

cbm manual

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This document serves as the manual of cbm (computational and behavioral modeling) toolbox. cbm provides tools for hierarchical Bayesian inference (HBI). See the corresponding manuscript ([here](#)) for more information about the HBI and its comparison with other methods. You can download cbm [here](#). In this manual, I present two well-known examples and explain how cbm tools should be used to perform Bayesian model comparison, parameter estimation and inference at the group level. To be able to follow this manual, you need to be familiar with matlab syntax (cbm will be published soon in other languages, particularly python).

1 Example 1: bandit task

I assume that the current directory contains this manual and “codes” directory, as well as “example_RL_task” and “example_2step_task” directories. The codes directory contains all cbm matlab functions.

For using cbm tools, you need to know what is your model-space and code your own models. You can then use cbm to make inference. For this example, models code and data have been stored in the example_RL_task directory.

Suppose you have 40 subjects’ choice data in a 2-armed bandit task, in which subjects chose between two actions and received binary outcomes.

All data have been stored in a mat-file called all_data.mat in a cell format, in which each cell contains choice data and outcomes for one subject. First, enter the example_RL_task directory and then load those data:

```
In [1]: % enter the example_RL_task folder,
        % which contains data and models for this example
        % (assuming that you are in the directory of the manual)
        cd(fullfile('example_RL_task'));

In [2]: % load data
        fdata = load('all_data.mat');
        data = fdata.data;

        % data for each subject
        subj1 = data{1}; % subject 1
        subj2 = data{2}; % subject 2
        % and so on
```

For example, subj1 contains information of subject 1: subj1.actions are all actions and subj1.outcome are the corresponding outcomes.

Also suppose you have 2 candidate models. An RL model, which has a learning rate (α) and a decision noise (β) parameter. The other model is a dual- α RL model with two separate learning rates for positive and negative prediction errors (α_1 and α_2 , respectively) and a decision noise (β) parameter. See matlab functions `model_RL` and `model_dualRL` as examples.

It is important to remember that `cbm` does not care how your model works! It assumes that your models take parameters and data (of one subject) as input and produce a log-probability of data given the parameters (i.e. log-likelihood function). Tools in `cbm` only require that the input and output of models follow a specific format:

```
loglik = model(parameters,subj)
```

For example, for the `model_RL`, we have:

```
loglik = model_RL(parameters,subj1)
```

here `parameters` is a vector, which its size depends on the number of parameters of the `model_RL` (for `model_RL`, its size is 2). `subj1` is the structure containing data of subject 1 as indicated above. `loglik` is the log-likelihood of `subj1` data given `parameters`, as computed by `model_RL`.

We now use `cbm` tools to fit models to data. For this example, we use the two models implemented in `model_RL` and `model_dualRL` together with the data stored in `all_data.mat`. Data stored in `all_data` is a synthetic dataset of 40 subjects. The data of the first 10 subjects are generated by `model_RL` and the data of the next 30 subjects are generated by `model_dualRL`. Note, however, that `cbm` is not meant to provide a collection of different computational models. You should code your models for questions of your interest yourself. The tools in `cbm` fit your models to your data and compare the models given the data.

First, make sure that `cbm` is added to your matlab path and then load the data:

```
In [3]: addpath(fullfile('..','codes'));

        % load data from all_data.mat file
        fdata = load('all_data.mat');
        data = fdata.data;
```

Before using `cbm` tools, it is always good to check whether the format of the models is compatible with the `cbm`. To do that, create a random vector `parameters` and call the models:

```
In [4]: % data of subject 1
        subj1 = data{1};

        parameters = randn(1,2);
        F1 = model_RL(parameters,subj1)

        parameters = randn(1,3);
        F2 = model_dualRL(parameters,subj1)
```

F1 =

-200.9599

F2 =

-57.2434

Note that because parameters were randomly drawn, when you run the same code, it generates different values for F1 and F2. Also note that parameters are drawn from a normal distribution. In theory, RL models require constrained parameters (e.g. alpha between 0 and 1). In `model_RL` and `model_dualRL`, some transformations applied to the normally-distributed parameters to meet their theoretical bounds (see `model_RL` and `model_dualRL`). I'll explain later a bit more about transforming (normally-distributed) parameters in your models.

We checked the models with some random parameters. It is also good to check them with more extreme parameter values:

```
In [5]: parameters = [-10 10];  
        F1 = model_RL(parameters,subj1)  
  
        parameters = [-10 10 10];  
        F2 = model_dualRL(parameters,subj1)
```

F1 =

-654.4651

F2 =

-169.2246

Again, F1 and F2 should be real negative scalars.

After making sure that `model_RL` and `model_dualRL` work fine, we now use `cbm` tools to fit models to data.

First, we should run `cbm_lap`, which fits every model to each subject data separately (i.e. in a non-hierarchical fashion). `cbm_lap` employs Laplace approximation, which needs a normal prior for every parameter. We set zero as the prior mean. We also assume that the prior variance for all parameters is 6.25. This variance is large enough to cover a wide range of parameters with no excessive penalty (see supplementary materials of the reference article for more details on how this variance is calculated).

```
In [6]: v = 6.25;  
        prior_RL = struct('mean',zeros(2,1),'variance',v); % note dimension of 'mean'  
        prior_dualRL = struct('mean',zeros(3,1),'variance',v); % note dimension of 'mean'
```

We also need to specify a file-address for saving the output of each model:

```
In [7]: fname_RL = 'lap_RL.mat';  
        fname_dualRL = 'lap_dualRL.mat';
```

Now we run `cbm_lap` for each model. Note that `model_RL` and `model_dualRL` are both in the current directory.

```
In [8]: cbm_lap(data, @model_RL, prior_RL, fname_RL);  
        % Running this command, prints a report on your matlab output  
        % (e.g. on the command window)
```

```
cbm_lap 18-Jun-2019 22:04:28
```

```
=====
```

```
Number of samples: 40
```

```
Number of parameters: 2
```

```
Number of initializations: 14
```

```
-----
```

```
Subject: 01
```

```
Subject: 02
```

```
Subject: 03
```

```
Subject: 04
```

```
Subject: 05
```

```
Subject: 06
```

```
Subject: 07
```

```
Subject: 08
```

```
Subject: 09
```

```
Subject: 10
```

```
Subject: 11
```

```
Subject: 12
```

```
Subject: 13
```

```
Subject: 14
```

```
Subject: 15
```

```
Subject: 16
```

```
Subject: 17
```

```
Subject: 18
```

```
Subject: 19
```

```
Subject: 20
```

```
Subject: 21
```

```
Subject: 22
```

```
Subject: 23
```

```
Subject: 24
```

```
Subject: 25
```

```
Subject: 26
```

```
Subject: 27
```

```
Subject: 28
```

```
Subject: 29
```

```
Subject: 30
```

```
Subject: 31
```

```
Subject: 32
Subject: 33
Subject: 34
Subject: 35
Subject: 36
Subject: 37
Subject: 38
Subject: 39
Subject: 40
done :]
```

Also run `cbm_lap` for `model_dualRL`

```
In [9]: cbm_lap(data, @model_dualRL, prior_dualRL, fname_dualRL);
        % Running this command, prints a report on your matlab output
        % (e.g. on the command window)
```

```
cbm_lap 18-Jun-2019 22:04:35
```

```
=====
```

```
Number of samples: 40
```

```
Number of parameters: 3
```

```
Number of initializations: 21
```

```
-----
```

```
Subject: 01
Subject: 02
Subject: 03
Subject: 04
Subject: 05
Subject: 06
Subject: 07
Subject: 08
Subject: 09
Subject: 10
Subject: 11
Subject: 12
Subject: 13
Subject: 14
Subject: 15
Subject: 16
Subject: 17
Subject: 18
Subject: 19
Subject: 20
Subject: 21
Subject: 22
Subject: 23
```

```
Subject: 24
Subject: 25
Subject: 26
Subject: 27
Subject: 28
Subject: 29
Subject: 30
Subject: 31
Subject: 32
Subject: 33
Subject: 34
Subject: 35
Subject: 36
Subject: 37
Subject: 38
Subject: 39
Subject: 40
done :]
```

Let's take a look at the file saved by the cbm_lap:

```
In [10]: fname = load('lap_RL.mat');
         cbm    = fname.cbm;
         % look at fitted parameters
         cbm.output.parameters
```

```
ans =
```

```
-0.9099    -0.1596
-2.2959     0.2281
-1.8879     0.0641
-2.9416     0.6446
 0.1626    -1.7082
-2.3983    -0.2423
-2.2385    -0.3139
-1.1035    -0.1045
-0.1508    -1.0967
-3.1319     0.3766
-1.6312     2.8806
-1.9657     1.4585
 1.3684     1.3809
 0.2462     1.2869
 0.5822     1.6409
 0.1195     0.7961
 0.2869     1.3080
-0.9798     2.4429
```

-0.2855	1.3087
0.6944	2.0278
1.3887	1.4371
0.0819	1.0805
-0.5053	1.9617
0.4317	1.4263
0.1695	0.8347
0.6204	-0.8997
0.0504	2.2729
-0.2048	-0.2258
0.4743	1.2425
0.5359	0.7142
1.0363	0.0334
0.7106	0.2387
-1.4016	1.7652
0.0332	2.4478
-0.8369	1.4053
-0.0262	0.6052
0.1145	1.2742
0.3787	1.6922
0.0006	2.0756
1.6417	0.6821

Note that these values are normally-distributed parameters (I'll explain later how to obtain bounded parameters). The order of parameters depend on how they have been coded in the corresponding model. In model_RL, the first parameter is alpha and the second one is beta. Therefore, here the first column corresponds to alpha and the second one to beta.

Now we can do hierarchical Bayesian inference using cbm_hbi. cbm_hbi needs 4 inputs. The good news is that you already have all of them!

```
In [11]: % 1st input: data for all subjects
         fdata = load('all_data.mat');
         data  = fdata.data;

         % 2nd input: a cell input containing function handle to models
         models = {@model_RL, @model_dualRL};
         % note that by handle, I mean @ before the name of the function

         % 3rd input: another cell input containing file-address to files saved by cbm_lap
         fcbm_maps = {'lap_RL.mat', 'lap_dualRL.mat'};
         % note that they corresponds to models (so pay attention to the order)

         % 4th input: a file address for saving the output
         fname_hbi = 'hbi_RL_dualRL.mat';
```

Now, we are ready to run cbm_hbi:

```
In [12]: cbm_hbi(data,models,fcbm_maps,fname_hbi);
         % Running this command, prints a report on your matlab output
         % (e.g. on the command window)
```

```
cbm_hbi_hbi                                     18-Jun-2019 22:04:43
Running hierarchical bayesian inference (HBI)...
```

```
HBI has been initialized according to
    lap_RL.mat [for model 1]
    lap_dualRL.mat [for model 2]
```

```
Number of samples: 40
```

```
Number of models: 2
```

```
=====
```

```
Iteration 01
```

```
Iteration 02
```

```
    model frequencies (percent)
```

```
    model 1: 50.5| model 2: 49.5|
```

```
                                dL:    6.62
```

```
                                dm:   49.48
```

```
                                dx:    0.22
```

```
Iteration 03
```

```
    model frequencies (percent)
```

```
    model 1: 48.6| model 2: 51.4|
```

```
                                dL:    2.14
```

```
                                dm:    1.91
```

```
                                dx:    0.12
```

```
Iteration 04
```

```
    model frequencies (percent)
```

```
    model 1: 46.3| model 2: 53.7|
```

```
                                dL:    3.09
```

```
                                dm:    2.30
```

```
                                dx:    0.13
```

```
Iteration 05
```

```
    model frequencies (percent)
```

```
    model 1: 43.3| model 2: 56.7|
```

```
                                dL:    4.28
```

```
                                dm:    3.04
```

```
                                dx:    0.16
```

```
Iteration 06
```

```
    model frequencies (percent)
```

```
    model 1: 39.4| model 2: 60.6|
```

```
                                dL:    4.91
```

```
                                dm:    3.84
```

```
                                dx:    0.18
```

```
Iteration 07
```

```
    model frequencies (percent)
```

```
    model 1: 35.6| model 2: 64.4|
```


	dL:	4.10
	dm:	3.81
	dx:	0.17
Iteration 08		
model frequencies (percent)		
model 1: 32.7 model 2: 67.3		
	dL:	3.42
	dm:	2.93
	dx:	0.15
Iteration 09		
model frequencies (percent)		
model 1: 31.2 model 2: 68.8		
	dL:	2.08
	dm:	1.47
	dx:	0.11
Iteration 10		
model frequencies (percent)		
model 1: 30.5 model 2: 69.5		
	dL:	1.40
	dm:	0.72
	dx:	0.12
Iteration 11		
model frequencies (percent)		
model 1: 30.0 model 2: 70.0		
	dL:	0.99
	dm:	0.53
	dx:	0.10
Iteration 12		
model frequencies (percent)		
model 1: 29.6 model 2: 70.4		
	dL:	0.65
	dm:	0.34
	dx:	0.08
Iteration 13		
model frequencies (percent)		
model 1: 29.4 model 2: 70.6		
	dL:	0.44
	dm:	0.21
	dx:	0.06
Iteration 14		
model frequencies (percent)		
model 1: 29.3 model 2: 70.7		
	dL:	0.30
	dm:	0.13
	dx:	0.04
Iteration 15		
model frequencies (percent)		
model 1: 29.2 model 2: 70.8		

```

dL: 0.21
dm: 0.07
dx: 0.03

Iteration 16
  model frequencies (percent)
  model 1: 29.2| model 2: 70.8|

dL: 0.15
dm: 0.04
dx: 0.02

Iteration 17
  model frequencies (percent)
  model 1: 29.1| model 2: 70.9|

dL: 0.11
dm: 0.02
dx: 0.01

Iteration 18
  model frequencies (percent)
  model 1: 29.1| model 2: 70.9|

dL: 0.08
dm: 0.01
dx: 0.01

Iteration 19
  model frequencies (percent)
  model 1: 29.1| model 2: 70.9|

dL: 0.06
dm: 0.00
dx: 0.01
Converged :]

```

Running `cbm_hbi` writes a report on your standard output (often the screen). On every iteration, `cbm_hbi` reports model frequency, which is the estimate of how many individual datasets (i.e. subjects) is explained by each model (in percent). Furthermore, on every iteration, there are 3 metrics showing the changes relative to the previous iteration: `dL` is the change in the log-likelihood of all data given the model space (more specifically a variational approximation of log-likelihood); `dm` is the (percentage of) change in model frequencies; `dx` indicates changes in (normalized value of) parameters. Although either of these measures or their combination can be used as stopping criteria, `cbm_hbi` uses `dx` as the stopping criteria. By default, `cbm_hbi` stops when `dx < 0.01`.

Let's now take a look at the saved file:

```

In [13]: fname_hbi = load('hbi_RL_dualRL.mat');
         cbm      = fname_hbi.cbm;
         cbm.output

```

ans =

struct with fields:

```

        parameters: {2x1 cell}
        responsibility: [40x2 double]
        group_mean: {[-1.8854 -0.0098] [1.0678 -0.2944 1.1510]}
group_hierarchical_errorbar: {[0.2954 0.0409] [0.1183 0.1038 0.0912]}
        model_frequency: [0.2913 0.7087]
        exceedance_prob: [0.0041 0.9959]
        protected_exceedance_prob: [NaN NaN]

```

Almost all useful parameters are stored in `cbm.output`, which we explain them here.

First, let's look at `model_frequency`, which is the HBI estimate of how much each model is expressed across the group:

```
In [14]: model_frequency = cbm.output.model_frequency
```

```

model_frequency =

    0.2913    0.7087

```

Note that the `model_frequency` is normalized here (so it sums to 1 across all models). Also note that the order depends on the order of models fed into to HBI as input. Therefore, in this example, HBI estimated that about 29% of all subjects are explained by the `model_RL` and about 71% by the `model_dualRL`.

Now let's take a look at estimated group mean stored in `cbm.output.group_mean`.

```

In [15]: group_mean_RL = cbm.output.group_mean{1}
         % group mean for parameters of model_RL

         group_mean_dualRL = cbm.output.group_mean{2}
         % group mean for parameters of model_dualRL

```

```

group_mean_RL =

    -1.8854    -0.0098

group_mean_dualRL =

    1.0678    -0.2944    1.1510

```

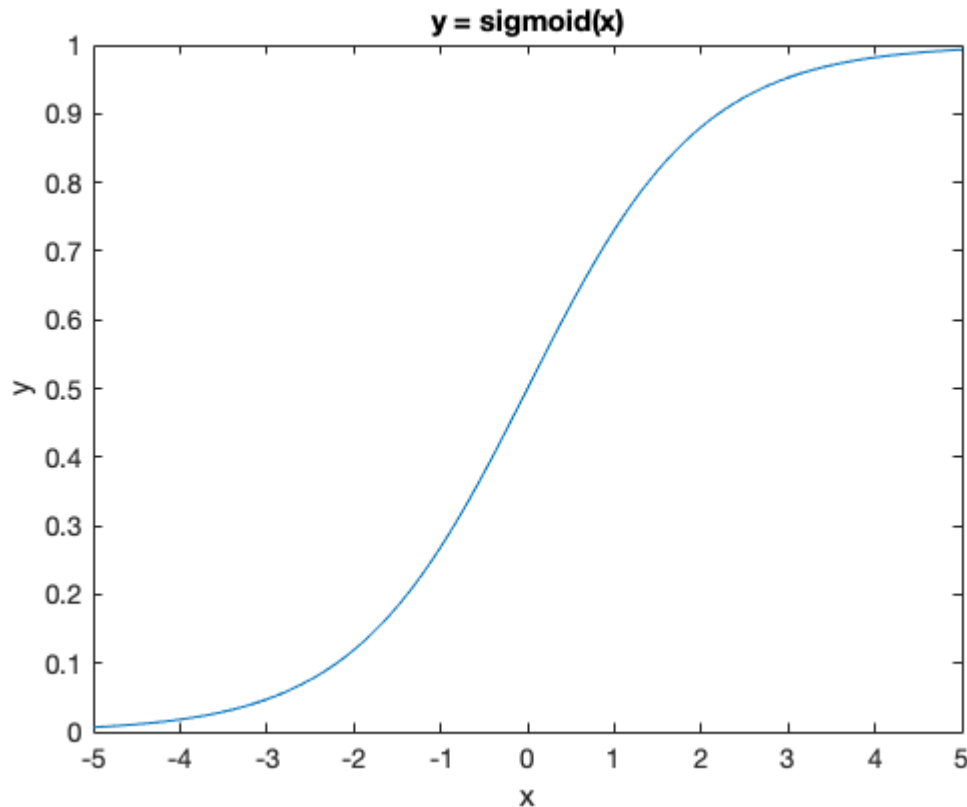
Note that these are normally distributed parameters. That's the reason that group learning rate (which is typically constrained to be between zero and one) is negative here. This is because HBI (and other tools in the cbm) assume that parameters are normally distributed. Therefore, if you have a model with some constraints on parameters (e.g. an RL), you should transform the normally distributed parameter in your model function. To make this point clear, take a look at the `model_RL` function. On the first two lines of this function, you see these codes:

```
nd_alpha = parameters(1); % normally-distributed alpha  
alpha = 1/(1+exp(-nd_alpha)); % alpha (transformed to be between zero and one)
```

Here, `nd_alpha` is the normally-distributed parameter passed to the model (for example by cbm tools). Before using it, the model transformed it to `alpha`, which is bounded between 0 and 1 and is served as the effective learning rate. To do this, a sigmoid function has been used:

$\text{sigmoid}(x) = \frac{1}{1+e^{-x}}$
which is illustrated here:

```
In [16]: x = -5:.1:5;  
y = 1./(1+exp(-x));  
plot(x,y);  
title('y = sigmoid(x)'); xlabel('x'); ylabel('y');
```



As you see, sigmoid is a monotonically increasing function, which transforms its input (x) to an output (y) between 0 and 1. Therefore, if you want to obtain the parameters of your model in their

theoretical range (e.g. a learning rate between 0 and 1), you should apply the same transformation (e.g. the sigmoid) to the normally distributed parameter (e.g. to the `group_mean_RL(1)`).

The second parameter of the `model_RL` is the decision noise parameter, which is theoretically constrained to be positive. For transforming this one, we did an exponential-transformation to the second parameter passed to the `model_RL`:

```
nd_beta = parameters(2);  
beta = exp(nd_beta);
```

The HBI also quantifies (hierarchical) errorbar of the `group_mean` parameters, which is saved in `cbm.output.group_hierarchical_errorbar`:

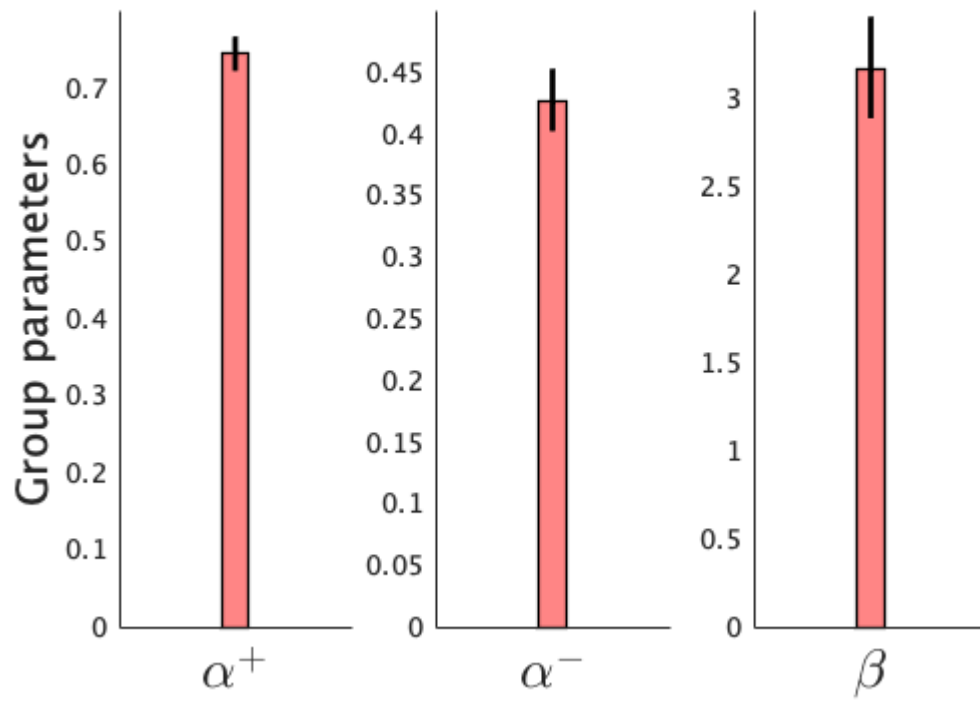
```
In [17]: group_errorbar_RL = cbm.output.group_hierarchical_errorbar{1};  
        group_errorbar_dualRL = cbm.output.group_hierarchical_errorbar{2};
```

You can use the `group_mean` and `group_hierarchical_errorbar` values to plot group parameters, or use `cbm_hbi_plot` to plot the main outputs of the HBI.

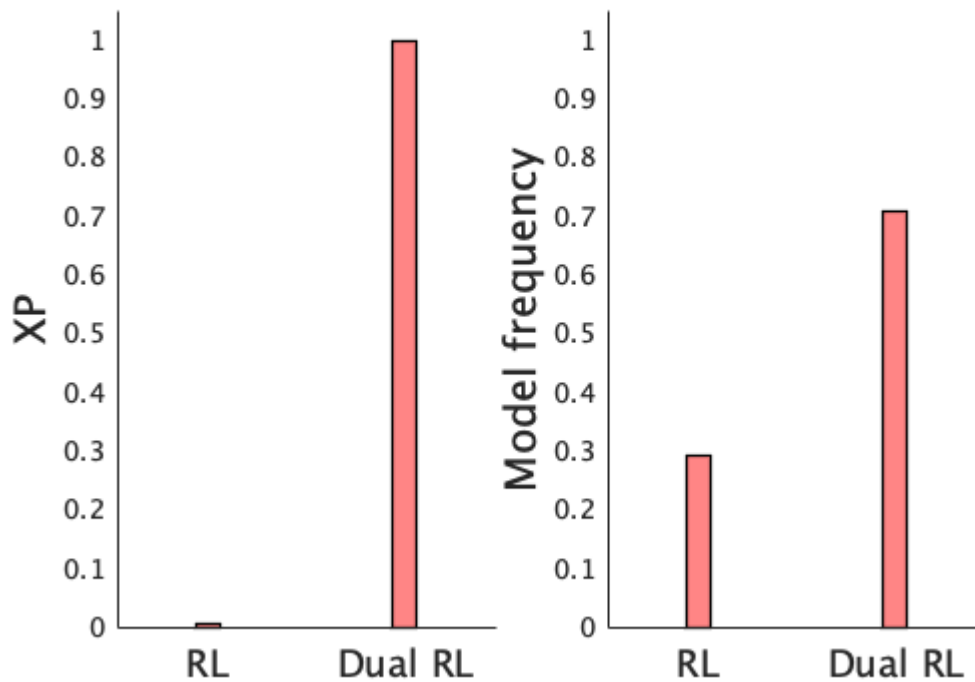
```
In [18]: % 1st input is the file-address of the file saved by cbm_hbi  
        fname_hbi = 'hbi_RL_dualRL.mat';  
  
        % 2nd input: a cell input containing model names  
        model_names = {'RL', 'Dual RL'};  
        % note that they corresponds to models (so pay attention to the order)  
  
        % 3rd input: another cell input containing parameter names of the winning model  
        param_names = {'\alpha^+', '\alpha^-', '\beta'};  
        % note that '\alpha^+' is in the latex format, which generates a latin alpha  
  
        % 4th input: another cell input containing transformation function associated with each  
        transform = {'sigmoid', 'sigmoid', 'exp'};  
        % note that if you use a less usual transformation function, you should pass the handle  
  
        cbm_hbi_plot(fname_hbi, model_names, param_names, transform)  
        % this function creates a model comparison plot (exceedance probability and model frequency)  
        % a plot of transformed parameters of the most frequent model.
```

plotting the group parameters of the most frequent model
There is no protected exceedance probability
Plotting exceedance probability instead...

Parameters of Dual RL



Bayesian model comparison



Similar to a t-test, you can use the hierarchical errorbars to make an inference about a parameter at the population level. We explain that feature in the next example.

The value of individual parameters are saved in the `cbm.output.parameters`

```
In [19]: parameters_RL = cbm.output.parameters{1};
         parameters_dualRL = cbm.output.parameters{2};
```

Also you can look at the estimated responsibility that each model generated each individual dataset. Across models, responsibilities sum to 1 for each subject.

```
In [20]: responsibility = cbm.output.responsibility
```

```
responsibility =
```

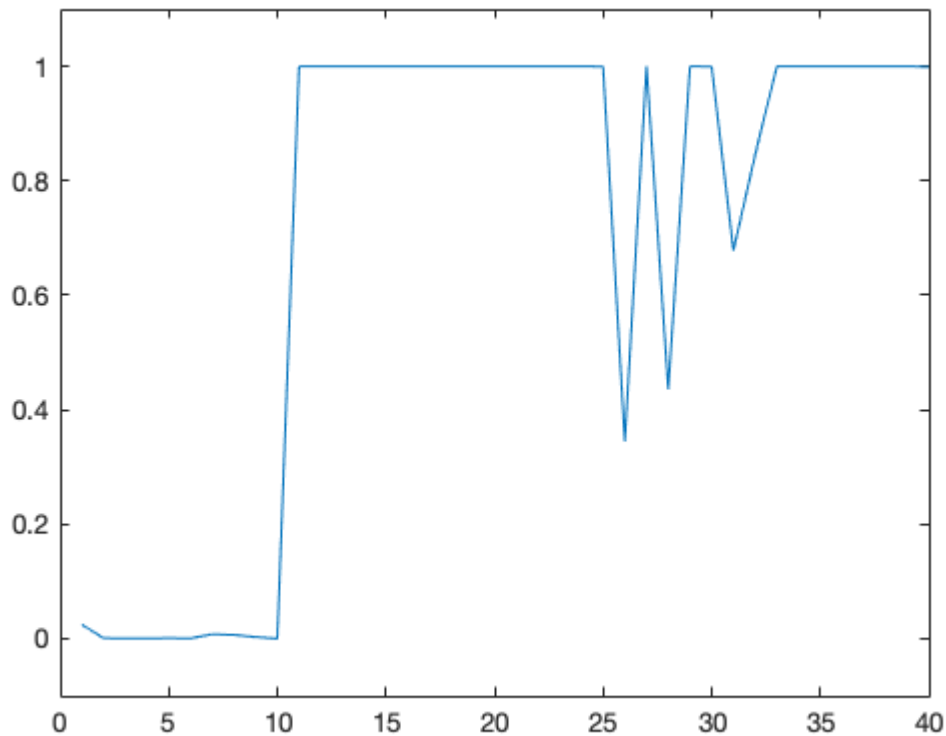
0.9755	0.0245
0.9992	0.0008
0.9993	0.0007
0.9996	0.0004
0.9990	0.0010
0.9995	0.0005
0.9923	0.0077

0.9934	0.0066
0.9972	0.0028
1.0000	0.0000
0.0000	1.0000
0.0000	1.0000
0.0000	1.0000
0.0000	1.0000
0.0000	1.0000
0.0000	1.0000
0.0002	0.9998
0.0000	1.0000
0.0000	1.0000
0.0000	1.0000
0.0000	1.0000
0.0000	1.0000
0.0000	1.0000
0.0000	1.0000
0.0000	1.0000
0.0007	0.9993
0.6553	0.3447
0.0000	1.0000
0.5644	0.4356
0.0000	1.0000
0.0007	0.9993
0.3221	0.6779
0.1548	0.8452
0.0000	1.0000
0.0000	1.0000
0.0000	1.0000
0.0002	0.9998
0.0000	1.0000
0.0000	1.0000
0.0000	1.0000
0.0012	0.9988

The first and second columns indicate the responsibility of model_RL and model_dualRL in generating the corresponding subject data, respectively.

Look at the estimated responsibility of model_dualRL:

```
In [21]: plot(responsibility(:,2)); ylim([-0.1 1.1])
```

As you see, the estimated responsibility of model_dualRL for the first 10 subjects is almost zero. These results make sense as this is a synthetic dataset and the first 10 subjects are actually generated using model_RL. The next 30 individual datasets are generated using model_dualRL.

Let's also take a look at exceedance probability, a metric typically used for model selection.

```
In [22]: xp = cbm.output.exceedance_prob
```

```
xp =
```

```
0.0041    0.9959
```

The exceedance probability indicates the probability that each model is the most likely model across the group.

A more useful metric is called protected exceedance probability, which also takes into account the null hypothesis that no model in the model space is most likely across the population (i.e. any difference between model frequencies is due to chance).

```
In [23]: pxp = cbm.output.protected_exceedance_prob
```

```
pxp =
```

```
NaN NaN
```

As you see, this is currently only NaN values. This is because for computing protected exceedance probabilities, the HBI should be re-run under the (prior) null hypothesis.

This is how you can do it:

```
In [24]: fdata = load('all_data.mat');
        data = fdata.data;

        fname_hbi = 'hbi_RL_dualRL';

        % 1st input is data,
        % 2nd input is the file-address of the file saved by cbm_hbi
        cbm_hbi_null(data,fname_hbi);
        % Running this command, prints a report on your matlab output
        % (e.g. on the command window)
```

```
cbm_hbi_hbi                                18-Jun-2019 22:05:01
Running hierarchical bayesian inference (HBI)- null mode...
```

```
HBI has been initialized according to
    lap_RL.mat [for model 1]
    lap_dualRL.mat [for model 2]
```

```
Number of samples: 40
```

```
Number of models: 2
```

```
=====
```

```
Iteration 01
```

```
Iteration 02
```

```
dL: 5.07
```

```
dx: 0.15
```

```
Iteration 03
```

```
dL: 1.14
```

```
dx: 0.05
```

```
Iteration 04
```

```
dL: -0.08
```

```
dx: 0.02
```

```
Iteration 05
```

```
dL: 0.06
```

```
dx: 0.01
```

```
Iteration 06
```

```
dL: 0.08
```

```
dx: 0.01
```

Converged :]

cbm_hbi_null saves a new file 'hbi_RL_dualRL_null.mat' and it also updates the cbm in hbi_RL_dualRL.mat.

Load again hbi_RL_dualRL.mat and look at the protected exceedance probability

```
In [25]: fname_hbi = load('hbi_RL_dualRL.mat');
        cbm      = fname_hbi.cbm;
        pxp      = cbm.output.protected_exceedance_prob
```

pxp =

0.0041 0.9959

Note that here values of xp and pxp are not really different (their difference is very small). In many datasets, however, their difference might be quite substantial.

2 Example 2: Two-step Markov decision task

We now use cbm tools for computational modeling in the two-step Markov decision task introduced by Daw et al. (2011). This task is a well-known paradigm to distinguish two behavioral modes, model-based and model-free learning. Daw et al. have proposed three reinforcement learning accounts, a model-based, a model-free and their hybrid (which nests the other two and combines their estimates according to a weight parameter), to disentangle contribution of these two behavioral modes on choices.

For this example, we use an empirical dataset reported in Piray et al. (2016) (20 subjects for this example), which is stored in the example_2step_task directory.

The hybrid, model-based and model-free algorithms contain 7, 4 and 6 parameters, respectively. Please see Daw et al. for formal description of the models.

loglik = model(parameters,subj);

Now enter the example_2step_task directory and load data.

```
In [26]: % assuming that the current directory is example_RL_task
        cd(fullfile('..','example_2step_task'));

        % load data from all_data.mat file
        fdata = load('all_data.mat');
        data  = fdata.data;

        subj1 = data{1};
        subj1
```

subj1 =

struct with fields:

```
choice1: [201x1 double]
transit: [201x1 double]
state2: [201x1 double]
choice2: [201x1 double]
outcome: [201x1 double]
description: {5x1 cell}
```

See subj1.description for a description of information stored for each subject.
Now, you should call cbm_lap with each model separately.

```
In [27]: prior_mb = struct('mean',zeros(4,1),'variance',6.25);
        fname_mb = 'lap_mb.mat';
        cbm_lap(data, @model_mb, prior_mb, fname_mb);
        % Running this command, prints a report on your matlab output
        % (e.g. on the command window)
```

If you have many subjects or a model with many parameters, the cbm_lap can take a long time to fit all of them. If you have access to cluster computing, however, you can run cbm_lap in parallel for subjects. For example, here we fit model_mf to the data of only subject 1:

```
In [28]: % create a directory for individual output files:
        mkdir('lap_subjects');

        % 1st input: data
        % now the input data should be the data of subject 1
        data_subj = data(1);

        % 2nd input: function handle of model (i.e. @model_mf)

        % 3rd input: a prior struct. The size of mean should
        % be equal to the number of parameters
        prior_mf = struct('mean',zeros(6,1),'variance',6.25);

        % 4th input: output file
        % note that here the output is associated with subject 1
        % we save all output files in the lap_subjects directory
        fname_mf_subj = fullfile('lap_subjects','lap_mf_1.mat');

        cbm_lap(data_subj, @model_mf, prior_mf, fname_mf_subj);
```

Warning: Directory already exists.

cbm_lap 18-Jun-2019 22:05:04

=====

Number of samples: 1

Number of parameters: 6

Number of initializations: 42

Subject: 01
done :]

After all jobs finished, you should call `cbm_lap_aggregate` to aggregate individual files:

```
In [29]: % first make a list of lap_mf_* files:
        fname_subjs = cell(20,1);
        for n=1:length(fname_subjs)
            fname_subjs{n} = fullfile('lap_subjects', ['lap_mf_' num2str(n) '.mat']);
        end
        fname_subjs
```

fname_subjs =

20x1 cell array

```
{'lap_subjects/lap_mf_1.mat' }
{'lap_subjects/lap_mf_2.mat' }
{'lap_subjects/lap_mf_3.mat' }
{'lap_subjects/lap_mf_4.mat' }
{'lap_subjects/lap_mf_5.mat' }
{'lap_subjects/lap_mf_6.mat' }
{'lap_subjects/lap_mf_7.mat' }
{'lap_subjects/lap_mf_8.mat' }
{'lap_subjects/lap_mf_9.mat' }
{'lap_subjects/lap_mf_10.mat'}
{'lap_subjects/lap_mf_11.mat'}
{'lap_subjects/lap_mf_12.mat'}
{'lap_subjects/lap_mf_13.mat'}
{'lap_subjects/lap_mf_14.mat'}
{'lap_subjects/lap_mf_15.mat'}
{'lap_subjects/lap_mf_16.mat'}
{'lap_subjects/lap_mf_17.mat'}
{'lap_subjects/lap_mf_18.mat'}
{'lap_subjects/lap_mf_19.mat'}
{'lap_subjects/lap_mf_20.mat'}
```

Now specify the final output file-address and call `cbm_lap_aggregate`

```
In [30]: fname_mf = 'lap_mf.mat';
        cbm_lap_aggregate(fname_subjs, fname_mf);
```

```
% Running this command prints a report on your matlab output
% (e.g. on the command window)
```

Aggregation is done over 20 subjects :]

You see that lap_mf.mat is saved by cbm_lap_aggregate. Similarly, you can fit model_hybrid to data using cbm_lap. I did that and saved lap_hybrid.mat.

Now that we have fitted models to data using cbm_lap, we can run cbm_hbi. Note that you can configure the algorithm using optional inputs:

```
In [31]: % 1st input: data for all subjects
fdata = load('all_data.mat');
data  = fdata.data;

% 2nd input: a cell input containing function handle to models
models = {@model_hybrid, @model_mb, @model_mf};
% note that by handle, I mean @ before the name of the function

% 3rd input: another cell input containing file-address to files saved by cbm_lap
fcbm_maps = {'lap_hybrid.mat', 'lap_mb.mat', 'lap_mf.mat'};
% note that they corresponds to models (so pay attention to the order)

% 4th input: a file address for saving the output
fname_hbi = 'hbi_2step.mat';

cbm_hbi(data,models,fcbm_maps,fname_hbi);
% Running this command prints a report on your matlab output
% (e.g. on the command window)
```

Now, we look at the hbi_2step.mat file saved by the cbm_hbi

```
In [32]: fname_hbi = load('hbi_2step.mat');
cbm      = fname_hbi.cbm;
```

First, take a look at model frequencies:

```
In [33]: cbm.output.model_frequency
```

```
ans =
```

```
0.6531    0.3469    0.0000
```

As you see the hybrid model takes about 65% of responsibility. Now let's take a look at the exceedance probability

```
In [34]: cbm.output.exceedance_prob
```

```
ans =
```

```
0.9102    0.0897    0.0000
```

Note that for computing the protected exceedance probability, the HBI should be re-run under the (prior) null hypothesis `cbm_hbi_null`.

Next, we look at the parameters of the hybrid model:

```
In [35]: cd(fullfile('..','example_2step_task'))
```

```
% 1st input is the file-address of the file saved by cbm_hbi  
fname_hbi = 'hbi_2step.mat';
```

```
% 2nd input: a cell input containing model names  
model_names = {'Hybrid', 'MB', 'MF'};  
% note that they corresponds to models (so pay attention to the order)
```

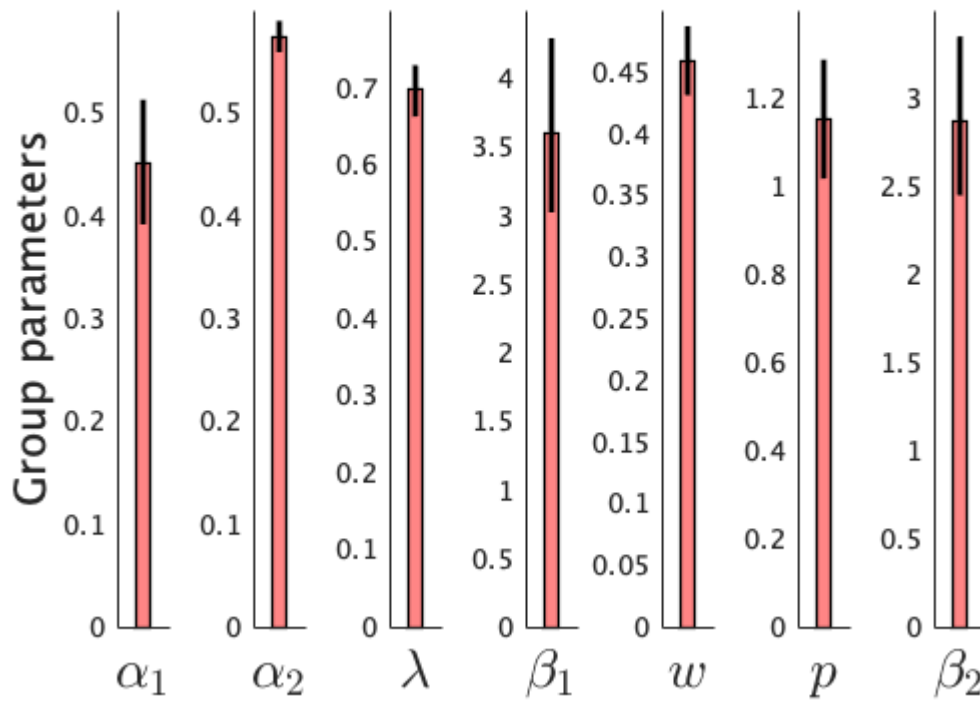
```
% 3rd input: another cell input containing parameter names of the winning model  
param_names = {'\alpha_1', '\alpha_2', '\lambda', '\beta_1', 'w', 'p', '\beta_2'};
```

```
% 4th input: another cell input containing transformation function associated with each  
transform = {'sigmoid', 'sigmoid', 'sigmoid', 'exp', 'sigmoid', 'none', 'exp'};  
% note that no transformation applied to parameter p (i.e perserveration) in the hybrid
```

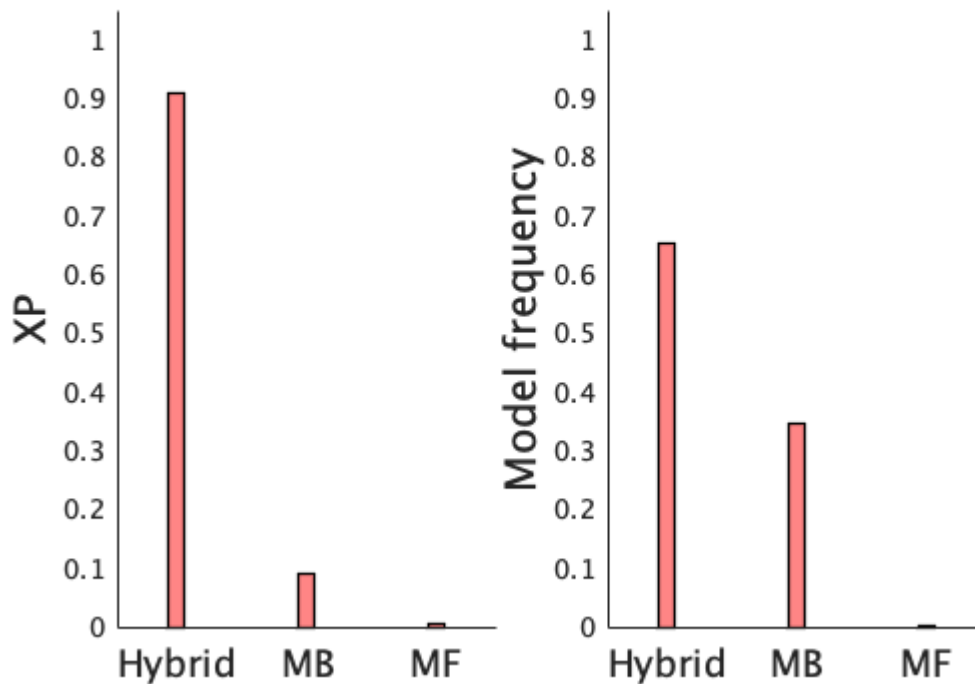
```
cbm_hbi_plot(fname_hbi, model_names, param_names, transform)  
% this function creates a model comparison plot (exceednace probability and model frequ  
% a plot of transformed parameters of the most frequent model.
```

plotting the group parameters of the most frequenct modelThere is no protected exceedance probab
Plotting exceedance probability instead...

Parameters of Hybrid



Bayesian model comparison



A critical parameter of the hybrid model is the weight parameter, which indicates the degree to which choices influenced by model-based and model-free values. Since the weight parameter is also constrained to be between 0 (i.e. pure model-free) and 1 (i.e. pure model-based), the normally distributed parameter has been transformed in `model_hybrid` using the sigmoid function.

Similar to a t-test, you can use the hierarchical errorbars to make an inference about a parameter at the population level. For example, suppose you are interested to test whether the subjects show significantly more model-based than model-free behavior. In terms of the hybrid model, this can be examined by testing whether the (transformed) weight parameter is significantly different from 0.5 (which indicates equal contribution of model-based and model-free values). Since sigmoid function transforms 0 to 0.5, we should test whether the normally distributed weight parameter is significantly different from 0. `cbm_hbi_ttest` performs this inference according to a Student's t-distribution:

```
In [36]: % 1st input: the fitted cbm by cbm_hbi
         fname_hbi = 'hbi_2step';

         % 2nd input: the index of the model of interest in the cbm file
         k = 1; % as the hybrid is the first model fed to cbm_hbi

         % 3rd input: the test will be done compared with this value (i.e. this value indicates
         m = 0; % here the weight parameter should be tested against m=0
```

```

    % 4th input: the index of the parameter of interest
    i = 5; % here the weight parameter is the 5th parameter of the hybrid model

    [p,stats] = cbm_hbi_ttest(cbm,k,m,i)

p =

    0.1667

```

```

stats =

struct with fields:

    tstat: -1.4585
    pval: 0.1667
    df: 14.0626

```

We see that the p-value is not smaller than 0.05, so there is no significant evidence that the weight is different from 0. In other words, there is no significant evidence that subjects are more influenced by model-based or model-free values.

As another example, let's see whether the perseveration parameter is significantly different from 0 (parameter p in the above plot). This parameter indicates whether subjects repeat their choices (or avoid if $p < 0$) regardless of the estimated values. This parameter has not been transformed, so the test should be against $m=0$.

```

In [37]: % 1st input: the fitted cbm by cbm_hbi
         fname_hbi = 'hbi_2step';

         % 2nd input: the index of the model of interest in the cbm file
         k = 1; % as the hybrid is the first model fed to cbm_hbi

         % 3rd input: the test will be done compared with this value (i.e. this value indicates
         m = 0; % here the perseveration parameter should be tested against m=0

         % 4th input: the index of the parameter of interest
         d = 6; % here the perseveration parameter is the 6th parameter of the hybrid model

         [p,stats] = cbm_hbi_ttest(cbm,k,m,d)

p =

    6.1737e-07

```

```
stats =
```

```
struct with fields:
```

```
tstat: 8.5369  
pval: 6.1737e-07  
df: 14.0626
```

Therefore, the perseveration parameter is significantly larger than zero ($p < 0.001$).

In this example, the model-free model does not take any responsibility. In this situation, the HBI assigns prior values to the individual parameters (with a large variance). This prior value is 0 before transformation. Therefore, for parameters bounded in the unit range (e.g. learning rate), this prior value (after transformation) is 0.5, for decision noise parameter is 1 and for the reservation parameter is 0.

```
In [38]: % 1st input is the file-address of the file saved by cbm_hbi
```

```
fname_hbi = 'hbi_2step.mat';
```

```
% 2nd input: a cell input containing model names
```

```
model_names = {'Hybrid', 'MB', 'MF'};
```

```
% note that they corresponds to models (so pay attention to the order)
```

```
% 3rd input: another cell input containing parameter names of the winning model
```

```
param_names = {'\alpha_1', '\alpha_2', '\lambda', '\beta_1', 'p', '\beta_2'};
```

```
% 4th input: another cell input containing transformation function associated with each
```

```
transform = {'sigmoid', 'sigmoid', 'sigmoid', 'exp', 'none', 'exp'};
```

```
% note that no transformation applied to parameter p (i.e perseveration) in the hybrid
```

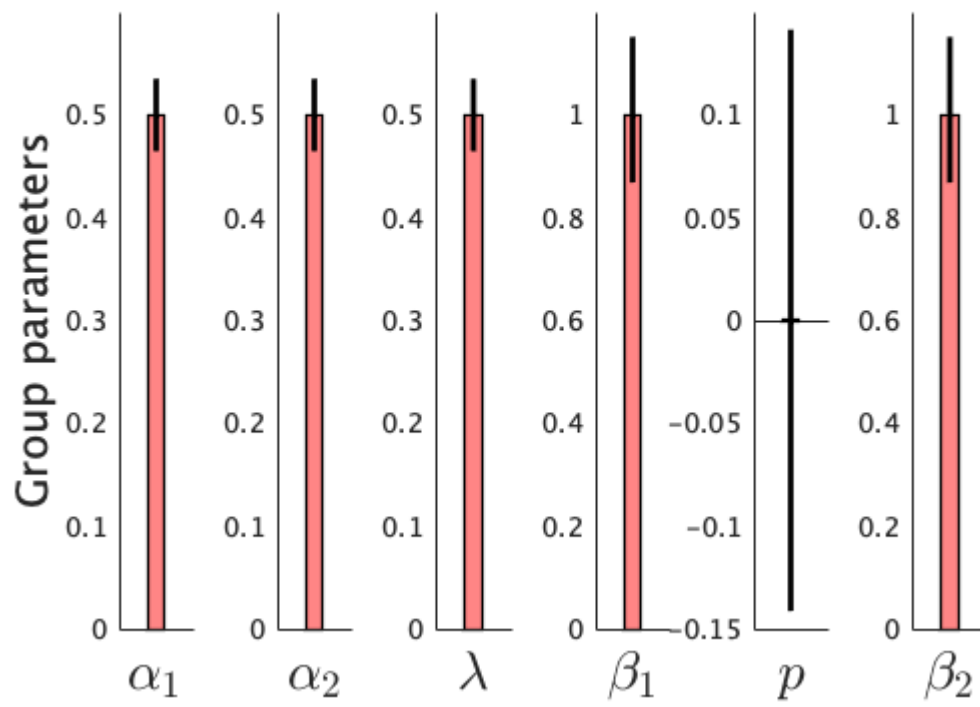
```
cbm_hbi_plot(fname_hbi, model_names, param_names, transform, 3)
```

```
% this function creates a model comparison plot (exceedance probability and model frequ
```

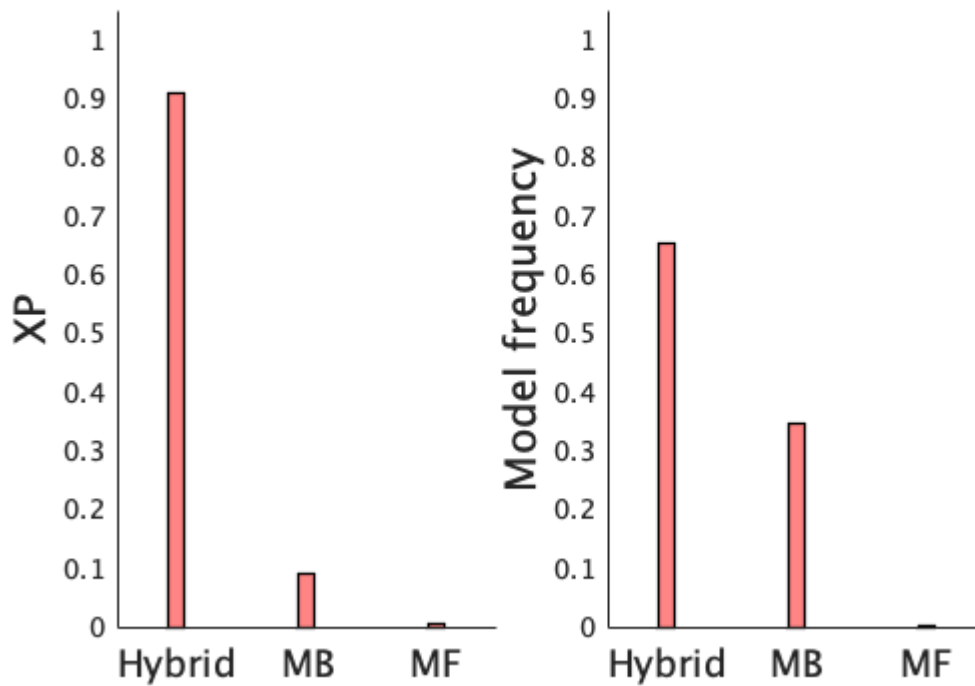
```
% a plot of transformed parameters of the most frequent model.
```

There is no protected exceedance probability as cbm_hbi_null has not been executed
Plotting exceedance probability instead...

Parameters of MF



Bayesian model comparison



2.1 Reference

If you use cbm, please cite this paper:

Piray P, Dezfouli A, Heskes T, Frank MJ, Daw ND. Hierarchical Bayesian inference for concurrent model fitting and comparison for group studies. bioRxiv <https://journals.plos.org/ploscompbiol/article?id=10.1371/journal.pcbi.1007043>

For a more formal description of the HBI algorithm, please see this paper.