Projection Prediction Inference

Supplementary material

Contents

Data pre-processing

Packages & Options

```
library(tidyverse)
library(brms)
library(projpred)
# library(doParallel)

# retrieve # of cores
ncores <- parallel::detectCores()
# registerDoParallel(cores = ncores)
options(mc.cores = ncores)

# for output clarity
options(scipen = 999)
```

Data

```
df_trials <- read_csv("../../../data/laac_data_trial.csv")
```

```
# remove variables not relevant to PPI analysis
df_trials <- df_trials %>%
  select(-c(time_waited, birth_date, comment, experimenter, pick, condition, heat))
```

```
# data pre-processing

sum_resp <- function(x, ...) {
  # helper function: sum over `correct response` variable (code)
  to_return = tibble(cogn = sum(x$code))
}

resp_sum <- df_trials %>%
  # contains summed code variable for [task, time point, session, subject]
```

```
  group_by(time_point, session, subject, task) %>%
  group_modify(sum_resp)

df_tmp <- df_trials %>%
  # helper for merging
  select(-c(date, trial_session, trial_time_point, code)) %>%
  unique(by = c("time_point", "session", "subject"))

df_trials_final <- inner_join(df_tmp, resp_sum)

df_trials_final <- df_trials_final %>%
  # grand mean center below variables
  mutate(across(c(sick_severity,
                  le_mean,
                  dist_mean,
                  time_outdoors,
                  age,
                  time_in_leipzig),
                ~scale(., center = T, scale = F))) %>%
  mutate(across(c(session,
                  subject,
                  group,
                  sex,
                  test_day,
                  le_present,
                  dist_present,
                  rearing,
                  observer),
                as_factor)) %>%
  mutate(observer = fct_relevel(observer, "no")) %>%
  mutate(rearing = fct_recode(rearing, "hand" = "unknown")) %>%
  # create new observer variable due to different measurements of observer between phases
  mutate(observer_mod = case_when(
    observer == "yes" ~ "yes",
    observer == "no" ~ "no",
    observer != "no" & observer != "yes" & observer != "NA" ~ "yes",
    TRUE ~ "no"
  ), observer_mod =  as_factor(observer_mod))

grp_size <- tibble(
  # number of apes for each species
  a_chimp = 20,
  b_chimp = 6,
  bonobo = 12,
  gorilla = 6,
  orangutan = 6
)

df_trials_final <- df_trials_final %>%
  # relative rank of ape within species (varies between time points)
  group_by(group, time_point) %>%
  mutate(
    rel_rank = case_when(
```

```
      group == "a_chimp" ~ percent_rank(grp_size$a_chimp:1)[rank],
      group == "b_chimp" ~ percent_rank(grp_size$b_chimp:1)[rank],
      group == "bonobo" ~ percent_rank(grp_size$bonobo:1)[rank],
      group == "gorilla" ~ percent_rank(grp_size$gorilla:1)[rank],
      group == "orangutan" ~ percent_rank(grp_size$orangutan:1)[rank]
    )
  ) %>%
  ungroup()

# create complete subsets for each task
t_cau <- filter(df_trials_final, task == "causality")
t_inf <- filter(df_trials_final, task == "inference")
t_quant <- filter(df_trials_final, task == "quantity")
t_gaze <- filter(df_trials_final, task == "gaze_following")
t_grat <- filter(df_trials_final, task == "delay_of_gratification")

t_gaze <- t_gaze %>%
  # create dummy variable indicating if in session 1 or 2
  group_by(time_point, session) %>%
  mutate(tp_mod = cur_group_id()) %>%
  ungroup() %>%
  mutate(day2 = case_when(session == 1 ~ "no",
                          session == 2 ~ "yes"),
         day2 = factor(day2)) %>%
  select(tp_mod, day2, everything())

t_gaze <- t_gaze %>%
  # remove duplicates created by day2
  group_by(subject) %>%
  filter(!duplicated(tp_mod)) %>%
  ungroup()
```

```
# filter data to only include time points from phase 1
t_cau_p1 <- filter(t_cau, time_point < 15)
t_inf_p1 <- filter(t_inf, time_point < 15)
t_quant_p1 <- filter(t_quant, time_point < 15)
t_gaze_p1 <- filter(t_gaze, time_point < 15)

# filter data to only include time points from phase 2
t_cau_p2 <- filter(t_cau, time_point >= 15)
t_inf_p2 <- filter(t_inf, time_point >= 15)
t_quant_p2 <- filter(t_quant, time_point >= 15)
t_gaze_p2 <- filter(t_gaze, time_point >= 15)
t_grat_p2 <- filter(t_grat, time_point >= 15)
```

Covariate selection

```
# formula for reference models
fm <- formula(cogn ~ sick_severity +
                test_tp + test_day +
                rel_rank +
                observer_mod +
```

```
                age + time_in_leipzig +
                sex + group +
                rearing +
                le_mean + dist_mean +
                time_outdoors +
                sociality +
                (1|subject))
# formula for gaze reference model
fm_gaze <- formula(cogn ~ sick_severity +
                     test_tp + test_day + time_point + day2 +
                     rel_rank +
                     observer_mod +
                     age + time_in_leipzig +
                     sex + group +
                     rearing +
                     le_mean + dist_mean +
                     time_outdoors +
                     sociality +
                     (1 + time_point|subject))
```

Reference Model: 2-level Multilevel Model

```
m_cau_2l_p1 <- brm(fm, data = t_cau_p1,
                   warmup = 1e3, iter = 4e3, cores = ncores, chains = 4,
                   seed = 2021
                   )
```

```
## Warning: Rows containing NAs were excluded from the model.
```

```
m_inf_2l_p1 <- brm(fm, data = t_inf_p1,
                   warmup = 1e3, iter = 4e3, cores = ncores, chains = 4,
                   seed = 2021
                   )
```

```
## Warning: Rows containing NAs were excluded from the model.
```

```
m_quant_2l_p1 <- brm(fm, data = t_quant_p1,
                     warmup = 1e3, iter = 4e3, cores = ncores, chains = 4,
                     seed = 2021
                     )
```

```
## Warning: Rows containing NAs were excluded from the model.
```

```
m_gaze_2l_p1 <- brm(fm_gaze, data = t_gaze_p1,
                    warmup = 1e3, iter = 4e3, cores = ncores, chains = 4,
                    seed = 2021
                    )
```

```
## Warning: Rows containing NAs were excluded from the model.
```

```
m_cau_2l_p2 <- brm(fm, data = t_cau_p2,
                   warmup = 1e3, iter = 4e3, cores = ncores, chains = 4,
                   seed = 2022
                   )
```

```
## Warning: Rows containing NAs were excluded from the model.
```

```
m_inf_2l_p2 <- brm(fm, data = t_inf_p2,
                  warmup = 1e3, iter = 4e3, cores = ncores, chains = 4,
                  seed = 2022
                  )
```

```
## Warning: Rows containing NAs were excluded from the model.
```

```
m_quant_2l_p2 <- brm(fm, data = t_quant_p2,
                     warmup = 1e3, iter = 4e3, cores = ncores, chains = 4,
                     seed = 2022
                     )
m_gaze_2l_p2 <- brm(fm_gaze, data = t_gaze_p2,
                    warmup = 1e3, iter = 4e3, cores = ncores, chains = 4,
                    seed = 2022
                    )
```

```
## Warning: Rows containing NAs were excluded from the model.
```

```
m_grat_2l_p2 <- brm(fm, data = t_grat_p2,
                    warmup = 1e3, iter = 4e3, cores = ncores, chains = 4,
                    seed = 2022
                    )
```

```
## Warning: Rows containing NAs were excluded from the model.
```

```
summary(m_cau_2l_p1)
summary(m_inf_2l_p1)
summary(m_quant_2l_p1)
summary(m_gaze_2l_p1)

summary(m_cau_2l_p2)
summary(m_inf_2l_p2)
summary(m_quant_2l_p2)
summary(m_gaze_2l_p2)
summary(m_grat_2l_p2)

loo_p1 <- lapply(list(m_cau_2l_p1, m_inf_2l_p1, m_quant_2l_p1, m_gaze_2l_p1), loo::loo)
loo_p2 <- lapply(list(m_cau_2l_p2, m_inf_2l_p2, m_quant_2l_p2, m_gaze_2l_p2, m_grat_2l_p2), loo::loo)
```

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```
all_fixed_effects <- c("sick_severity",
                       "test_tp", "test_day",
                       "rel_rank",
                       "observer_mod",
                       "age", "time_in_leipzig",
                       "sex", "group",
                       "rearing",
                       "le_mean", "dist_mean",
                       "time_outdoors",
                       "sociality")
# delay random intercept to last place so that it doesn't soak up all the variance
s_terms <- c("1", all_fixed_effects,
             paste0(paste(all_fixed_effects, collapse = " + "),
                    " + (1 | subject)"))
```

```
# gaze task gets its own search terms vector (including day2 and time_point (fixed/random))
s_terms_gaze <- c("1", c(all_fixed_effects, "day2", "time_point"),
                  paste0(paste(all_fixed_effects, collapse = " + "),
                    " + (1 | subject)"),
                  paste0(paste(all_fixed_effects, collapse = " + "),
                    " + (time_point | subject)"))
```

Phase 1

```
cvs_cau_p1 <- cv_varsel(m_cau_2l_p1,
                        search_terms = s_terms,
                        cv_method = "LOO", method = "forward",
                        seed = 2020)
```

```
## Warning in cv_varsel.refmodel(refmodel, ...): K provided, but cv_method is LOO.
```

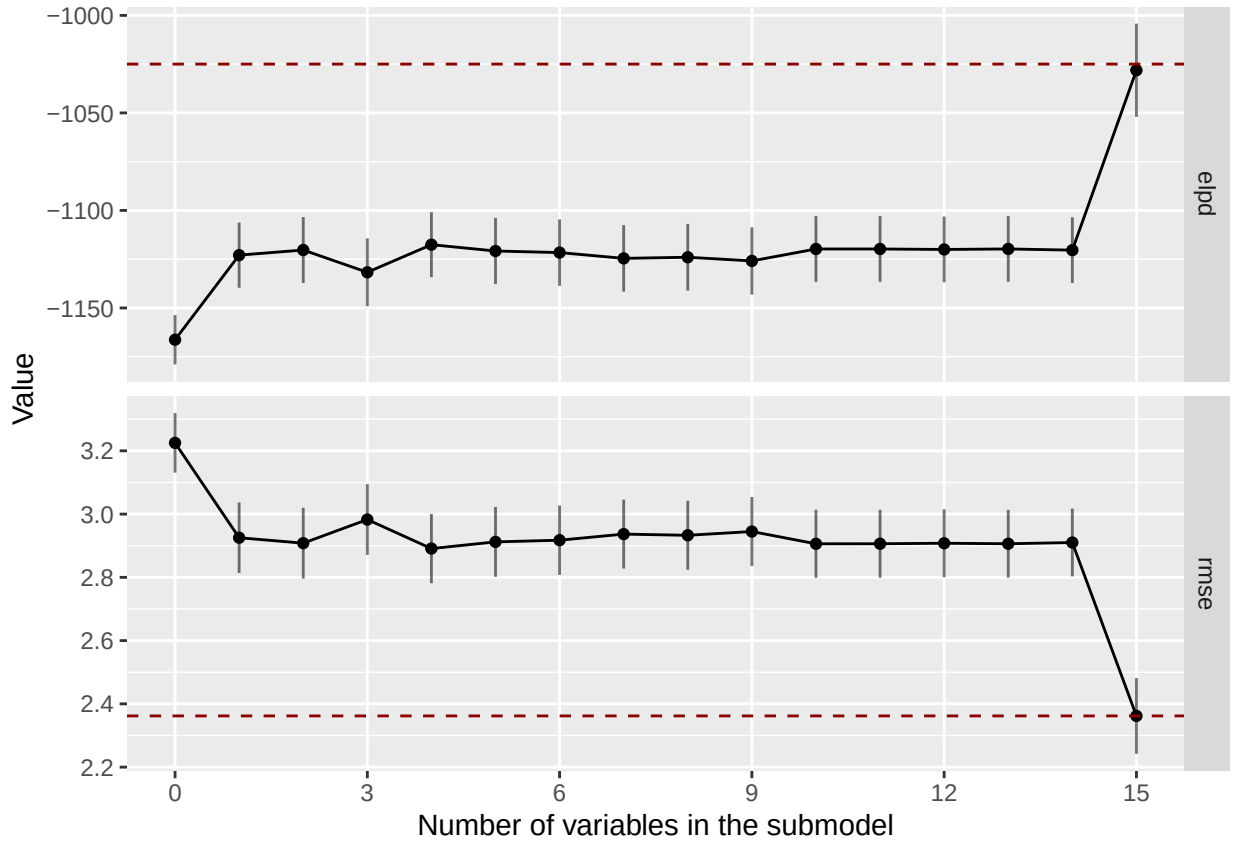
```
## Warning: Some Pareto k diagnostic values are too high. See help('pareto-k-diagnostic') for details.
```

```
## [1] "Computing LOOs..."
##   |                                                                              |
```

```
summary(cvs_cau_p1)
```

```
##    size  solution_terms      elpd  elpd.se
## 2     0            <NA> -1166.284 12.72482
## 3     1           group -1122.926 16.80129
## 4     2 time_in_leipzig -1120.298 16.99272
## 5     3       sociality -1131.701 17.49355
## 6     4       dist_mean -1117.568 16.73176
## 7     5   sick_severity -1120.800 17.06588
## 8     6             age -1121.606 17.13295
## 9     7        test_day -1124.578 17.15932
## 10    8         le_mean -1124.001 17.19919
## 11    9        rel_rank -1125.890 17.34207
## 12   10    observer_mod -1119.764 16.95308
## 13   11   time_outdoors -1119.762 16.92067
## 14   12             sex -1120.003 16.96137
## 15   13         rearing -1119.745 16.90651
## 16   14         test_tp -1120.351 16.94601
## 17   15   (1 | subject) -1028.134 24.02604
```

```
plot(cvs_cau_p1, stats = c('elpd', 'rmse'))
```



selected covariates: (1 | subject), group

```
cvs_inf_p1 <- cv_varsel(m_inf_2l_p1,
                        search_terms = s_terms,
                        cv_method = "LOO", method = "forward",
                        seed = 2020)
```

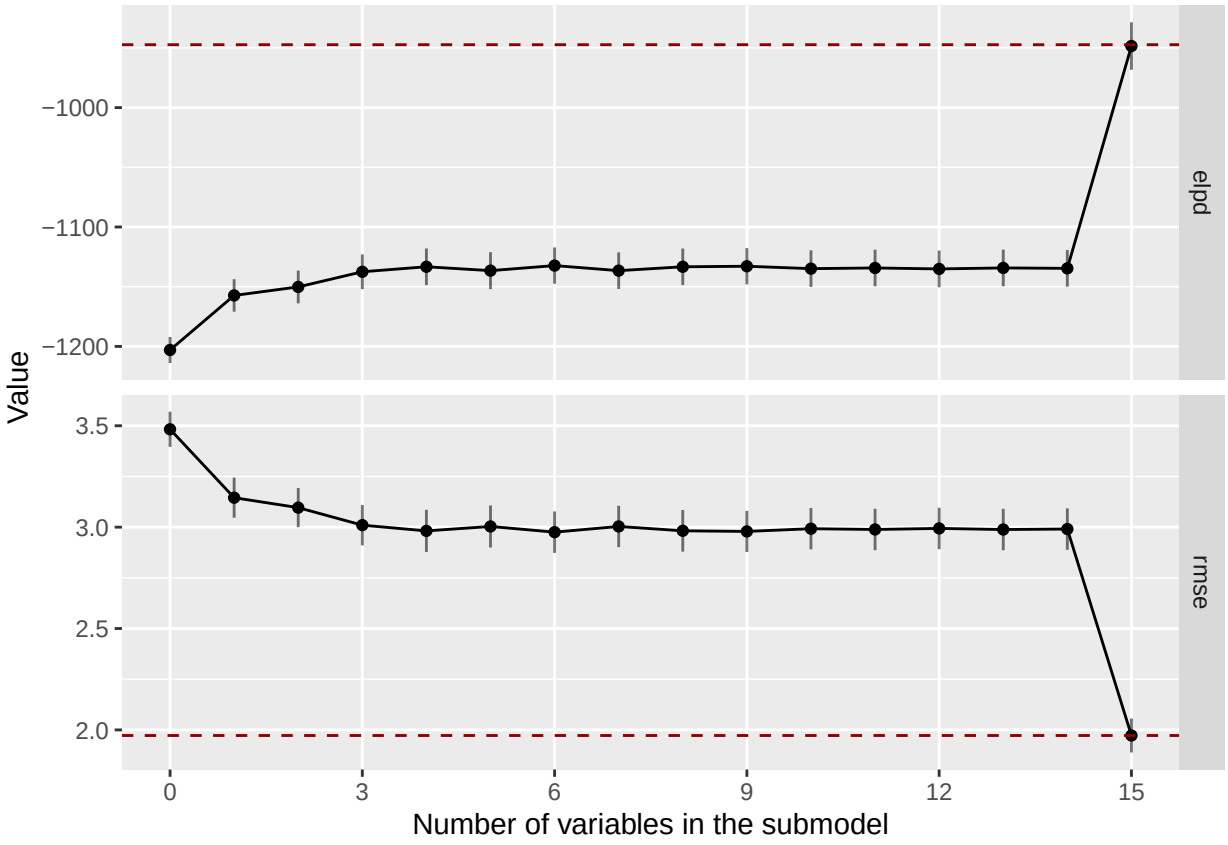
```
## Warning in cv_varsel.refmodel(refmodel, ...): K provided, but cv_method is LOO.

## Warning: Some Pareto k diagnostic values are slightly high. See help('pareto-k-diagnostic') for deta

## [1] "Computing LOOs..."
##   |                                                                              |
```

```
summary(cvs_inf_p1)
```

```
##    size  solution_terms       elpd  elpd.se
```

```
## 2     0            <NA> -1202.9839 10.97475
## 3     1 time_in_leipzig -1157.3107 13.67198
## 4     2           group -1150.1792 13.80130
## 5     3             age -1137.4899 14.64495
## 6     4   sick_severity -1133.2909 15.41999
## 7     5        test_day -1136.5384 15.52882
## 8     6   time_outdoors -1132.3066 15.28879
## 9     7    observer_mod -1136.5442 15.41194
## 10    8       sociality -1133.3114 15.38975
## 11    9         rearing -1132.8525 15.25838
## 12   10        rel_rank -1134.8773 15.41398
## 13   11       dist_mean -1134.2995 15.41905
## 14   12         test_tp -1135.0920 15.47459
## 15   13         le_mean -1134.2714 15.43826
## 16   14             sex -1134.6379 15.44841
## 17   15   (1 | subject)  -948.4261 20.02142
```

```
plot(cvs_inf_p1, stats = c('elpd', 'rmse'))
```



selected covariates: (1 | subject), time_in_leipzig, group, age

```
cvs_quant_p1 <- cv_varsel(m_quant_2l_p1,
                          search_terms = s_terms,
                          cv_method = "LOO", method = "forward",
                          seed = 2020)
```

```
## Warning in cv_varsel.refmodel(refmodel, ...): K provided, but cv_method is LOO.
```

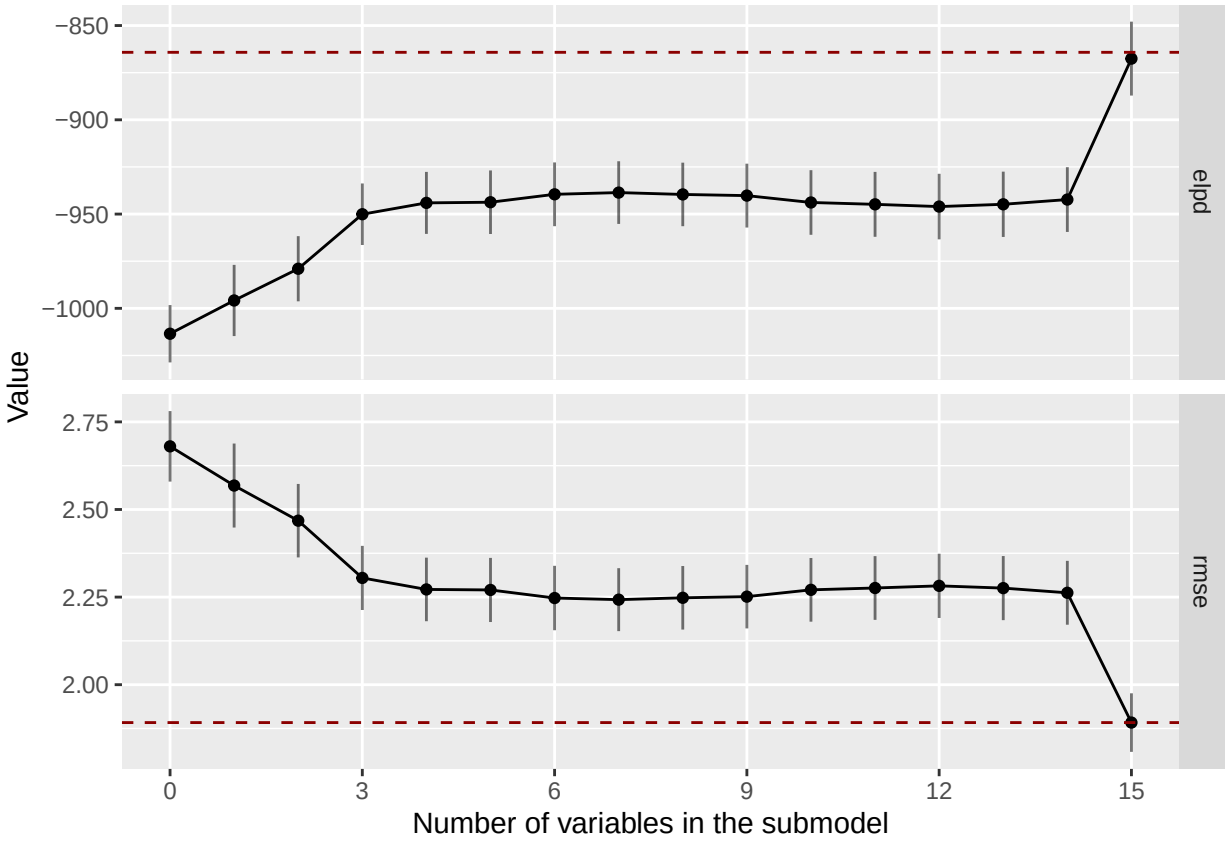
```
## Warning: Some Pareto k diagnostic values are too high. See help('pareto-k-diagnostic') for details.
```

```
## [1] "Computing LOOs..."
##   |                                                                      |
```

```
summary(cvs_quant_p1)
```

```
##    size  solution_terms       elpd  elpd.se
## 2     0            <NA> -1013.4742 15.29171
## 3     1 time_in_leipzig  -995.8257 18.98727
## 4     2         rearing  -979.0000 17.37981
## 5     3           group  -950.0854 16.41186
## 6     4    observer_mod  -944.0649 16.53589
## 7     5             sex  -943.7152 16.95251
## 8     6        rel_rank  -939.5206 17.01434
## 9     7             age  -938.6060 16.71206
## 10    8   sick_severity  -939.5859 16.94362
## 11    9         test_tp  -940.2080 17.02886
## 12   10        test_day  -943.8538 17.23026
## 13   11   time_outdoors  -944.8374 17.30622
## 14   12       dist_mean  -946.0202 17.48274
## 15   13       sociality  -944.8157 17.41873
## 16   14         le_mean  -942.3036 17.26396
## 17   15   (1 | subject)  -867.5398 19.71658
```

```
plot(cvs_quant_p1, stats = c('elpd', 'rmse'))
```



selected covariates: (1 | subject), time_in_leipzig, rearing, group

```
cvs_gaze_p1 <- cv_varsel(m_gaze_2l_p1,
                         search_terms = s_terms_gaze,
                         cv_method = "LOO", method = "forward",
                         seed = 2020)
```

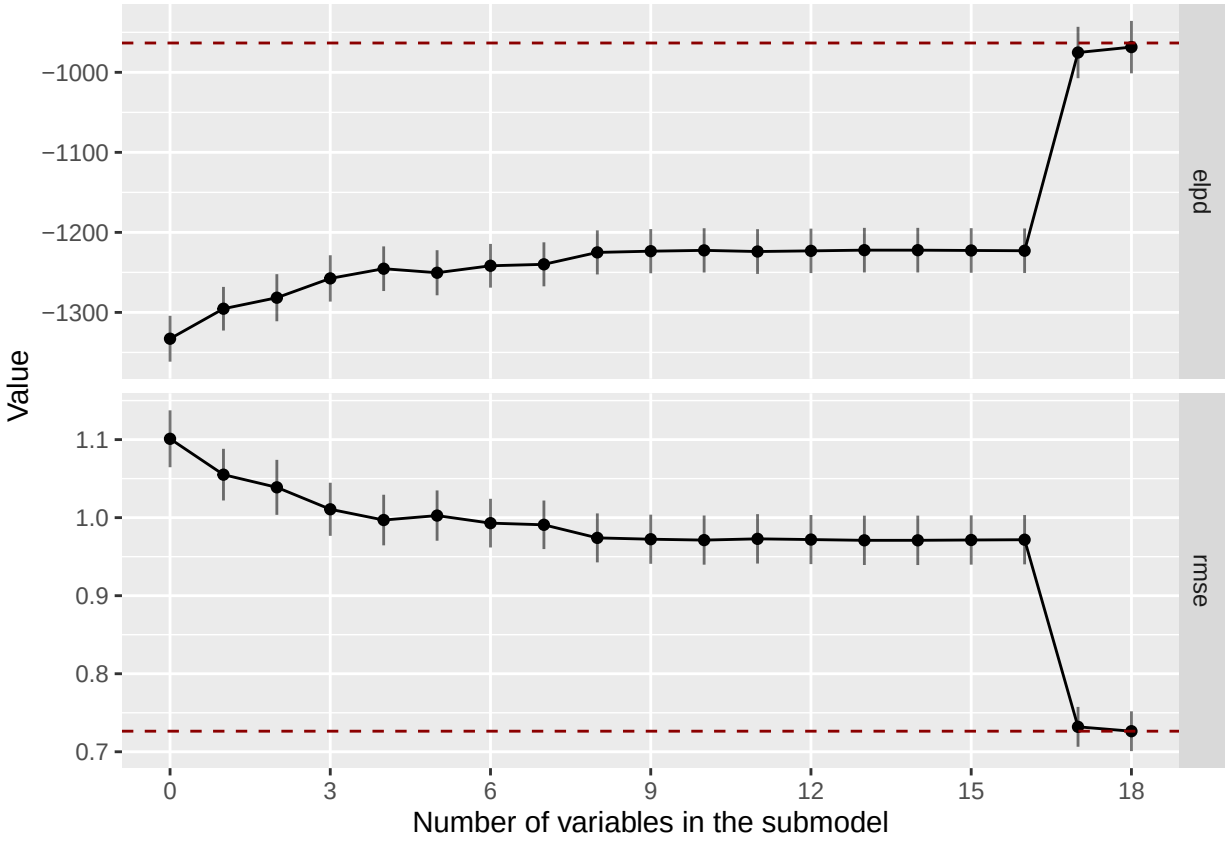
```
## Warning in cv_varsel.refmodel(refmodel, ...): K provided, but cv_method is LOO.

## Warning: Some Pareto k diagnostic values are too high. See help('pareto-k-diagnostic') for details.

## [1] "Computing LOOs..."
##   |                                                                              |
```

```
summary(cvs_gaze_p1)
```

```
##    size         solution_terms       elpd  elpd.se
```

```
## 2     0                   <NA> -1332.8640 28.82966
## 3     1                  group -1295.3877 27.42496
## 4     2                rearing -1281.6340 29.58314
## 5     3          time_outdoors -1257.5132 29.12716
## 6     4                    age -1245.3894 28.05369
## 7     5              sociality -1250.4262 28.32989
## 8     6                    sex -1241.7161 27.47326
## 9     7           sick_severity -1239.9077 27.67060
## 10    8            observer_mod -1225.0218 27.67382
## 11    9         time_in_leipzig -1223.4863 27.78601
## 12   10                    day2 -1222.4733 27.83285
## 13   11               dist_mean -1223.9155 28.11508
## 14   12              time_point -1223.0766 27.91434
## 15   13                test_day -1222.2077 28.02984
## 16   14                 test_tp -1222.2278 28.04756
## 17   15                rel_rank -1222.5950 28.00839
## 18   16                 le_mean -1222.9229 28.02147
## 19   17           (1 | subject)  -975.2275 32.28426
## 20   18 (time_point | subject)  -968.4631 32.93261
```

```
plot(cvs_gaze_p1, stats = c('elpd', 'rmse'))
```



selected covariates: (1 | subject), group, rearing, time_outdoors, age, sociality, sex, sick_severity, observer_mod

Phase 2

```
cvs_cau_p2 <- cv_varsel(m_cau_2l_p2,
                        search_terms = s_terms,
                        cv_method = "LOO", method = "forward",
                        seed = 2022)
```

```
## Warning in cv_varsel.refmodel(refmodel, ...): K provided, but cv_method is LOO.
```

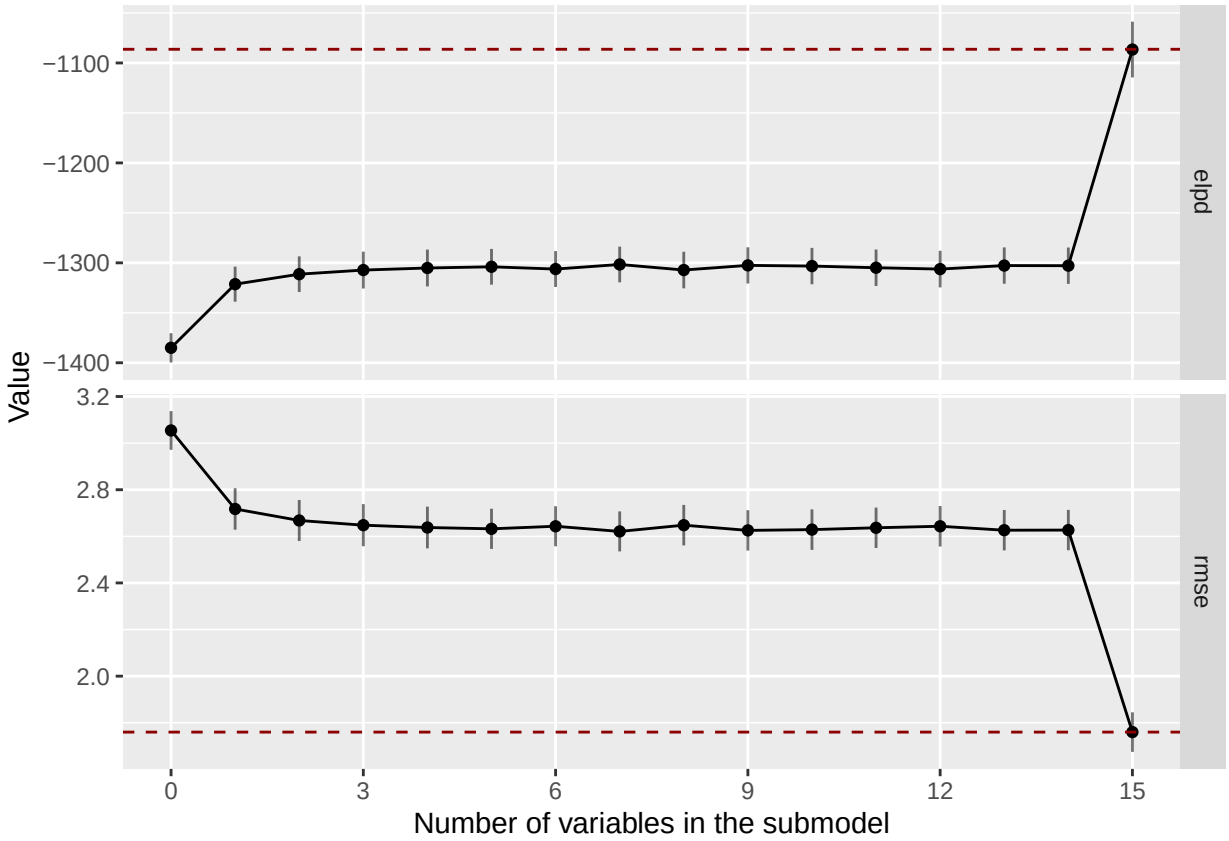
```
## Warning: Some Pareto k diagnostic values are too high. See help('pareto-k-diagnostic') for details.
```

```
## [1] "Computing LOOs..."
##   |                                                                              |
```

```
summary(cvs_cau_p2)
```

```
##    size  solution_terms      elpd  elpd.se
## 2     0            <NA> -1385.016 14.69496
## 3     1           group -1321.352 17.64576
## 4     2   time_outdoors -1311.360 17.94981
## 5     3 time_in_leipzig -1307.235 18.54256
## 6     4             age -1305.158 18.56643
## 7     5         rearing -1303.951 17.98294
## 8     6    observer_mod -1306.220 18.07087
## 9     7   sick_severity -1301.649 17.94775
## 10    8       sociality -1307.202 18.40965
## 11    9             sex -1302.558 18.23648
## 12   10        test_day -1303.249 18.32480
## 13   11        rel_rank -1304.890 18.34704
## 14   12       dist_mean -1306.265 18.43430
## 15   13         test_tp -1302.741 18.27451
## 16   14         le_mean -1302.859 18.27852
## 17   15   (1 | subject) -1086.583 28.06979
```

```
plot(cvs_cau_p2, stats = c('elpd', 'rmse'))
```



selected covariates: (1 | subject), group, time_outdoors, (time_in_leipzig?)

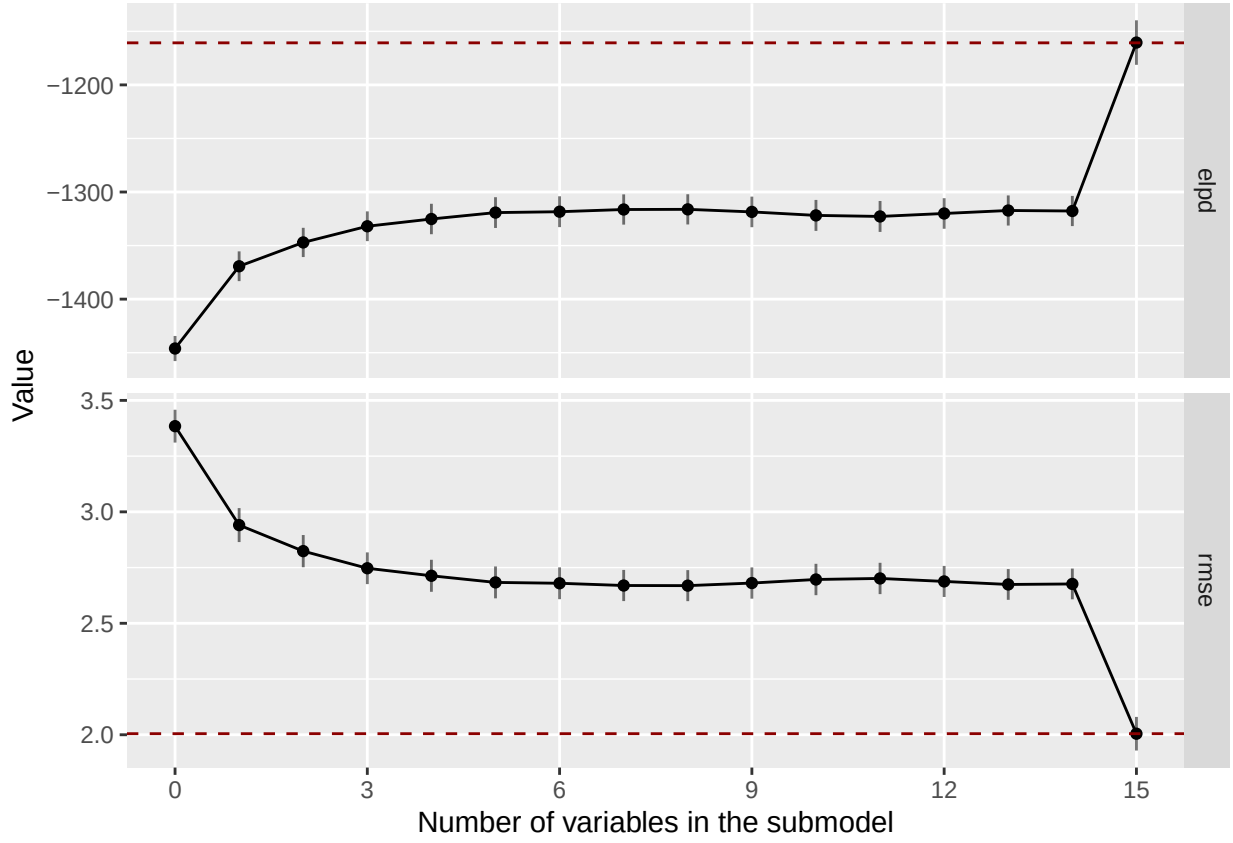
```
cvs_inf_p2 <- cv_varsel(m_inf_2l_p2,
                        search_terms = s_terms,
                        cv_method = "LOO", method = "forward",
                        seed = 2022)
```

```
## Warning in cv_varsel.refmodel(refmodel, ...): K provided, but cv_method is LOO.

## Warning: Quick-TRANSfer stage steps exceeded maximum (= 600000)

## Warning: Some Pareto k diagnostic values are slightly high. See help('pareto-k-diagnostic') for deta

## [1] "Computing LOOs..."
##   |                                                                              |
```

```
summary(cvs_inf_p2)
```

```
##    size  solution_terms      elpd  elpd.se
## 2     0            <NA> -1446.101 11.77939
## 3     1 time_in_leipzig -1369.305 13.97695
## 4     2           group -1347.068 13.73156
## 5     3             age -1331.969 13.97187
## 6     4   time_outdoors -1325.193 14.28571
## 7     5             sex -1319.204 14.43684
## 8     6       sociality -1318.384 14.48859
## 9     7   sick_severity -1316.323 14.19400
## 10    8         rearing -1316.190 14.17482
## 11    9       dist_mean -1318.566 14.36981
## 12   10         le_mean -1321.842 14.52652
## 13   11        rel_rank -1322.805 14.52641
## 14   12        test_day -1320.042 14.34843
## 15   13    observer_mod -1317.258 14.14640
## 16   14         test_tp -1317.728 14.16571
## 17   15   (1 | subject) -1160.477 20.89182
```

```
plot(cvs_inf_p2, stats = c('elpd', 'rmse'))
```



selected covariates: (1 | subject), time_in_leipzig, group, age, time_outdoors

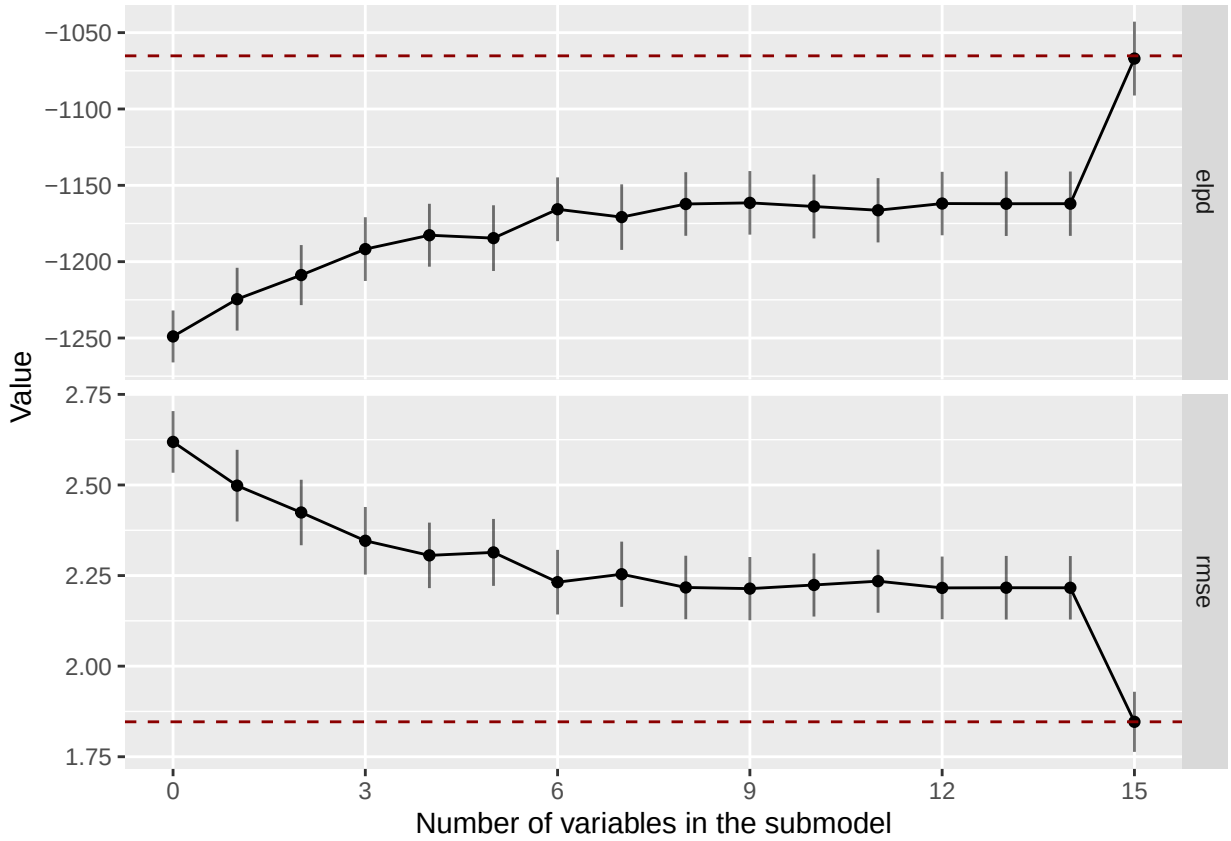
```
cvs_quant_p2 <- cv_varsel(m_quant_2l_p2,
                          search_terms = s_terms,
                          cv_method = "LOO", method = "forward",
                          seed = 2022)
```

```
## Warning in cv_varsel.refmodel(refmodel, ...): K provided, but cv_method is LOO.

## Warning: Quick-TRANSfer stage steps exceeded maximum (= 600000)

## Warning: Some Pareto k diagnostic values are slightly high. See help('pareto-k-diagnostic') for deta

## [1] "Computing LOOs..."
##   |                                                                              |
```

```
summary(cvs_quant_p2)
```

```
##    size  solution_terms      elpd  elpd.se
## 2     0            <NA> -1248.971 17.10132
## 3     1        rel_rank -1224.566 20.68574
## 4     2         rearing -1208.788 19.77086
## 5     3 time_in_leipzig -1191.770 20.98866
## 6     4           group -1182.687 20.72264
## 7     5    observer_mod -1184.582 21.63684
## 8     6   time_outdoors -1165.682 21.00602
## 9     7         test_tp -1170.812 21.58873
## 10    8       dist_mean -1162.232 20.93727
## 11    9        test_day -1161.480 20.93512
## 12   10         le_mean -1163.851 21.03599
## 13   11   sick_severity -1166.339 21.17300
## 14   12             age -1161.928 20.89748
## 15   13             sex -1162.056 21.23606
## 16   14       sociality -1162.023 21.19257
## 17   15   (1 | subject) -1066.990 24.32482
```

```
plot(cvs_quant_p2, stats = c('elpd', 'rmse'))
```



selected covariates: (1 | subject), rel_rank, rearing, time_in_leipzig, group, time_outdoors, test_tp

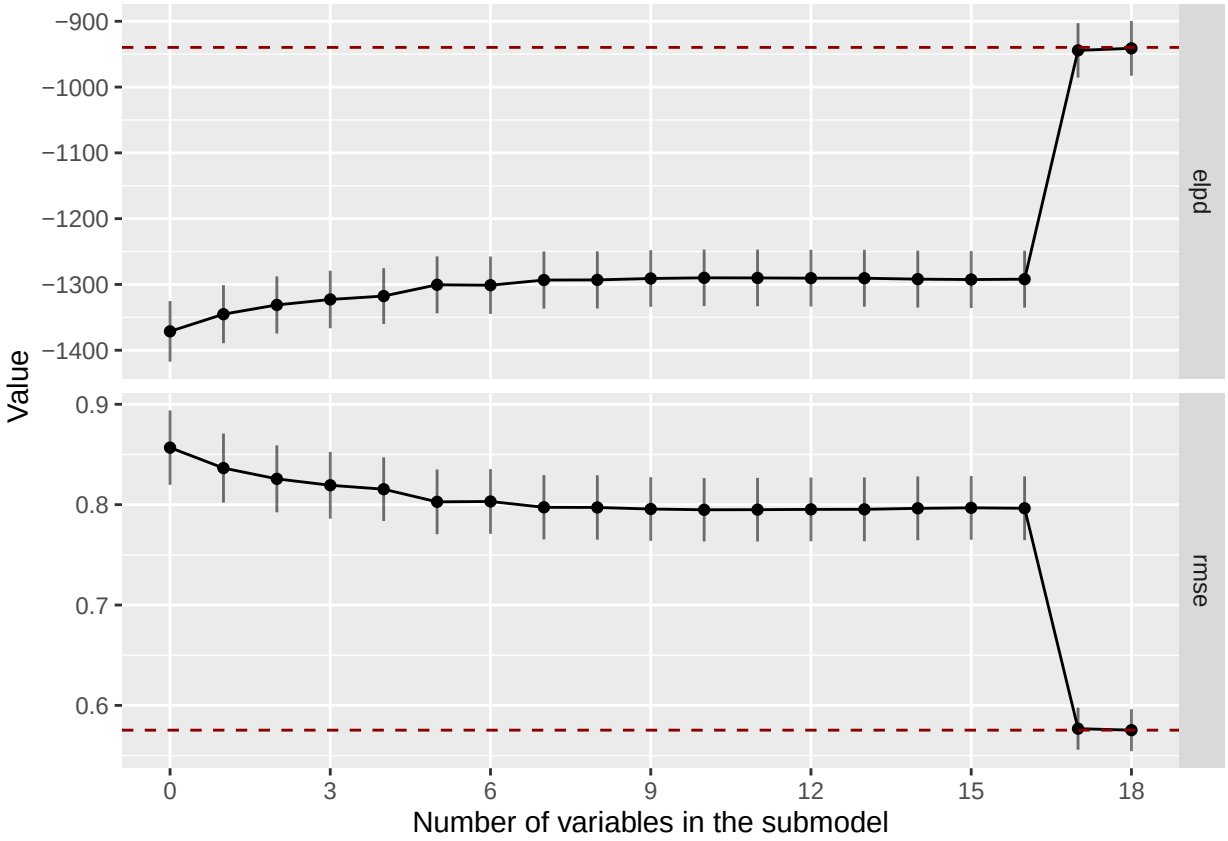
```
cvs_gaze_p2 <- cv_varsel(m_gaze_2l_p2,
                         search_terms = s_terms_gaze,
                         cv_method = "LOO", method = "forward",
                         seed = 2022)
```

```
## Warning in cv_varsel.refmodel(refmodel, ...): K provided, but cv_method is LOO.

## Warning: Quick-TRANSfer stage steps exceeded maximum (= 600000)

## Warning: Some Pareto k diagnostic values are slightly high. See help('pareto-k-diagnostic') for deta

## [1] "Computing LOOs..."
##   |                                                                              |
```

```
summary(cvs_gaze_p2)
```

```
##    size         solution_terms       elpd  elpd.se
## 2     0                   <NA> -1371.3280 46.37679
## 3     1                  group -1345.2073 44.37327
## 4     2                    sex -1331.1870 43.67917
## 5     3           observer_mod -1322.8534 44.06713
## 6     4                    age -1317.6484 42.56238
## 7     5                rearing -1300.5452 43.45194
## 8     6          sick_severity -1301.1635 43.83051
## 9     7              sociality -1293.3058 43.57111
## 10    8        time_in_leipzig -1293.1034 43.69256
## 11    9               rel_rank -1290.9634 43.25502
## 12   10              test_day -1289.9420 43.15980
## 13   11                  day2 -1290.1149 43.27658
## 14   12            time_point -1290.4706 43.39314
## 15   13               le_mean -1290.5677 43.41433
## 16   14             dist_mean -1291.9200 43.52289
## 17   15               test_tp -1292.5802 43.56191
## 18   16          time_outdoors -1292.0216 43.54598
## 19   17          (1 | subject)  -944.2455 41.60639
## 20   18 (time_point | subject)  -941.1030 41.83415
```

```
plot(cvs_gaze_p2, stats = c('elpd', 'rmse'))
```



selected covariates: (1 | subject), group, sex, observer_mod, age, (rearing?)

```
cvs_grat_p2 <- cv_varsel(m_grat_2l_p2,
                         search_terms = s_terms,
                         cv_method = "LOO", method = "forward",
                         seed = 2022)
```

```
## Warning in cv_varsel.refmodel(refmodel, ...): K provided, but cv_method is LOO.
```

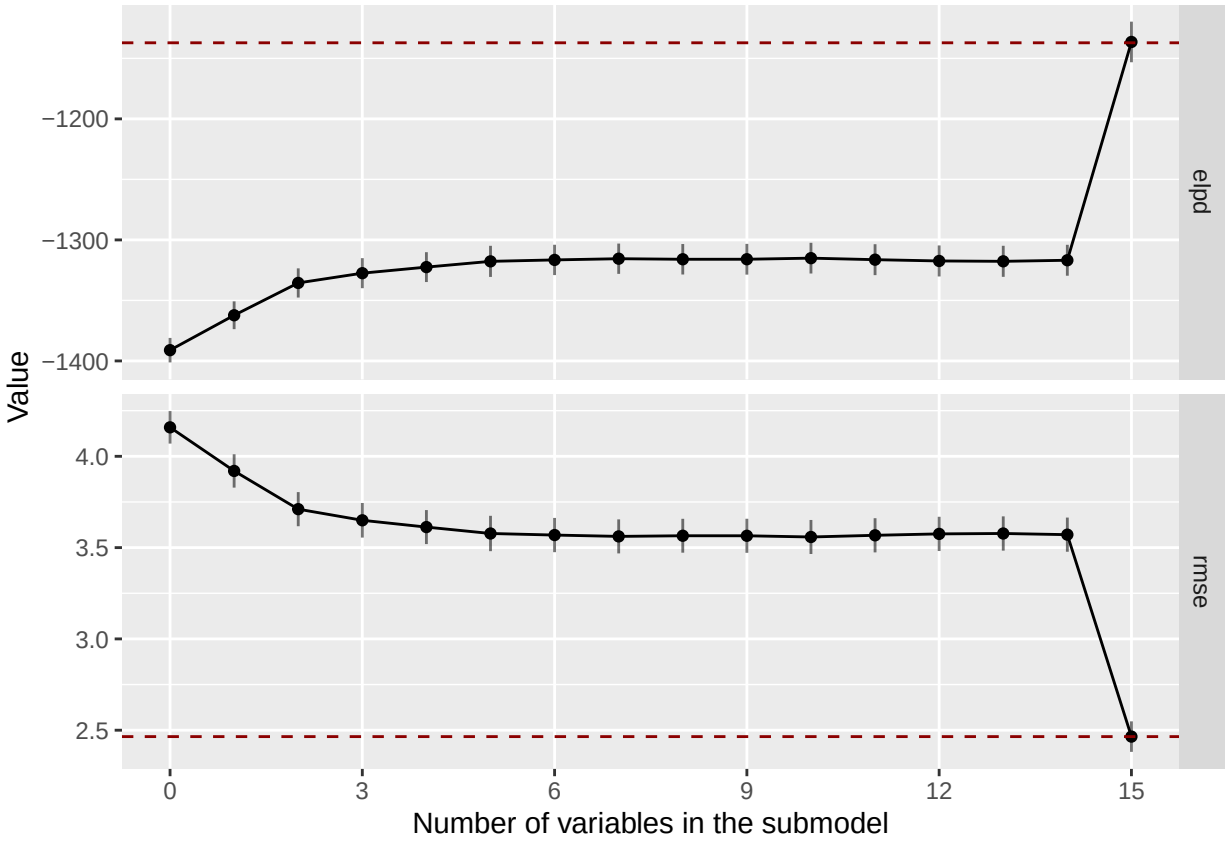
```
## Warning: Some Pareto k diagnostic values are slightly high. See help('pareto-k-diagnostic') for deta
```

```
## [1] "Computing LOOs..."
##   |                                                                              |
```

```
summary(cvs_grat_p2)
```

```
##    size  solution_terms      elpd  elpd.se
## 2     0            <NA> -1391.109 10.17323
## 3     1 time_in_leipzig -1362.270 11.55423
## 4     2    observer_mod -1335.562 12.12460
## 5     3             sex -1327.493 12.48185
## 6     4        rel_rank -1322.476 12.40804
## 7     5   sick_severity -1317.736 12.92059
## 8     6   time_outdoors -1316.543 12.61068
## 9     7         test_tp -1315.540 12.58188
## 10    8           group -1315.999 12.66718
## 11    9       sociality -1315.976 12.78212
## 12   10        test_day -1315.085 12.75679
## 13   11             age -1316.340 12.84615
## 14   12         rearing -1317.399 12.89820
## 15   13         le_mean -1317.696 12.90063
## 16   14       dist_mean -1316.820 12.85426
## 17   15   (1 | subject) -1136.435 16.87488
```

```
plot(cvs_grat_p2, stats = c('elpd', 'rmse'))
```



selected covariates: (1 | subject), time_in_leipzig, observer_mod, sex, rel_rank, sick_severity

```
saveRDS(list(m_cau_2l_p1, m_inf_2l_p1, m_quant_2l_p1, m_gaze_2l_p1,
             m_cau_2l_p2, m_inf_2l_p2, m_quant_2l_p2, m_gaze_2l_p2, m_grat_2l_p2,
             loo_p1, loo_p2),
     file = "results/ref_models.rds")

saveRDS(list(cvs_cau_p1, cvs_inf_p1, cvs_quant_p1, cvs_gaze_p1,
             cvs_cau_p2, cvs_inf_p2, cvs_quant_p2, cvs_gaze_p2, cvs_grat_p2),
     file = "results/projection_results.rds")
```