sig.data$sig < 0.1 &
#                    sig.data$sig >=0.05] = "orange"

sig.data$fade = sig.data$sig > 0.05
```

Plot the strength of the fixed effects:

```
x = get_model_data(finalModel, 'est')
```

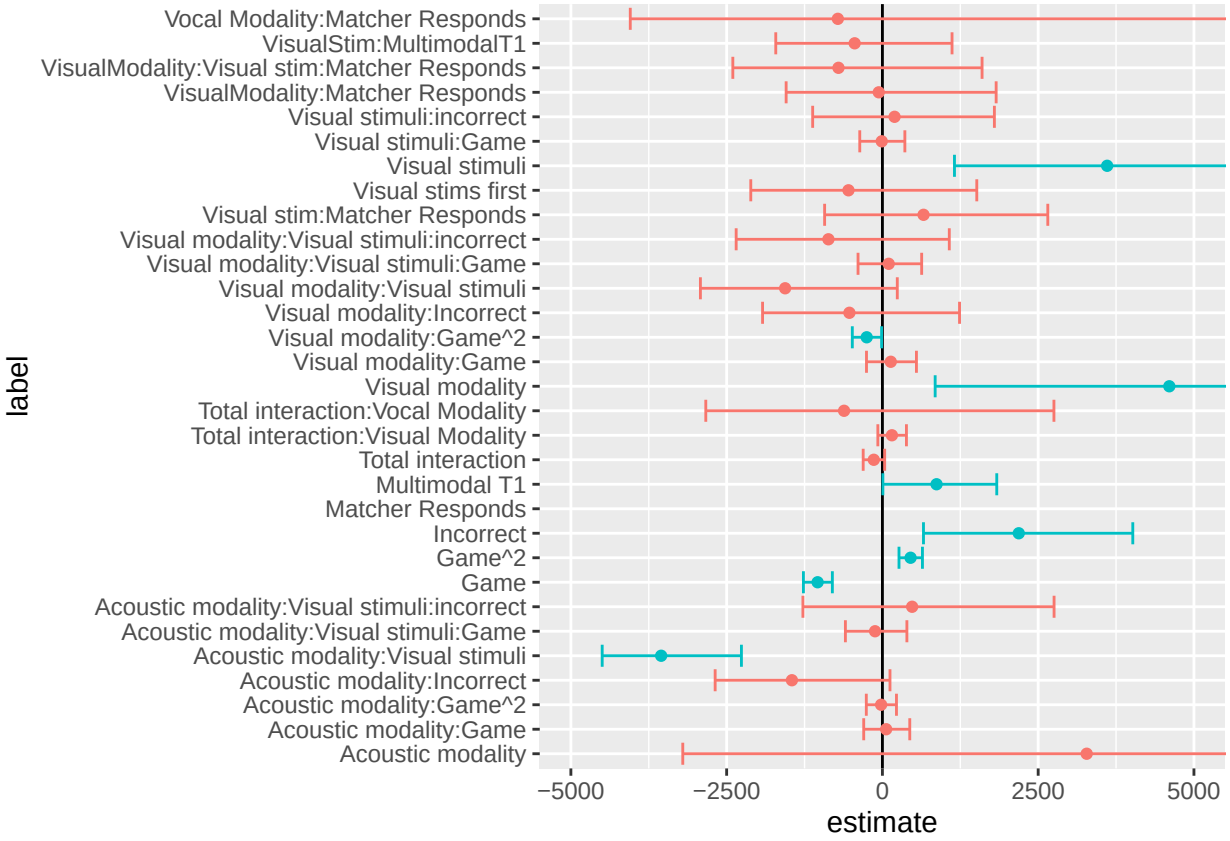
```
## Computing p-values via Wald-statistics approximation (treating t as Wald z).
```

```
x$label = feLabels2[2:length(feLabels2)]
x$col = c("sig","nonsig")[1+(x$p.value>=0.05)]
ggplot(x, aes(y=estimate,x=label,colour=col)) +
  geom_hline(yintercept = 0) +
  geom_point() +
  geom_errorbar(aes(ymin=x$conf.low,ymax=x$conf.high)) +
  coord_flip() +
  theme(legend.position = 'none')
```


label
Vocal Modality:Matcher Responds
VisualStim:MultimodalT1
VisualModality:Visual stim:Matcher Responds
VisualModality:Matcher Responds
Visual stimuli:incorrect
Visual stimuli:Game
Visual stimuli
Visual stims first
Visual stim:Matcher Responds
Visual modality:Visual stimuli:incorrect
Visual modality:Visual stimuli:Game
Visual modality:Visual stimuli
Visual modality:Incorrect
Visual modality:Game^2
Visual modality:Game
Visual modality
Total interaction:Vocal Modality
Total interaction:Visual Modality
Total interaction
Multimodal T1
Matcher Responds
Incorrect
Game^2
Game
Acoustic modality:Visual stimuli:incorrect
Acoustic modality:Visual stimuli:Game
Acoustic modality:Visual stimuli
Acoustic modality:Incorrect
Acoustic modality:Game^2
Acoustic modality:Game
Acoustic modality
−1.0
−0.5
0.0
0.5
1.0
estimate

Attempt plot with axes in milliseconds.

```
convertEst = function(X){
  exp(meanLogTrialLength+X) - exp(meanLogTrialLength)
}

x$estimate = convertEst(x$estimate)
x$conf.low = convertEst(x$conf.low)
x$conf.high = convertEst(x$conf.high)

ggplot(x, aes(y=estimate,x=label,colour=col)) +
  geom_hline(yintercept = 0) +
  geom_point() +
  geom_errorbar(aes(ymin=x$conf.low,ymax=x$conf.high)) +
  theme(legend.position = 'none') +
  coord_flip(ylim = c(-5000,5000))
```



for every 10 trials where a matcher responded, subsequent trials were shorter by:

```
noInteraction = convertEst(
  fixef(finalModel)["(Intercept)"]
)
tenResponses = convertEst(
  fixef(finalModel)["(Intercept)"] +
  (10 * fixef(finalModel)["matcherResponds.cumulative"])
)
noInteraction - tenResponses
```

```
## (Intercept)
```

```
##     745.7498
```

Table for paper

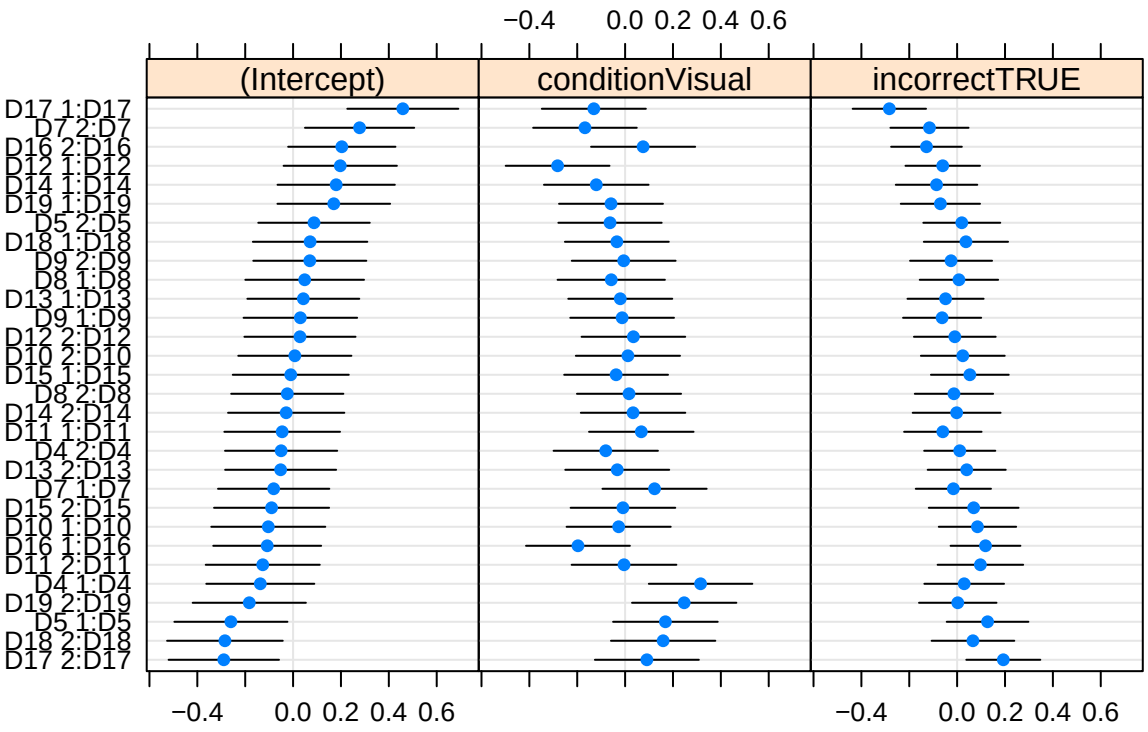
```
outdata = x[,c("term","label","estimate","conf.low",'conf.high')]

outdata$estimate = base::round(outdata$estimate)
outdata$conf.low = base::round(outdata$conf.low)
outdata$conf.high = base::round(outdata$conf.high)

xd = as.data.frame(summary(finalModel)$coef)
outdata$wald.t = xd[match(outdata$term,rownames(xd)),'t value']

outdata = cbind(outdata,
      modelComparison[feModel[2:length(feModel)],c("logLik","Chisq","Pr(>Chisq)")])
outdata$estimate = paste(
  c("","+")[1+(outdata$estimate>0)],
  as.character(outdata$estimate),sep='')

outdata = outdata[,c("label","estimate","conf.low",
                     "conf.high","wald.t","Chisq",
                     "Pr(>Chisq)")]
finalRes = outdata
write.csv(finalRes,file="../../results/tables/Efficiency_FixedEffects.csv")
```

Random effects

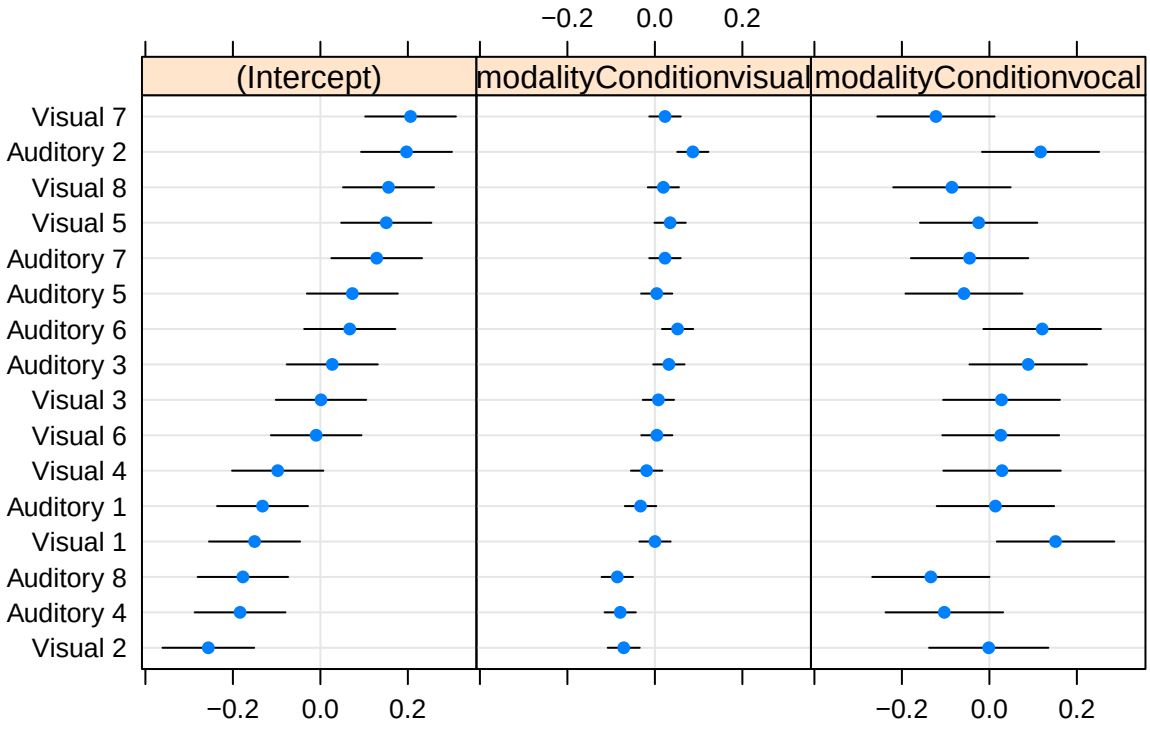
There is a reasonable amount of variaition in the random effects, suggesting that dyads and players differ. This justifies the use of mixed effects modelling.

```
dotplot(ranef(finalModel))
```

```
## $`playerId:dyadNumber`
```

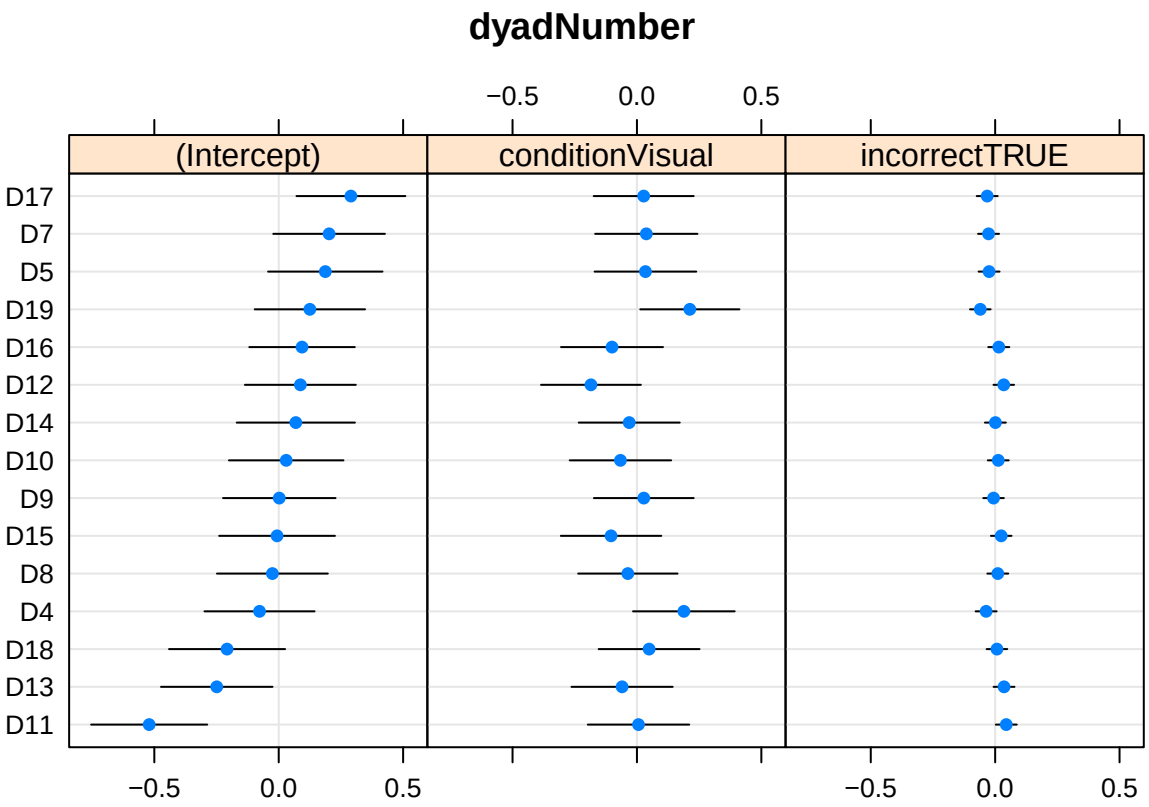

playerId:dyadNumber
(Intercept)
conditionVisual
incorrectTRUE
D17 1:D17
D7 2:D7
D16 2:D16
D12 1:D12
D14 1:D14
D19 1:D19
D5 2:D5
D18 1:D18
D9 2:D9
D8 1:D8
D13 1:D13
D9 1:D9
D12 2:D12
D10 2:D10
D15 1:D15
D8 2:D8
D14 2:D14
D11 1:D11
D4 2:D4
D13 2:D13
D7 1:D7
D15 2:D15
D10 1:D10
D16 1:D16
D11 2:D11
D4 1:D4
D19 2:D19
D5 1:D5
D18 2:D18
D17 2:D17
−0.4 0.0 0.2 0.4 0.6

```
##
## $itemId
```


itemId
(Intercept)
modalityConditionvisual
modalityConditionvocal
Visual 7
Auditory 2
Visual 8
Visual 5
Auditory 7
Auditory 5
Auditory 6
Auditory 3
Visual 3
Visual 6
Visual 4
Auditory 1
Visual 1
Auditory 8
Auditory 4
Visual 2
−0.2 0.0 0.2

```
##
```

```
## $dyadNumber
```



Relevel factors to see other comparisons

```
d2 = d
d2$condition = relevel(d2$condition,"Visual")
fm2 = update(finalModel, data=d2)
```

```
## fixed-effect model matrix is rank deficient so dropping 1 column / coefficient
```

```
## boundary (singular) fit: see ?isSingular
```

```
summary(fm2)
```

```
## Linear mixed model fit by REML ['lmerMod']
## Formula:
## trialLength.log ~ 1 + modalityCondition * condition * trialTotal +
##     I(trialTotal^2) + (modalityCondition:I(trialTotal^2)) + matcherResponds *
##     modalityCondition * condition + matcherResponds.cumulative +
##     matcherResponds.cumulative:modalityCondition + incorrect *
##     modalityCondition * condition + multimodal + multimodal:condition +
##     matcherResponds + firstBlock + (1 + condition + incorrect |
##     dyadNumber/playerId) + (1 + modalityCondition | itemId)
##    Data: d2
## Control: ctrl
##
## REML criterion at convergence: 1744.1
##
## Scaled residuals:
```

```
##     Min      1Q  Median      3Q     Max
## -3.4137 -0.6137 -0.0552  0.5712  5.7083
##
## Random effects:
##  Groups               Name                     Variance Std.Dev. Corr
##  playerId:dyadNumber (Intercept)              0.030839 0.17561
##                      conditionAuditory        0.028599 0.16911  -0.27
##                      incorrectTRUE            0.015801 0.12570  -0.70 -0.16
##  itemId              (Intercept)              0.025369 0.15928
##                      modalityConditionvisual 0.002625 0.05123   0.80
##                      modalityConditionvocal  0.012299 0.11090  -0.09  0.52
##  dyadNumber          (Intercept)              0.079952 0.28276
##                      conditionAuditory        0.023988 0.15488  -0.43
##                      incorrectTRUE            0.001567 0.03959  -0.87  0.82
##  Residual                                     0.123399 0.35128
## Number of obs: 1882, groups:
## playerId:dyadNumber, 30; itemId, 16; dyadNumber, 15
##
## Fixed effects:
##                                                                  Estimate
## (Intercept)                                                     -0.120964
## modalityConditionvisual                                          0.251238
## modalityConditionvocal                                          -0.311830
## conditionAuditory                                               -0.409872
## trialTotal                                                      -0.159418
## I(trialTotal^2)                                                  0.061550
## matcherRespondsTRUE                                              0.996439
## matcherResponds.cumulative                                      -0.019613
## incorrectTRUE                                                    0.295030
## multimodalTRUE                                                   0.050572
## firstBlockVisual                                                -0.079581
## modalityConditionvisual:conditionAuditory                        0.247559
## modalityConditionvocal:conditionAuditory                         0.690612
## modalityConditionvisual:trialTotal                               0.032808
## modalityConditionvocal:trialTotal                               -0.008309
## conditionAuditory:trialTotal                                     0.001521
## modalityConditionvisual:I(trialTotal^2)                         -0.036022
## modalityConditionvocal:I(trialTotal^2)                          -0.002917
## modalityConditionvisual:matcherRespondsTRUE                     -0.112507
## modalityConditionvocal:matcherRespondsTRUE                      -0.105875
## conditionAuditory:matcherRespondsTRUE                           -0.088654
## modalityConditionvisual:matcherResponds.cumulative               0.021201
## modalityConditionvocal:matcherResponds.cumulative               -0.090406
## modalityConditionvisual:incorrectTRUE                           -0.207109
## modalityConditionvocal:incorrectTRUE                            -0.163323
## conditionAuditory:incorrectTRUE                                 -0.027018
## conditionAuditory:multimodalTRUE                                 0.064590
## modalityConditionvisual:conditionAuditory:trialTotal            -0.014131
## modalityConditionvocal:conditionAuditory:trialTotal              0.016712
## modalityConditionvisual:conditionAuditory:matcherRespondsTRUE    0.104292
## modalityConditionvisual:conditionAuditory:incorrectTRUE          0.129780
## modalityConditionvocal:conditionAuditory:incorrectTRUE          -0.064822
##                                                                 Std. Error
## (Intercept)                                                       0.176530
```

```
## modalityConditionvisual                                          0.202962
## modalityConditionvocal                                           0.539640
## conditionAuditory                                                0.132324
## trialTotal                                                       0.022960
## I(trialTotal^2)                                                  0.012668
## matcherRespondsTRUE                                              0.072111
## matcherResponds.cumulative                                       0.012612
## incorrectTRUE                                                    0.076437
## multimodalTRUE                                                   0.089998
## firstBlockVisual                                                 0.139012
## modalityConditionvisual:conditionAuditory                        0.143128
## modalityConditionvocal:conditionAuditory                         0.157212
## modalityConditionvisual:trialTotal                               0.031605
## modalityConditionvocal:trialTotal                                0.028902
## conditionAuditory:trialTotal                                     0.025965
## modalityConditionvisual:I(trialTotal^2)                          0.017465
## modalityConditionvocal:I(trialTotal^2)                           0.017385
## modalityConditionvisual:matcherRespondsTRUE                      0.101445
## modalityConditionvocal:matcherRespondsTRUE                       0.374660
## conditionAuditory:matcherRespondsTRUE                            0.116446
## modalityConditionvisual:matcherResponds.cumulative               0.016084
## modalityConditionvocal:matcherResponds.cumulative                0.212914
## modalityConditionvisual:incorrectTRUE                            0.109659
## modalityConditionvocal:incorrectTRUE                             0.100925
## conditionAuditory:incorrectTRUE                                  0.101040
## conditionAuditory:multimodalTRUE                                 0.107341
## modalityConditionvisual:conditionAuditory:trialTotal             0.036040
## modalityConditionvocal:conditionAuditory:trialTotal              0.035938
## modalityConditionvisual:conditionAuditory:matcherRespondsTRUE    0.156611
## modalityConditionvisual:conditionAuditory:incorrectTRUE          0.137873
## modalityConditionvocal:conditionAuditory:incorrectTRUE           0.133813
##                                                                 t value
## (Intercept)                                                      -0.685
## modalityConditionvisual                                           1.238
## modalityConditionvocal                                           -0.578
## conditionAuditory                                                -3.097
## trialTotal                                                       -6.943
## I(trialTotal^2)                                                   4.859
## matcherRespondsTRUE                                              13.818
## matcherResponds.cumulative                                       -1.555
## incorrectTRUE                                                     3.860
## multimodalTRUE                                                    0.562
## firstBlockVisual                                                 -0.572
## modalityConditionvisual:conditionAuditory                         1.730
## modalityConditionvocal:conditionAuditory                          4.393
## modalityConditionvisual:trialTotal                                1.038
## modalityConditionvocal:trialTotal                                -0.287
## conditionAuditory:trialTotal                                      0.059
## modalityConditionvisual:I(trialTotal^2)                          -2.063
## modalityConditionvocal:I(trialTotal^2)                           -0.168
## modalityConditionvisual:matcherRespondsTRUE                      -1.109
## modalityConditionvocal:matcherRespondsTRUE                       -0.283
## conditionAuditory:matcherRespondsTRUE                            -0.761
## modalityConditionvisual:matcherResponds.cumulative                1.318
```

```
## modalityConditionvocal:matcherResponds.cumulative              -0.425
## modalityConditionvisual:incorrectTRUE                          -1.889
## modalityConditionvocal:incorrectTRUE                           -1.618
## conditionAuditory:incorrectTRUE                                -0.267
## conditionAuditory:multimodalTRUE                                0.602
## modalityConditionvisual:conditionAuditory:trialTotal           -0.392
## modalityConditionvocal:conditionAuditory:trialTotal             0.465
## modalityConditionvisual:conditionAuditory:matcherRespondsTRUE   0.666
## modalityConditionvisual:conditionAuditory:incorrectTRUE         0.941
## modalityConditionvocal:conditionAuditory:incorrectTRUE         -0.484
##
## Correlation matrix not shown by default, as p = 32 > 12.
## Use print(x, correlation=TRUE)  or
##     vcov(x)        if you need it
## fit warnings:
## fixed-effect model matrix is rank deficient so dropping 1 column / coefficient
## convergence code: 0
## boundary (singular) fit: see ?isSingular
```

```
d2 = d
d2$modalityCondition = relevel(d2$modalityCondition,"visual")
fm2 = update(finalModel, data=d2)
```

```
## fixed-effect model matrix is rank deficient so dropping 1 column / coefficient
## boundary (singular) fit: see ?isSingular
```

```
summary(fm2)
```

```
## Linear mixed model fit by REML ['lmerMod']
## Formula:
## trialLength.log ~ 1 + modalityCondition * condition * trialTotal +
##     I(trialTotal^2) + (modalityCondition:I(trialTotal^2)) + matcherResponds *
##     modalityCondition * condition + matcherResponds.cumulative +
##     matcherResponds.cumulative:modalityCondition + incorrect *
##     modalityCondition * condition + multimodal + multimodal:condition +
##     matcherResponds + firstBlock + (1 + condition + incorrect |
##     dyadNumber/playerId) + (1 + modalityCondition | itemId)
##    Data: d2
## Control: ctrl
##
## REML criterion at convergence: 1744.1
##
## Scaled residuals:
##     Min      1Q  Median      3Q     Max
## -3.4137 -0.6137 -0.0552  0.5712  5.7083
##
## Random effects:
##  Groups              Name                    Variance Std.Dev. Corr
##  playerId:dyadNumber (Intercept)             0.043220 0.20790
##                      conditionVisual         0.028599 0.16911  -0.58
##                      incorrectTRUE           0.015801 0.12570  -0.72  0.16
##  itemId              (Intercept)             0.041101 0.20273
##                      modalityConditionmulti  0.002625 0.05123  -0.88
##                      modalityConditionvocal  0.009038 0.09507  -0.41 -0.07
```

```
##  dyadNumber          (Intercept)            0.066131 0.25716
##                      conditionVisual        0.023988 0.15488  -0.13
##                      incorrectTRUE          0.001567 0.03959  -0.46 -0.82
##  Residual                                   0.123399 0.35128
## Number of obs: 1882, groups:
## playerId:dyadNumber, 30; itemId, 16; dyadNumber, 15
##
## Fixed effects:
##                                                                 Estimate
## (Intercept)                                                    -0.032037
## modalityConditionmulti                                         -0.498797
## modalityConditionvocal                                         -0.120017
## conditionVisual                                                 0.162312
## trialTotal                                                     -0.139220
## I(trialTotal^2)                                                 0.025529
## matcherRespondsTRUE                                             0.899571
## matcherResponds.cumulative                                      0.001588
## incorrectTRUE                                                   0.190682
## multimodalTRUE                                                  0.115162
## firstBlockVisual                                               -0.079582
## modalityConditionmulti:conditionVisual                          0.247559
## modalityConditionvocal:conditionVisual                         -0.443053
## modalityConditionmulti:trialTotal                              -0.018677
## modalityConditionvocal:trialTotal                              -0.010274
## conditionVisual:trialTotal                                      0.012610
## modalityConditionmulti:I(trialTotal^2)                          0.036022
## modalityConditionvocal:I(trialTotal^2)                          0.033105
## modalityConditionmulti:matcherRespondsTRUE                      0.008214
## modalityConditionvocal:matcherRespondsTRUE                     -0.097661
## conditionVisual:matcherRespondsTRUE                            -0.015639
## modalityConditionmulti:matcherResponds.cumulative              -0.021201
## modalityConditionvocal:matcherResponds.cumulative              -0.111608
## modalityConditionmulti:incorrectTRUE                            0.077329
## modalityConditionvocal:incorrectTRUE                           -0.150815
## conditionVisual:incorrectTRUE                                  -0.102762
## conditionVisual:multimodalTRUE                                 -0.064590
## modalityConditionmulti:conditionVisual:trialTotal              -0.014131
## modalityConditionvocal:conditionVisual:trialTotal              -0.030843
## modalityConditionmulti:conditionVisual:matcherRespondsTRUE      0.104292
## modalityConditionmulti:conditionVisual:incorrectTRUE            0.129780
## modalityConditionvocal:conditionVisual:incorrectTRUE            0.194602
##                                                                Std. Error
## (Intercept)                                                      0.174969
## modalityConditionmulti                                           0.197178
## modalityConditionvocal                                           0.496076
## conditionVisual                                                  0.137681
## trialTotal                                                       0.020395
## I(trialTotal^2)                                                  0.012021
## matcherRespondsTRUE                                              0.077698
## matcherResponds.cumulative                                       0.010028
## incorrectTRUE                                                    0.080744
## multimodalTRUE                                                   0.058240
## firstBlockVisual                                                 0.139012
## modalityConditionmulti:conditionVisual                           0.143128
```

```
## modalityConditionvocal:conditionVisual                          0.146378
## modalityConditionmulti:trialTotal                               0.028170
## modalityConditionvocal:trialTotal                               0.026928
## conditionVisual:trialTotal                                      0.025117
## modalityConditionmulti:I(trialTotal^2)                          0.017465
## modalityConditionvocal:I(trialTotal^2)                          0.016917
## modalityConditionmulti:matcherRespondsTRUE                      0.120640
## modalityConditionvocal:matcherRespondsTRUE                      0.371386
## conditionVisual:matcherRespondsTRUE                             0.104926
## modalityConditionmulti:matcherResponds.cumulative               0.016084
## modalityConditionvocal:matcherResponds.cumulative               0.212751
## modalityConditionmulti:incorrectTRUE                            0.121223
## modalityConditionvocal:incorrectTRUE                            0.117060
## conditionVisual:incorrectTRUE                                   0.095733
## conditionVisual:multimodalTRUE                                  0.107341
## modalityConditionmulti:conditionVisual:trialTotal               0.036040
## modalityConditionvocal:conditionVisual:trialTotal               0.035299
## modalityConditionmulti:conditionVisual:matcherRespondsTRUE      0.156611
## modalityConditionmulti:conditionVisual:incorrectTRUE            0.137872
## modalityConditionvocal:conditionVisual:incorrectTRUE            0.129480
##                                                                t value
## (Intercept)                                                     -0.183
## modalityConditionmulti                                          -2.530
## modalityConditionvocal                                          -0.242
## conditionVisual                                                  1.179
## trialTotal                                                      -6.826
## I(trialTotal^2)                                                  2.124
## matcherRespondsTRUE                                             11.578
## matcherResponds.cumulative                                       0.158
## incorrectTRUE                                                    2.362
## multimodalTRUE                                                   1.977
## firstBlockVisual                                                -0.572
## modalityConditionmulti:conditionVisual                           1.730
## modalityConditionvocal:conditionVisual                          -3.027
## modalityConditionmulti:trialTotal                               -0.663
## modalityConditionvocal:trialTotal                               -0.382
## conditionVisual:trialTotal                                       0.502
## modalityConditionmulti:I(trialTotal^2)                           2.063
## modalityConditionvocal:I(trialTotal^2)                           1.957
## modalityConditionmulti:matcherRespondsTRUE                       0.068
## modalityConditionvocal:matcherRespondsTRUE                      -0.263
## conditionVisual:matcherRespondsTRUE                             -0.149
## modalityConditionmulti:matcherResponds.cumulative               -1.318
## modalityConditionvocal:matcherResponds.cumulative               -0.525
## modalityConditionmulti:incorrectTRUE                             0.638
## modalityConditionvocal:incorrectTRUE                            -1.288
## conditionVisual:incorrectTRUE                                   -1.073
## conditionVisual:multimodalTRUE                                  -0.602
## modalityConditionmulti:conditionVisual:trialTotal               -0.392
## modalityConditionvocal:conditionVisual:trialTotal               -0.874
## modalityConditionmulti:conditionVisual:matcherRespondsTRUE       0.666
## modalityConditionmulti:conditionVisual:incorrectTRUE             0.941
## modalityConditionvocal:conditionVisual:incorrectTRUE             1.503
```

```
##
## Correlation matrix not shown by default, as p = 32 > 12.
## Use print(x, correlation=TRUE)  or
##     vcov(x)        if you need it
```

```
## fit warnings:
## fixed-effect model matrix is rank deficient so dropping 1 column / coefficient
## convergence code: 0
## boundary (singular) fit: see ?isSingular
```

Variance explained

Total variance explained by the model: Calculated by pseudo R squared method from the *MuMIn* package to calculate the variance explained by fixed effects and random effects in a model (Nakagawa & Schielzeth 2013).

```
MuMIn::r.squaredGLMM(finalModel)
```

```
## Warning: 'r.squaredGLMM' now calculates a revised statistic. See the help
## page.
```

```
##            R2m       R2c
## [1,] 0.3466664 0.6931262
```

Fixed effects explain 34.67% of the variance. Total varaince explained = 69.31%. (random effects = 34.65).

For each model in the bottom-up procedure, we then calculate the increase in variance explained. This is an estiamte of how much variance a particular variable accounts for.

```
mList = list("m0"=m0,"mtchTrn"=mtchTrn,"modality"=modality,"cond"=cond,
"game"=game,"modXcond"=modXcond,"conXgame"=conXgame,"modXgame"=modXgame,
"moXcoXga"=moXcoXga,"tMtchTr"=tMtchTr,"tMaTxMod"=tMaTxMod,"nTurnXmo"=nTurnXmo,
"nTurnXco"=nTurnXco,"tuXmoXco"=tuXmoXco,"incor"=incor,
"moXincor"=moXincor,"coXincor"=coXincor,"coXmoXin"=coXmoXin,
"multim"=multim,"multiXco"=multiXco,"gamQuad"=gamQuad,
"modXgamQ"=modXgamQ,"block"=block,"blocXmod"=blocXmod)
mList = mList[rownames(modelComparison)]
varExplained = sapply(mList,MuMIn::r.squaredGLMM)
varExplained.fixed = diff(varExplained[1,])
t(t(varExplained.fixed[c("game","gamQuad","mtchTrn",
                         "tMtchTr","incor","modXcond",
                         "modXgame","modXgamQ")]))
```

```
##                  [,1]
## game      0.108670034
## gamQuad   0.020150604
## mtchTrn   0.112321829
## tMtchTr  -0.001109019
## incor     0.038508550
## modXcond  0.039721398
## modXgame  0.003964707
## modXgamQ  0.001637667
```

Plot for cumulative matcher turn effects (ignore vocal condition who hardly respond). Note that we found that the cumulative number of trials is a significant predictor, except when the number of trials is included in the model. This may be because the total number of trials is an upper bound on the total number of matcher responses and so the model uses cumulative matcher turns as a proxy for number of trials. In the raw data, there appears to be no relationship between cumulative matcher responses and trial length:

```
ggplot(d[d$modalityCondition!="vocal",],
       aes(x=matcherResponds.cumulative,
           y=trialLength.log)) +
  stat_smooth() + geom_point()
```

Alternative models

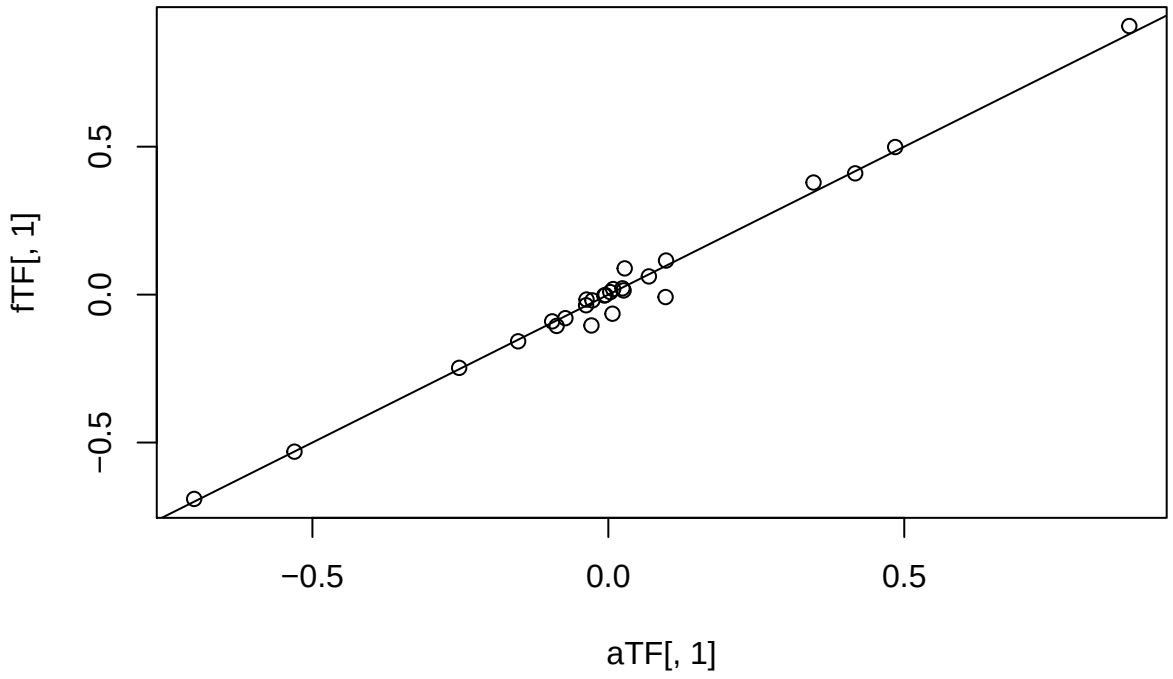
Model for only accurate trials

```
accTrials =  lmer(trialLength.log ~ 1 + modalityCondition*condition*trialTotal +
             I(trialTotal^2) +(modalityCondition:I(trialTotal^2)) +
            matcherResponds*modalityCondition*condition +
            matcherResponds.cumulative +
            matcherResponds.cumulative:modalityCondition +
            modalityCondition*condition +
            multimodal + multimodal:condition +
            matcherResponds +
            firstBlock +
            (1 + condition |dyadNumber/playerId) +
            (1 + modalityCondition|itemId),
          data=d[!d$incorrect,], REML = TRUE)
```

```
## fixed-effect model matrix is rank deficient so dropping 1 column / coefficient
```

```
## boundary (singular) fit: see ?isSingular
```

```
aTF = summary(accTrials)$coefficients
fTF = summary(finalModel)$coefficients
cF = intersect(rownames(aTF),rownames(fTF))
aTF = aTF[cF,]
fTF = fTF[cF,]
plot(aTF[,1],fTF[,1])
abline(0,1)
```




```
# Print large differences in t-value
diffF = abs(aTF[,'t value'] - fTF[,'t value'])
diffFV = names(diffF[diffF> (2 * sd(fixef(finalModel)))])
round(cbind(all=fTF[diffFV,3],correct=aTF[diffFV,3]),3)
```

```
##                                                 all correct
## matcherRespondsTRUE                           9.841   9.172
## modalityConditionvisual:matcherRespondsTRUE -0.068   0.739
## conditionVisual:multimodalTRUE              -0.602   0.060
```

There are no large qualitative differences when analysing only correct trials.

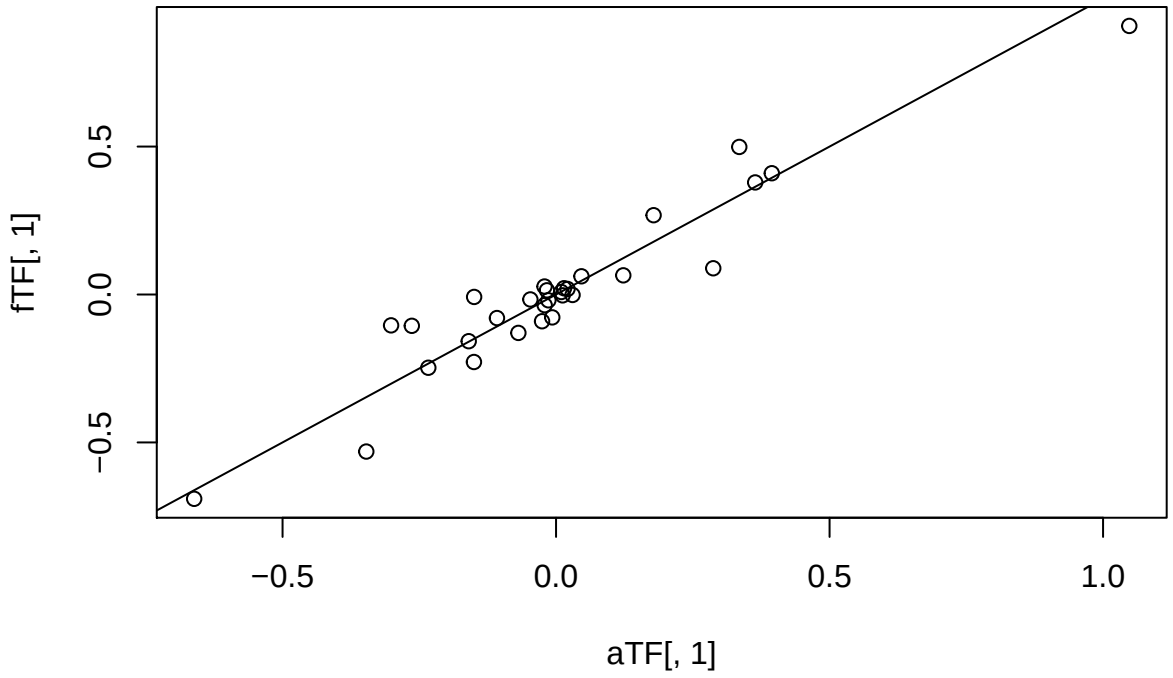
Model for only multimodal trials

```
multTrials =  lmer(trialLength.log ~ 1 + modalityCondition*condition*trialTotal +
             I(trialTotal^2) +(modalityCondition:I(trialTotal^2)) +
            matcherResponds*modalityCondition*condition +
            matcherResponds.cumulative +
              matcherResponds.cumulative:modalityCondition +
            incorrect *modalityCondition*condition +
            matcherResponds +
            firstBlock +
            (1 + condition + incorrect |dyadNumber/playerId) +
            (1 + modalityCondition|itemId),
          data=d[(d$modalityCondition!="multi") | (d$multimodal),], REML = TRUE)
```

```
## fixed-effect model matrix is rank deficient so dropping 1 column / coefficient
```

```
## boundary (singular) fit: see ?isSingular
```

```
aTF = summary(multTrials)$coefficients
fTF = summary(finalModel)$coefficients
cF = intersect(rownames(aTF),rownames(fTF))
aTF = aTF[cF,]
fTF = fTF[cF,]
plot(aTF[,1],fTF[,1])
abline(0,1)
```



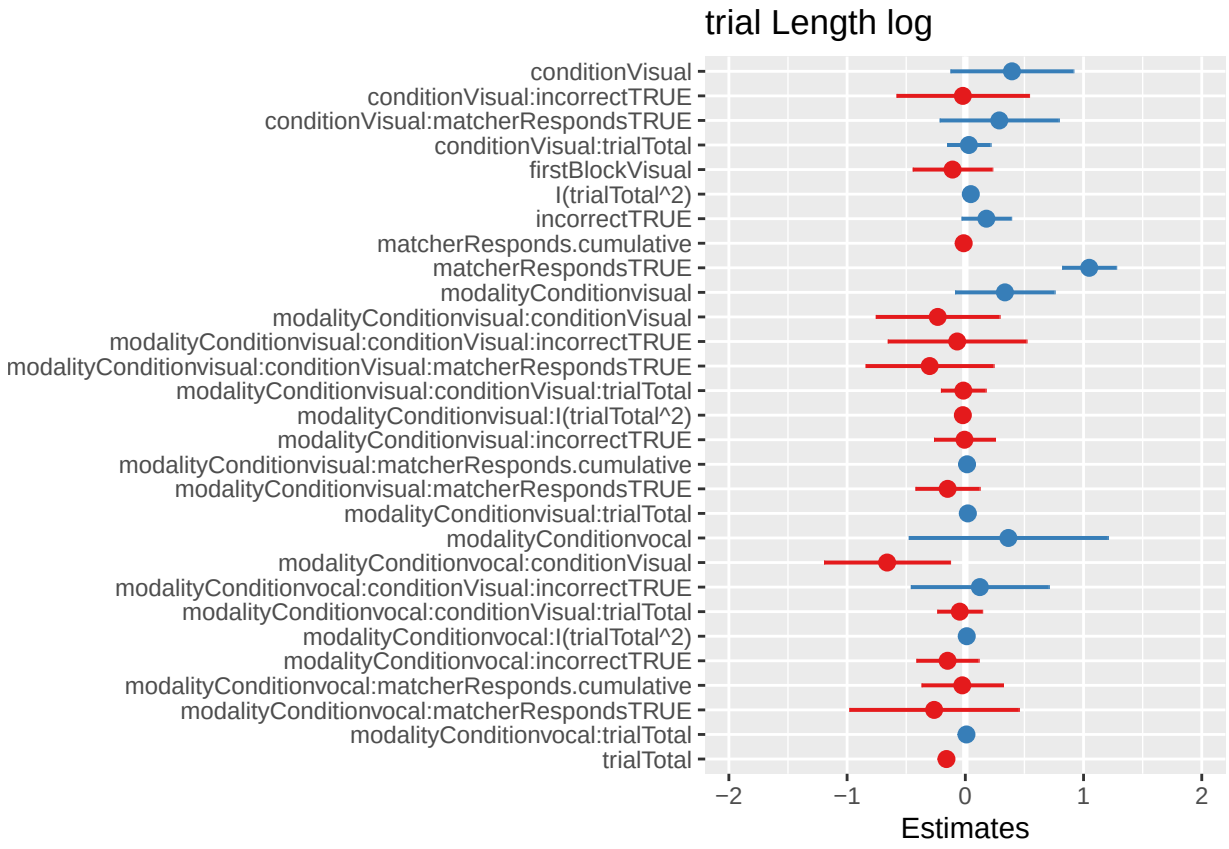

```
# Print large differences in t-value
diffF = abs(aTF[,'t value'] - fTF[,'t value'])
diffFV = names(diffF[diffF> (2 * sd(fixef(finalModel)))])
round(cbind(all=fTF[diffFV,3],correct=aTF[diffFV,3]),3)
```

```
##                                              all correct
## (Intercept)                               -3.055  -1.797
## modalityConditionvisual                    2.530   1.560
```

```
## conditionVisual                                        3.097   1.487
## trialTotal                                            -8.107  -6.193
## I(trialTotal^2)                                        4.859   2.370
## matcherRespondsTRUE                                    9.841   8.993
## matcherResponds.cumulative                            -1.555  -0.475
## incorrectTRUE                                          2.926   1.666
## modalityConditionvisual:conditionVisual               -1.730  -0.874
## modalityConditionvocal:conditionVisual                -4.393  -2.434
## modalityConditionvisual:I(trialTotal^2)               -2.063  -0.919
## modalityConditionvocal:I(trialTotal^2)                -0.168   0.530
## modalityConditionvisual:matcherRespondsTRUE           -0.068  -1.082
## modalityConditionvisual:matcherResponds.cumulative     1.318   0.474
## modalityConditionvisual:incorrectTRUE                 -0.638  -0.053
## modalityConditionvocal:incorrectTRUE                  -1.825  -1.118
## modalityConditionvisual:conditionVisual:trialTotal     0.392  -0.173
## modalityConditionvisual:conditionVisual:incorrectTRUE -0.941  -0.230
```

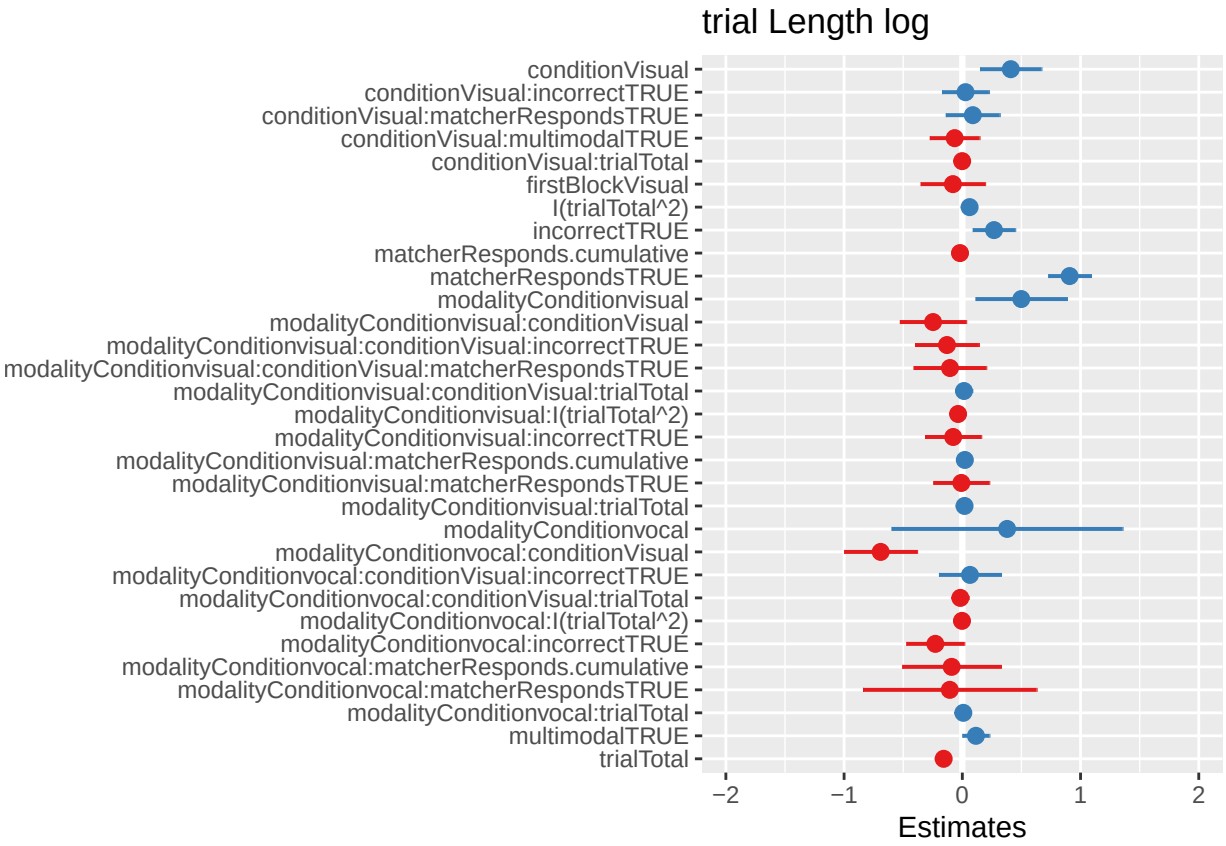
```
plot_model(multTrials,axis.labels = "")
```

```
## Computing p-values via Wald-statistics approximation (treating t as Wald z).
```




```
plot_model(finalModel,axis.labels = "")
```

```
## Computing p-values via Wald-statistics approximation (treating t as Wald z).
```



Summary:

We also analysed only correctly guessed trials and found no qualitative differences. Running the analysis while excluding trials with unimodal descriptions from the multimodal condition lead to weaker effects for condition, stimulus type and the interaction between the two. In line with the analysis above, this suggests that the advantage for participants in the multimodal condition is not just due to multimodal signals in themselves, but may be due to the relationship between multimodality and the communicative interaction between the director and matcher (see section 6.1).

Minimal model

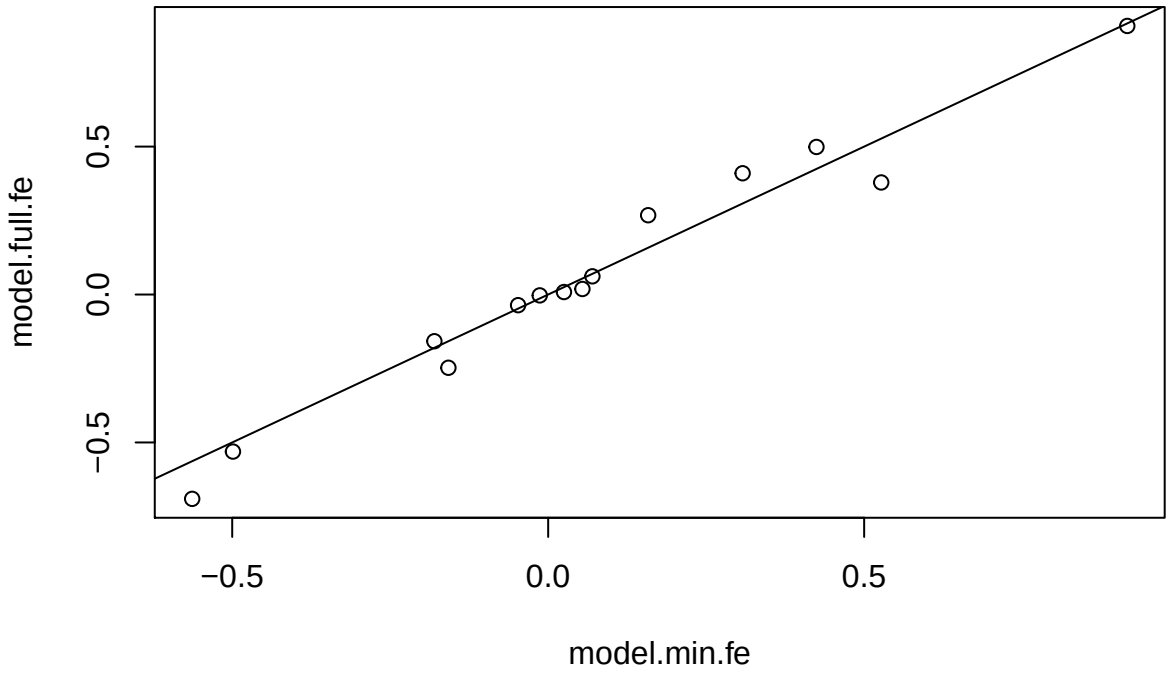
Model including only variables that explained a significant amnount of variance according to the model comparison procedure above.

```
model.min = lmer(trialLength.log ~ 1 +
            matcherResponds +
            incorrect +
            modalityCondition:trialTotal +
            trialTotal + I(trialTotal^2) +
            modalityCondition*condition +
            modalityCondition:I(trialTotal^2) +
            (1 + condition |dyadNumber/playerId) +
            (1 + modalityCondition|itemId),
          data=d, REML = FALSE,control = ctrl)
```

```
## boundary (singular) fit: see ?isSingular
```

Compare the estimates:

```
model.min.fe = fixef(model.min)
model.full.fe = fixef(finalModel)[names(model.min.fe)]
plot(model.min.fe,model.full.fe)
abline(0,1)
```




```
cor(model.min.fe,model.full.fe)
```

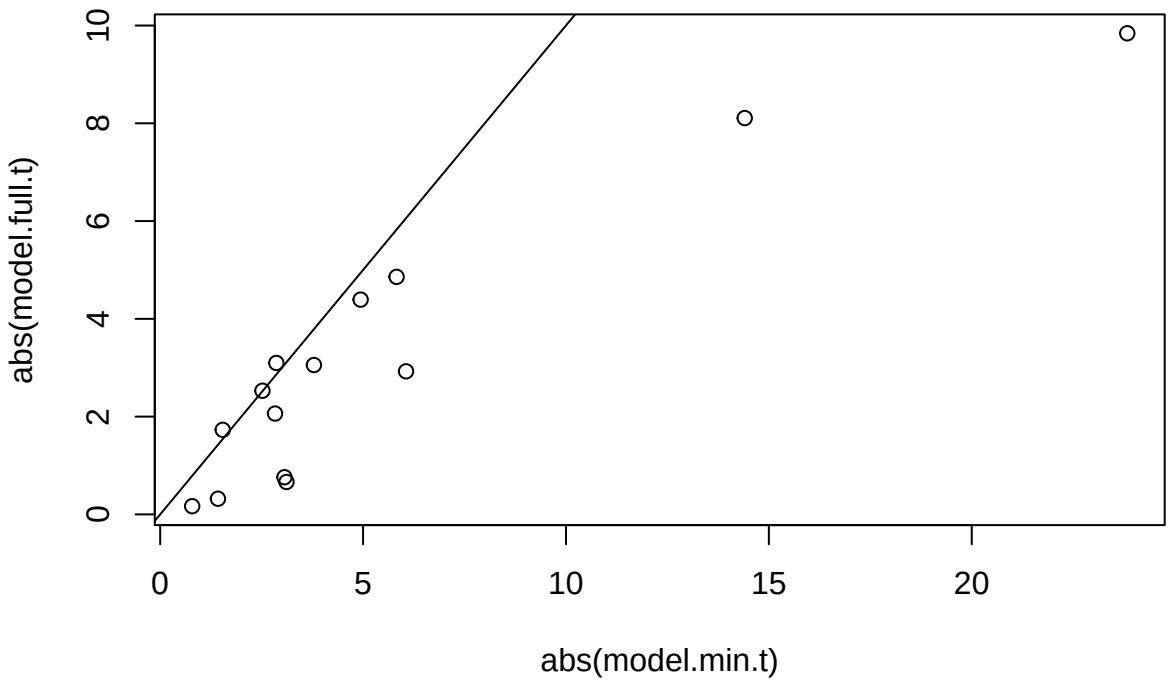
```
## [1] 0.9839989
```

Estimates are correlated with r = 0.98, suggesting that there is little difference.

Compare the t-values. Note that in almost all cases, the restuls for the minimal model are the same or stronger:

```
getTval = function(X){summary(X)$coef[,"t value"]}
model.min.t = getTval(model.min)
```

```
model.full.t = getTval(finalModel)
model.full.t = model.full.t[names(model.min.t)]
plot(abs(model.min.t),abs(model.full.t))
abline(0,1)
```



Model with only modality condition and stimulus type, with random slopes for both fixed effects:

```
model.min2 = lmer(trialLength.log ~ 1 +
            modalityCondition + condition +
            (1 + condition |dyadNumber/playerId) +
            (1 + modalityCondition  |itemId) ,
          data=d, REML=FALSE, control=ctrl)
```

```
## boundary (singular) fit: see ?isSingular
```

```
summary(model.min2)
```

```
## Linear mixed model fit by maximum likelihood  ['lmerMod']
## Formula:
## trialLength.log ~ 1 + modalityCondition + condition + (1 + condition |
##     dyadNumber/playerId) + (1 + modalityCondition | itemId)
##    Data: d
## Control: ctrl
##
##      AIC      BIC   logLik deviance df.resid
##   2767.0   2861.2  -1366.5   2733.0     1865
##
## Scaled residuals:
##     Min      1Q  Median      3Q     Max
## -2.3511 -0.6491 -0.1284  0.4809  5.9237
##
## Random effects:
##  Groups              Name                    Variance Std.Dev. Corr
##  playerId:dyadNumber (Intercept)             0.034473 0.18567
```

```
##                       conditionVisual         0.028392 0.16850  -0.61
##  itemId               (Intercept)             0.030562 0.17482
##                       modalityConditionvisual 0.004214 0.06491   1.00
##                       modalityConditionvocal  0.011805 0.10865  -0.27 -0.27
##  dyadNumber           (Intercept)             0.077336 0.27809
##                       conditionVisual         0.057259 0.23929  -0.50
##  Residual                                     0.225748 0.47513
## Number of obs: 1882, groups:
## playerId:dyadNumber, 30; itemId, 16; dyadNumber, 15
##
## Fixed effects:
##                          Estimate Std. Error t value
## (Intercept)              -0.17692    0.14180  -1.248
## modalityConditionvisual   0.27891    0.16887   1.652
## modalityConditionvocal    0.11988    0.17032   0.704
## conditionVisual           0.08168    0.11763   0.694
##
## Correlation of Fixed Effects:
##              (Intr) mdltyCndtnvs mdltyCndtnvc
## mdltyCndtnvs -0.566
## mdltyCndtnvc -0.598  0.487
## conditinVsl  -0.449  0.013       -0.001
## convergence code: 0
## boundary (singular) fit: see ?isSingular
```

```
model.min2B = lmer(trialLength.log ~ 1 +
            modalityCondition * condition +
            (1 + condition |dyadNumber/playerId) +
            (1 + modalityCondition  |itemId) ,
          data=d, REML=FALSE, control=ctrl)
```

```
## boundary (singular) fit: see ?isSingular
```

```
summary(model.min2B)
```

```
## Linear mixed model fit by maximum likelihood  ['lmerMod']
## Formula:
## trialLength.log ~ 1 + modalityCondition * condition + (1 + condition |
##     dyadNumber/playerId) + (1 + modalityCondition | itemId)
##    Data: d
## Control: ctrl
##
##      AIC      BIC   logLik deviance df.resid
##   2755.6   2860.9  -1358.8   2717.6     1863
##
## Scaled residuals:
##     Min      1Q  Median      3Q     Max
## -2.3103 -0.6586 -0.1290  0.4774  5.9279
##
## Random effects:
##  Groups              Name                    Variance Std.Dev. Corr
##  playerId:dyadNumber (Intercept)             0.034518 0.18579
##                      conditionVisual         0.028406 0.16854  -0.62
##  itemId              (Intercept)             0.029482 0.17170
##                      modalityConditionvisual 0.004311 0.06566   0.98
```

```
##                       modalityConditionvocal  0.010289 0.10144  -0.26 -0.08
##  dyadNumber           (Intercept)             0.060184 0.24533
##                       conditionVisual         0.008050 0.08972  -0.20
##  Residual                                     0.225830 0.47522
## Number of obs: 1882, groups:
## playerId:dyadNumber, 30; itemId, 16; dyadNumber, 15
##
## Fixed effects:
##                                          Estimate Std. Error t value
## (Intercept)                               -0.3365     0.1411  -2.385
## modalityConditionvisual                    0.3922     0.1816   2.160
## modalityConditionvocal                     0.4596     0.1836   2.503
## conditionVisual                            0.3557     0.1152   3.087
## modalityConditionvisual:conditionVisual   -0.1892     0.1135  -1.668
## modalityConditionvocal:conditionVisual    -0.5823     0.1198  -4.858
##
## Correlation of Fixed Effects:
##                (Intr) mdltyCndtnvs mdltyCndtnvc cndtnV mdltyCndtnvs:V
## mdltyCndtnvs   -0.579
## mdltyCndtnvc   -0.648  0.484
## conditinVsl    -0.444  0.102        0.193
## mdltyCndtnvs:V  0.134 -0.368       -0.166       -0.240
## mdltyCndtnvc:V  0.242 -0.159       -0.378       -0.509  0.424
## convergence code: 0
## boundary (singular) fit: see ?isSingular
```

```
anova(model.min2,model.min2B)
```

```
## Data: d
## Models:
## model.min2: trialLength.log ~ 1 + modalityCondition + condition + (1 + condition |
## model.min2:     dyadNumber/playerId) + (1 + modalityCondition | itemId)
## model.min2B: trialLength.log ~ 1 + modalityCondition * condition + (1 + condition |
## model.min2B:     dyadNumber/playerId) + (1 + modalityCondition | itemId)
##             Df    AIC    BIC  logLik deviance  Chisq Chi Df Pr(>Chisq)
## model.min2  17 2767.0 2861.2 -1366.5   2733.0
## model.min2B 19 2755.6 2860.9 -1358.8   2717.6 15.337      2  0.0004673 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

Alternative distribution

Below we run the final model from the procedure above, but fitting the raw trial length in milliseconds with a poisson distribution, rather than the log-transformed trial Length.

```
block.poisson =  glmer(trialLength ~ 1 +
            modalityCondition*condition*trialTotal +
            I(trialTotal^2) +(modalityCondition:I(trialTotal^2)) +
            matcherResponds*modalityCondition*condition +
            matcherResponds.cumulative +
            matcherResponds.cumulative:modalityCondition +
            incorrect * modalityCondition*condition +
            multimodal + multimodal:condition +
            matcherResponds +
```

```
            firstBlock +
            (1 + condition + incorrect |dyadNumber/playerId) +
            (1 + modalityCondition|itemId),
          data=d, REML = TRUE,
          family = poisson())
```

```
## Warning: extra argument(s) 'REML' disregarded
```

```
## fixed-effect model matrix is rank deficient so dropping 1 column / coefficient
```

```
## boundary (singular) fit: see ?isSingular
```

```
summary(block.poisson)
```

```
## Generalized linear mixed model fit by maximum likelihood (Laplace
##   Approximation) [glmerMod]
##  Family: poisson  ( log )
## Formula: trialLength ~ 1 + modalityCondition * condition * trialTotal +
##     I(trialTotal^2) + (modalityCondition:I(trialTotal^2)) + matcherResponds *
##     modalityCondition * condition + matcherResponds.cumulative +
##     matcherResponds.cumulative:modalityCondition + incorrect *
##     modalityCondition * condition + multimodal + multimodal:condition +
##     matcherResponds + firstBlock + (1 + condition + incorrect |
##     dyadNumber/playerId) + (1 + modalityCondition | itemId)
##    Data: d
##
##      AIC      BIC   logLik deviance df.resid
##  2386781  2387058 -1193340  2386681     1832
##
## Scaled residuals:
##     Min      1Q  Median      3Q     Max
## -177.99  -21.51   -5.35   13.47  390.03
##
## Random effects:
##  Groups              Name                    Variance Std.Dev. Corr
##  playerId:dyadNumber (Intercept)             0.04897  0.2213
##                      conditionVisual         0.04350  0.2086   -0.63
##                      incorrectTRUE           0.04639  0.2154   -0.22 -0.09
##  itemId              (Intercept)             0.03748  0.1936
##                      modalityConditionvisual 0.01607  0.1268   -0.17
##                      modalityConditionvocal  0.01812  0.1346   -0.44  0.62
##  dyadNumber          (Intercept)             0.05725  0.2393
##                      conditionVisual         0.01012  0.1006   -0.11
##                      incorrectTRUE           0.01050  0.1025   -0.99  0.21
## Number of obs: 1882, groups:
## playerId:dyadNumber, 30; itemId, 16; dyadNumber, 15
##
## Fixed effects:
##                                                      Estimate
## (Intercept)                                         8.227e+00
## modalityConditionvisual                             6.810e-01
## modalityConditionvocal                              5.839e-01
## conditionVisual                                     5.409e-01
## trialTotal                                         -1.760e-01
## I(trialTotal^2)                                     8.757e-02
```

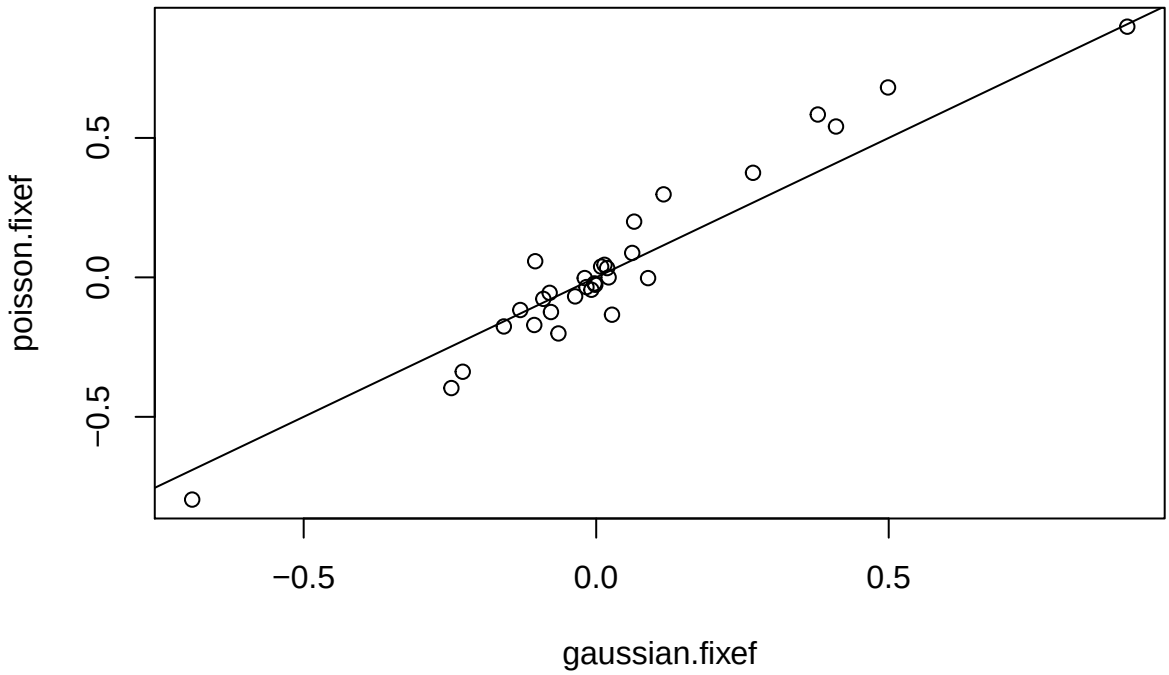
```
## matcherRespondsTRUE                                              8.988e-01
## matcherResponds.cumulative                                      -2.413e-03
## incorrectTRUE                                                    3.749e-01
## multimodalTRUE                                                   2.977e-01
## firstBlockVisual                                                -5.543e-02
## modalityConditionvisual:conditionVisual                         -3.968e-01
## modalityConditionvocal:conditionVisual                          -7.966e-01
## modalityConditionvisual:trialTotal                               3.335e-02
## modalityConditionvocal:trialTotal                                3.861e-02
## conditionVisual:trialTotal                                      -2.647e-02
## modalityConditionvisual:I(trialTotal^2)                         -6.819e-02
## modalityConditionvocal:I(trialTotal^2)                          -2.165e-02
## modalityConditionvisual:matcherRespondsTRUE                     -4.436e-02
## modalityConditionvocal:matcherRespondsTRUE                      -1.707e-01
## conditionVisual:matcherRespondsTRUE                             -2.626e-03
## modalityConditionvisual:matcherResponds.cumulative              -1.506e-05
## modalityConditionvocal:matcherResponds.cumulative               -7.703e-02
## modalityConditionvisual:incorrectTRUE                           -1.242e-01
## modalityConditionvocal:incorrectTRUE                            -3.383e-01
## conditionVisual:incorrectTRUE                                   -1.338e-01
## conditionVisual:multimodalTRUE                                  -2.011e-01
## modalityConditionvisual:conditionVisual:trialTotal               4.511e-02
## modalityConditionvocal:conditionVisual:trialTotal               -3.480e-02
## modalityConditionvisual:conditionVisual:matcherRespondsTRUE      5.790e-02
## modalityConditionvisual:conditionVisual:incorrectTRUE           -1.170e-01
## modalityConditionvocal:conditionVisual:incorrectTRUE             1.999e-01
##                                                                 Std. Error
## (Intercept)                                                      1.651e-01
## modalityConditionvisual                                          1.869e-01
## modalityConditionvocal                                           4.904e-01
## conditionVisual                                                  1.257e-01
## trialTotal                                                       6.958e-04
## I(trialTotal^2)                                                  4.159e-04
## matcherRespondsTRUE                                              2.264e-03
## matcherResponds.cumulative                                       3.877e-04
## incorrectTRUE                                                    8.215e-02
## multimodalTRUE                                                   2.165e-03
## firstBlockVisual                                                 1.298e-01
## modalityConditionvisual:conditionVisual                          1.298e-01
## modalityConditionvocal:conditionVisual                           1.382e-01
## modalityConditionvisual:trialTotal                               9.365e-04
## modalityConditionvocal:trialTotal                                8.706e-04
## conditionVisual:trialTotal                                       8.373e-04
## modalityConditionvisual:I(trialTotal^2)                          5.395e-04
## modalityConditionvocal:I(trialTotal^2)                           5.590e-04
## modalityConditionvisual:matcherRespondsTRUE                      2.868e-03
## modalityConditionvocal:matcherRespondsTRUE                       7.748e-03
## conditionVisual:matcherRespondsTRUE                              2.804e-03
## modalityConditionvisual:matcherResponds.cumulative               4.806e-04
## modalityConditionvocal:matcherResponds.cumulative                2.096e-01
## modalityConditionvisual:incorrectTRUE                            1.162e-01
## modalityConditionvocal:incorrectTRUE                             1.162e-01
## conditionVisual:incorrectTRUE                                    3.207e-03
## conditionVisual:multimodalTRUE                                   3.641e-03
```

```
## modalityConditionvisual:conditionVisual:trialTotal           1.102e-03
## modalityConditionvocal:conditionVisual:trialTotal            1.146e-03
## modalityConditionvisual:conditionVisual:matcherRespondsTRUE  3.637e-03
## modalityConditionvisual:conditionVisual:incorrectTRUE        4.194e-03
## modalityConditionvocal:conditionVisual:incorrectTRUE         4.260e-03
##                                                              z value
## (Intercept)                                                   49.816
## modalityConditionvisual                                        3.644
## modalityConditionvocal                                         1.191
## conditionVisual                                                4.305
## trialTotal                                                  -252.928
## I(trialTotal^2)                                              210.534
## matcherRespondsTRUE                                          396.971
## matcherResponds.cumulative                                    -6.223
## incorrectTRUE                                                  4.564
## multimodalTRUE                                               137.488
## firstBlockVisual                                              -0.427
## modalityConditionvisual:conditionVisual                       -3.057
## modalityConditionvocal:conditionVisual                        -5.764
## modalityConditionvisual:trialTotal                            35.609
## modalityConditionvocal:trialTotal                             44.344
## conditionVisual:trialTotal                                   -31.608
## modalityConditionvisual:I(trialTotal^2)                     -126.410
## modalityConditionvocal:I(trialTotal^2)                       -38.737
## modalityConditionvisual:matcherRespondsTRUE                  -15.469
## modalityConditionvocal:matcherRespondsTRUE                   -22.035
## conditionVisual:matcherRespondsTRUE                           -0.937
## modalityConditionvisual:matcherResponds.cumulative            -0.031
## modalityConditionvocal:matcherResponds.cumulative             -0.367
## modalityConditionvisual:incorrectTRUE                         -1.069
## modalityConditionvocal:incorrectTRUE                          -2.912
## conditionVisual:incorrectTRUE                                -41.724
## conditionVisual:multimodalTRUE                               -55.223
## modalityConditionvisual:conditionVisual:trialTotal            40.922
## modalityConditionvocal:conditionVisual:trialTotal            -30.369
## modalityConditionvisual:conditionVisual:matcherRespondsTRUE   15.920
## modalityConditionvisual:conditionVisual:incorrectTRUE        -27.903
## modalityConditionvocal:conditionVisual:incorrectTRUE          46.925
##                                                             Pr(>|z|)
## (Intercept)                                                  < 2e-16 ***
## modalityConditionvisual                                     0.000268 ***
## modalityConditionvocal                                      0.233819
## conditionVisual                                             1.67e-05 ***
## trialTotal                                                   < 2e-16 ***
## I(trialTotal^2)                                              < 2e-16 ***
## matcherRespondsTRUE                                          < 2e-16 ***
## matcherResponds.cumulative                                  4.87e-10 ***
## incorrectTRUE                                               5.02e-06 ***
## multimodalTRUE                                               < 2e-16 ***
## firstBlockVisual                                            0.669464
## modalityConditionvisual:conditionVisual                     0.002237 **
## modalityConditionvocal:conditionVisual                      8.22e-09 ***
## modalityConditionvisual:trialTotal                           < 2e-16 ***
## modalityConditionvocal:trialTotal                            < 2e-16 ***
```

```
## conditionVisual:trialTotal                                      < 2e-16 ***
## modalityConditionvisual:I(trialTotal^2)                         < 2e-16 ***
## modalityConditionvocal:I(trialTotal^2)                          < 2e-16 ***
## modalityConditionvisual:matcherRespondsTRUE                     < 2e-16 ***
## modalityConditionvocal:matcherRespondsTRUE                      < 2e-16 ***
## conditionVisual:matcherRespondsTRUE                            0.348969
## modalityConditionvisual:matcherResponds.cumulative             0.975003
## modalityConditionvocal:matcherResponds.cumulative              0.713263
## modalityConditionvisual:incorrectTRUE                          0.285186
## modalityConditionvocal:incorrectTRUE                           0.003590 **
## conditionVisual:incorrectTRUE                                   < 2e-16 ***
## conditionVisual:multimodalTRUE                                  < 2e-16 ***
## modalityConditionvisual:conditionVisual:trialTotal              < 2e-16 ***
## modalityConditionvocal:conditionVisual:trialTotal               < 2e-16 ***
## modalityConditionvisual:conditionVisual:matcherRespondsTRUE     < 2e-16 ***
## modalityConditionvisual:conditionVisual:incorrectTRUE           < 2e-16 ***
## modalityConditionvocal:conditionVisual:incorrectTRUE            < 2e-16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

##
## Correlation matrix not shown by default, as p = 32 > 12.
## Use print(x, correlation=TRUE)  or
##     vcov(x)        if you need it

## fit warnings:
## fixed-effect model matrix is rank deficient so dropping 1 column / coefficient
## convergence code: 0
## boundary (singular) fit: see ?isSingular
```

Compare estimates for the two distribution functions (the intercepts will obviously be different, so we ignore those):

```
gaussian.fixef = fixef(block)
gaussian.fixef = gaussian.fixef[names(gaussian.fixef)!="(Intercept)"]
poisson.fixef = fixef(block.poisson)
poisson.fixef = poisson.fixef[names(poisson.fixef)!="(Intercept)"]

plot(gaussian.fixef,poisson.fixef)
abline(0,1)
```




```
cor(gaussian.fixef,poisson.fixef)
```

```
## [1] 0.9651025
```

The estimates are highly correlated, suggesting that the choice to log-transform the trial length isn't particularly important.

Turn length versus comprehension time

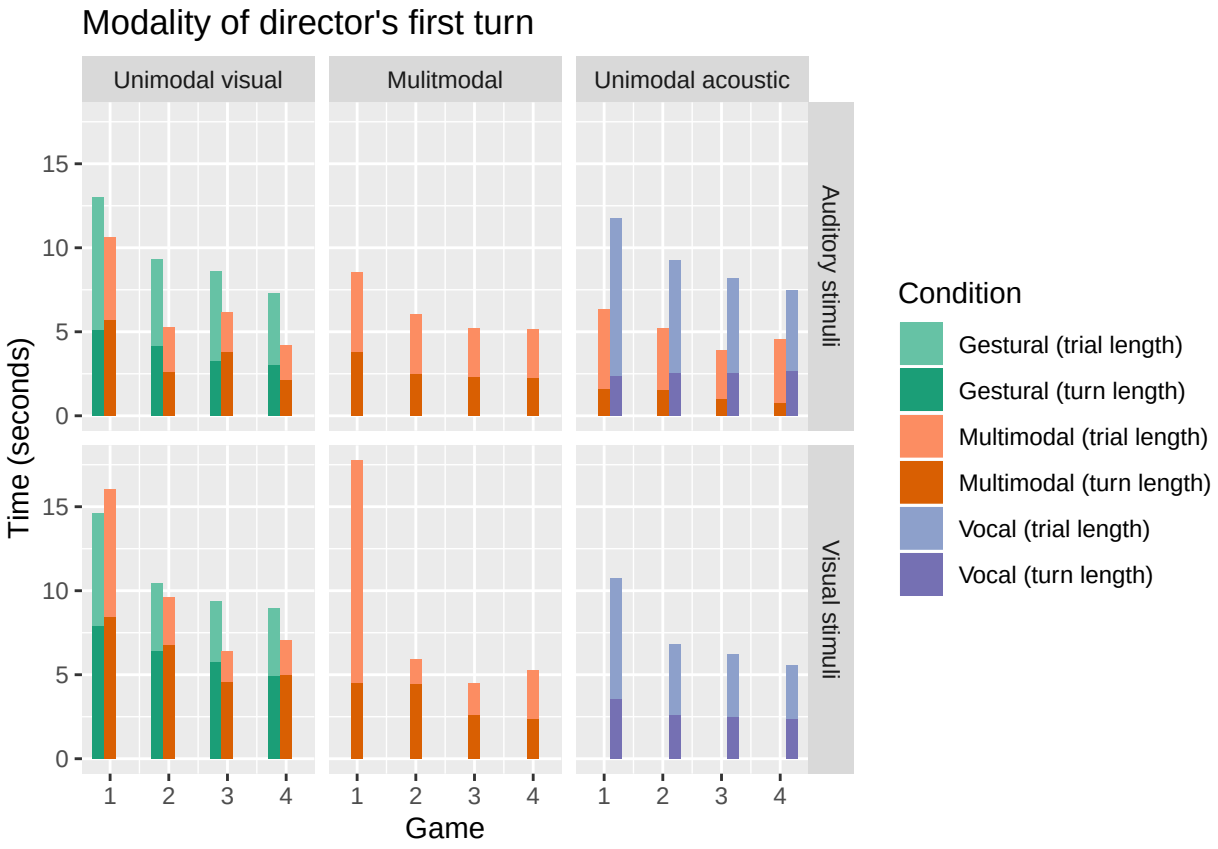
This section compares two values:

- Director's turn length: Time from the start of the director's first turn to the end of the director's first turn.
- Comprehension time: Time from the start of the director's first turn to the point at which the matcher makes a choice. Note that this can in principle be negative if the matcher makes a choice while the director is still producing their first turn.

The main analysis finds that multimodal participants end up being more efficient than the gestural condition. Fig. 4 shows the mean total trial times and the amount of time that the director spent producing the first turn in the trial. The difference between the total trial time and the length of the director's turn include the time spent by the matcher making their choice and any negotiation, so we'll call this the comprehension time (lighter parts of the bars). The data are split by the modality of the director's first turn and by stimulus type, and show that there are different advantages for different combinations of stimuli and modality.

The code for calculating the numbers is available in the Rmd file.

Figure 4 is below. Mean efficiency in seconds split by the length of the director's first turn (darker bars), and total trial length (lighter bars). Bars are coloured by experimental condition (gestural vs. mulitmodal vs. vocal). The panels divide the data by stimulus type (rows) and the modality of the director's first turn (columns). Directors in the gestural and vocal conditions only produced unimodal turns, while directors in the multimodal condition were free to produce unimodal visual, unimodal acoustic or multimodal turns. There were too few cases of unimodal acoustic turns in the multimodal condition to plot.




```
## pdf
##   2
```

```
dx$comprehensionTime = dx$trialLength - dx$turnLength
dx$turnLength.norm = scale(log(dx$turnLength))
dx$comprehensionTime.norm = scale(log(dx$comprehensionTime))
```

The purpose of this figure was to visualise the data to try to understand where the multimodal advantage comes from. We would like to quantify some of the post-hoc observations about this visualisation. However, a regression becomes complicated because of the number of interactions and lack of data for some comparisons. Instead, we just run a set of t-tests comparing key values in the six boxes above. We perform 5 tests for comprehension time, so we adjust the p-values for multiple comparisons accordingly. We do the same for the 4 tests for turn length.

If we compare trials where the director used unimodal visual turns to describe visual stimuli (bottom left panel), we see that the gestural and multimodal conditions look similar in game 1, but by game 4 the participants in the multimodal condition have shorter comprehension times.

```
dxx = dx[dx$turnModalityType=="unimodal visual" & dx$condition=="Visual",]
comp.t1 = t.test(dxx[dxx$game==0,]$comprehensionTime~ dxx[dxx$game==0,]$modalityCondition)
comp.t1$p.value = p.adjust(comp.t1$p.value,n=5)
comp.t1
```

```
##
##  Welch Two Sample t-test
##
## data:  dxx[dxx$game == 0, ]$comprehensionTime by dxx[dxx$game == 0, ]$modalityCondition
## t = 0.38721, df = 107, p-value = 1
## alternative hypothesis: true difference in means is not equal to 0
## 95 percent confidence interval:
##  -3739.629  5555.110
## sample estimates:
##  mean in group multi mean in group visual
##             7616.918             6709.177
```

```
comp.t1b = t.test(dxx[dxx$game==3,]$comprehensionTime~ dxx[dxx$game==3,]$modalityCondition)
comp.t1b$p.value = p.adjust(comp.t1b$p.value,n=5)
comp.t1b
```

```
##
##  Welch Two Sample t-test
##
## data:  dxx[dxx$game == 3, ]$comprehensionTime by dxx[dxx$game == 3, ]$modalityCondition
## t = -2.6883, df = 140.43, p-value = 0.04025
## alternative hypothesis: true difference in means is not equal to 0
## 95 percent confidence interval:
##  -3350.5913  -510.8763
## sample estimates:
##  mean in group multi mean in group visual
##             2080.254             4010.988
```

In contrast, if we compare trials where the director used unimodal acoustic turns to describe auditory stimuli (top right panel), by game 4 the advantage in the multimodal condition is mainly in the length of the director's turn.

```
dxx = dx[dx$turnModalityType=="unimodal acoustic" & dx$condition=="Auditory",]
comp.t2 = t.test(dxx[dxx$game==3,]$comprehensionTime~ dxx[dxx$game==3,]$modalityCondition)
comp.t2$p.value = p.adjust(comp.t2$p.value,n=5)
comp.t2
```

```
##
##  Welch Two Sample t-test
##
## data:  dxx[dxx$game == 3, ]$comprehensionTime by dxx[dxx$game == 3, ]$modalityCondition
## t = -0.67186, df = 3.6575, p-value = 1
## alternative hypothesis: true difference in means is not equal to 0
## 95 percent confidence interval:
##  -5102.041  3172.990
## sample estimates:
## mean in group multi mean in group vocal
##            3802.500            4767.026
```

```
tlen.t2 = t.test(dxx[dxx$game==3,]$turnLength~ dxx[dxx$game==3,]$modalityCondition)
tlen.t2$p.value = p.adjust(tlen.t2$p.value,n=4)
tlen.t2
```

```
##
##  Welch Two Sample t-test
##
## data:  dxx[dxx$game == 3, ]$turnLength by dxx[dxx$game == 3, ]$modalityCondition
## t = -8.4728, df = 15.592, p-value = 1.267e-06
## alternative hypothesis: true difference in means is not equal to 0
## 95 percent confidence interval:
##  -2402.099 -1439.004
## sample estimates:
## mean in group multi mean in group vocal
##             746.500            2667.051
```

Further, comparing trials where the director used unimodal visual turns to describe auditory stimuli (top left panel), by game 4 we see an advantage for participants in the multimodal condition for both the director's turn and comprehension time.

```
dxx = dx[dx$turnModalityType=="unimodal visual" & dx$condition=="Auditory",]
comp.t3 = t.test(dxx[dxx$game==3,]$comprehensionTime~ dxx[dxx$game==3,]$modalityCondition)
comp.t3$p.value = p.adjust(comp.t3$p.value,n=5)
comp.t3
```

```
##
##  Welch Two Sample t-test
##
## data:  dxx[dxx$game == 3, ]$comprehensionTime by dxx[dxx$game == 3, ]$modalityCondition
## t = -3.606, df = 63.443, p-value = 0.003063
## alternative hypothesis: true difference in means is not equal to 0
## 95 percent confidence interval:
##  -3390.5305  -972.8192
## sample estimates:
##  mean in group multi mean in group visual
##             2055.312             4236.987
```

```
tlen.t3 = t.test(dxx[dxx$game==3,]$turnLength~ dxx[dxx$game==3,]$modalityCondition)
tlen.t3$p.value = p.adjust(tlen.t3$p.value,n=4)
tlen.t3
```

```
##
##  Welch Two Sample t-test
##
## data:  dxx[dxx$game == 3, ]$turnLength by dxx[dxx$game == 3, ]$modalityCondition
```

```
## t = -2.8467, df = 71.156, p-value = 0.02307
## alternative hypothesis: true difference in means is not equal to 0
## 95 percent confidence interval:
##  -1527.3559  -269.0903
## sample estimates:
##  mean in group multi mean in group visual
##             2154.625             3052.848
```

Finally, comparing game 4 for the multimodal turns in the multimodal condition (central column) to the unimodal turns in the gesture-only and vocal-only conditions, we see that participants in the multimodal condition have shorter comprehension times for auditory stimuli and equal or shorter turn lengths for visual stimuli.

```
dxx = dx[dx$condition=="Auditory",]
comp.t4 = t.test(dxx[dxx$game==3,]$comprehensionTime~ dxx[dxx$game==3,]$modalityCondition=="multi")
comp.t4$p.value = p.adjust(comp.t4$p.value,n=5)
comp.t4
```

```
##
##  Welch Two Sample t-test
##
## data:  dxx[dxx$game == 3, ]$comprehensionTime by dxx[dxx$game == 3, ]$modalityCondition == "multi"
## t = 2.4635, df = 115.15, p-value = 0.07619
## alternative hypothesis: true difference in means is not equal to 0
## 95 percent confidence interval:
##   340.5189 3135.0917
## sample estimates:
## mean in group FALSE  mean in group TRUE
##            4500.318            2762.513
```

```
dxx = dx[dx$condition=="Visual",]
tlen.t4 = t.test(dxx[dxx$game==3,]$turnLength~ dxx[dxx$game==3,]$modalityCondition=="multi")
tlen.t4$p.value = p.adjust(tlen.t4$p.value,n=4)
tlen.t4
```

```
##
##  Welch Two Sample t-test
##
## data:  dxx[dxx$game == 3, ]$turnLength by dxx[dxx$game == 3, ]$modalityCondition == "multi"
## t = -2.3154, df = 134.06, p-value = 0.08844
## alternative hypothesis: true difference in means is not equal to 0
## 95 percent confidence interval:
##  -1705.0141  -134.0624
## sample estimates:
## mean in group FALSE  mean in group TRUE
##            3681.654            4601.192
```

Summary results

```
rownames(finalRes) = NULL
cbind(finalRes[,c("label","estimate","conf.low",'conf.high')],
      signif(finalRes[,c("wald.t","Chisq","Pr(>Chisq)")],2))
```

```
##                                          label estimate conf.low conf.high
## 1                              Visual modality    +4605      847     10136
## 2                            Acoustic modality    +3279    -3204     20495
## 3                               Visual stimuli    +3607     1157      6784
## 4                                         Game    -1040    -1268      -803
## 5                                       Game^2     +452      266       642
## 6                             Matcher Responds   +10530     7610     14027
## 7                            Total interaction     -138     -309        36
## 8                                    Incorrect    +2188      659      4019
## 9                                 Multimodal T1     +869        7      1835
## 10                           Visual stims first     -545    -2113      1515
## 11              Visual modality:Visual stimuli    -1561    -2921       239
## 12            Acoustic modality:Visual stimuli    -3551    -4498     -2263
## 13                        Visual modality:Game     +134     -255       546
## 14                      Acoustic modality:Game      +60     -300       439
## 15                         Visual stimuli:Game      -11     -364       360
## 16                      Visual modality:Game^2     -252     -483       -13
## 17                    Acoustic modality:Game^2      -21     -259       225
## 18             VisualModality:Matcher Responds      -58    -1545      1825
## 19             Vocal Modality:Matcher Responds     -715    -4047      6228
## 20                Visual stim:Matcher Responds     +660     -928      2655
## 21           Total interaction:Visual Modality     +153      -73       385
## 22            Total interaction:Vocal Modality     -615    -2835      2753
## 23                   Visual modality:Incorrect     -530    -1924      1238
## 24                 Acoustic modality:Incorrect    -1452    -2684       122
## 25                    Visual stimuli:incorrect     +195    -1119      1797
## 26                     VisualStim:MultimodalT1     -445    -1712      1118
## 27         Visual modality:Visual stimuli:Game     +101     -391       630
## 28       Acoustic modality:Visual stimuli:Game     -118     -594       393
## 29 VisualModality:Visual stim:Matcher Responds     -705    -2401      1600
## 30    Visual modality:Visual stimuli:incorrect     -867    -2347      1074
## 31  Acoustic modality:Visual stimuli:incorrect     +477    -1276      2755
##    wald.t   Chisq Pr(>Chisq)
## 1   2.500   0.630    7.3e-01
## 2   0.760   0.630    7.3e-01
## 3   3.100   0.540    4.6e-01
## 4  -8.100 400.000    4.7e-89
## 5   4.900  79.000    7.2e-19
## 6   9.800 490.000   7.2e-109
## 7  -1.600   0.068    7.9e-01
## 8   2.900  13.000    2.7e-04
## 9   2.000   1.500    2.2e-01
## 10 -0.570   0.420    5.2e-01
## 11 -1.700  15.000    4.4e-04
## 12 -4.400  15.000    4.4e-04
## 13  0.660  11.000    5.2e-03
## 14  0.320  11.000    5.2e-03
```

```
## 15 -0.059   0.190    6.6e-01
## 16 -2.100   6.800    3.3e-02
## 17 -0.170   6.800    3.3e-02
## 18 -0.068   2.900    4.0e-01
## 19 -0.280   2.900    4.0e-01
## 20  0.760   0.140    7.1e-01
## 21  1.300   1.900    4.0e-01
## 22 -0.420   1.900    4.0e-01
## 23 -0.640   5.200    7.5e-02
## 24 -1.800   5.200    7.5e-02
## 25  0.270   0.063    8.0e-01
## 26 -0.600   0.400    5.3e-01
## 27  0.390   0.620    4.3e-01
## 28 -0.470   0.620    4.3e-01
## 29 -0.670   0.860    3.5e-01
## 30 -0.940   2.200    3.4e-01
## 31  0.480   2.200    3.4e-01
```