

Package ‘MPTmultiverse’

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Title Multiverse Analysis of Multinomial Processing Tree Models

Version 0.4-3

Description Statistical or cognitive modeling usually requires a number of more or less arbitrary choices creating one specific path through a 'garden of forking paths'. The multiverse approach (Steegen, Tuerlinckx, Gelman, & Vanpaemel, 2016, <[doi:10.1177/1745691616658637](https://doi.org/10.1177/1745691616658637)>) offers a principled alternative in which results for all possible combinations of reasonable modeling choices are reported. MPTmultiverse performs a multiverse analysis for multinomial processing tree (MPT, Riefer & Batchelder, 1988, <[doi:10.1037/0033-295X.95.3.318](https://doi.org/10.1037/0033-295X.95.3.318)>) models combining maximum-likelihood/frequentist and Bayesian estimation approaches with different levels of pooling (i.e., data aggregation) as described in Singmann et al. (2024, <[doi:10.1037/bul0000434](https://doi.org/10.1037/bul0000434)>). For the frequentist approaches, no pooling (with and without parametric or nonparametric bootstrap) and complete pooling are implemented using MPTinR <<https://cran.r-project.org/package=MPTinR>>. For the Bayesian approaches, no pooling, complete pooling, and three different variants of partial pooling are implemented using TreeBUGS <<https://cran.r-project.org/package=TreeBUGS>>. The main function is fit_mpt() which performs the multiverse analysis in one call.

URL <https://github.com/mpt-network/MPTmultiverse>

BugReports <https://github.com/mpt-network/MPTmultiverse/issues>

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check_results	<i>Check results from MPTmultiverse</i>
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Description

Set of helper functions that allow checking if model estimation worked as intended. Depending on the method and function, these functions return slightly different information.

Usage

```
check_results(results)

write_check_results(DATA_FILE, results, append = FALSE)

check_set(results)
```

Arguments

results	An object of class multiverseMPT.
DATA_FILE	character string. File name to use.
append	logical. If TRUE, output will be appended to DATA_FILE; otherwise, it will overwrite the contents of DATA_FILE.

Details

`check_results` prints relatively verbose output detailing diagnostic information for each method to the console. For the frequentist methods, this is based on either the rank of the observed Fischer (or Hessian) matrix of the MLE estimate or based on empirical identifiability (based either on repeated re-runs or the width of the bootstrapped parameter distribution). For the Bayesian methods, this is convergence statistics R-hat and number of effective samples. `write_check_results` writes the results of `check_results` to a specified file (instead of printing it to the console).

`check_set` returns a tibble with one row, where each expected method corresponds to a column with a boolean (TRUE/FALSE) value. Entries TRUE correspond to no problem and FALSE correspond to problems. FALSE means the method is either missing from the results file or (for the Bayesian methods) there are core parameters for which the convergence criteria defined in `getOption("MPTmultiverse")` are not met.

Examples

```
load(file = system.file("extdata", "results_bayen_kuhlmann.RData",
                       package = "MPTmultiverse"))
## prints checks to console
check_results(results)

## returns tibble with single row
check_set(results)
```

Description

Performs a multiverse analysis for multinomial processing tree (MPT) models across different levels of pooling (i.e., data aggregation) and across maximum-likelihood/frequentist and Bayesian estimation approaches as described in Singmann et al. (2024). For the frequentist approaches, no pooling (with and without parametric or nonparametric bootstrap) and complete pooling are implemented using **MPTinR**. For the Bayesian approaches, no pooling, complete pooling, and three different variants of partial pooling are implemented using **TreeBUGS**. Requires data on a by-participant level with each row corresponding to data from one participant (i.e., different response categories correspond to different columns) and the data can contain a single between-subjects condition. Model equations need to be passed as a .eqn model file and category labels (first column in .eqn file) need to match the column names in data. Results are returned in one tibble with one row per estimation method.

Usage

```
fit_mpt(model, dataset, data, id = NULL, condition = NULL, core = NULL, method)
```

Arguments

model	A model definition, typically the path to an .eqn model file containing the model equations. Category names need to match column names in data.
dataset	scalar character vector. Name of the data set that will be copied to the results tibble.
data	A <code>data.frame</code> containing the data. Column names need to match category names in <code>model</code> (i.e., different from MPTinR behavior, order of categories is not important, matching is done via name).
id	scalar character vector. Name of the column that contains the subject identifier. If not specified, it is assumed that each row represents observations from one participant.
condition	scalar character vector. Name of the column specifying a between-subjects factor. If not specified, no between-subjects comparisons are performed.
core	character vector defining the core parameters of interest, e.g., <code>core = c("Dn", "Do")</code> . All other parameters are treated as auxiliary parameters.
method	character vector specifying which analysis approaches should be performed (see Description below). Defaults to all available methods.

Details

This function is a fancy wrapper for packages **MPTinR** and **TreeBUGS** applying various frequentist and Bayesian estimation methods to the same data set with different levels of pooling/aggregation using a single MPT model and collecting the results in one `tibble` where each row corresponds to one estimation method. Note that parameter restrictions (e.g., equating different parameters or fixing them to a constant) need to be part of the model (i.e., the .eqn file) and cannot be passed as an argument.

The settings for the various methods are specified via function `mpt_options`. The default settings use all available cores for calculating the bootstrap distribution as well as independent MCMC chains and should be appropriate for most situations.

The data can have a single between-subjects condition (specified via `condition`). This condition can have more than two levels. If specified, the pairwise differences between each level, the standard error of the differences, and confidence-intervals of the differences are calculated for each parameter. Please note that `condition` is silently converted to character in the output. Thus, a specific ordering of the factor levels in the output cannot be guaranteed. If the data has more than one between-subjects condition, these need to be combined into one condition for this function.

To include multiple within-subjects conditions, include separate trees and separate sets of parameters for each within-subjects condition in your .eqn file.

Pooling: The following pooling levels are provided (not all by all estimation approaches, see below).

- *Complete pooling:* The traditional analysis approach in the MPT literature in which data is aggregated across participants within each between-subjects condition. This approach assumes that there are no individual differences. Produces one set of model parameters per condition.

- *No pooling*: The model is fitted to the individual-level data in an independent manner (i.e., no data aggregation). This approach assumes that there is no similarity across participants and usually requires considerable amounts of data on the individual-level. Produces one set of model parameters per participant. Group-level estimates are based on averaging the individual-level estimates.
- *Partial pooling*: Data is fitted simultaneously to the individual-level data assuming that the individual-level parameters come from a group-level distribution. Individual-level parameters are often treated as random-effects which are nested in the group-level parameters, which is why this approach is also called hierarchical modeling. This approach assumes both individual-level differences and similarities. Produces one set of model parameters per participant plus one set of group-level parameters. Thus, although partial pooling models usually have more parameters than the no-pooling approaches, they are usually less flexible as the hierarchical-structure provides regularization of the individual-level parameters.

Implemented Estimation Methods: Maximum-likelihood estimation with **MPTinR** via [fit.mpt](#):

- "asymptotic_complete": Asymptotic ML theory, complete pooling
- "asymptotic_no": Asymptotic ML theory, no pooling
- "pb_no": Parametric bootstrap, no pooling
- "npb_no": Nonparametric bootstrap, no pooling

Bayesian estimation with **TreeBUGS**

- "simple": Bayesian estimation, no pooling (C++, [simpleMPT](#))
- "simple_pooling": Bayesian estimation, complete pooling (C++, [simpleMPT](#))
- "trait": latent-trait model, partial pooling (JAGS, [traitMPT](#))
- "trait_uncorrelated": latent-trait model without correlation parameters, partial pooling (JAGS, [traitMPT](#))
- "beta": beta-MPT model, partial pooling (JAGS, [betaMPT](#))
- "betacpp": beta-MPT model, partial pooling (C++, [betaMPTcpp](#))

Frequentist/Maximum-Likelihood Methods: For the *complete pooling asymptotic approach*, the group-level parameter estimates and goodness-of-fit statistics are the maximum-likelihood and G-squared values returned by **MPTinR**. The parameter differences are based on these values. for between-subjects comparisons, the standard errors of the differences are simply the pooled standard error of the individual parameters; for within-subjects comparisons, the standard errors of the differences are based on the respective linear transform of the estimated variance-covariance matrix calculated from the Hessian matrix. The overall fit (column *gof*) is based on an additional fit to the completely aggregated data.

For the *no pooling asymptotic approach*, the individual-level maximum-likelihood estimates are reported in column *est_indiv* and *gof_indiv* and provide the basis for the other results. Whether or not an individual-level parameter estimate is judged as identifiable (column *identifiable*) is based on separate fits with different random starting values. If, in these separate, fits the same objective criterion is reached several times (i.e., *Log_Likelihood* within .01 of best fit), but the parameter estimate differs (i.e., different estimates within .01 of each other), then an estimate is flagged as non-identifiable. If they are the same (i.e., within .01 of each other) they are marked as identifiable. The group-level parameters are simply the means of the identifiable individual-level parameters, the SE is the SE of the mean for these parameter (i.e., SD/\sqrt{N}), where N excludes non-identifiable parameters and these estimated as NA), and the CI is based on mean and SE. The group-level and overall fit is the sum of the individual G-squares, sum of individual-level

df, and corresponding chi-square df. The difference between the conditions and corresponding statistics are based on a t-test comparing the individual-level estimates (again, after excluding non-identifiable estimates). The CIs of the difference are based on the SEs (which are derived from a linear model equivalent to the t-test). Within-subjects comparisons are based on t-tests for paired observations.

The individual-level estimates of the bootstrap based no-pooling approaches are identical to the asymptotic ones. However, the SE is the SD of the bootstrapped distribution of parameter estimates, the CIs are the corresponding quantiles of the bootstrapped distribution, and the p-value is obtained from the bootstrapped G-square distribution. Identifiability of individual-level parameter estimates is also based on the bootstrap distribution of estimates. Specifically, we calculate the range of the CI (i.e., maximum minus minimum CI value) and flag those parameters as non-identifiable for which the range is larger than `mpt_options()$max_ci_indiv`, which defaults to 0.99. Thus, in the default settings we say a parameter is non-identifiable if the bootstrap based CI extends from 0 to 1. The group-level estimates are the mean of the identifiable individual-level estimates. The difference between conditions (as well as within conditions) is calculated in the same manner as for the asymptotic case using the identifiable individual-level parameter estimates.

Bayesian Methods: The *simple approaches* fit fixed-effects MPT models. "simple" uses no pooling and thus assumes independent uniform priors for the individual-level parameters. Group-level means are obtained as generated quantities by averaging the posterior samples across participants. "simple_pooling" aggregates observed frequencies across participants and assumes a uniform prior for the group-level parameters.

The *latent-trait approaches* transform the individual-level parameters to a latent probit scale using the inverse cumulative standard normal distribution. For these probit values, a multivariate normal distribution is assumed at the group level. Whereas "trait" estimates the corresponding correlation matrix of the parameters (reported in the column `est_rho`), "trait_uncorrelated" does not estimate this correlation matrix (i.e., parameters can still be correlated across individuals, but this is not accounted for in the model).

For all Bayesian methods, the posterior distribution of the parameters is summarized by the posterior mean (in the column `est`), posterior standard deviation (`se`), and credibility intervals (`ci_*`). For parameter differences (`test_between` and `test_within`) and correlations (`est_rho`), Bayesian p-values are computed (column `p`) by counting the relative proportion of posterior samples that are smaller than zero. Goodness of fit is tested with the `T1` statistic (observed vs. posterior-predicted average frequencies, `focus = "mean"`) and the `T2` statistic (observed vs. posterior-predicted covariance of frequencies, `focus = "cov"`).

Value

A tibble with one row per estimation method and the following columns:

1. `model`: Name of model file (copied from `model` argument), character
2. `dataset`: Name of data set (copied from `dataset` argument), character
3. `pooling`: character specifying the level of pooling with three potential values: `c("complete", "no", "partial")`
4. `package`: character specifying the package used for estimation with two potential values: `c("MPTinR", "TreeBUGS")`
5. `method`: character specifying the method used with the following potential values: `c("asymptotic", "PB/MLE", "NPB/MLE", "simple", "trait", "trait_uncorrelated", "beta", "betacpp")`

6. est_group: Group-level parameter estimates per condition/group.
7. est_indiv: Individual-level parameter estimates (if provided by method).
8. est_rho: Estimated correlation of individual-level parameters on the probit scale (only in method="trait").
9. test_between: Parameter differences between the levels of the between-subjects condition (if specified).
10. test_within: Within-subjects parameter differences.
11. gof: Overall goodness of fit across all individuals.
12. gof_group: Group-level goodness of fit.
13. gof_indiv: Individual-level goodness of fit.
14. fungibility: Posterior correlation of the group-level means `pnorm(mu)` (only in method="trait").
15. test_homogeneity: Chi-square based test of participant homogeneity proposed by Smith and Batchelder (2008). This test is the same for each estimation method.
16. convergence: Convergence information provided by the respective estimation method. For the asymptotic frequentist methods this is a `tibble` with rank of the Fisher matrix, the number of parameters (which should match the rank of the Fisher matrix), and the convergence code provided by the optimization algorithm (which is `nlinb`). The bootstrap methods contain an additional column, `parameter`, that contains the information which (if any) parameters are empirically non-identifiable based on the bootstrapped distribution of parameter estimates (see above for exact description). For the Bayesian methods this is a `tibble` containing information of the posterior distribution (i.e., mean, quantiles, SD, SE, n_eff, and R-hat) for each parameter.
17. estimation: Time it took for each estimation method and group.
18. options: Options used for estimation. Obtained by running `mpt_options()`

With the exception of the first five columns (i.e., after `method`) all columns are `list` columns typically holding one `tibble` per cell. The simplest way to analyze the results is separately per column using `unnest`. Examples for this are given below.

References

Singmann, H., Heck, D. W., Barth, M., Erdfelder, E., Arnold, N. R., Aust, F., Calanchini, J., Gümüs-dagli, F. E., Horn, S. S., Kellen, D., Klauer, K. C., Matzke, D., Meissner, F., Michalkiewicz, M., Schaper, M. L., Stahl, C., Kuhlmann, B. G., & Groß, J. (2024). Evaluating the robustness of parameter estimates in cognitive models: A meta-analytic review of multinomial processing tree models across the multiverse of estimation methods. *Psychological Bulletin*, 150(8), 965–1003. [doi:10.1037/bul0000434](https://doi.org/10.1037/bul0000434)

Smith, J. B., & Batchelder, W. H. (2008). Assessing individual differences in categorical data. *Psychonomic Bulletin & Review*, 15(4), 713-731. [doi:10.3758/PBR.15.4.713](https://doi.org/10.3758/PBR.15.4.713)

Examples

```
# -----
# MPT model definition & Data

EQN_FILE <- system.file("extdata", "prospective_memory.eqn", package = "MPTmultiverse")
```

```

DATA_FILE <- system.file("extdata", "smith_et_al_2011.csv", package = "MPTmultiverse")

### if .csv format uses semicolons ";" (e.g., German format):
# data <- read.csv2(DATA_FILE, fileEncoding = "UTF-8-BOM")
### if .csv format uses commata "," (international format):
data <- read.csv(DATA_FILE, fileEncoding = "UTF-8-BOM")
data <- data[c(1:10, 113:122),] ## select only subset of data for example
head(data)

COL_CONDITION <- "WM_EX" # name of the variable encoding group membership

# experimental condition should be labeled meaningfully ----
unique(data[[COL_CONDITION]])

data[[COL_CONDITION]] <- factor(
  data[[COL_CONDITION]]
  , levels = 1:2
  , labels = c("low_WM", "high_WM")
)

# define core parameters:
CORE <- c("C1", "C2")

## Not run:
op <- mpt_options()
## to reset default options (which you would want) use:
mpt_options("default")

mpt_options() # to see the settings
## Note: settings are also saved in the results tibble

## without specifying method, all are used per default
fit_all <- fit_mpt(
  model = EQN_FILE
  , dataset = DATA_FILE
  , data = data
  , condition = COL_CONDITION
  , core = CORE
)

mpt_options(op) ## reset options

## End(Not run)

load(system.file("extdata", "prospective_memory_example.rda", package = "MPTmultiverse"))

# Although we requested all 10 methods, only 9 worked:
fit_all$method
# Jags variant of beta MPT is missing.

# the returned method has a plot method. For example, for the group-level estimates:
plot(fit_all, which = "est")

```

```
## Not run:
### Full analysis of results requires dplyr and tidyr (or just 'tidyverse')
library("dplyr")
library("tidyr")

## first few columns identify model, data, and estimation approach/method
## remaining columns are list columns containing the results for each method
## use unnest to work with each of the results columns
glimpse(fit_all)

## Let us inspect the group-level estimates
fit_all %>%
  select(method, pooling, est_group) %>%
  unnest(c(est_group))

## which we can plot again
plot(fit_all, which = "est")

## Next we take a look at the GoF
fit_all %>%
  select(method, pooling, gof_group) %>%
  unnest(c(gof_group)) %>%
  as.data.frame()

# Again, we can plot it as well
plot(fit_all, which = "gof2") ## use "gof1" for overall GoF

## Finally, we take a look at the differences between conditions
fit_all %>%
  select(method, pooling, test_between) %>%
  unnest(test_between)

# and then we plot it
plot(fit_all, which = "test_between")

### Also possible to only use individual methods:
only_asymptotic <- fit_mpt(
  model = EQN_FILE
, dataset = DATA_FILE
, data = data
, condition = COL_CONDITION
, core = CORE
, method = "asymptotic_no"
)
only_asymptotic$est_group

bayes_complete <- fit_mpt(
  model = EQN_FILE
, dataset = DATA_FILE
, data = data
, condition = COL_CONDITION
, core = CORE
```

```

, method = "simple_pooling"
)
bayes_complete$est_group

## End(Not run)

```

get_info

Collect Model Equations and Data per Tree

Description

Helper function that collects model equation and data per tree for further analysis.

Usage

```

get_info(
  model,
  dataset,
  data,
  id = NULL,
  condition = NULL,
  include_data = FALSE,
  core = NULL,
  autosave = TRUE
)

```

Arguments

model	A model definition, typically the path to an .eqn model file containing the model equations. Category names need to match column names in data.
dataset	scalar character vector. Name of the data set that will be copied to the results tibble.
data	A data.frame containing the data. Column names need to match category names in model (i.e., different from MPTinR behavior, order of categories is not important, matching is done via name).
id	scalar character vector. Name of the column that contains the subject identifier. If not specified, it is assumed that each row represents observations from one participant.
condition	scalar character vector. Name of the column specifying a between-subjects factor. If not specified, no between-subjects comparisons are performed.
include_data	If FALSE (the default) the response frequencies are not part of the output, but only the number of observations per tree. If TRUE, the full data is part of the output.
core	character vector defining the core parameters of interest, e.g., core = c("Dn", "Do"). All other parameters are treated as auxiliary parameters.
autosave	If TRUE (the default) the results are automatically saved in the current working directory in a file with name derived from both model and data.

Value

A list. If `autosave = TRUE`, the list is also saved in the current working directory.

`mpt_options`

Options Settings for MPT Comparison

Description

Set and examine a variety of *options* which affect the way MPT models are estimated.

Usage

`mpt_options(...)`

Arguments

...

Named parameters to set. Possible values are:

- `bootstrap_samples`: Numeric. The number of bootstrap samples to be drawn for the calculation parametric bootstrap confidence intervals.
- `n.optim`: Numeric. The number of optimization runs for the models estimated with maximum-likelihood methods.
- `n.chains`: Numeric. The number of MCMC chains for the Bayesian models.
- `n.adapt`: Numeric. The number of iterations for adaptation.
- `n.burnin`: Numeric. The number of burn-in/warm-up iterations.
- `n.iiter`: Numeric. The total number of iterations to be drawn *after* adaptation (including burnin).
- `n.thin`: Numeric. Thinning interval.
- `Rhat_max`: Numeric. The maximum rhat.
- `Neff_min`: Numeric. The minimum number of effective samples you are willing to accept.
- `extend_max`: Numeric.
- `n.PPP`: Numeric. The number of posterior predictive samples drawn for the calculation of fit statistics T_1 and T_2 .
- `n.CPU`: Numeric. The number of CPU cores to use for obtaining the parametric bootstrap distribution. Defaults to the number of available cores on your machine.
- `ci_size`: Numeric.
- `max_ci_indiv`: Numeric. Used for excluding individual parameter estimates in the bootstrap approaches. If the range of the CI (i.e., distance between minimum and maximum) is larger than this value, the estimate is excluded from the group-level estimates.
- `silent_jags`: Logical. Whether to suppress JAGS output.
- `save_models`: Logical. Default is `FALSE` which does not save the individual MCMC samples in `.RData` files. Instead only summaries are retained in `results` object.

Examples

```
# Examine options:
mpt_options()

# Set number of MCMC chains to 20:
mpt_options(n.chains = 20)
mpt_options()
```

plot.multiverseMPT	<i>Plot multiverseMPT</i>
--------------------	---------------------------

Description

Plot the results from a multiverse MPT analysis.

Usage

```
## S3 method for class 'multiverseMPT'
plot(x, which = "est", save = FALSE, ...)
```

Arguments

x	An object of class <code>multiverseMPT</code> .
which	Character. Which information should be plotted? Possible values are "est" for parameter estimates, "test_between" for between-subjects comparisions, "gof1" for overall goodness-of-fit statistics, and "gof2" for group-wise goodness-of-fit statistics.
save	Logical. Indicates whether the plot should also be saved as a .pdf file.
...	ignored.

write_results	<i>Write Results of Multiverse Analysis to csv-Files</i>
---------------	--

Description

Exports the results to csv format.

Usage

```
write_results(results, path = "MPTmultiverse_")
```

Arguments

results	An object of class <code>multiverseMPT</code> .
path	a path where to save the files (e.g., "C:/results/modelX_dataY_")

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