

1 Analytic Meditation vs. Mindfulness Meditation an EEG analysis of monastic meditation
2 practices

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Abstract

9
10 Analytic meditation is commonly practiced by Tibetan Buddhist monks. This consists of two
11 meditation practices: monastic debate and self-debate. These meditation practices are very
12 different from mindfulness meditation in their practice and goal(s). Little is known how
13 these meditation practices compare based on their associated EEG data. This so we can see
14 if there is overlap in cognitive processes between these meditation practices. We found
15 significant differences between monastic debate and self-debate, mindfulness for mid-occipital
16 9-14 Hz alpha, over time. For mid-frontal 4-9 Hz theta we did not find any significant
17 differences between these meditation practices, apart from (partially) 1/2 monastic debate
18 conditions, over time. Furthermore, we found significant differences in the frontal and
19 occipital areas for alpha, based on average power over time. This study gives novel insight
20 into how analytic meditation and mindfulness meditation compare, based on their associated
21 EEG data.

22 *Keywords:* meditation, eeg, debate

23 Word count: X

Analytic Meditation vs. Mindfulness Meditation an EEG analysis of monastic meditation practices

```
# Seed for random number generation
#set.seed(42)
#knitr::opts_chunk$set(cache.extra = knitr::rand_seed)
figDir <- "/Users/roydavid/Documents/FYRP/latex/figs/"
```

Methods

We report how we determined our sample size, all data exclusions (if any), all manipulations, and all measures in the study.

Data analysis

We used R [Version 4.1.1; R Core Team (2021)] for all our analyses.

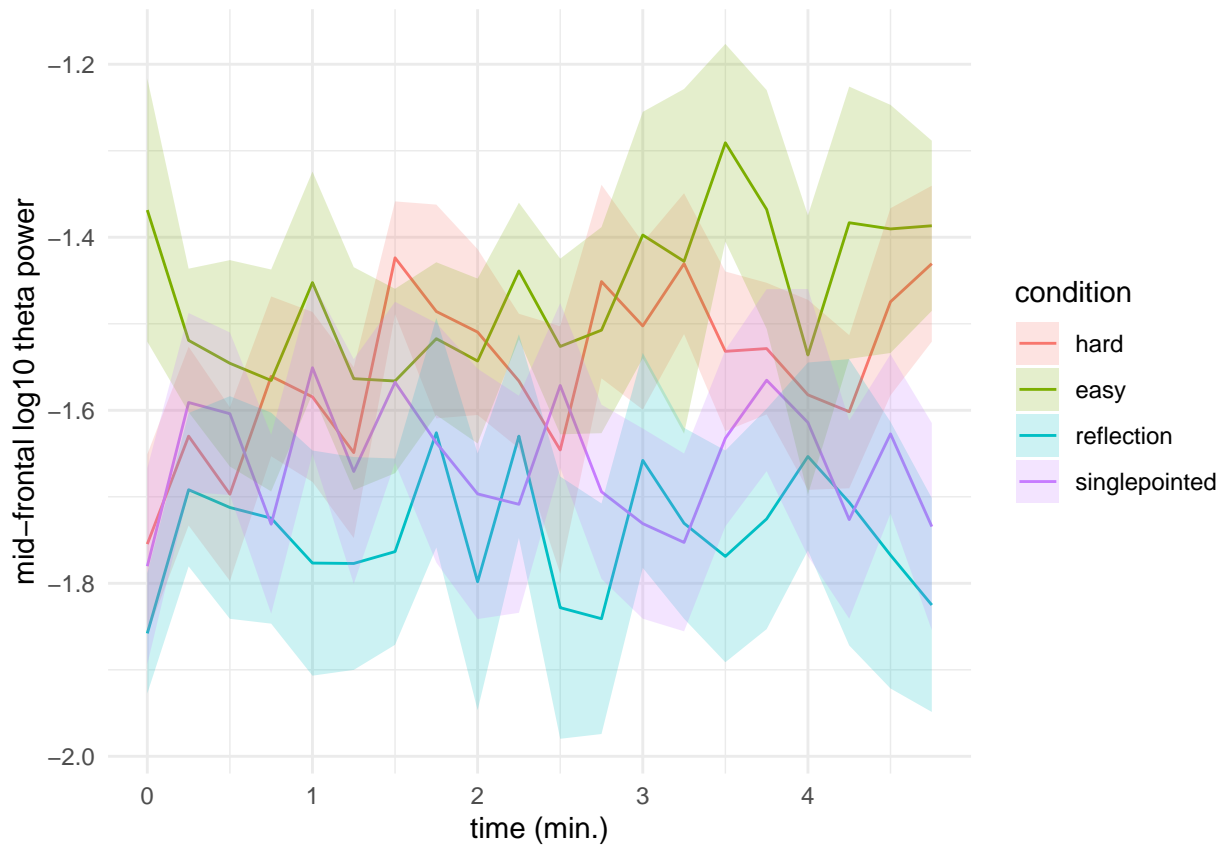
Results

```
# load data generated by continousFreqAnalysis.m
#setwd("/Users/roydavid/Downloads/Monks/")

EEG_theta_data <- read.csv(file = 'powspecAllChannelsTheta.csv')
names(EEG_theta_data) <- c("subj", "condition", "channel", "thetaPow", "time")
EEG_theta_data <- EEG_theta_data[complete.cases(EEG_theta_data),]
EEG_theta_data$subj <- as.factor(EEG_theta_data$subj)
EEG_theta_data$condition <- as.factor(EEG_theta_data$condition)
levels(EEG_theta_data$condition) <- c("hard", "easy", "reflection", "singlepointed")
EEG_theta_data <- EEG_theta_data[EEG_theta_data$time<=4.75,]
# subset mid-frontal theta
```

```
MFtheta <- EEG_theta_data[EEG_theta_data$channel==31,] # Fz
MFtheta_time_average <- ddply(MFtheta, c("time", "condition"), summarise,
                               meanPow = mean(thetaPow, na.rm=TRUE),
                               SE = se(thetaPow, na.rm=TRUE))

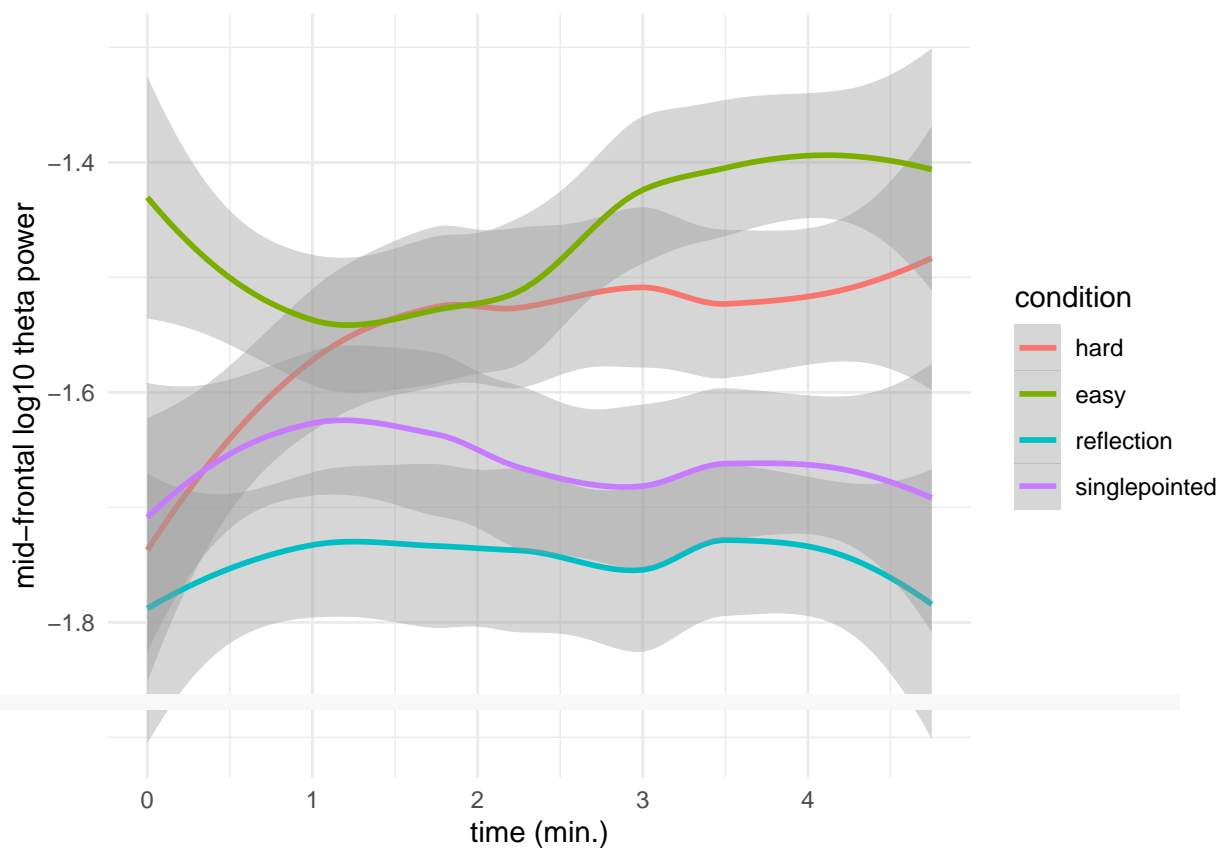
# plot mean mid-frontal theta power over time per condition
ggplot(MFtheta_time_average, aes(x=time, y=meanPow,
                                ymax=meanPow+SE, ymin=meanPow-SE,
                                group=condition)) +
  geom_line(aes(color=condition)) +
  geom_ribbon(alpha = 0.2, aes(fill=condition)) +
  labs(y='mid-frontal log10 theta power', x="time (min.)") +
  theme_minimal()
```



```

ggsave(file="/Users/roydavid/Documents/FYRP/latex/figs/FzTheta_avg_time.pdf", width=7, h
# with loess
ggplot(MFtheta_time_average, aes(x=time, y=meanPow, color=condition)) +
  geom_smooth(method='loess') +
  labs(y='mid-frontal log10 theta power', x="time (min.)") +
  guides(color=guide_legend(title="condition")) +
  theme_minimal()

```



```
# mid-frontal theta GAMM analysis
```

```
# random intercepts
```

```
MFtheta.g1 <- bam(thetaPow ~ condition + s(time, by=condition) + s(subj,bs="re"), data=M
summary(MFtheta.g1)
```

Mid-frontal theta.

```
##
```

```
## Family: gaussian
```

```
## Link function: identity
```

```
##
```

```
## Formula:
```

```
## thetaPow ~ condition + s(time, by = condition) + s(subj, bs = "re")
```

```
##
```

```
## Parametric coefficients:
```

```
##           Estimate Std. Error t value Pr(>|t|)
```

```
## (Intercept)      -1.55204    0.06708 -23.136 < 2e-16 ***
```

```
## conditioneasy      0.08733    0.03063   2.851 0.004454 **
```

```
## conditionreflection -0.19109    0.03063  -6.239 6.67e-10 ***
```

```
## conditionsinglepointed -0.10737    0.03063  -3.505 0.000478 ***
```

```
## ---
```

```
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

```
##
```

```
## Approximate significance of smooth terms:
```

```
##           edf Ref.df      F p-value
```

```

53 ## s(time):conditionhard      1.631  2.025  3.161  0.0439 *
54 ## s(time):conditioneasy      1.251  1.460  3.051  0.0913 .
55 ## s(time):conditionreflection 1.000  1.000  0.021  0.8835
56 ## s(time):conditionsinglepointed 1.000  1.000  0.088  0.7663
57 ## s(subj)                    10.689 11.000 34.372 <2e-16 ***
58 ## ---
59 ## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
60 ##
61 ## R-sq.(adj) =  0.332   Deviance explained = 34.5%
62 ## fREML = 353.32   Scale est. = 0.11259   n = 960

# random slopes
MFtheta.g2 <- bam(thetaPow ~ condition + s(time, by=condition) + s(subj,bs="re") +
                  s(subj,condition,bs="re"), data=MFtheta)
summary(MFtheta.g2)

63 ##
64 ## Family: gaussian
65 ## Link function: identity
66 ##
67 ## Formula:
68 ## thetaPow ~ condition + s(time, by = condition) + s(subj, bs = "re") +
69 ##      s(subj, condition, bs = "re")
70 ##
71 ## Parametric coefficients:
72 ##              Estimate Std. Error t value Pr(>|t|)
73 ## (Intercept)   -1.55204    0.09050 -17.149  <2e-16 ***
74 ## conditioneasy    0.08733    0.10382   0.841   0.401

```

```

75 ## conditionreflection      -0.19109      0.10382  -1.841      0.066 .
76 ## conditionsinglepointed -0.10737      0.10382  -1.034      0.301
77 ## ---
78 ## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
79 ##
80 ## Approximate significance of smooth terms:
81 ##
82 ##          edf Ref.df      F  p-value
83 ## s(time):conditionhard      2.113   2.635   4.591 0.008249 **
84 ## s(time):conditioneasy      2.153   2.684   3.271 0.037939 *
85 ## s(time):conditionreflection  1.000   1.000   0.035 0.851952
86 ## s(time):conditionsinglepointed 1.000   1.000   0.143 0.705070
87 ## s(subj)                    7.427 11.000 487.763 0.000451 ***
88 ## s(subj,condition)          34.610 44.000  67.112 0.053418 .
89 ## ---
90 ## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
91 ##
92 ## R-sq.(adj) =  0.588   Deviance explained =  61%
93 ## fREML = 175.39   Scale est. = 0.069437   n = 960
94 ##
95 ## compareML(MFtheta.g1,MFtheta.g2)
96 ##
97 ## MFtheta.g1: thetaPow ~ condition + s(time, by = condition) + s(subj, bs = "re")
98 ##
99 ## MFtheta.g2: thetaPow ~ condition + s(time, by = condition) + s(subj, bs = "re") +
100 ##      s(subj, condition, bs = "re")
101 ##
102 ## Warning in sprintf("***", h1): one argument not used by format '***'
103 ##

```



```

99  ## Chi-square test of fREML scores
100 ## -----
101 ##           Model      Score Edf Difference    Df  p.value Sig.
102 ## 1 MFtheta.g1 353.3174   13
103 ## 2 MFtheta.g2 175.3866   14      177.931 1.000 < 2e-16 ***
104 ##
105 ## AIC difference: 429.45, model MFtheta.g2 has lower AIC.

# factor smooths
MFtheta.g3 <- bam(thetaPow ~ condition + s(time, by=condition) + s(subj,condition,bs="re
              s(time,subj,bs="fs",m=1), data=MFtheta)
summary(MFtheta.g3)

106 ##
107 ## Family: gaussian
108 ## Link function: identity
109 ##
110 ## Formula:
111 ## thetaPow ~ condition + s(time, by = condition) + s(subj, condition,
112 ##      bs = "re") + s(time, subj, bs = "fs", m = 1)
113 ##
114 ## Parametric coefficients:
115 ##              Estimate Std. Error t value Pr(>|t|)
116 ## (Intercept)      -1.55204     0.09050 -17.149  <2e-16 ***
117 ## conditioneasy       0.08733     0.10382   0.841   0.401
118 ## conditionreflection -0.19109     0.10382  -1.841   0.066 .
119 ## conditionsinglepointed -0.10737     0.10382  -1.034   0.301
120 ## ---

```

```
121 ## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

```
122 ##
```

```
123 ## Approximate significance of smooth terms:
```

```
124 ##                edf  Ref.df      F  p-value
```

```
125 ## s(time):conditionhard      2.113    2.635  4.591 0.008249 **
```

```
126 ## s(time):conditioneasy      2.153    2.684  3.271 0.037939 *
```

```
127 ## s(time):conditionreflection 1.000    1.000  0.035 0.851951
```

```
128 ## s(time):conditionsinglepointed 1.000    1.000  0.143 0.705068
```

```
129 ## s(subj,condition)          34.610   44.000 13.333 < 2e-16 ***
```

```
130 ## s(time,subj)              7.427 107.000 50.144 0.000451 ***
```

```
131 ## ---
```

```
132 ## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

```
133 ##
```

```
134 ## R-sq.(adj) =  0.588   Deviance explained =  61%
```

```
135 ## fREML = 175.39   Scale est. = 0.069437   n = 960
```

```
compareML(MFtheta.g2,MFtheta.g3)
```

```
136 ## MFtheta.g2: thetaPow ~ condition + s(time, by = condition) + s(subj, bs = "re") +
```

```
137 ##      s(subj, condition, bs = "re")
```

```
138 ##
```

```
139 ## MFtheta.g3: thetaPow ~ condition + s(time, by = condition) + s(subj, condition,
```

```
140 ##      bs = "re") + s(time, subj, bs = "fs", m = 1)
```

```
141 ##
```

```
142 ## Model MFtheta.g2 preferred: lower fREML score (0.000), and lower df (1.000).
```

```
143 ## -----
```

```
144 ##           Model      Score Edf Difference      Df
```

```
145 ## 1 MFtheta.g3 175.3866  15
```

```

146 ## 2 MFtheta.g2 175.3866 14      0.000 -1.000
147 ##
148 ## AIC difference: -0.00, model MFtheta.g2 has lower AIC.
149 ## Warning in compareML(MFtheta.g2, MFtheta.g3): Only small difference in fREML...

# model power by condition
# smooth over time by condition
# factor smooth over time for each subject by condition:
# (potential) nonlinear difference over time wrt the general pattern for each subject
# by condition

MFtheta.g4 <- bam(thetaPow ~ condition + s(time, by=condition) +
                  s(time,subj,by=condition,bs="fs",m=1),
                  data=MFtheta)

150 ## Warning in gam.side(sm, X, tol = .Machine$double.eps^0.5): model has repeated 1-
151 ## d smooths of same variable.

summary(MFtheta.g4)

152 ##
153 ## Family: gaussian
154 ## Link function: identity
155 ##
156 ## Formula:
157 ## thetaPow ~ condition + s(time, by = condition) + s(time, subj,
158 ##      by = condition, bs = "fs", m = 1)
159 ##
160 ## Parametric coefficients:
161 ##              Estimate Std. Error t value Pr(>|t|)

```

```

162 ## (Intercept)          -1.55204    0.07088 -21.896   <2e-16 ***
163 ## conditioneasy        0.08733    0.11907   0.733     0.464
164 ## conditionreflection  -0.19109    0.12778  -1.495     0.135
165 ## conditionsinglepointed -0.10737    0.11094  -0.968     0.333
166 ## ---
167 ## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
168 ##
169 ## Approximate significance of smooth terms:
170 ##
171 ## s(time):conditionhard      2.253    2.807 4.989 0.00418 **
172 ## s(time):conditioneasy      1.207    1.289 0.443 0.65518
173 ## s(time):conditionreflection 1.000    1.000 0.017 0.89775
174 ## s(time):conditionsinglepointed 1.000    1.000 0.068 0.79392
175 ## s(time,subj):conditionhard 10.440 107.000 1.918 < 2e-16 ***
176 ## s(time,subj):conditioneasy 45.130 107.000 4.419 < 2e-16 ***
177 ## s(time,subj):conditionreflection 22.083 107.000 4.607 < 2e-16 ***
178 ## s(time,subj):conditionsinglepointed 20.084 107.000 2.952 < 2e-16 ***
179 ## ---
180 ## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
181 ##
182 ## R-sq.(adj) = 0.636   Deviance explained = 67.6%
183 ## fREML = 161.26   Scale est. = 0.061353   n = 960

```

```
compareML(MFtheta.g2,MFtheta.g4)
```

```

184 ## MFtheta.g2: thetaPow ~ condition + s(time, by = condition) + s(subj, bs = "re") +
185 ##      s(subj, condition, bs = "re")
186 ##

```

```

187 ## MFtheta.g4: thetaPow ~ condition + s(time, by = condition) + s(time, subj,
188 ##      by = condition, bs = "fs", m = 1)

189 ## Warning in sprintf("***", h1): one argument not used by format '***'

190 ##

191 ## Chi-square test of fREML scores

192 ## -----

193 ##           Model      Score Edf Difference    Df   p.value Sig.
194 ## 1 MFtheta.g2 175.3866   14
195 ## 2 MFtheta.g4 161.2591   20      14.128 6.000 8.412e-05  ***
196 ##

197 ## AIC difference: 62.50, model MFtheta.g4 has lower AIC.

compareML(MFtheta.g3,MFtheta.g4)

198 ## MFtheta.g3: thetaPow ~ condition + s(time, by = condition) + s(subj, condition,
199 ##      bs = "re") + s(time, subj, bs = "fs", m = 1)

200 ##

201 ## MFtheta.g4: thetaPow ~ condition + s(time, by = condition) + s(time, subj,
202 ##      by = condition, bs = "fs", m = 1)

203 ## Warning in sprintf("***", h1): one argument not used by format '***'

204 ##

205 ## Chi-square test of fREML scores

206 ## -----

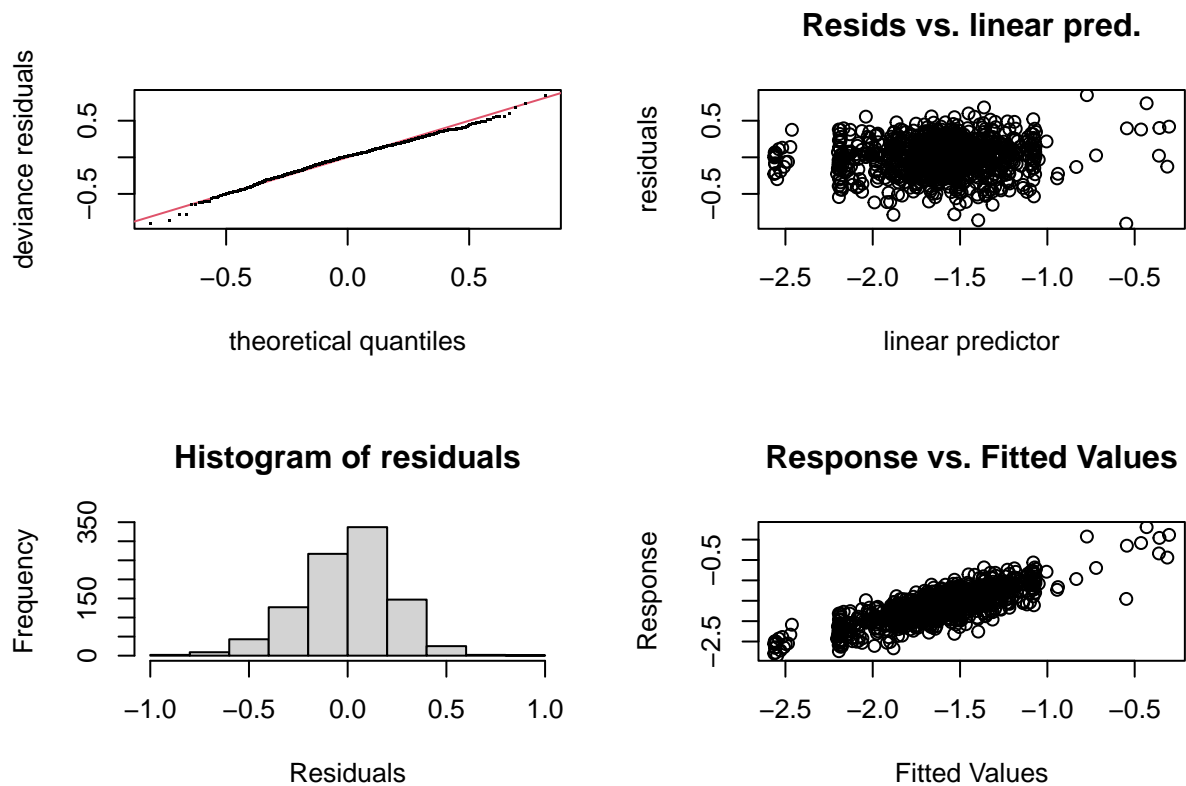
207 ##           Model      Score Edf Difference    Df   p.value Sig.
208 ## 1 MFtheta.g3 175.3866   15
209 ## 2 MFtheta.g4 161.2591   20      14.128 5.000 3.245e-05  ***

```

210 ##

211 ## AIC difference: 62.50, model MFtheta.g4 has lower AIC.

```
par(mfrow=c(2,2))
gam.check(MFtheta.g4)
```



212

213 ##

214 ## Method: fREML Optimizer: perf newton

215 ## full convergence after 13 iterations.

216 ## Gradient range $[-1.788331e-06, 2.279423e-06]$

217 ## (score 161.2591 & scale 0.06135305).

218 ## Hessian positive definite, eigenvalue range $[1.139239e-06, 476.9854]$.

219 ## Model rank = 472 / 472

220 ##

221 ## Basis dimension (k) checking results. Low p-value (k-index<1) may

```

222 ## indicate that k is too low, especially if edf is close to k'.
223 ##
224 ##
225 ## s(time):conditionhard          9.00  2.25  0.98  0.28
226 ## s(time):conditioneasy         9.00  1.21  0.98  0.29
227 ## s(time):conditionreflection    9.00  1.00  0.98  0.29
228 ## s(time):conditionsinglepointed 9.00  1.00  0.98  0.28
229 ## s(time,subj):conditionhard     108.00 10.44  0.98  0.26
230 ## s(time,subj):conditioneasy     108.00 45.13  0.98  0.28
231 ## s(time,subj):conditionreflection 108.00 22.08  0.98  0.23
232 ## s(time,subj):conditionsinglepointed 108.00 20.08  0.98  0.26

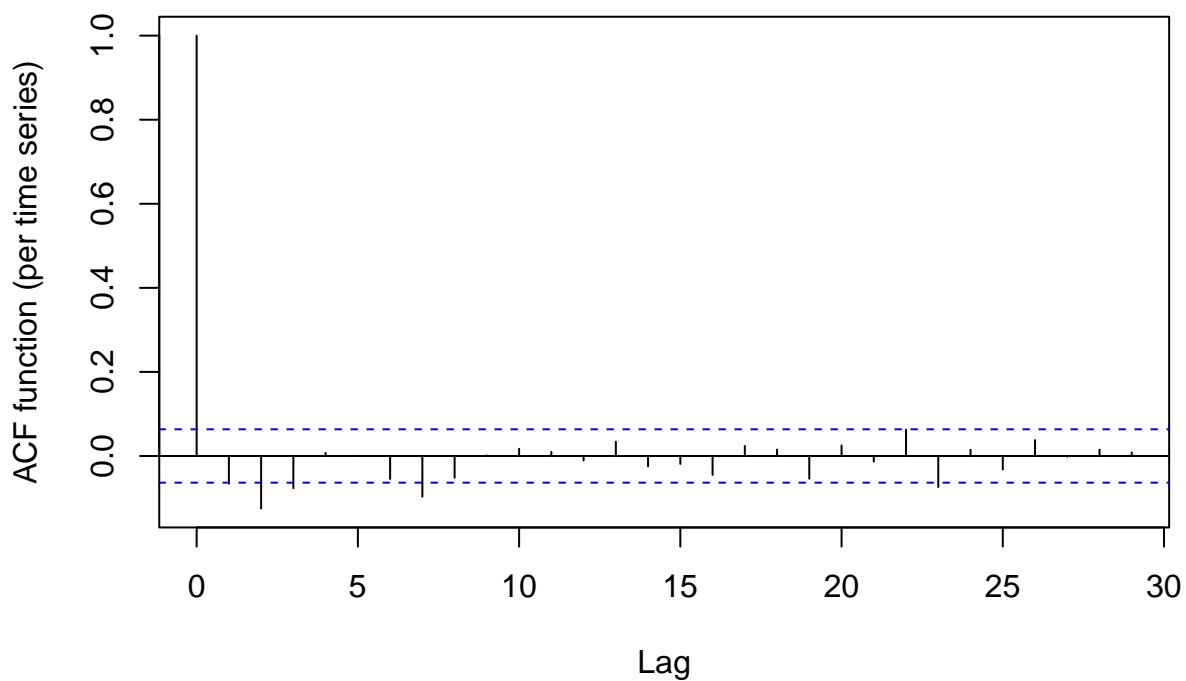
```

```

par(mfrow=c(1,1))
acf_resid(MFtheta.g4)

```

ACF resid_gam(MFtheta.g4)



```
# mid-frontal theta smooths
```

```
plot_smooth(MFtheta.g4, view="time", plot_all="condition",
            xlab = "time (min.)", ylab = "theta power", cex.lab=1.5)
```

```
234 ## Summary:
```

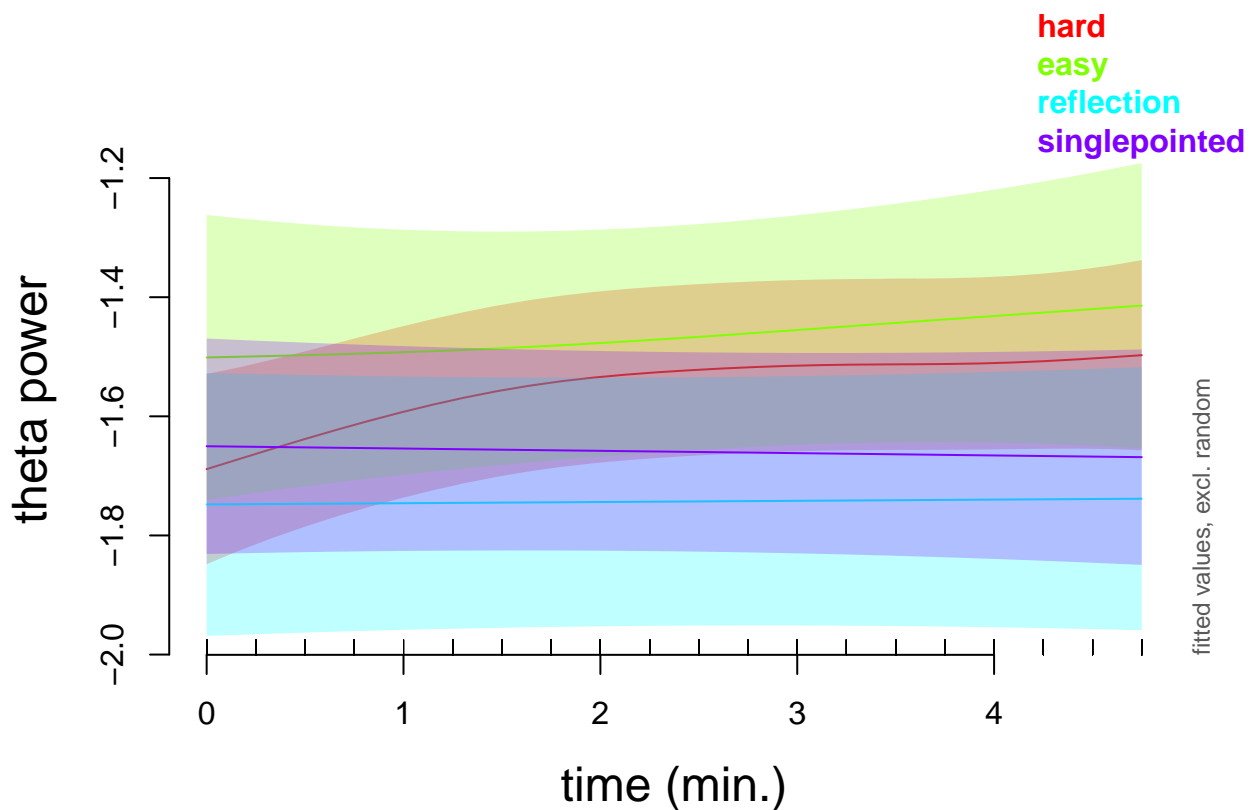
```
235 ## * condition : factor; set to the value(s): easy, hard, reflection, singlepointed.
```

```
236 ## * time : numeric predictor; with 30 values ranging from 0.000000 to 4.750000.
```

```
237 ## * subj : factor; set to the value(s): 283. (Might be canceled as random effect, check)
```

```
238 ## * NOTE : The following random effects columns are canceled: s(time,subj):conditionha
```

```
239 ##
```



```
240
```

```
# monastic debate hard vs. easy
```

```
plot_diff(MFtheta.g4, view="time", comp=list(condition=c("hard", "easy")))
```

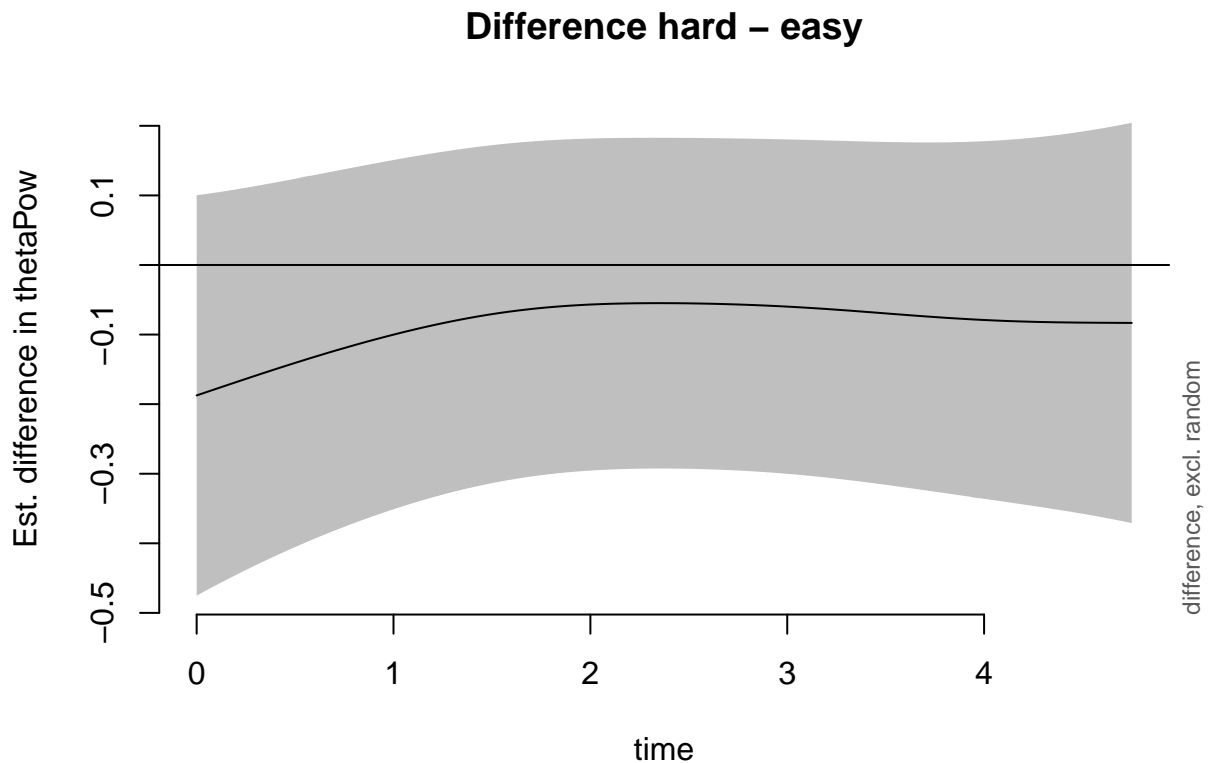
```
241 ## Summary:
```



```

242 ## * time : numeric predictor; with 100 values ranging from 0.000000 to 4.750000.
243 ## * subj : factor; set to the value(s): 283. (Might be canceled as random effect, check)
244 ## * NOTE : The following random effects columns are canceled: s(time,subj):conditionha
245 ##

```



```

246

```

```

247 ##

```

```

248 ## Difference is not significant.

```

```

# monastic debate vs. self-debate

```

```

plot_diff(MFtheta.g4, view="time", comp=list(condition=c("hard", "reflection")))

```

```

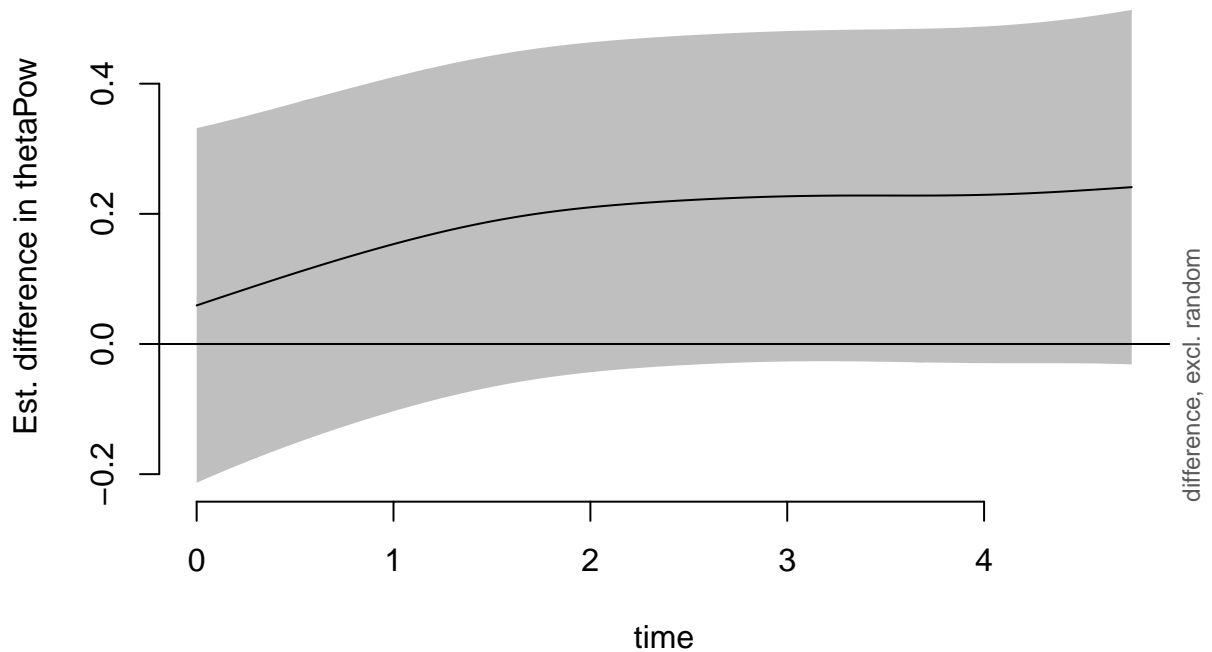
249 ## Summary:

```

```

250 ## * time : numeric predictor; with 100 values ranging from 0.000000 to 4.750000.
251 ## * subj : factor; set to the value(s): 283. (Might be canceled as random effect, check)
252 ## * NOTE : The following random effects columns are canceled: s(time,subj):conditionha
253 ##

```

Difference hard – reflection

254

255 ##

256 ## Difference is not significant.

```
plot_diff(MFtheta.g4, view="time", comp=list(condition=c("easy", "reflection")))
```

257 ## Summary:

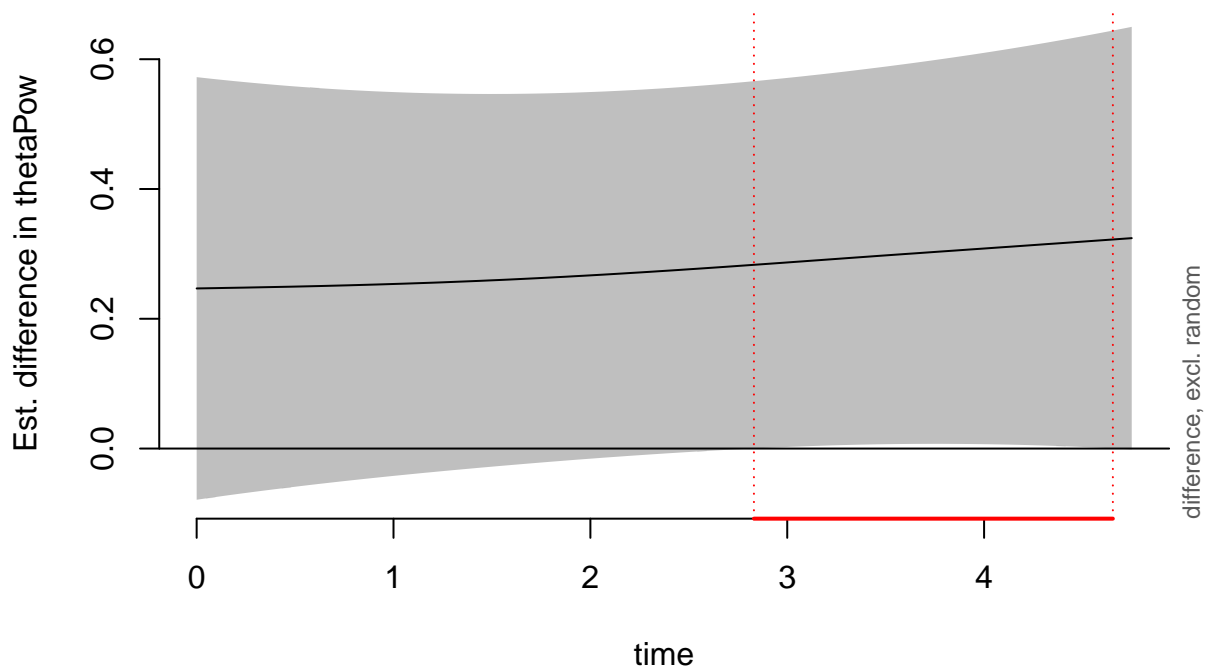
258 ## * time : numeric predictor; with 100 values ranging from 0.000000 to 4.750000.

259 ## * subj : factor; set to the value(s): 283. (Might be canceled as random effect, check)

260 ## * NOTE : The following random effects columns are canceled: s(time,subj):conditionha

261 ##

Difference easy – reflection



262

263 ##

264 ## time window(s) of significant difference(s):

265 ## 2.830808 - 4.654040

```
# monastic debate vs. mindfulness
```

```
plot_diff(MFtheta.g4, view="time", comp=list(condition=c("hard", "singlepointed")))
```

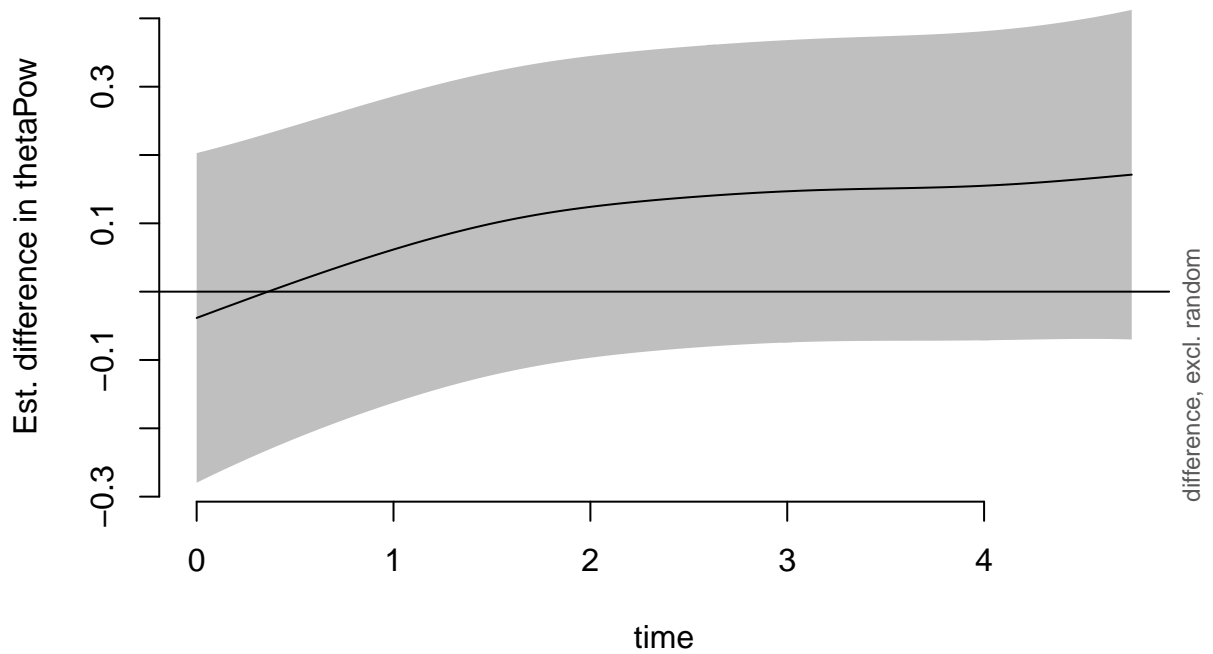
266 ## Summary:

267 ## * time : numeric predictor; with 100 values ranging from 0.000000 to 4.750000.

268 ## * subj : factor; set to the value(s): 283. (Might be canceled as random effect, check)

269 ## * NOTE : The following random effects columns are canceled: s(time,subj):conditionha

270 ##

Difference hard – singlepointed

271

272 ##

273 ## Difference is not significant.

```
plot_diff(MFtheta.g4, view="time", comp=list(condition=c("easy", "singlepointed")))
```

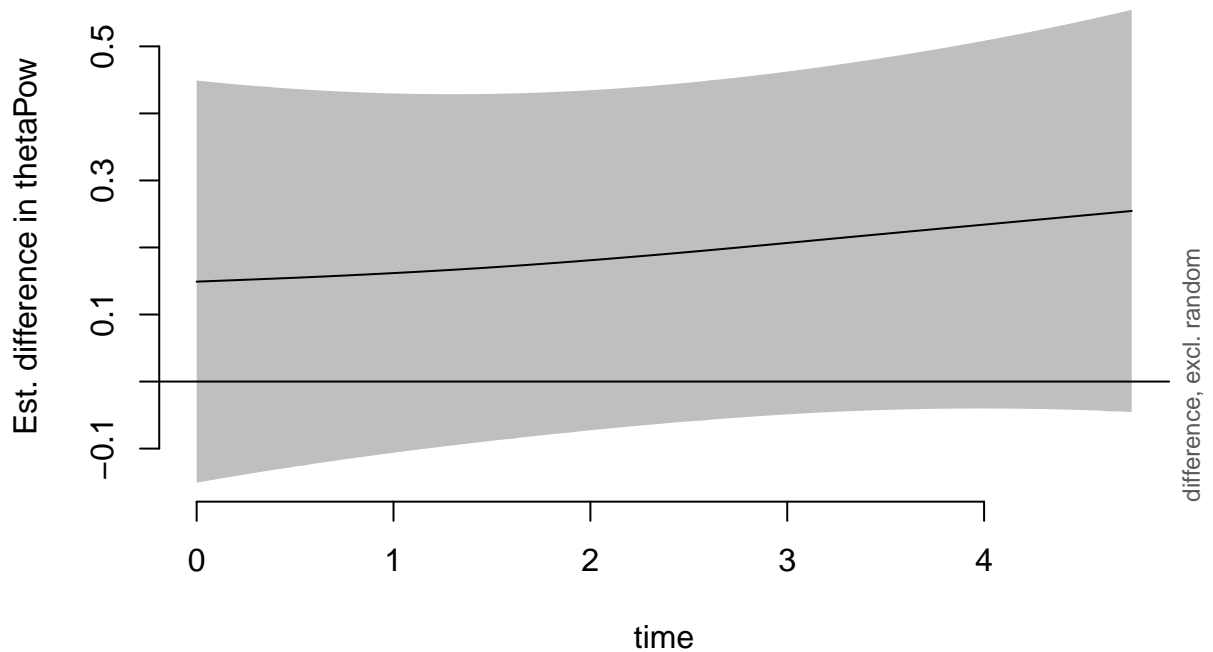
274 ## Summary:

275 ## * time : numeric predictor; with 100 values ranging from 0.000000 to 4.750000.

276 ## * subj : factor; set to the value(s): 283. (Might be canceled as random effect, check)

277 ## * NOTE : The following random effects columns are canceled: s(time,subj):conditionha

278 ##

Difference easy – singlepointed

279

280 ##

281 ## Difference is not significant.

```
# self-debate vs. mindfulness
```

```
plot_diff(MFtheta.g4, view="time", comp=list(condition=c("reflection", "singlepointed")))
```

282 ## Summary:

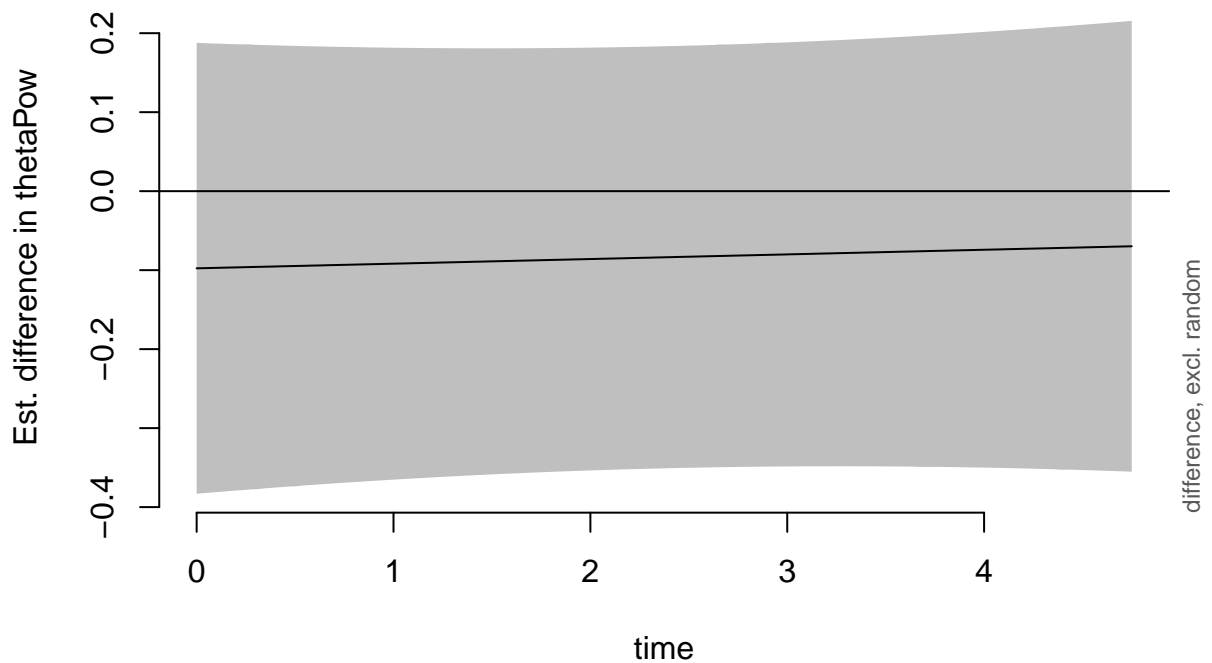
283 ## * time : numeric predictor; with 100 values ranging from 0.000000 to 4.750000.

284 ## * subj : factor; set to the value(s): 283. (Might be canceled as random effect, check)

285 ## * NOTE : The following random effects columns are canceled: s(time,subj):conditionha

286 ##

Difference reflection – singlepointed



287

288 ##

289 ## Difference is not significant.

```
# (binary) models with difference smooths
```

```
MFtheta$IsHard <- ifelse(MFtheta$condition=='hard', 1, 0)
```

```
MFtheta$IsEasy <- ifelse(MFtheta$condition=='easy', 1, 0)
```

```
MFtheta$IsRefl <- ifelse(MFtheta$condition=='reflection', 1, 0)
```

```
MFtheta$IsSingl <- ifelse(MFtheta$condition=='singlepointed', 1, 0)
```

```
# (binary) model with difference smooths comparing
```

```
# monastic debate hard vs.
```

```
MFtheta.g4.bin1 <- bam(thetaPow ~ s(time)
```

```
      + s(time, by=IsSingl) + s(time, by=IsRefl) + s(time, by=IsEasy)
```

```
      + s(time, subj, by=condition, bs="fs", m=1)
```

```

      ,data=MFtheta)
#summary(MFtheta.g4.bin1)
# (binary) model with difference smooths comparing
# monastic debate easy vs.
MFtheta.g4.bin2 <- bam(thetaPow ~ s(time)
      + s(time, by=IsSingl) + s(time, by=IsRefl) + s(time, by=IsHard)
      + s(time,subj,by=condition,bs="fs",m=1)
      ,data=MFtheta)
#summary(MFtheta.g4.bin2)
# (binary) model with difference smooths comparing
# self-debate vs.
MFtheta.g4.bin3 <- bam(thetaPow ~ s(time)
      + s(time, by=IsSingl) + s(time, by=IsEasy) + s(time, by=IsHard)
      + s(time,subj,by=condition,bs="fs",m=1)
      ,data=MFtheta)
#summary(MFtheta.g4.bin3)
# (binary) model with difference smooths comparing
# mindfulness vs.
MFtheta.g4.bin4 <- bam(thetaPow ~ s(time)
      + s(time, by=IsRefl) + s(time, by=IsEasy) + s(time, by=IsHard)
      + s(time,subj,by=condition,bs="fs",m=1)
      ,data=MFtheta)
#summary(MFtheta.g4.bin4)

report_stats(MFtheta.g4.bin1)

```

```

291 ## 1          s(time)    F(1.835, 853.155)=5.18; p<.01
292 ## 2          s(time):IsSingl F(2.000, 853.155)=2.66; p=0.070
293 ## 3          s(time):IsRefl F(2.000, 853.155)=2.59; p=0.076
294 ## 4          s(time):IsEasy F(2.904, 853.155)=0.68; p=0.658
295 ## 5          s(time,subj):conditionhard F(10.440, 853.155)=1.91; p<.001
296 ## 6          s(time,subj):conditioneasy F(44.588, 853.155)=4.40; p<.001
297 ## 7          s(time,subj):conditionreflection F(21.991, 853.155)=4.60; p<.001
298 ## 8 s(time,subj):conditionsinglepointed F(20.088, 853.155)=2.95; p<.001

```

```
report_stats(MFtheta.g4.bin2)
```

```

299 ##          smooth.term          report
300 ## 1          s(time) F(1.000, 852.790)=0.37; p=0.545
301 ## 2          s(time):IsSingl F(2.000, 852.790)=1.37; p=0.255
302 ## 3          s(time):IsRefl F(2.000, 852.790)=2.01; p=0.135
303 ## 4          s(time):IsHard F(3.253, 852.790)=1.29; p=0.369
304 ## 5          s(time,subj):conditionhard F(10.440, 852.790)=1.92; p<.001
305 ## 6          s(time,subj):conditioneasy F(45.351, 852.790)=4.43; p<.001
306 ## 7          s(time,subj):conditionreflection F(22.082, 852.790)=4.61; p<.001
307 ## 8 s(time,subj):conditionsinglepointed F(20.084, 852.790)=2.95; p<.001

```

```
report_stats(MFtheta.g4.bin3)
```

```

308 ##          smooth.term          report
309 ## 1          s(time) F(1.000, 852.803)=0.02; p=0.898
310 ## 2          s(time):IsSingl F(2.000, 852.803)=0.23; p=0.798
311 ## 3          s(time):IsEasy F(2.207, 852.803)=1.83; p=0.161
312 ## 4          s(time):IsHard F(3.253, 852.803)=2.44; p=0.069
313 ## 5          s(time,subj):conditionhard F(10.440, 852.803)=1.92; p<.001

```



```

314 ## 6          s(time,subj):conditioneasy F(45.130, 852.803)=4.42; p<.001
315 ## 7    s(time,subj):conditionreflection F(22.083, 852.803)=4.61; p<.001
316 ## 8 s(time,subj):conditionsinglepointed F(20.084, 852.803)=2.95; p<.001

```

```
report_stats(MFtheta.g4.bin4)
```

```

317 ##              smooth.term              report
318 ## 1              s(time) F(1.000, 852.803)=0.07; p=0.794
319 ## 2          s(time):IsRefl F(2.000, 852.803)=0.23; p=0.798
320 ## 3          s(time):IsEasy F(2.207, 852.803)=1.29; p=0.293
321 ## 4          s(time):IsHard F(3.253, 852.803)=2.48; p=0.065
322 ## 5          s(time,subj):conditionhard F(10.440, 852.803)=1.92; p<.001
323 ## 6          s(time,subj):conditioneasy F(45.130, 852.803)=4.42; p<.001
324 ## 7    s(time,subj):conditionreflection F(22.083, 852.803)=4.61; p<.001
325 ## 8 s(time,subj):conditionsinglepointed F(20.084, 852.803)=2.95; p<.001

```

(1) The summary statistics of the models with difference smooths show that Reflection
 (F(2.000, 853.155)=2.59; p=0.076), Singlepointed (F(2.000, 853.155)=2.66; p=0.070)
 and Easy (F(2.904, 853.155)=0.68; p=0.658), do not differ from Hard.

(2) Singlepointed (F(2.000, 852.790)=1.37; p=0.255), Reflection (F(2.000, 852.790)=2.01;
 p=0.135), Hard (F(3.253, 852.790)=1.29; p=0.369) not different from Easy.

(3) Singlepointed (F(2.000, 852.803)=0.23; p=0.798), Easy (F(2.207, 852.803)=1.83;
 p=0.161), Hard (F(3.253, 852.803)=2.44; p=0.069) not different from Reflection.

(4) Reflection (F(2.000, 852.803)=0.23; p=0.798), Easy (F(2.207, 852.803)=1.29; p=0.293),
 Hard (F(3.253, 852.803)=2.48; p=0.065) not different from Singlepointed.

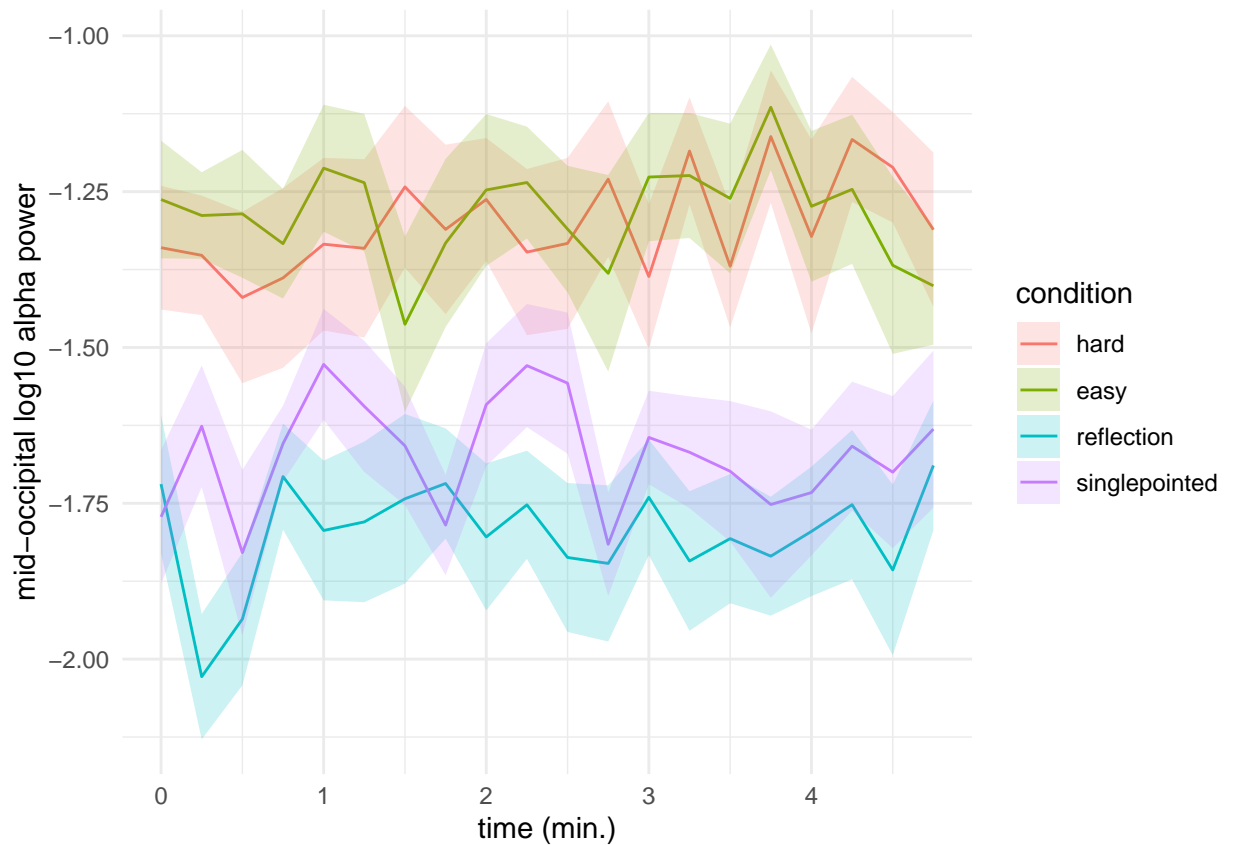
```
# load data generated by continousFreqAnalysis.m

#setwd("/Users/roydavid/Downloads/Monks/")

EEG_alpha_data <- read.csv(file = 'powspecAllChannelsAlpha.csv')
names(EEG_alpha_data) <- c("subj", "condition", "channel", "alphaPow", "time")
EEG_alpha_data <- EEG_alpha_data[complete.cases(EEG_alpha_data),]
EEG_alpha_data$subj <- as.factor(EEG_alpha_data$subj)
EEG_alpha_data$condition <- as.factor(EEG_alpha_data$condition)
levels(EEG_alpha_data$condition) <- c("hard", "easy", "reflection", "singlepointed")
EEG_alpha_data <- EEG_alpha_data[EEG_alpha_data$time<=4.75,]

# subset mid-occipital alpha
MOalpha <- EEG_alpha_data[EEG_alpha_data$channel==16,] # Oz
MOalpha_time_average <- ddply(MOalpha, c("time", "condition"), summarise,
                               meanPow = mean(alphaPow, na.rm=TRUE),
                               SE = se(alphaPow, na.rm=TRUE))

# plot mean mid-occipital alpha power over time per condition
ggplot(MOalpha_time_average, aes(x=time, y=meanPow,
                                ymax=meanPow+SE, ymin=meanPow-SE,
                                group=condition)) +
  geom_line(aes(color=condition)) +
  geom_ribbon(alpha = 0.2, aes(fill=condition)) +
  labs(y='mid-occipital log10 alpha power', x="time (min.)") +
  theme_minimal()
```

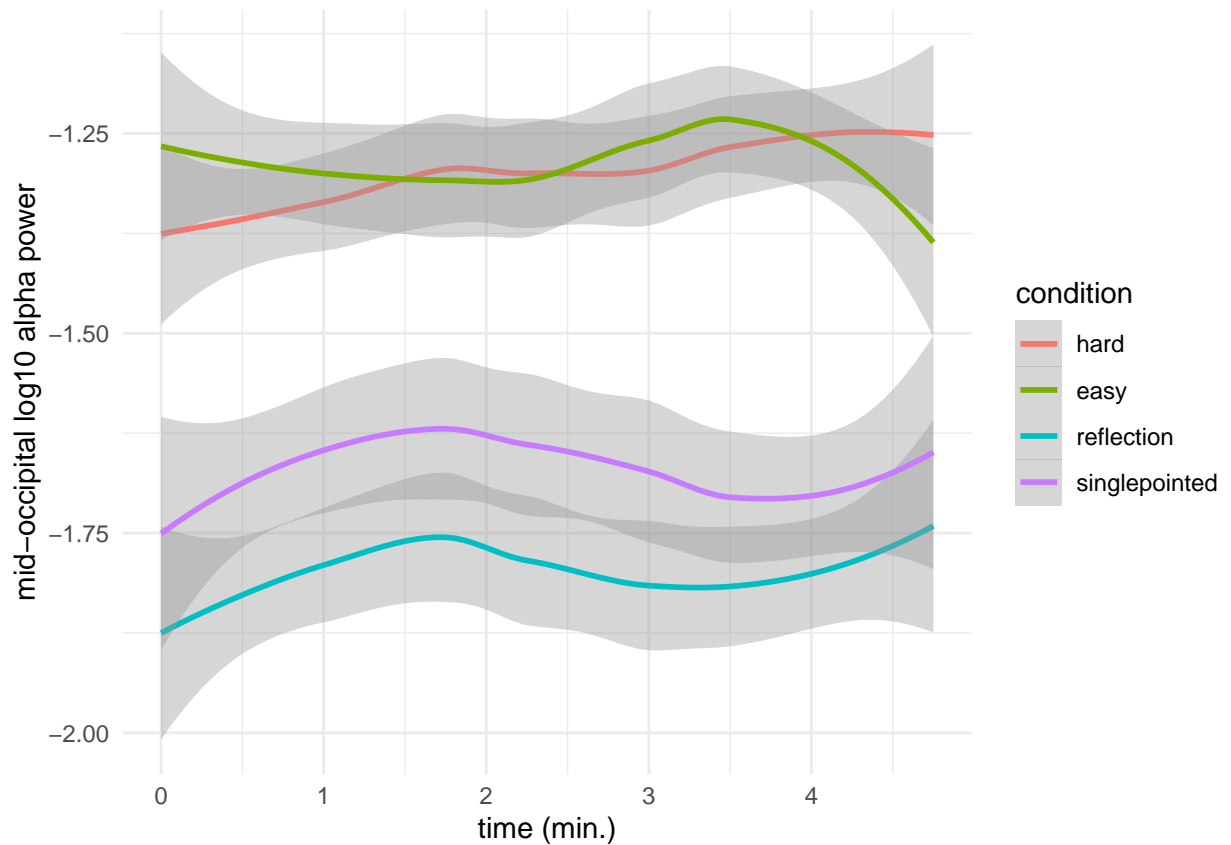


335

```

ggsave(file="/Users/roydavid/Documents/FYRP/latex/figs/0zAlpha_avg_time.pdf", width=7, h
# with loess
ggplot(M0alpha_time_average, aes(x=time, y=meanPow, color=condition)) +
  geom_smooth(method='loess') +
  labs(y='mid-occipital log10 alpha power', x="time (min.)") +
  guides(color=guide_legend(title="condition")) +
  theme_minimal()

```



336

```
ggsave(file="/Users/roydavid/Documents/FYRP/latex/figs/0zAlpha_avg_time_loess.pdf", width=
```

```
# mid-occipital alpha GAMM analysis
```

```
# random intercepts
```

```
M0alpha.g1 <- bam(alphaPow ~ condition + s(time, by=condition) + s(subj,bs="re"), data=M0alpha)
```

```
#summary(M0alpha.g1)
```

```
# random slopes
```

```
M0alpha.g2 <- bam(alphaPow ~ condition + s(time, by=condition) + s(subj,bs="re") +  
                  s(subj,condition,bs="re"), data=M0alpha)
```

```
#summary(M0alpha.g2)
```

```
compareML(M0alpha.g1,M0alpha.g2)
```

Mid-occipital alpha.

337

```
338 ## M0alpha.g1: alphaPow ~ condition + s(time, by = condition) + s(subj, bs = "re")
```

```
339 ##
```

```
340 ## M0alpha.g2: alphaPow ~ condition + s(time, by = condition) + s(subj, bs = "re") +
```

```
341 ##      s(subj, condition, bs = "re")
```

```
342 ## Warning in sprintf("***", h1): one argument not used by format '***'
```

```
343 ##
```

```
344 ## Chi-square test of fREML scores
```

```
345 ## -----
```

```
346 ##           Model      Score Edf Difference    Df  p.value Sig.
```

```
347 ## 1 M0alpha.g1 395.3681  13
```

```
348 ## 2 M0alpha.g2 170.5496  14    224.818 1.000  < 2e-16  ***
```

```
349 ##
```

```
350 ## AIC difference: 532.01, model M0alpha.g2 has lower AIC.
```

```
# factor smooths
```

```
M0alpha.g3 <- bam(alphaPow ~ condition + s(time, by=condition) + s(subj,condition,bs="re")
              s(time,subj,bs="fs",m=1), data=M0alpha)
```

```
#summary(M0alpha.g3)
```

```
compareML(M0alpha.g2,M0alpha.g3)
```

```
351 ## M0alpha.g2: alphaPow ~ condition + s(time, by = condition) + s(subj, bs = "re") +
```

```
352 ##      s(subj, condition, bs = "re")
```

```
353 ##
```

```
354 ## M0alpha.g3: alphaPow ~ condition + s(time, by = condition) + s(subj, condition,
```

```
355 ##      bs = "re") + s(time, subj, bs = "fs", m = 1)
```

```

356 ## Warning in sprintf(" ", h1): one argument not used by format ' '
357 ##
358 ## Chi-square test of fREML scores
359 ## -----
360 ##           Model      Score Edf Difference      Df p.value Sig.
361 ## 1 M0alpha.g2 170.5496  14
362 ## 2 M0alpha.g3 170.5496  15      0.000 1.000   0.999
363 ##
364 ## AIC difference: -0.00, model M0alpha.g2 has lower AIC.
365 ## Warning in compareML(M0alpha.g2, M0alpha.g3): Only small difference in fREML...

# model power by condition
# smooth over time by condition
# factor smooth over time for each subject by condition:
# (potential) nonlinear difference over time wrt the general pattern for each subject
# by condition
M0alpha.g4 <- bam(alphaPow ~ condition + s(time, by=condition) + s(time,subj,by=condition)
                  data=M0alpha)

366 ## Warning in gam.side(sm, X, tol = .Machine$double.eps^0.5): model has repeated 1-
367 ## d smooths of same variable.

summary(M0alpha.g4)

368 ##
369 ## Family: gaussian
370 ## Link function: identity
371 ##

```

```

372 ## Formula:
373 ## alphaPow ~ condition + s(time, by = condition) + s(time, subj,
374 ##      by = condition, bs = "fs", m = 1)
375 ##
376 ## Parametric coefficients:
377 ##              Estimate Std. Error t value Pr(>|t|)
378 ## (Intercept)      -1.30070    0.09420 -13.808  < 2e-16 ***
379 ## conditioneasy       0.01555    0.12116   0.128  0.897903
380 ## conditionreflection -0.49844    0.12983  -3.839  0.000132 ***
381 ## conditionsinglepointed -0.37056    0.12271  -3.020  0.002602 **
382 ## ---
383 ## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
384 ##
385 ## Approximate significance of smooth terms:
386 ##              edf  Ref.df    F p-value
387 ## s(time):conditionhard      1.000   1.000  5.707  0.0171 *
388 ## s(time):conditioneasy      1.000   1.000  0.070  0.7908
389 ## s(time):conditionreflection 1.000   1.000  0.777  0.3783
390 ## s(time):conditionsinglepointed 1.938   2.418  0.771  0.6378
391 ## s(time,subj):conditionhard 11.601 107.000  3.223  <2e-16 ***
392 ## s(time,subj):conditioneasy 31.639 107.000  2.419  <2e-16 ***
393 ## s(time,subj):conditionreflection 10.621 107.000  2.880  <2e-16 ***
394 ## s(time,subj):conditionsinglepointed 10.754 107.000  2.211  <2e-16 ***
395 ## ---
396 ## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
397 ##
398 ## R-sq.(adj) = 0.664  Deviance explained = 68.9%

```

```
399 ## fREML = 166.76  Scale est. = 0.066016  n = 960
```

```
compareML(MOalpha.g2,MOalpha.g4)
```

```
400 ## MOalpha.g2: alphaPow ~ condition + s(time, by = condition) + s(subj, bs = "re") +
```

```
401 ##      s(subj, condition, bs = "re")
```

```
402 ##
```

```
403 ## MOalpha.g4: alphaPow ~ condition + s(time, by = condition) + s(time, subj,
```

```
404 ##      by = condition, bs = "fs", m = 1)
```

```
405 ## Warning in sprintf(" ", h1): one argument not used by format ' '
```

```
406 ##
```

```
407 ## Chi-square test of fREML scores
```

```
408 ## -----
```

```
409 ##      Model      Score Edf Difference      Df p.value Sig.
```

```
410 ## 1 MOalpha.g2 170.5496  14
```

```
411 ## 2 MOalpha.g4 166.7584  20      3.791 6.000   0.270
```

```
412 ##
```

```
413 ## AIC difference: 7.83, model MOalpha.g4 has lower AIC.
```

```
414 ## Warning in compareML(MOalpha.g2, MOalpha.g4): Only small difference in fREML...
```

```
compareML(MOalpha.g3,MOalpha.g4)
```

```
415 ## MOalpha.g3: alphaPow ~ condition + s(time, by = condition) + s(subj, condition,
```

```
416 ##      bs = "re") + s(time, subj, bs = "fs", m = 1)
```

```
417 ##
```

```
418 ## MOalpha.g4: alphaPow ~ condition + s(time, by = condition) + s(time, subj,
```

```
419 ##      by = condition, bs = "fs", m = 1)
```



```

420 ## Warning in sprintf(" ", h1): one argument not used by format ' '

421 ##

422 ## Chi-square test of fREML scores

423 ## -----

424 ##           Model      Score Edf Difference      Df p.value Sig.

425 ## 1 M0alpha.g3 170.5496  15

426 ## 2 M0alpha.g4 166.7584  20           3.791 5.000   0.181

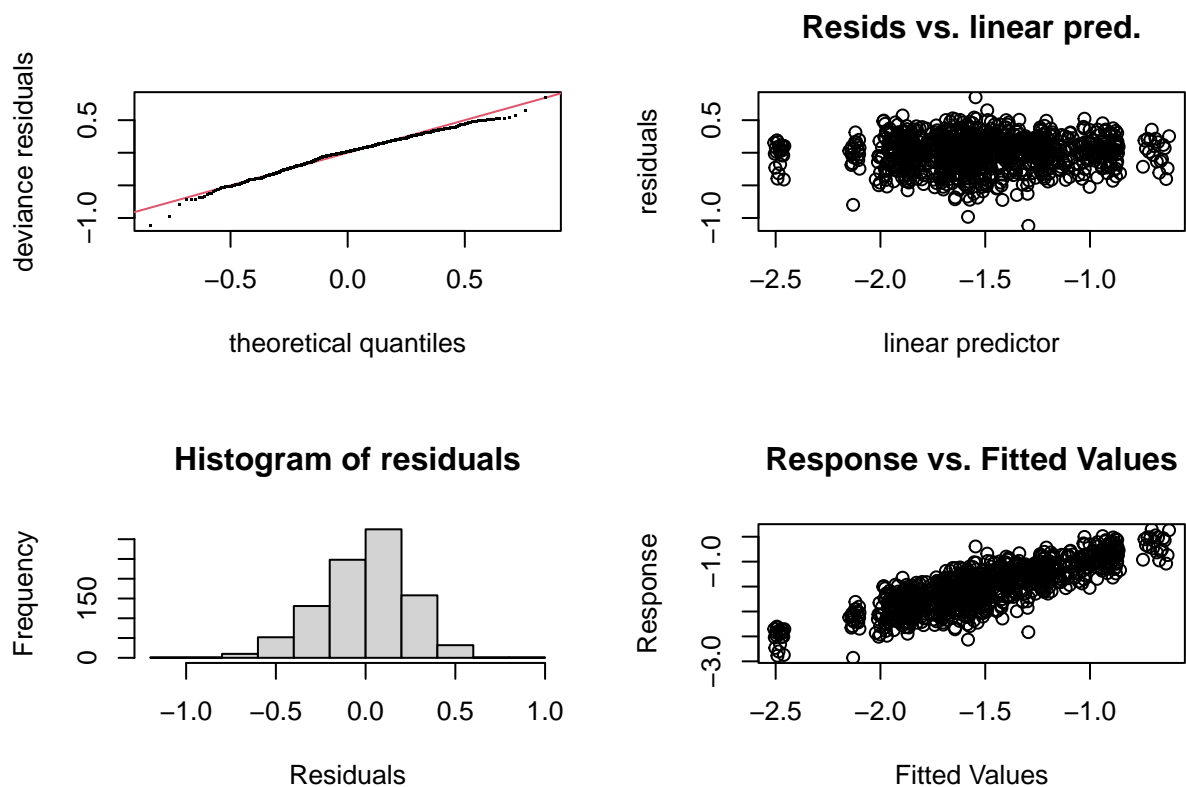
427 ##

428 ## AIC difference: 7.83, model M0alpha.g4 has lower AIC.

429 ## Warning in compareML(M0alpha.g3, M0alpha.g4): Only small difference in fREML...

par(mfrow=c(2,2))
gam.check(M0alpha.g4)

```

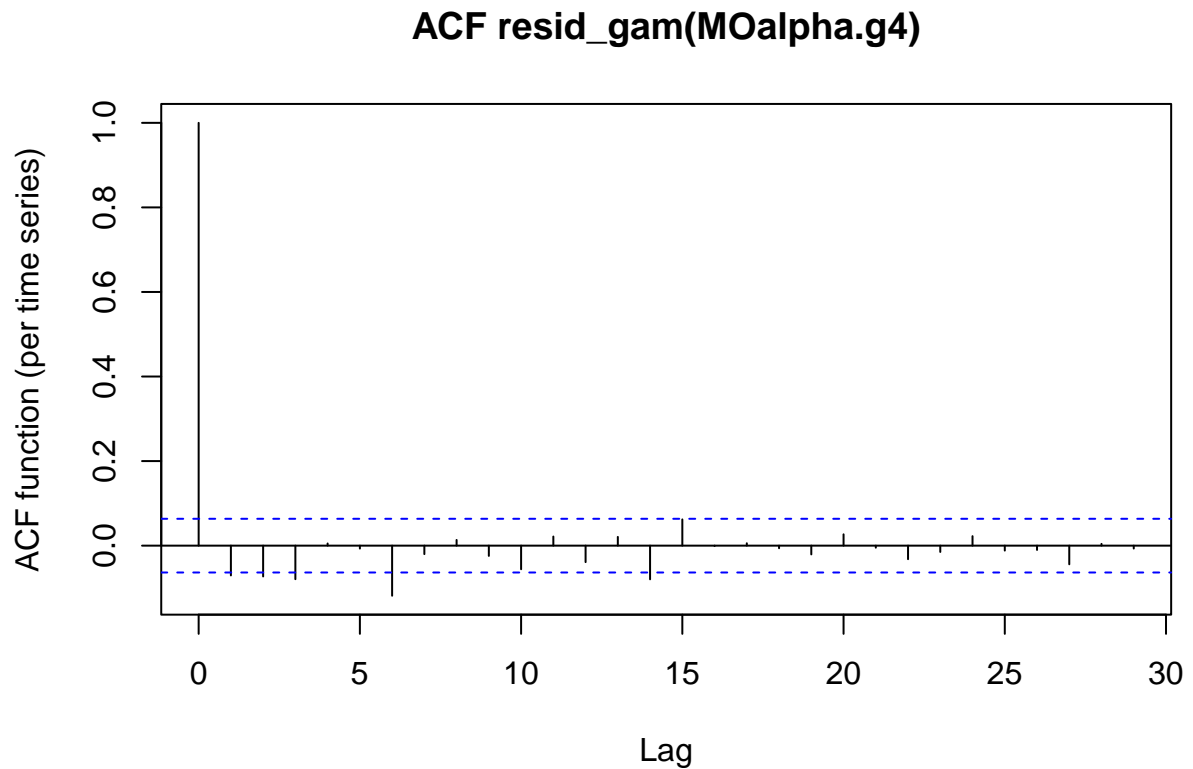


```

431 ##
432 ## Method: fREML   Optimizer: perf newton
433 ## full convergence after 18 iterations.
434 ## Gradient range [-1.65273e-06,5.605752e-07]
435 ## (score 166.7584 & scale 0.06601583).
436 ## Hessian positive definite, eigenvalue range [6.349199e-07,476.4741].
437 ## Model rank = 472 / 472
438 ##
439 ## Basis dimension (k) checking results. Low p-value (k-index<1) may
440 ## indicate that k is too low, especially if edf is close to k'.
441 ##
442 ##           k'    edf k-index p-value
443 ## s(time):conditionhard      9.00   1.00   0.98   0.29
444 ## s(time):conditioneasy      9.00   1.00   0.98   0.23
445 ## s(time):conditionreflection 9.00   1.00   0.98   0.25
446 ## s(time):conditionsinglepointed 9.00   1.94   0.98   0.29
447 ## s(time,subj):conditionhard 108.00  11.60   0.98   0.26
448 ## s(time,subj):conditioneasy  108.00  31.64   0.98   0.23
449 ## s(time,subj):conditionreflection 108.00  10.62   0.98   0.24
450 ## s(time,subj):conditionsinglepointed 108.00  10.75   0.98   0.27

par(mfrow=c(1,1))
acf_resid(M0alpha.g4)

```



451

```
plot_smooth(MOalpha.g4, view="time", plot_all="condition",
             xlab = "time (min.)", ylab = "alpha power", cex.lab=1.5)
```

```
452 ## Summary:
```

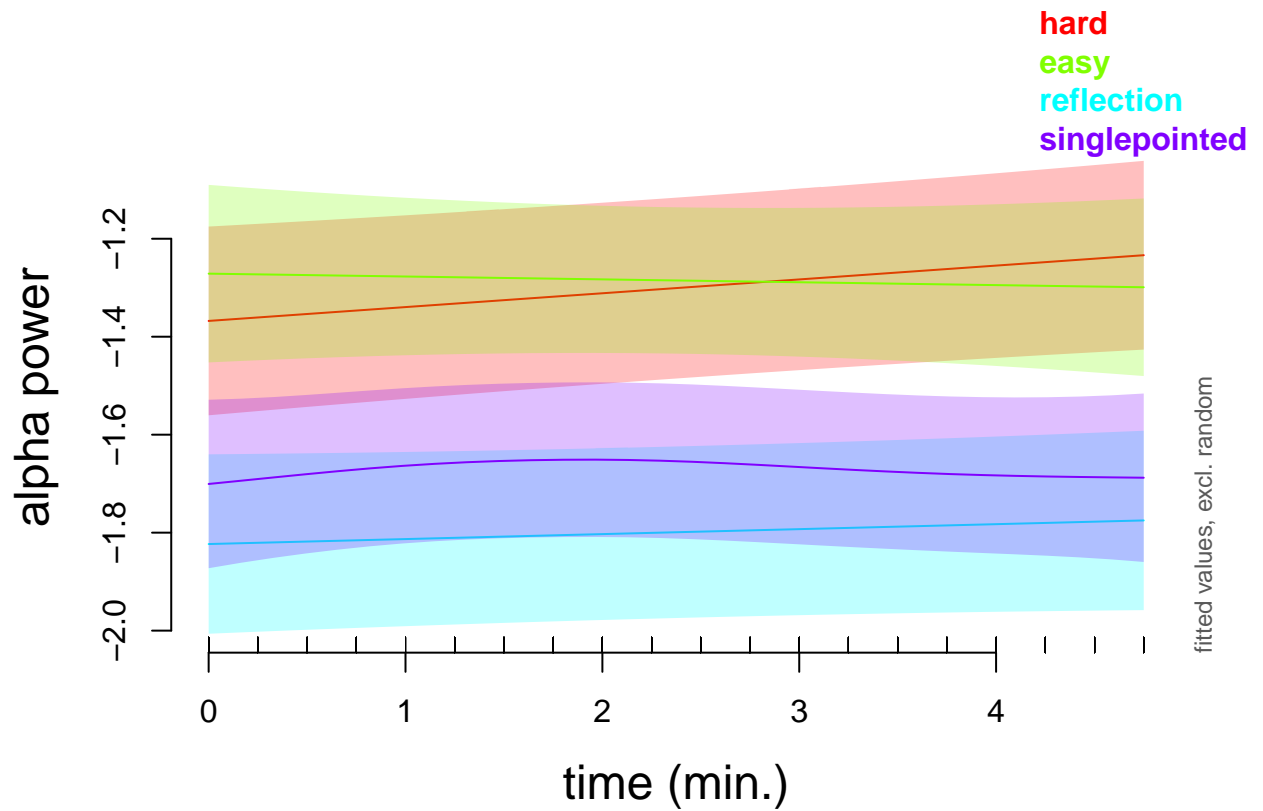
```
453 ## * condition : factor; set to the value(s): easy, hard, reflection, singlepointed.
```

```
454 ## * time : numeric predictor; with 30 values ranging from 0.000000 to 4.750000.
```

```
455 ## * subj : factor; set to the value(s): 283. (Might be canceled as random effect, check)
```

```
456 ## * NOTE : The following random effects columns are canceled: s(time,subj):conditionha
```

```
457 ##
```



```
# monastic debate hard vs. easy
```

```
plot_diff(M0alpha.g4, view="time", comp=list(condition=c("hard", "easy")))
```

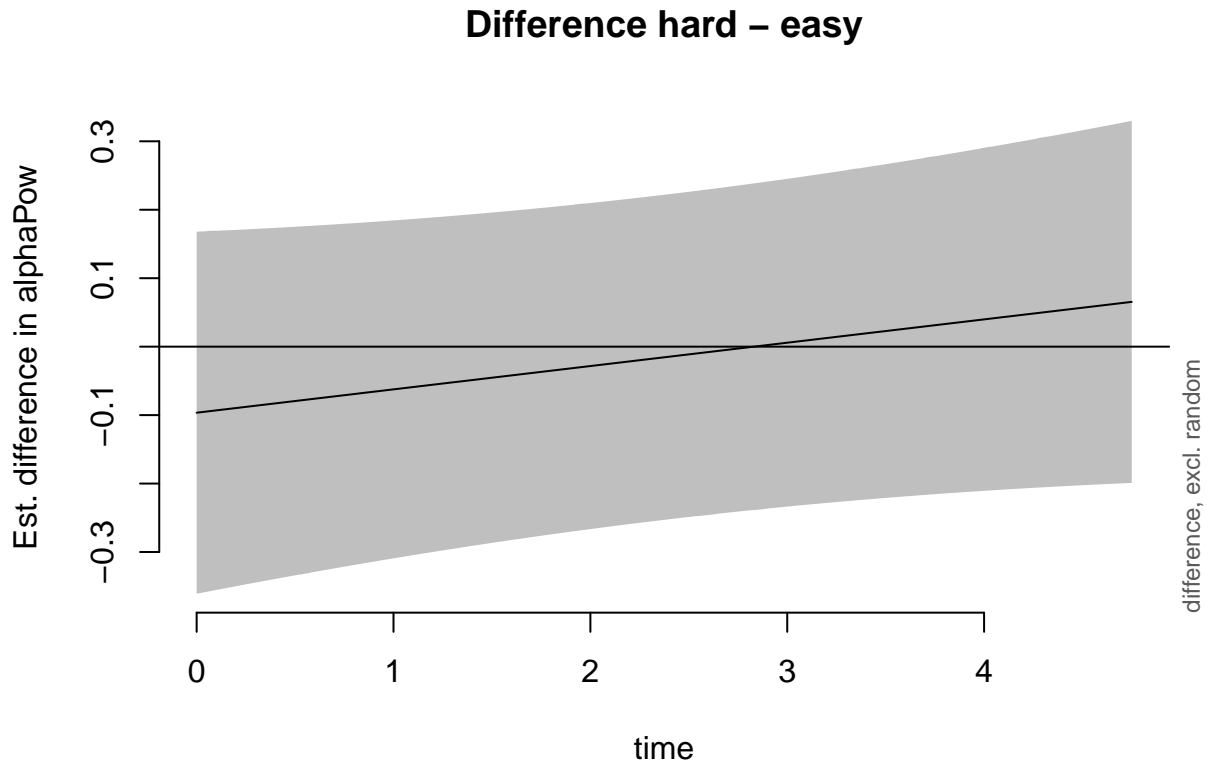
```
## Summary:
```

```
## * time : numeric predictor; with 100 values ranging from 0.000000 to 4.750000.
```

```
## * subj : factor; set to the value(s): 283. (Might be canceled as random effect, check)
```

```
## * NOTE : The following random effects columns are canceled: s(time,subj):conditionha
```

```
##
```



464

465 ##

466 ## Difference is not significant.

```
# monastic debate vs. self-debate
```

```
plot_diff(M0alpha.g4, view="time", comp=list(condition=c("hard", "reflection")))
```

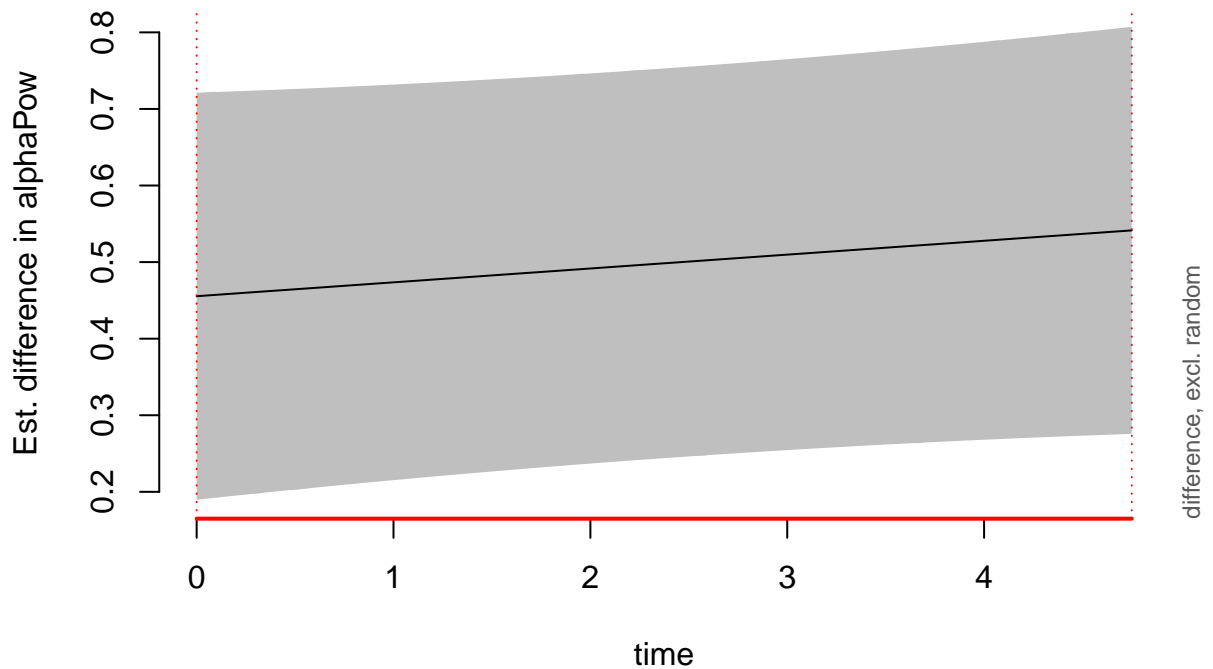
467 ## Summary:

468 ## * time : numeric predictor; with 100 values ranging from 0.000000 to 4.750000.

469 ## * subj : factor; set to the value(s): 283. (Might be canceled as random effect, check)

470 ## * NOTE : The following random effects columns are canceled: s(time,subj):conditionha

471 ##

Difference hard – reflection

472

473 ##

474 ## time window(s) of significant difference(s):

475 ## 0.000000 - 4.750000

```
plot_diff(M0alpha.g4, view="time", comp=list(condition=c("easy", "reflection")))
```

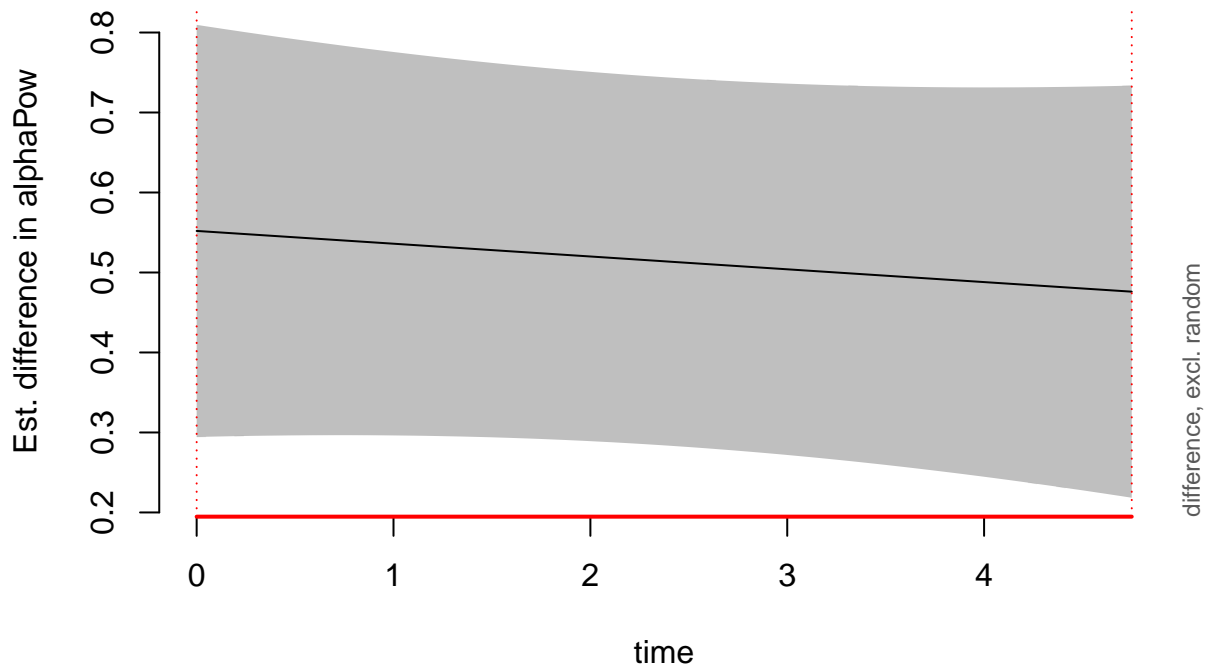
476 ## Summary:

477 ## * time : numeric predictor; with 100 values ranging from 0.000000 to 4.750000.

478 ## * subj : factor; set to the value(s): 283. (Might be canceled as random effect, check)

479 ## * NOTE : The following random effects columns are canceled: s(time,subj):conditionha

480 ##

Difference easy – reflection

481

482 ##

483 ## time window(s) of significant difference(s):

484 ## 0.000000 - 4.750000

```
# monastic debate vs. mindfulness
```

```
plot_diff(M0alpha.g4, view="time", comp=list(condition=c("hard", "singlepointed")))
```

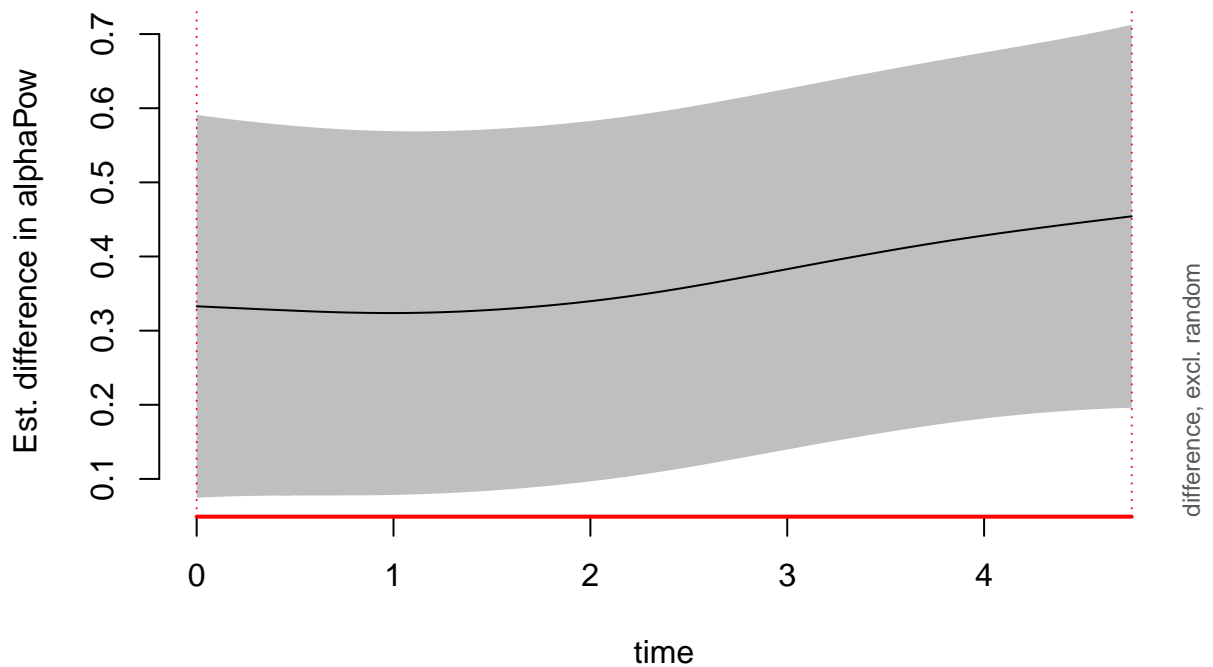
485 ## Summary:

486 ## * time : numeric predictor; with 100 values ranging from 0.000000 to 4.750000.

487 ## * subj : factor; set to the value(s): 283. (Might be canceled as random effect, check)

488 ## * NOTE : The following random effects columns are canceled: s(time,subj):conditionha

489 ##

Difference hard – singlepointed

490

491 ##

492 ## time window(s) of significant difference(s):

493 ## 0.000000 - 4.750000

```
plot_diff(M0alpha.g4, view="time", comp=list(condition=c("easy", "singlepointed")))
```

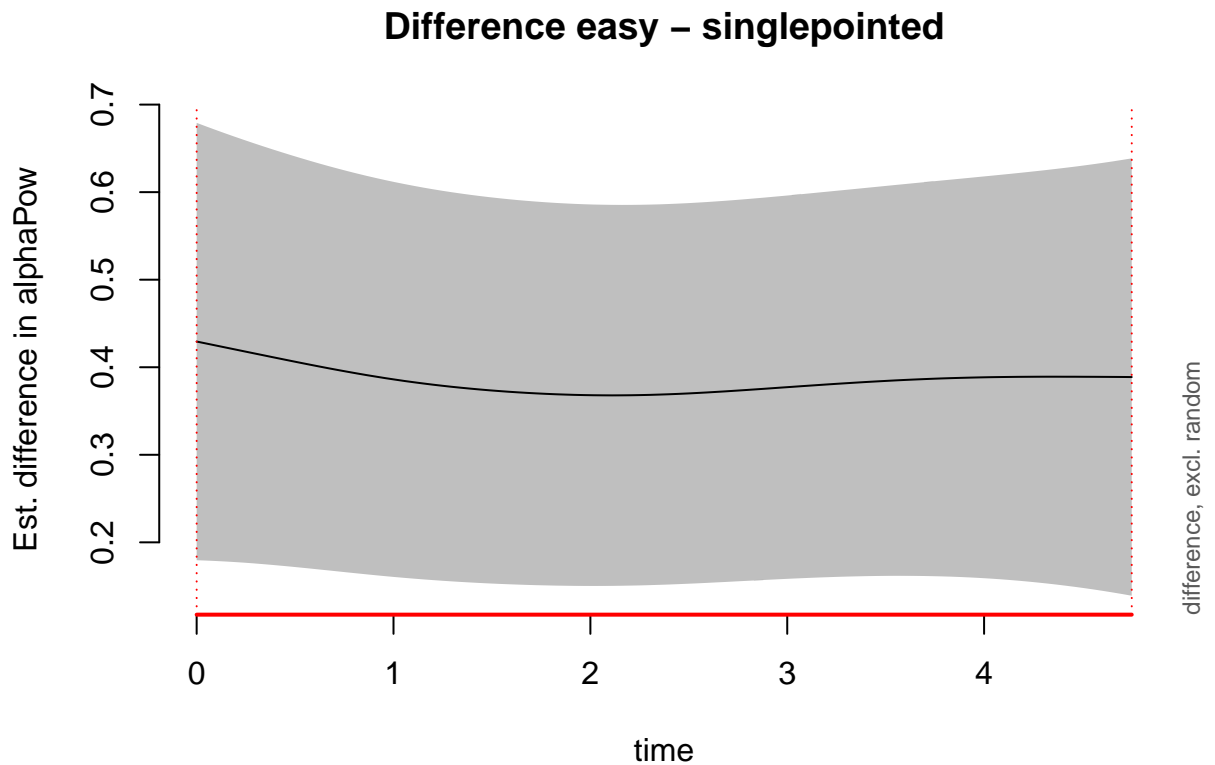
494 ## Summary:

495 ## * time : numeric predictor; with 100 values ranging from 0.000000 to 4.750000.

496 ## * subj : factor; set to the value(s): 283. (Might be canceled as random effect, check)

497 ## * NOTE : The following random effects columns are canceled: s(time,subj):conditionha

498 ##



499

500 ##

501 ## time window(s) of significant difference(s):

502 ## 0.000000 - 4.750000

```
# self-debate vs. mindfulness
```

```
plot_diff(M0alpha.g4, view="time", comp=list(condition=c("reflection", "singlepointed")))
```

503 ## Summary:

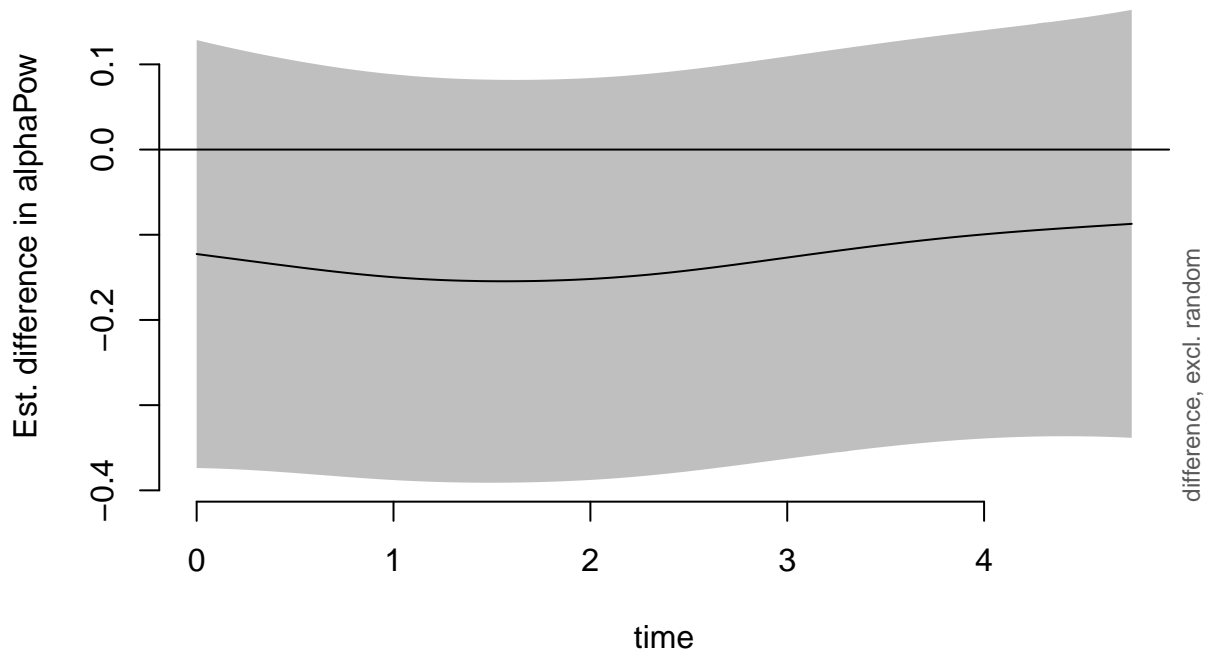
504 ## * time : numeric predictor; with 100 values ranging from 0.000000 to 4.750000.

505 ## * subj : factor; set to the value(s): 283. (Might be canceled as random effect, check)

506 ## * NOTE : The following random effects columns are canceled: s(time,subj):conditionha

507 ##

Difference reflection – singlepointed



508

509 ##

510 ## Difference is not significant.

```
# (binary) models with difference smooths
```

```
M0alpha$IsHard <- ifelse(M0alpha$condition=='hard', 1, 0)
```

```
M0alpha$IsEasy <- ifelse(M0alpha$condition=='easy', 1, 0)
```

```
M0alpha$IsRefl <- ifelse(M0alpha$condition=='reflection', 1, 0)
```

```
M0alpha$IsSingl <- ifelse(M0alpha$condition=='singlepointed', 1, 0)
```

```
# (binary) model with difference smooths comparing
```

```
# monastic debate hard vs.
```

```
M0alpha.g4.bin1 <- bam(alphaPow ~ s(time)
```

```
  + s(time, by=IsSingl) + s(time, by=IsRefl) + s(time, by=IsEasy)
```

```
  + s(time, subj, by=condition, bs="fs", m=1)
```

```

      ,data=M0alpha)
#summary(M0alpha.g4.bin1)
# (binary) model with difference smooths comparing
# monastic debate easy vs.
M0alpha.g4.bin2 <- bam(alphaPow ~ s(time)
      + s(time, by=IsSingl) + s(time, by=IsRefl) + s(time, by=IsHard)
      + s(time,subj,by=condition,bs="fs",m=1)
      ,data=M0alpha)
#summary(M0alpha.g4.bin2)
# (binary) model with difference smooths comparing
# self-debate vs.
M0alpha.g4.bin3 <- bam(alphaPow ~ s(time)
      + s(time, by=IsSingl) + s(time, by=IsEasy) + s(time, by=IsHard)
      + s(time,subj,by=condition,bs="fs",m=1)
      ,data=M0alpha)
#summary(M0alpha.g4.bin3)
# (binary) model with difference smooths comparing
# mindfulness vs.
M0alpha.g4.bin4 <- bam(alphaPow ~ s(time)
      + s(time, by=IsEasy) + s(time, by=IsRefl) + s(time, by=IsHard)
      + s(time,subj,by=condition,bs="fs",m=1)
      ,data=M0alpha)
#summary(M0alpha.g4.bin4)

report_stats(M0alpha.g4.bin1)

```

```

512 ## 1                s(time) F(1.000, 886.446)=5.71; p=0.017
513 ## 2                s(time):IsSingl  F(2.938, 886.446)=4.15; p<.01
514 ## 3                s(time):IsRefl  F(2.000, 886.446)=7.97; p<.001
515 ## 4                s(time):IsEasy F(2.000, 886.446)=0.94; p=0.392
516 ## 5                s(time,subj):conditionhard F(11.601, 886.446)=3.22; p<.001
517 ## 6                s(time,subj):conditioneasy F(31.639, 886.446)=2.42; p<.001
518 ## 7                s(time,subj):conditionreflection F(10.621, 886.446)=2.88; p<.001
519 ## 8 s(time,subj):conditionsinglepointed F(10.754, 886.446)=2.21; p<.001

```

```
report_stats(M0alpha.g4.bin2)
```

```

520 ##                smooth.term                report
521 ## 1                s(time) F(1.000, 886.446)=0.07; p=0.791
522 ## 2                s(time):IsSingl  F(2.938, 886.446)=4.19; p<.01
523 ## 3                s(time):IsRefl  F(2.000, 886.446)=9.79; p<.001
524 ## 4                s(time):IsHard F(2.000, 886.446)=0.94; p=0.392
525 ## 5                s(time,subj):conditionhard F(11.601, 886.446)=3.22; p<.001
526 ## 6                s(time,subj):conditioneasy F(31.639, 886.446)=2.42; p<.001
527 ## 7                s(time,subj):conditionreflection F(10.621, 886.446)=2.88; p<.001
528 ## 8 s(time,subj):conditionsinglepointed F(10.754, 886.446)=2.21; p<.001

```

```
report_stats(M0alpha.g4.bin3)
```

```

529 ##                smooth.term                report
530 ## 1                s(time) F(1.000, 886.446)=0.78; p=0.378
531 ## 2                s(time):IsSingl F(2.938, 886.446)=1.03; p=0.477
532 ## 3                s(time):IsEasy  F(2.000, 886.446)=9.79; p<.001
533 ## 4                s(time):IsHard  F(2.000, 886.446)=7.97; p<.001
534 ## 5                s(time,subj):conditionhard F(11.601, 886.446)=3.22; p<.001

```

```

535 ## 6          s(time,subj):conditioneasy F(31.639, 886.446)=2.42; p<.001
536 ## 7    s(time,subj):conditionreflection F(10.621, 886.446)=2.88; p<.001
537 ## 8 s(time,subj):conditionsinglepointed F(10.754, 886.446)=2.21; p<.001

```

```
report_stats(M0alpha.g4.bin4)
```

```

538 ##              smooth.term              report
539 ## 1              s(time) F(1.462, 886.714)=0.30; p=0.756
540 ## 2          s(time):IsEasy   F(2.000, 886.714)=6.23; p<.01
541 ## 3          s(time):IsRefl F(2.000, 886.714)=0.83; p=0.437
542 ## 4          s(time):IsHard   F(2.000, 886.714)=6.16; p<.01
543 ## 5          s(time,subj):conditionhard F(11.594, 886.714)=3.22; p<.001
544 ## 6          s(time,subj):conditioneasy F(31.616, 886.714)=2.42; p<.001
545 ## 7    s(time,subj):conditionreflection F(10.621, 886.714)=2.88; p<.001
546 ## 8 s(time,subj):conditionsinglepointed F(10.993, 886.714)=2.21; p<.001

```

547 (1) The summary statistics of the models with difference smooths show that Reflection
548 (F(2.000, 886.446)=7.97; p<.001), Singlepointed (F(2.938, 886.446)=4.15; p<.01),
549 differ from Hard but not Easy (F(2.000, 886.446)=0.94; p=0.392).

550 (2) Singlepointed (F(2.938, 886.446)=4.19; p<.01), Reflection (F(2.000, 886.446)=9.79;
551 p<.001), differ from Easy but not Hard (F(2.000, 886.446)=0.94; p=0.392).

552 (3) Easy (F(2.000, 886.446)=9.79; p<.001), Hard (F(2.000, 886.446)=7.97; p<.001) differ
553 from Reflection but not Singlepointed (F(2.938, 886.446)=1.03; p=0.477).

554 (4) Easy (F(2.000, 886.714)=6.23; p<.01), Hard (F(2.000, 886.714)=6.16; p<.01) differ
555 from Singlepointed but not Reflection (F(2.000, 886.714)=0.83; p=0.437).

Discussion

References

557

558 R Core Team. (2021). *R: A language and environment for statistical computing*. Vienna,

559

Austria: R Foundation for Statistical Computing. Retrieved from

560

<https://www.R-project.org/>