

# Modality effects in a signalling game: Efficiency

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## 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
- trialString: 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: Unique 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
```

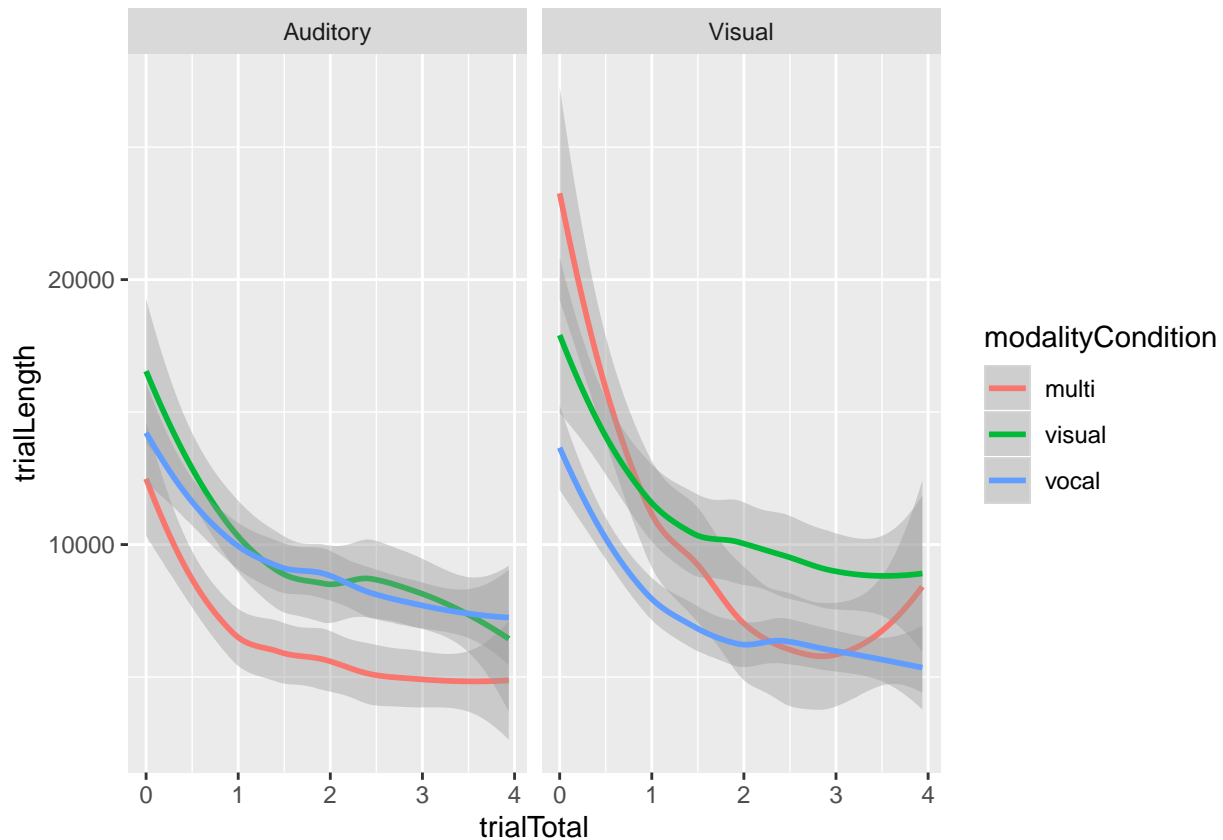
Here is a graph showing the distribution of trial lengths by conditions:

```
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"))

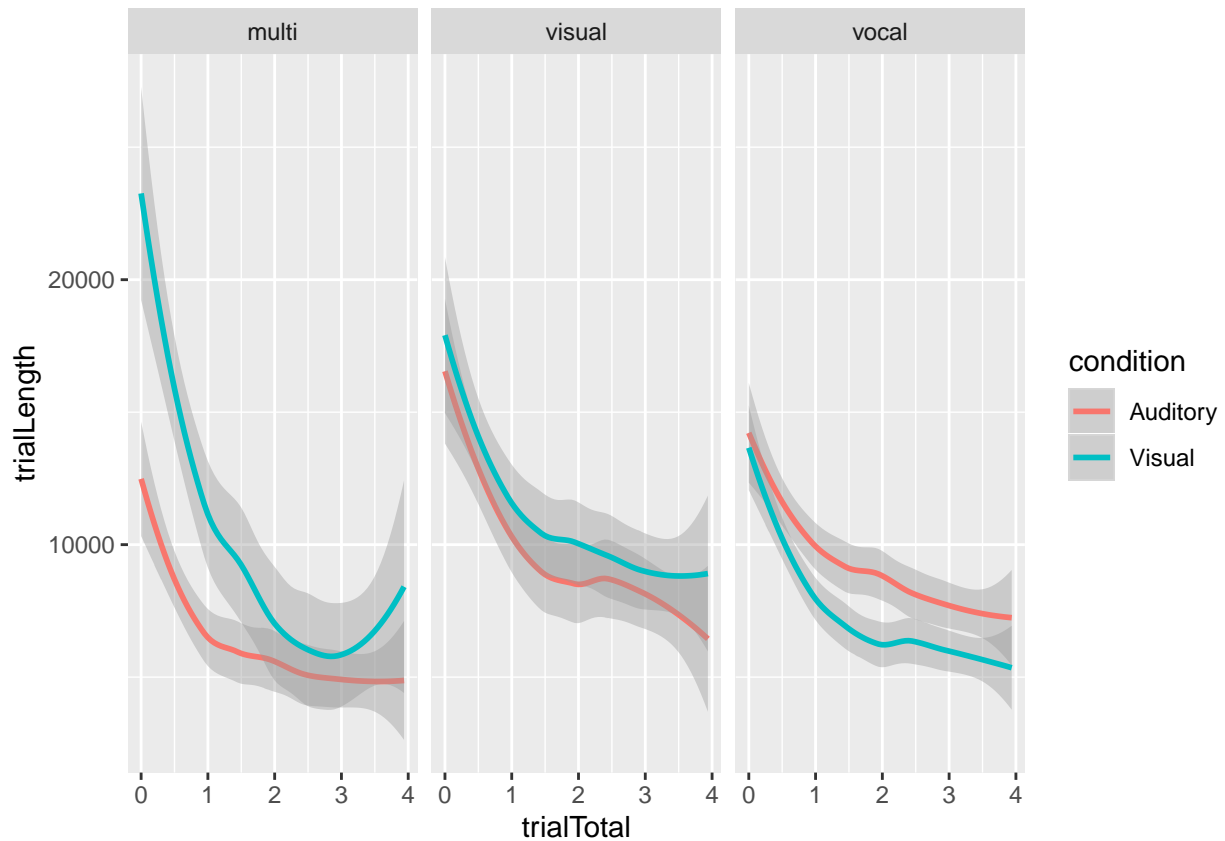
ggplot(d, aes(x=trialTotal, y=trialLength, colour=modalityCondition)) +
  geom_smooth() + facet_grid(.~condition)
```

## `geom\_smooth()` using method = 'loess' and formula 'y ~ x'



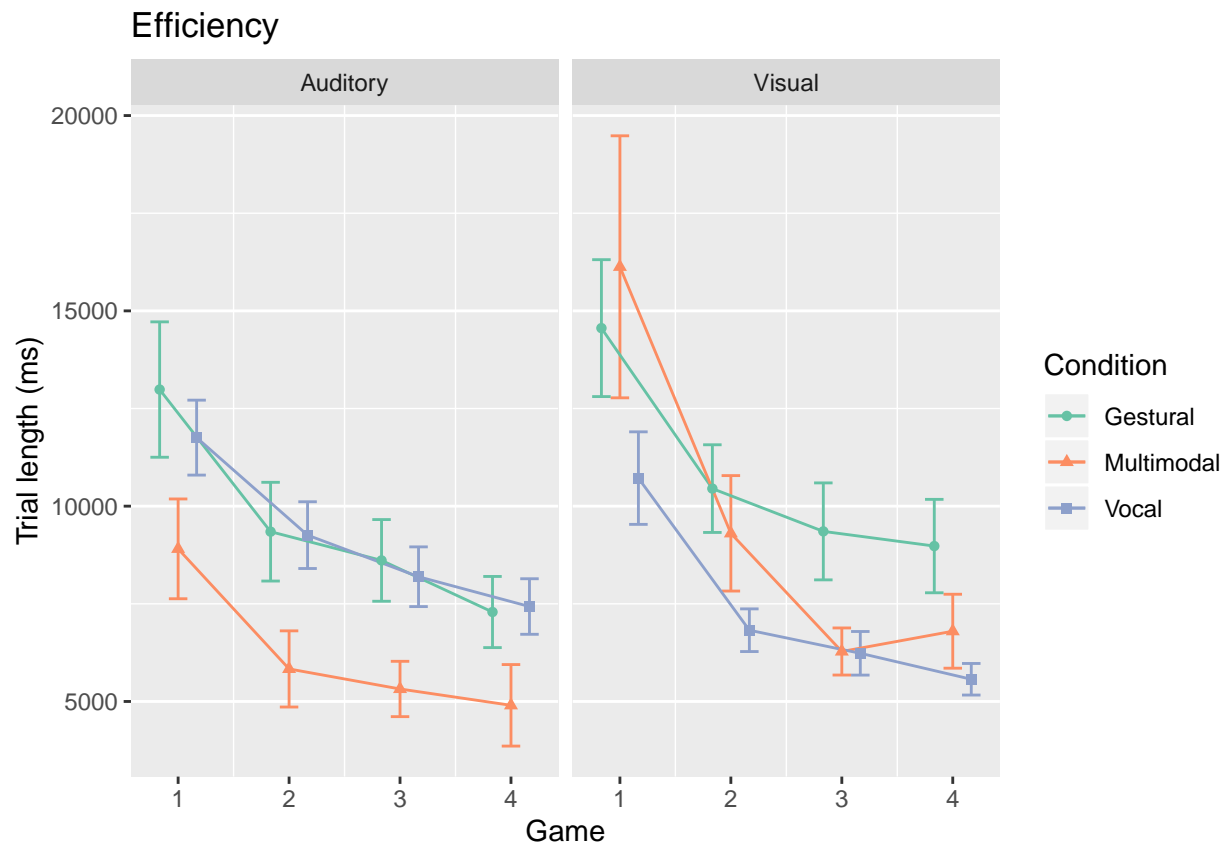
```
ggplot(d, aes(x=trialTotal, y=trialLength, colour=condition)) +
  geom_smooth() + facet_grid(.~modalityCondition)
```

## `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

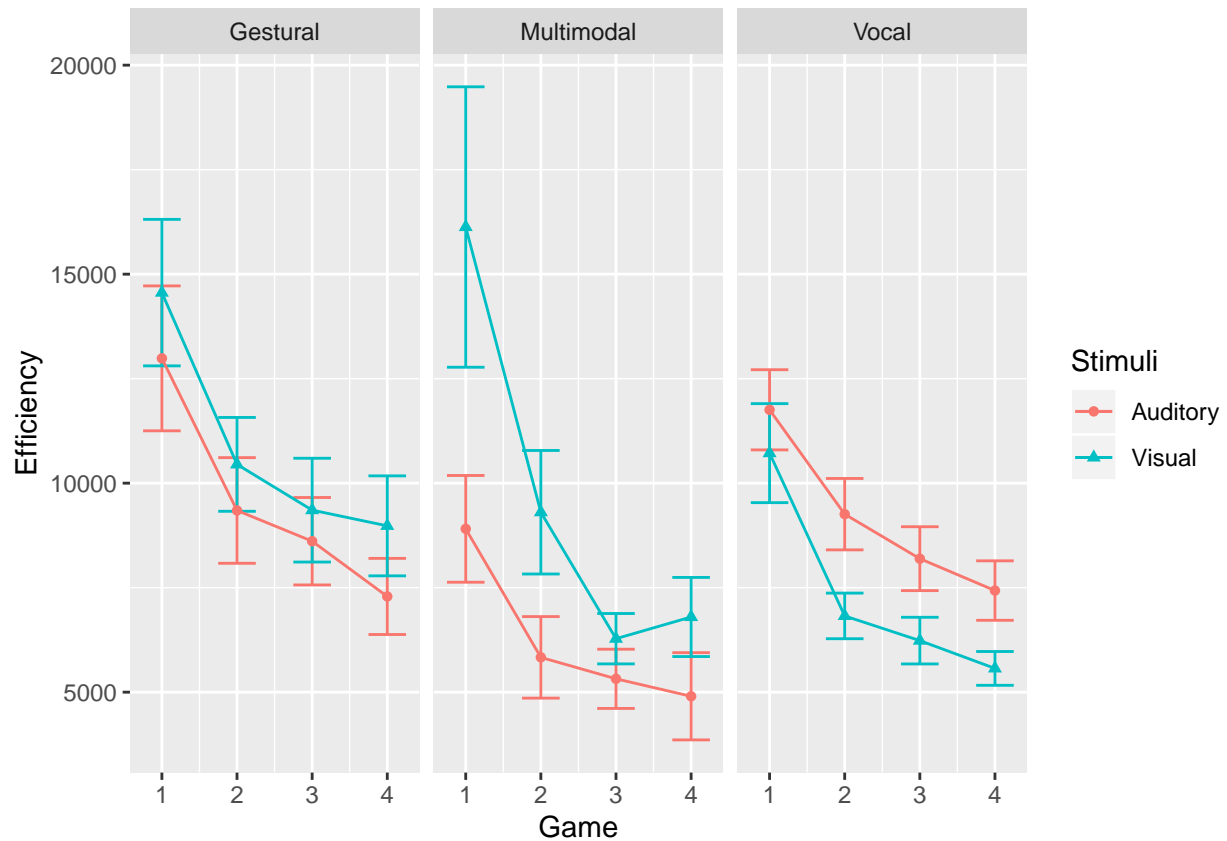


```
pdf("../results/graphs/Efficiency_gg.pdf",
     width = 5, height=3)
gx1
dev.off()

## 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)
```

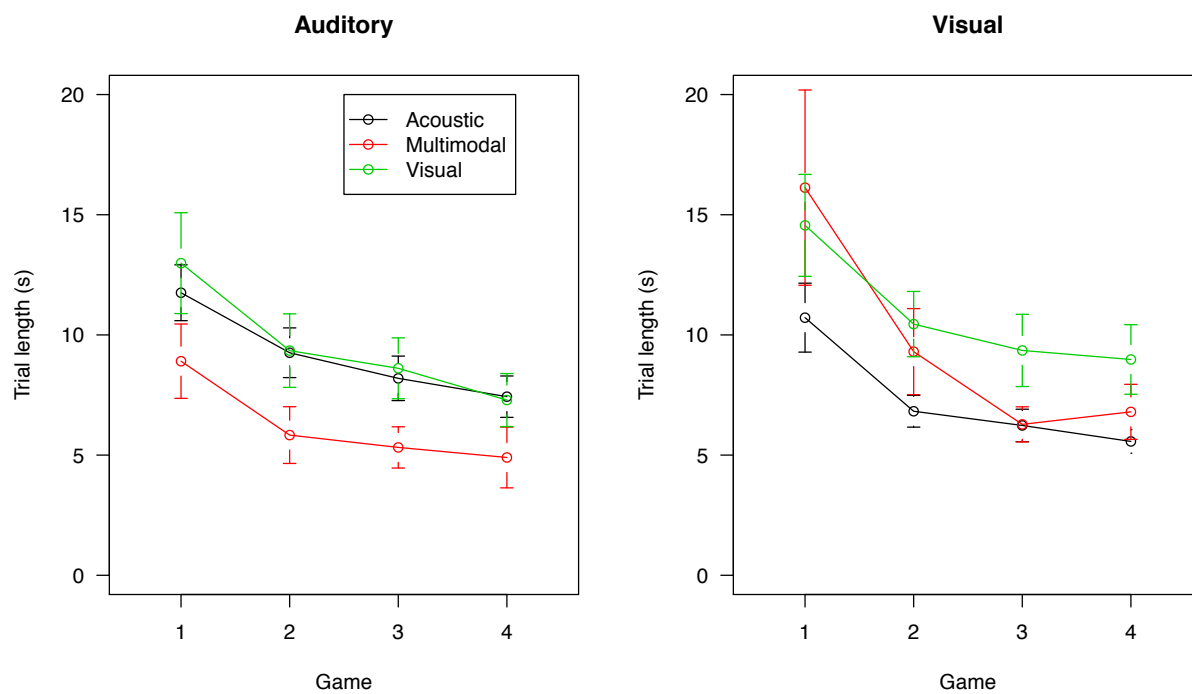
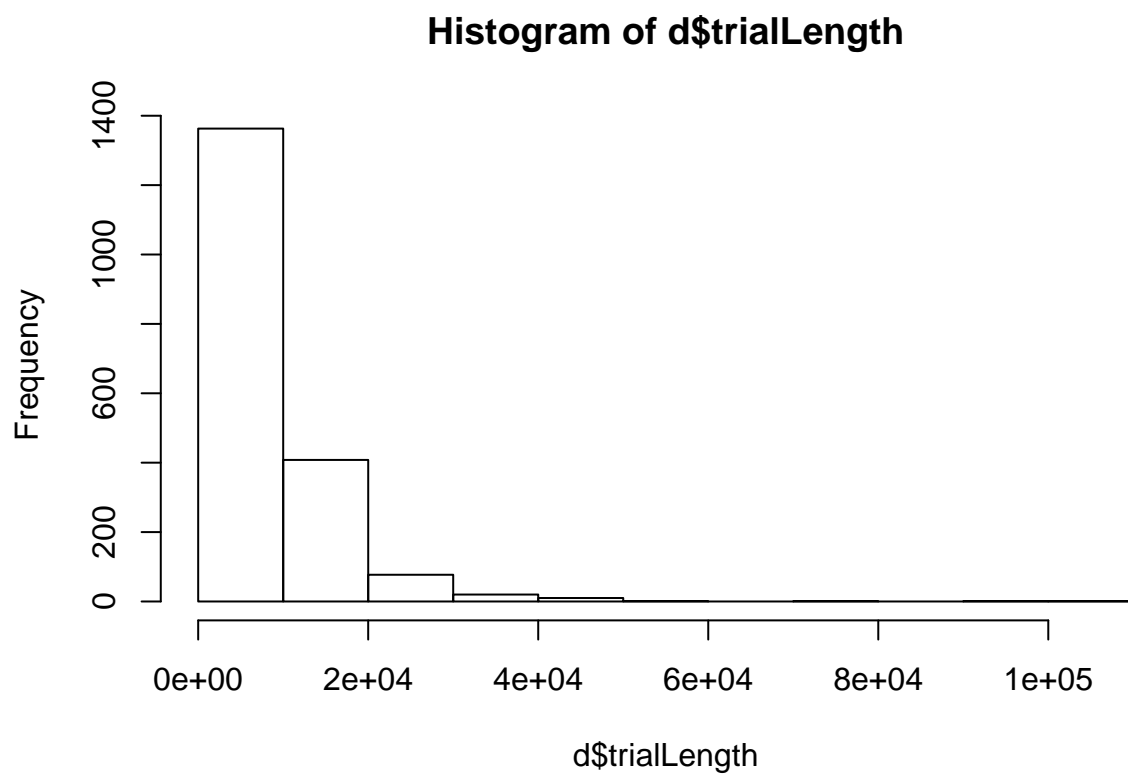


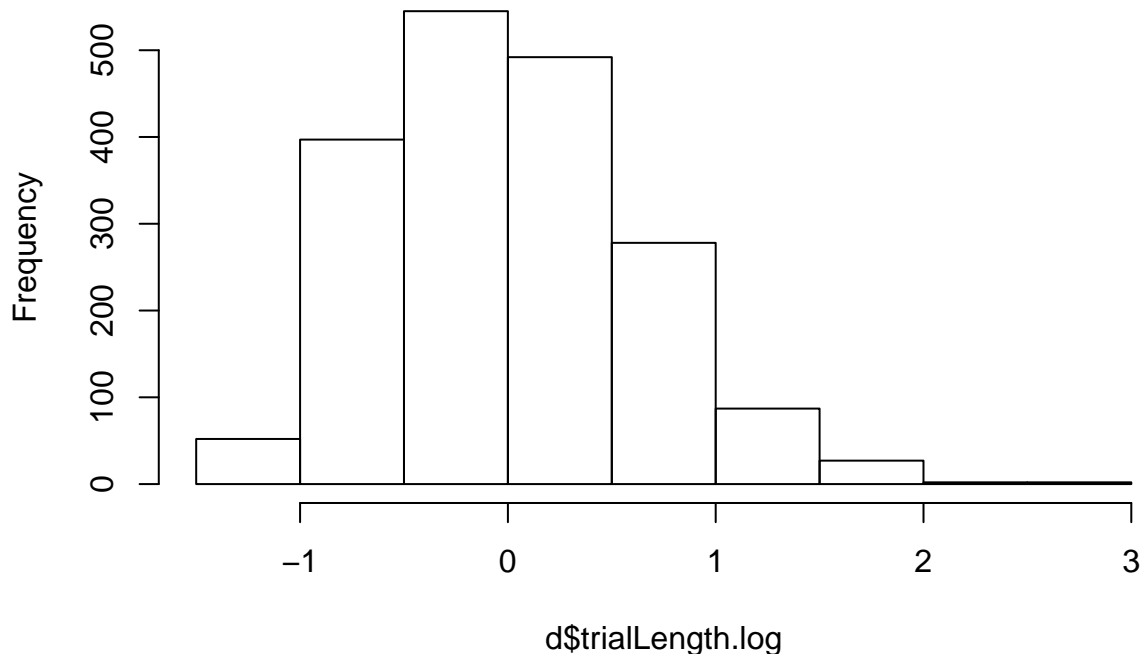
Figure 1: The efficiency of trials in different conditions



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)
```

**Histogram of 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 condition
# Note that the acoustic 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

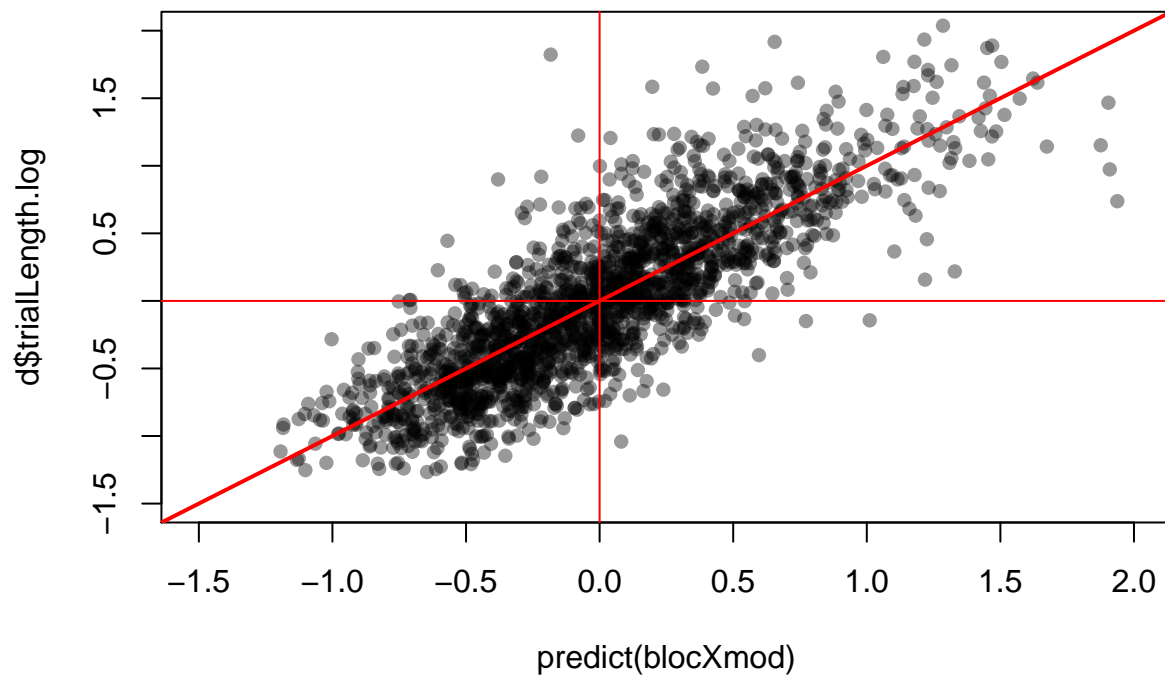
```

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)

```



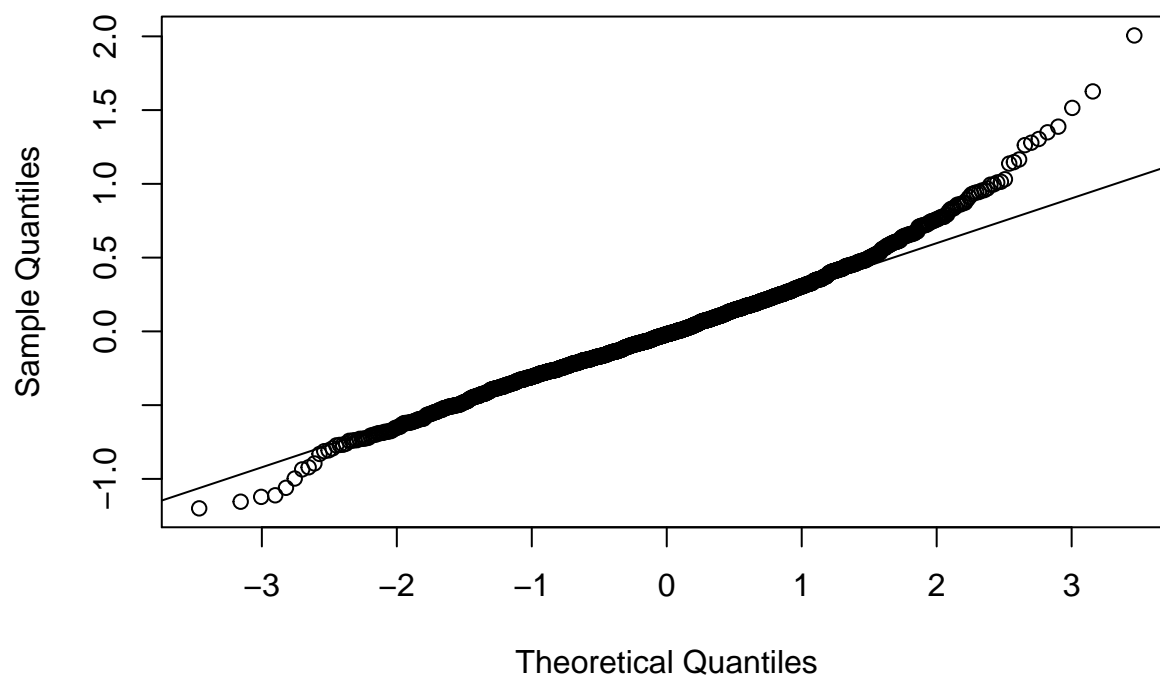
```
cor(predict(finalModel), d$trialLength.log)
```

```
## [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))
```

### Normal Q-Q Plot



## 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", "coXincor",
  "modalityConditionvocal:conditionVisual:incorrectTRUE", "Acoustic modality:Visual stimuli:incorrect", "coXincor",
  "modalityConditionvisual:conditionVisual:numberOfTurns", "VisualModality:Visual stim:NumTurns", "tuXmoXco",
  "modalityConditionvisual:conditionVisual:matcherRespondsTRUE", "VisualModality:Visual stim:Matcher Responds", "tuXmoXco",
  "modalityConditionvocal:conditionVisual:numberOfTurns", "Vocal Modality:Visual stim:NumTurns", "tuXmoXco",
  "modalityConditionvocal:conditionVisual:matcherRespondsTRUE", "Vocal Modality:Visual stim:Matcher Responds", "tuXmoXco",
  "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

```

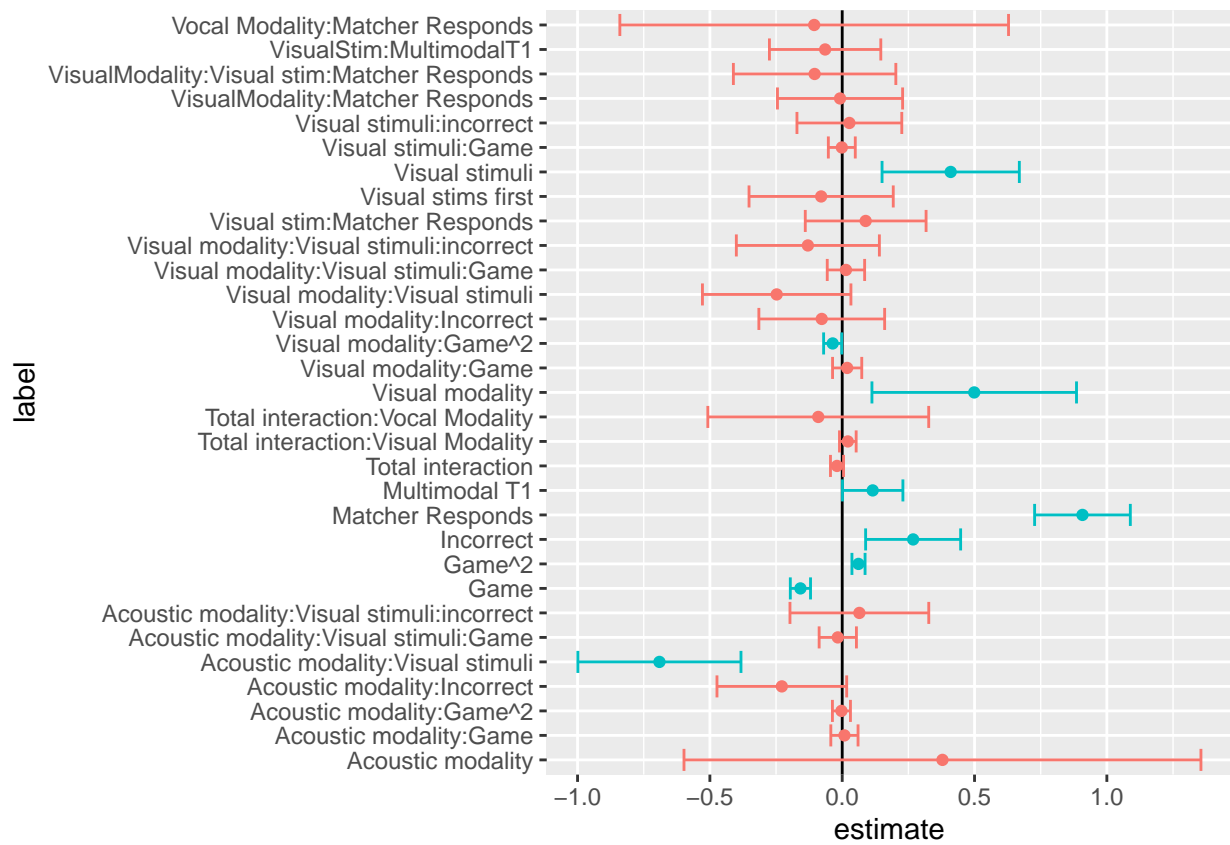
Plot the strength of the fixed effects:

```

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')

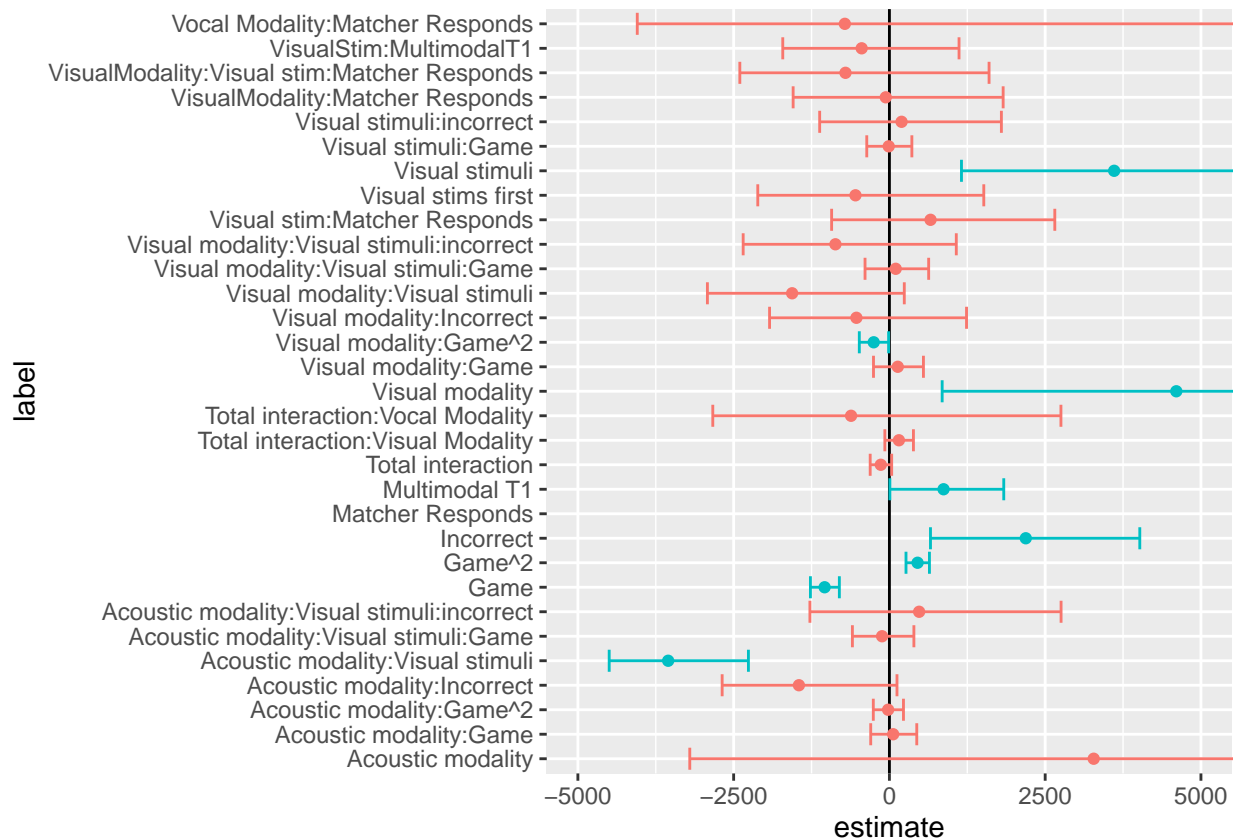
```



Attempt plot with axes in milliseconds.

```
convertEst = function(X){
  exp(meanLogTrialLength+X) - exp(meanLogTrialLength)
}
x$beta = x$estimate
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", "beta", "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", "beta", "estimate", "conf.low",
  "conf.high", "wald.t", "Chisq",
  "Pr(>Chisq)")]

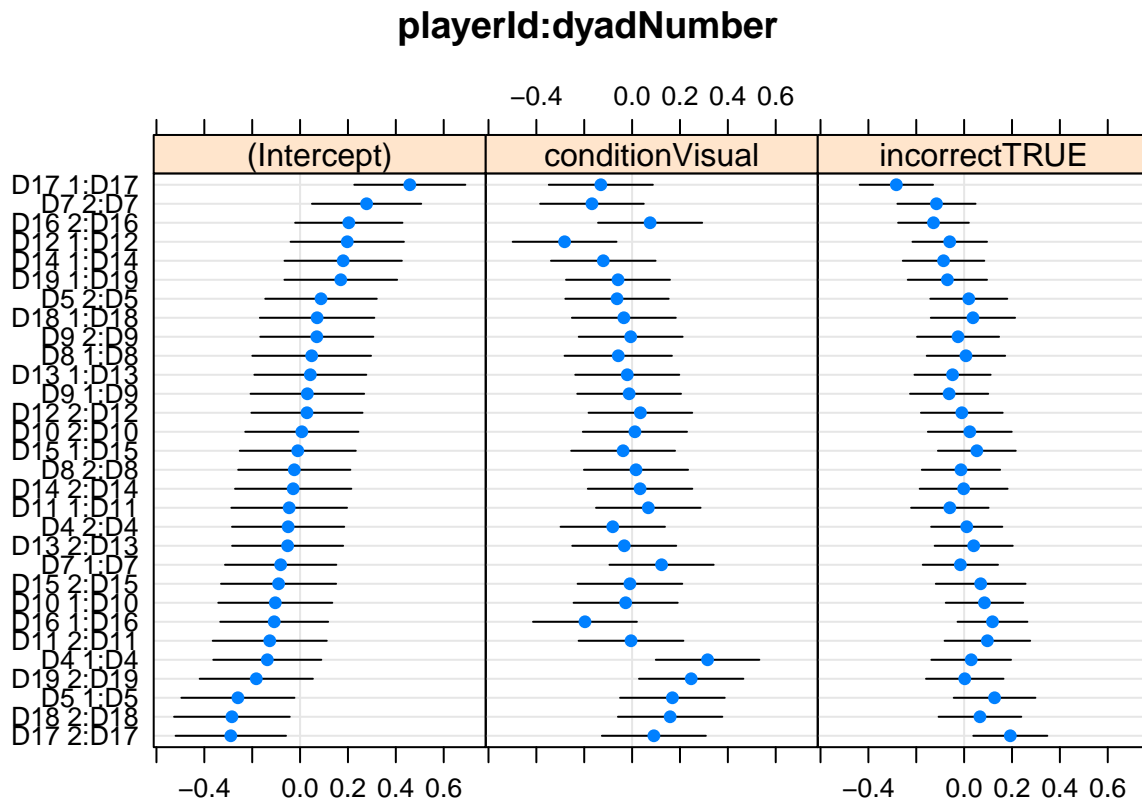
finalRes = outdata
write.csv(finalRes, file="../../results/tables/Efficiency_FixedEffects.csv")
```

## Random effects

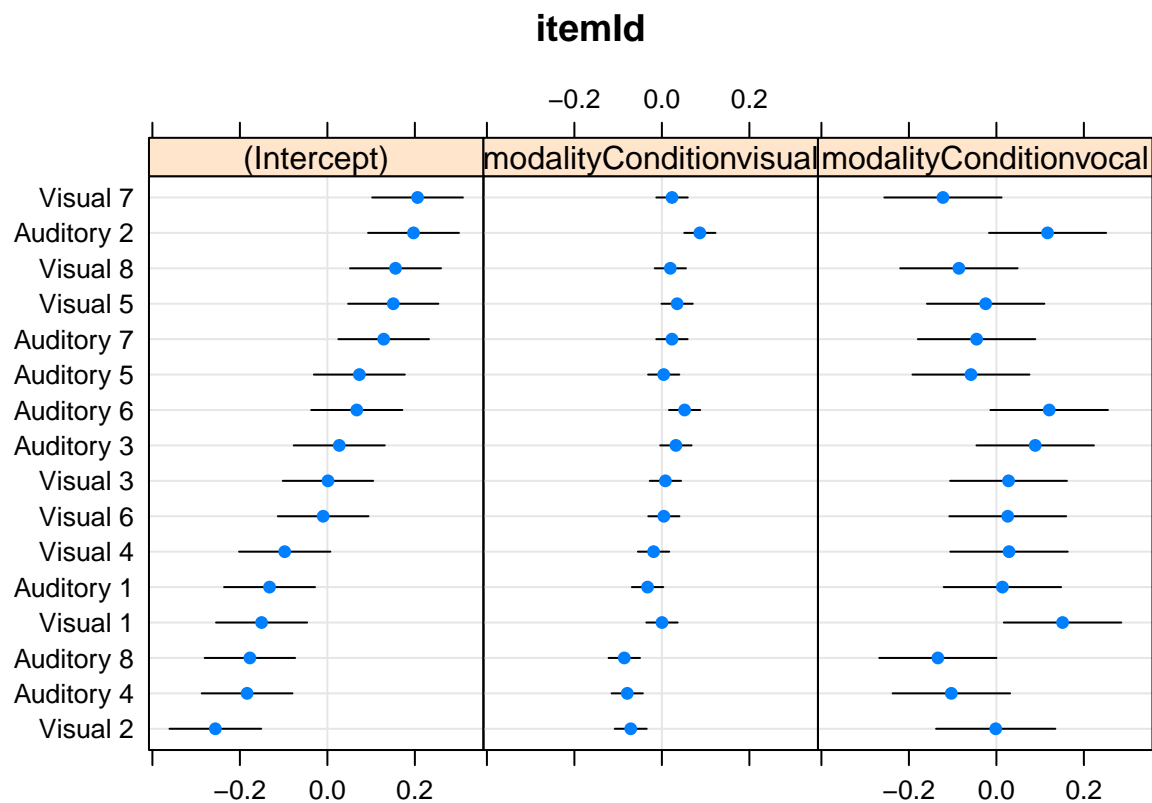
There is a reasonable amount of variation in the random effects, suggesting that dyads and players differ. This justifies the use of mixed effects modelling.

```
dotplot(ranef(finalModel))

## $`playerId:dyadNumber`
```

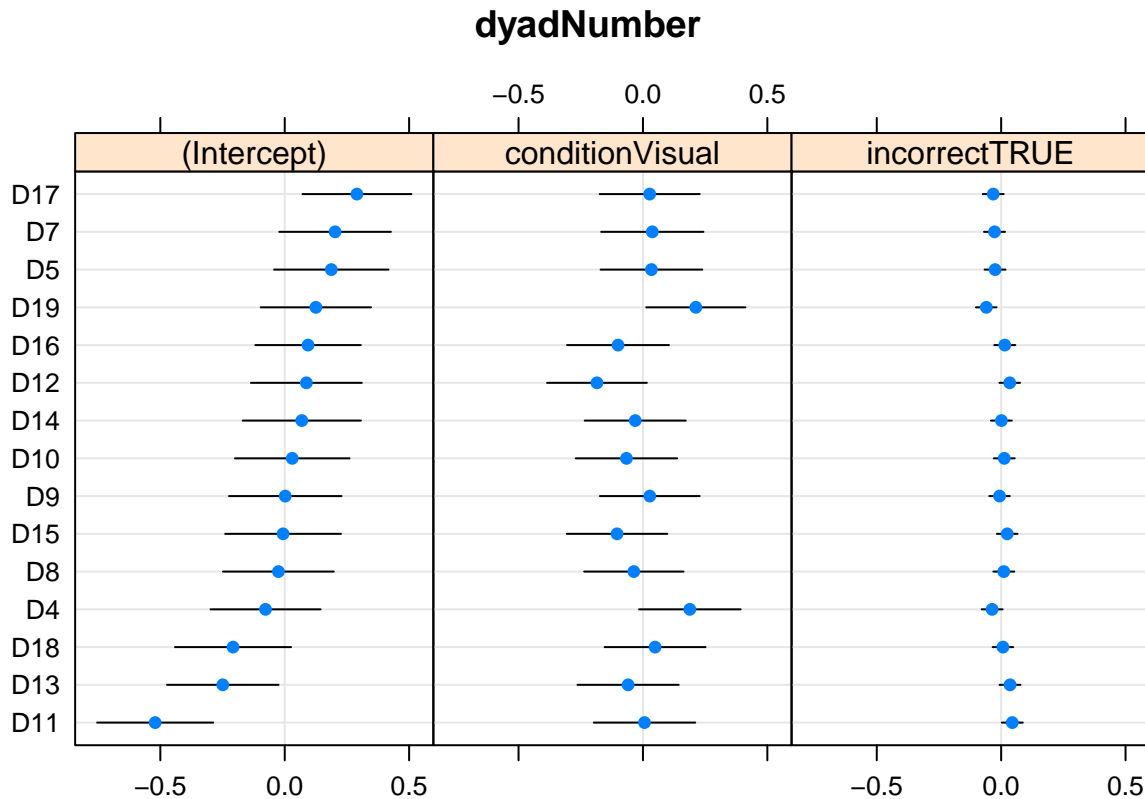


##  
## \$ItemId



##

```
## $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 variance 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 estimate 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

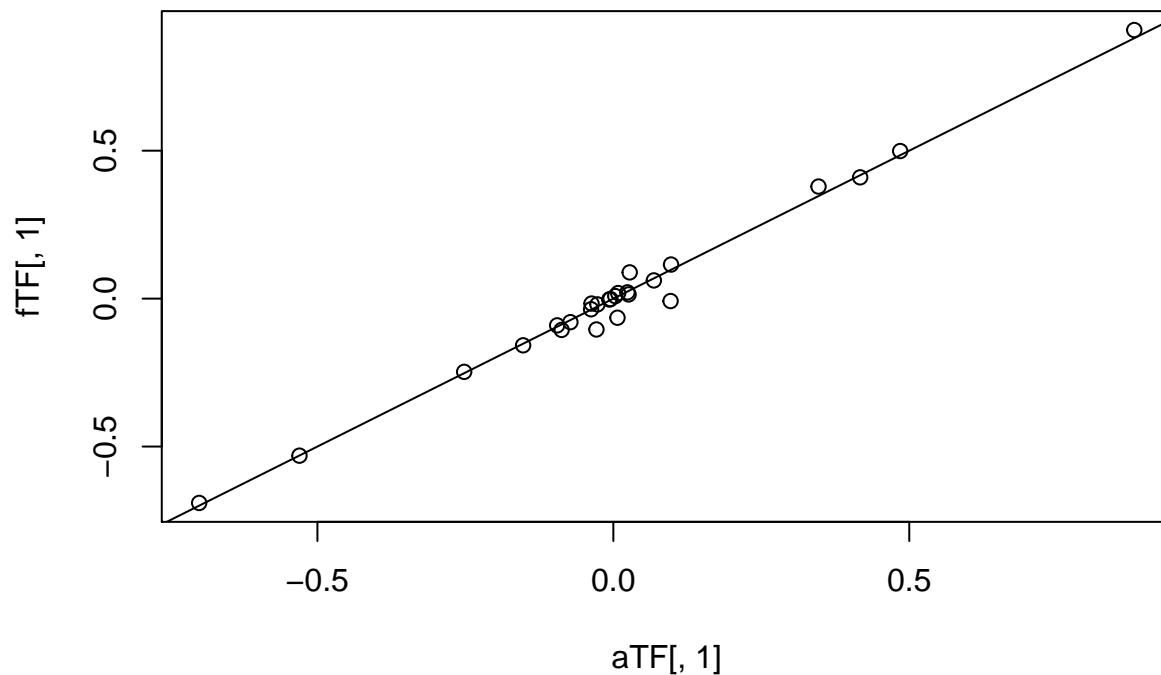
### Model for only accurate trials

```
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.

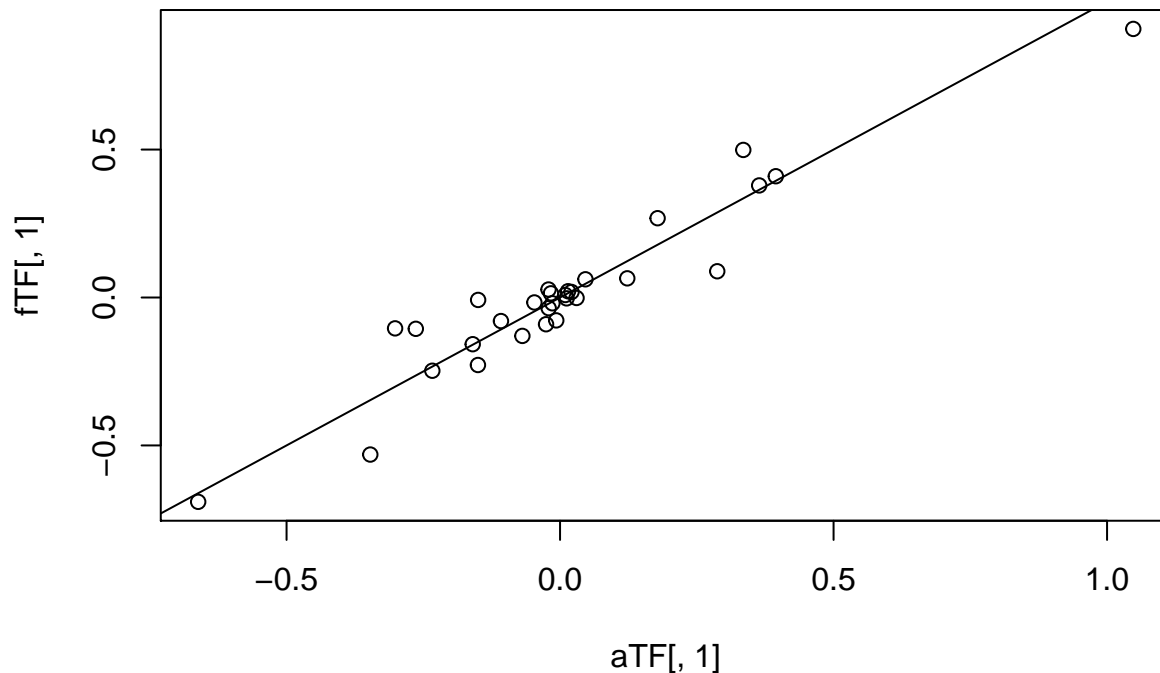
## Model for only multimodal trials

```
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)
```



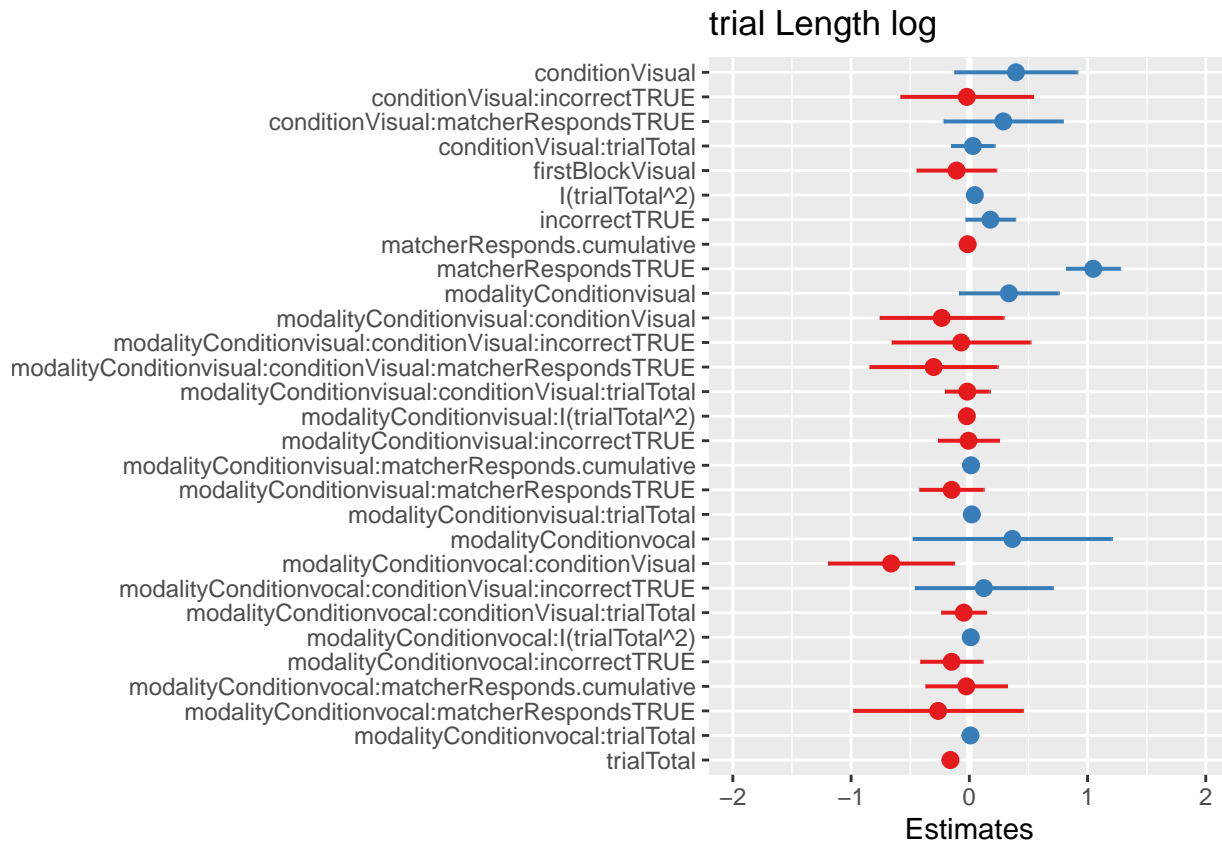
```
# Print large differences in t-value
diffF = abs(aTF[, 't value'] - fTF[, 't value'])
diffFV = names(diffF[diffF > (2 * sd(fixef(finalModel)))]))
round(cbind(all=fTF[diffFV,3],correct=aTF[diffFV,3]),3)
```

##	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
```

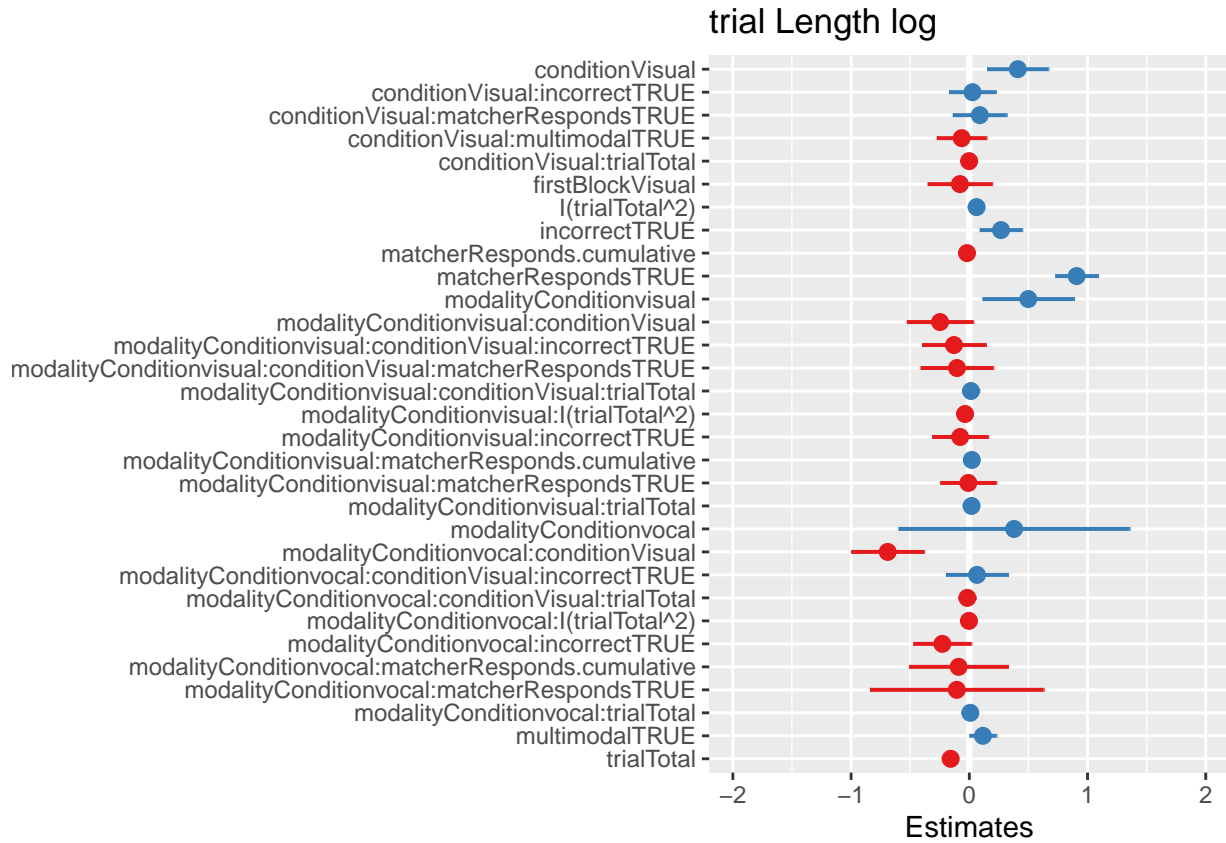
```
plot_model(multTrials,axis.labels = "")
```

```
## 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

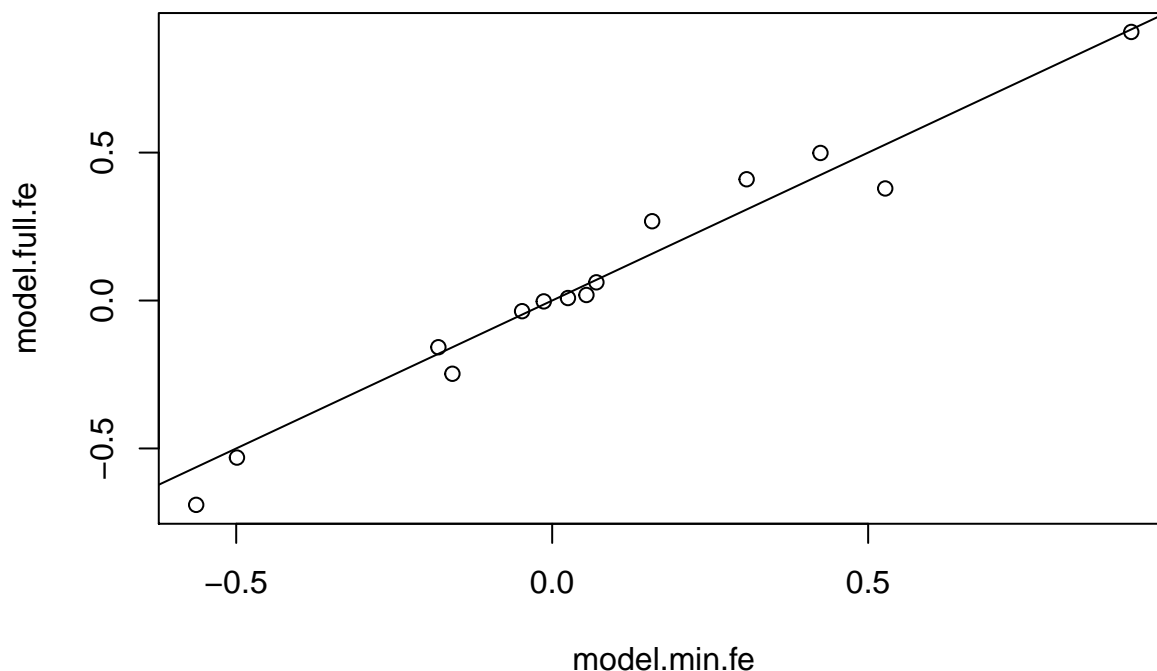
Model including only variables that explained a significant amount of variance according to the model comparison procedure above.

```
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 results for the minimal model are the same or stronger:

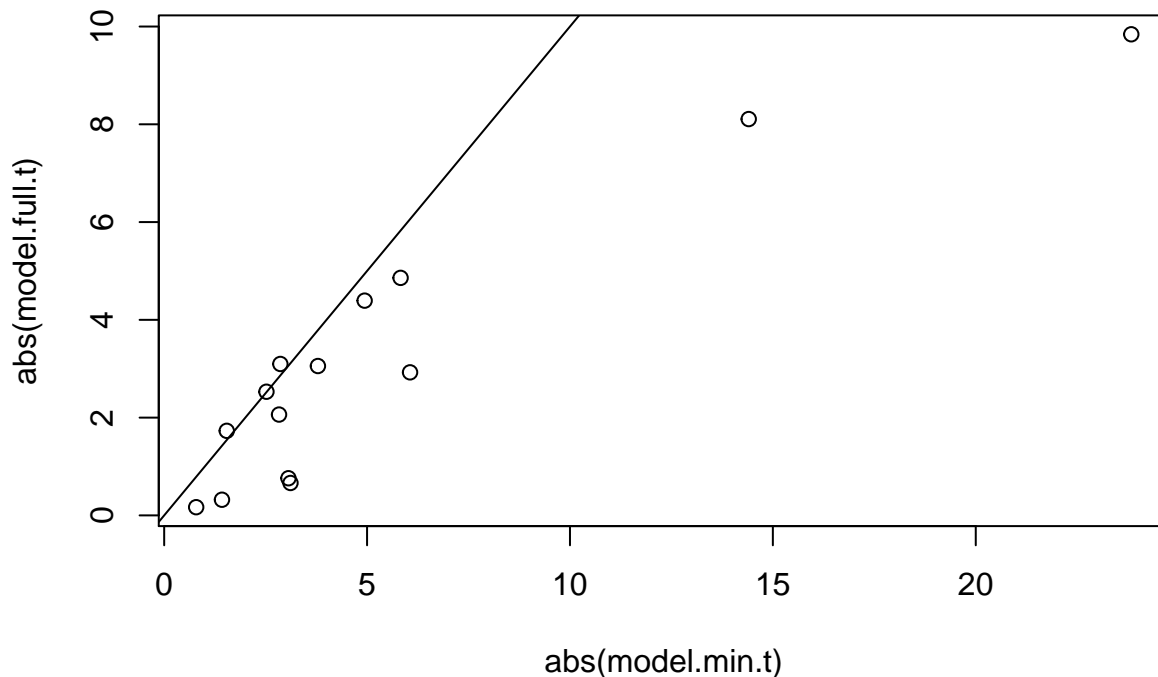
```
getTval = function(X){summary(X)$coef[, "t value"]}  
model.min.t = getTval(model.min)
```



```

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

```

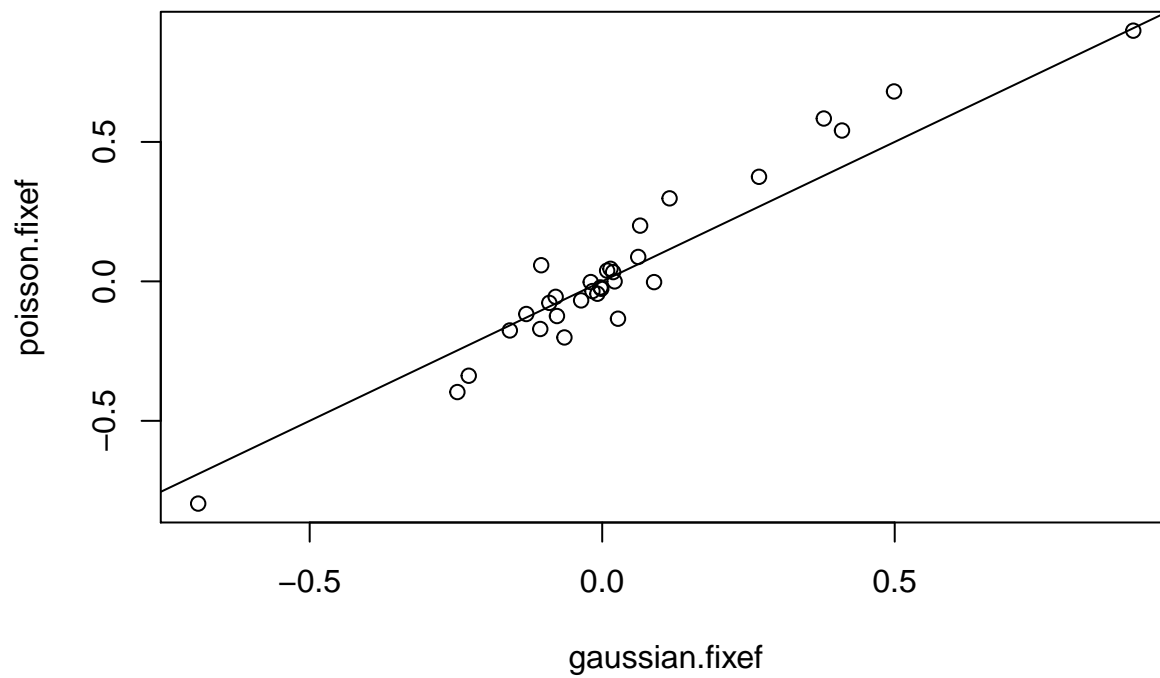
Compare estimates for the two distribution functions (the intercepts will obviously be different, so we ignore those):

```

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

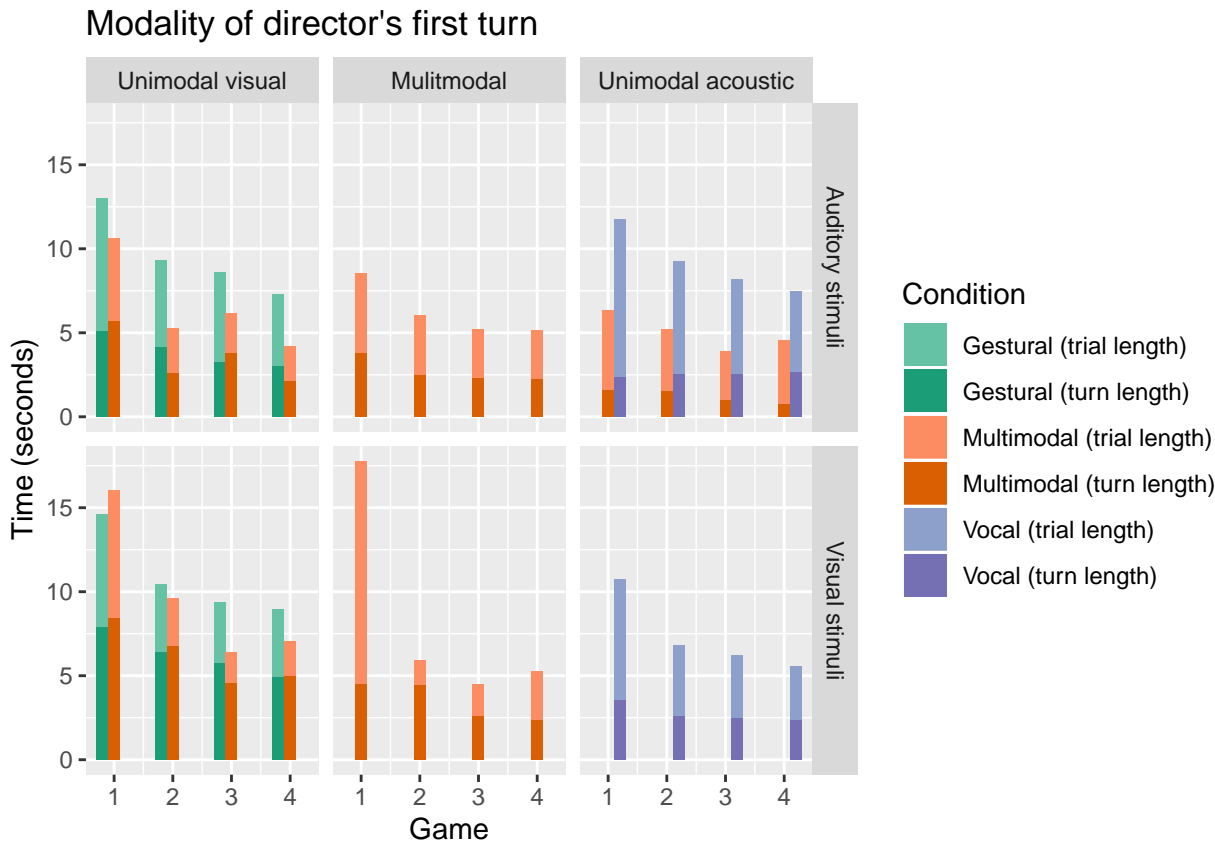
This section compares two values:

- 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. multimodal 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 using Bonferroni correction (multiplying p-value by 5). 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