

Bayesian analysis of qRT-PCR data using MCMC.qpcr package: a tutorial

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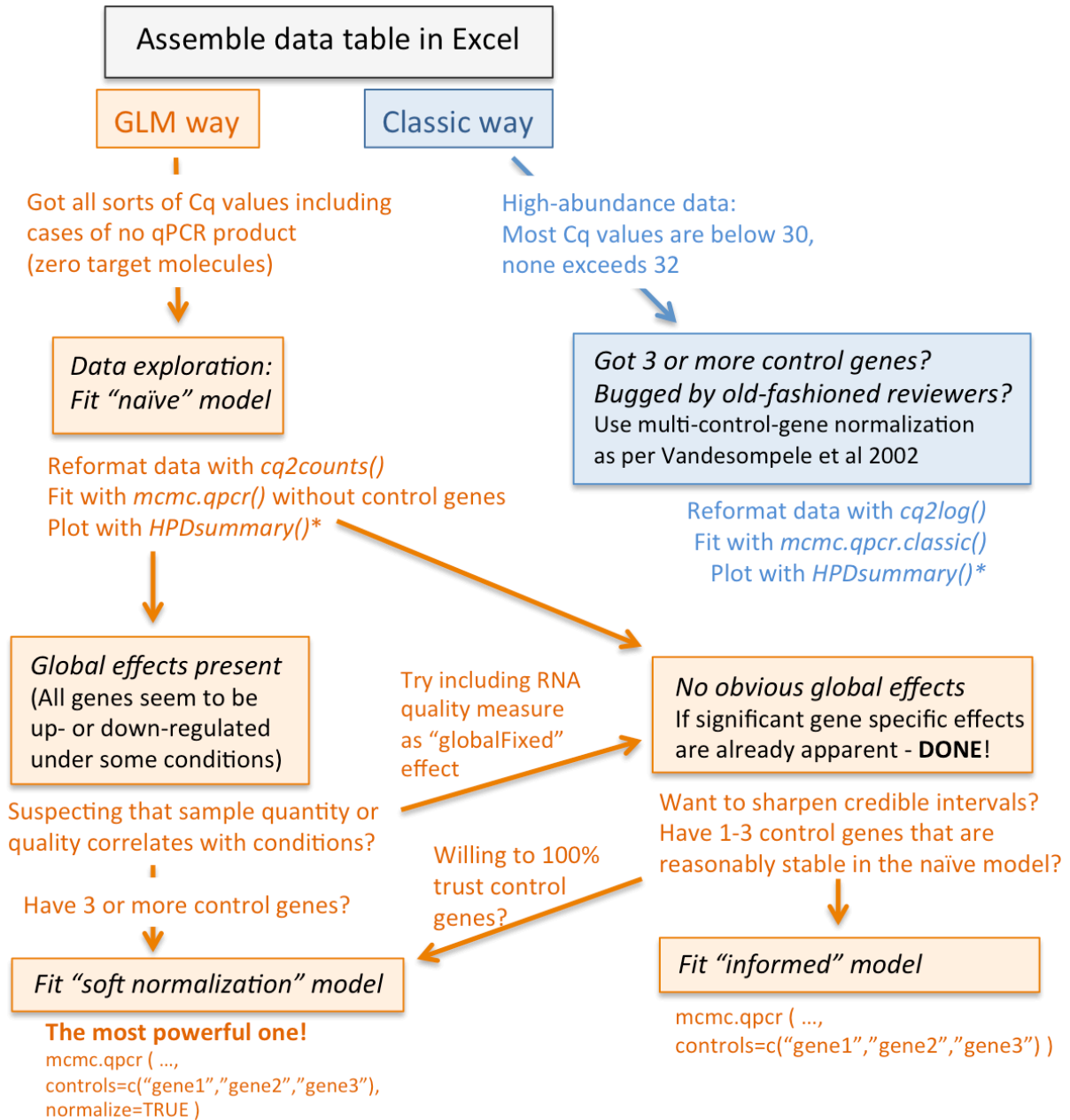
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May 2015, version 1.2

download the MCMC.qpcr package from CRAN

Short Tutorial

Flow chart and decision tree:



*`HPDsummary()` works for one-way and two-way designs (each factor can have multiple levels).
Use `HPDplot` family of functions for more flexible plotting.
Make sure to try `trellisByGene()` for gene-by-gene plotting

Input:

For practicing we will use the dataset on cellular heat stress from the paper by Beckham et al (2010). In the “heat” treatment the cells received a severe 20-minute heat stress at 45°C and were sampled 1 and 3 hours later. In the “pre-stress” treatment the cells were first heated for 30 minutes at 43°C and 4 hours later subjected to the same severe heat stress as above. In the control the cells were neither pre-stressed nor heated. Since the control has no time dimension we cannot run a fully crossed 2-way design with factors “treatment” and “time”; instead it makes sense to run a one-way design comparing all the treatments to the untreated control. Such a design, involving a global control and a series of treatments, is one of the most typical in biomedical qPCR experiments.

Two input files are required; the main one with raw qPCR data and another with efficiencies (amplification factor per PCR cycle) for each target. The input files can be assembled in excel, exported as comma-separated values (.csv format) and read into R using the generic `read.csv()` function. Beckham et al data and amplification efficiencies are included with the `MCMC.qpcr` package; to load them, say:

```
data(beckham.data)
data(beckham.eff)
```

The main data table (`beckham.data`) looks like this:

| sample | tr | time | gapdh | hsp110 | hsppb | egr | gadd | dnajb1 | dnajb4 | atf | dnaja4 | fos |
|--------|---------|------|-------|--------|-------|------|------|--------|--------|------|--------|------|
| a | heat | 1h | 15.0 | NA | 21.7 | 30.6 | 22.5 | NA | 23.3 | NA | 29.9 | 31.8 |
| a | heat | 1h | 15.3 | 22.9 | 22.4 | 29.3 | 22.9 | 24.4 | 24.8 | 29.4 | 29.1 | 30.8 |
| a | heat | 1h | 15.4 | 21.8 | NA | 28.5 | NA | 23.6 | NA | 28.1 | 29.8 | 29.9 |
| i | heat | 3h | 15.7 | NA | 22.3 | NA | 21.6 | 23.0 | 24.7 | 28.6 | 28.1 | 29.0 |
| i | heat | 3h | NA | 21.7 | NA | 23.6 | 23.2 | 21.9 | 26.4 | 27.7 | 28.2 | 28.9 |
| i | heat | 3h | 15.6 | 21.1 | 22.8 | 23.5 | 22.0 | 22.2 | 25.6 | 27.2 | 27.6 | 28.7 |
| ... | | | | | | | | | | | | |
| m | control | 0h | NA | 19.7 | 23.1 | 25.9 | 22.5 | 21.6 | 24.1 | 28.4 | 26.4 | 28.4 |
| m | control | 0h | 15.0 | 19.7 | 22.1 | 24.4 | 22.0 | 21.5 | 24.5 | 28.2 | 27.7 | 28.4 |
| m | control | 0h | 14.3 | NA | 21.2 | NA | 21.4 | NA | 23.9 | NA | 26.4 | NA |
| ... | | | | | | | | | | | | |

The “sample” column is required; it denotes biological replicates (cDNA preparations). “tr” and “time” are experimental conditions (factors). The rest of columns are raw Cq values (they might be called Ct or Cp depending on your qPCR instrument), one column per gene. Missing data are coded as NA; the trials that failed to amplify because the target concentration was too low should be coded -1 (this will be informative for the method). Very importantly, technical replicates should not be averaged but all listed in the table. For example, the first three lines in the table above are technical replicates, i.e, the results obtained for the same cDNA sample.

The efficiencies are a two-column table giving gene-efficiency correspondence:

| gene | efficiency |
|--------|------------|
| atf | 2.00 |
| gapdh | 1.99 |
| dnajb1 | 1.99 |
| dnajb4 | 1.99 |
| gadd | 1.99 |
| hsppb | 1.99 |
| egr | 1.95 |
| ... | |

There must be an efficiency entry for every gene. If you don’t have them experimentally determined for some genes but still want to run the method just to try it out, use 2.00.

Recalculating the data into molecule counts and reformatting:

One of the central ideas of the MCMC.qpcr methodology is to treat qPCR data as molecule count data. Function `cq2counts()` does the reformatting. It needs to be told the name of the main dataset, the name of efficiencies dataset, and also which columns correspond to the actual qPCR data for genes (`'genecols'`) and which columns contain experimental conditions (`'condcols'`):

```
qs=cq2counts(data=beckham.data, effic=beckham.eff, genecols=c(4:13),condcols=c(1:3))
```

Model fitting (one-way design):

Since we are interested in comparing all our samples to a global control, we can simplify the design of the experiment by combining the experimental factors (`tr` and `time`) into a single factor, which we will call `treatment.time` in the reformatted `qs` dataset ¹:

```
qs$treatment.time=as.factor(paste(qs$tr,qs$time,sep="."))
```

We will then specify our global control as the “reference” condition for model fitting using generic `relevel()` function :

```
qs$treatment.time=relevel(qs$treatment.time,ref="control.0h")
```

Now for model fitting. By far the greatest advantage of MCMC.qpcr method is the possibility to perform the analysis without relying on “control genes” that are presumably stable. Under the currently prevailing qPCR paradigm, the stability of control genes should be confirmed for each type of experiment (Vandesompele et al 2002). Dismissing the assumption of gene stability not only saves effort required to select control genes, but also makes the qPCR analysis fully objective, which is very important for biomedical applications.

To fit a “naïve” model (assuming no control genes) using function `mcmc.qpcr()`, all we need to do is to specify the name of our dataset (`qs`) and experimental factors (`'fixed'` argument ²):

```
naive=mcmc.qpcr(data=qs, fixed="treatment.time")
```

The MCMC.qpcr package actually provides means to analyze data using control genes information, since any prior knowledge helps sharpen the Bayesian inference upon which the method relies. An “informed” model lets the user indicate control genes and specify their assumed degree of stability. The package even implements the “classic” analysis involving multi-gene normalization. Random blocking factors can also be specified. Read the Very Long tutorial to learn more about these options.

Extracting and plotting the results:

For experimental designs involving a single multi-level factor (such as the Beckham et al dataset) or two fully crossed multi-level factors (such as the coral stress dataset described in the long tutorial), the easiest way to extract gene expression changes, calculate their statistical significance, and plot the results is to use the function `HPDsummary()`. To generate the line-and-points plot of the inferred transcript abundances with whiskers denoting 95% credible intervals, we only need to specify the name of the model and the name of the reformatted dataset (Fig.1):

```
s1=HPDsummary(model=naive,data=qs)
```

¹ If you have a two-way design (with or without the interaction term) rather than design with a single global control, do not combine your factors!

² For a two-way design, see example on page 7

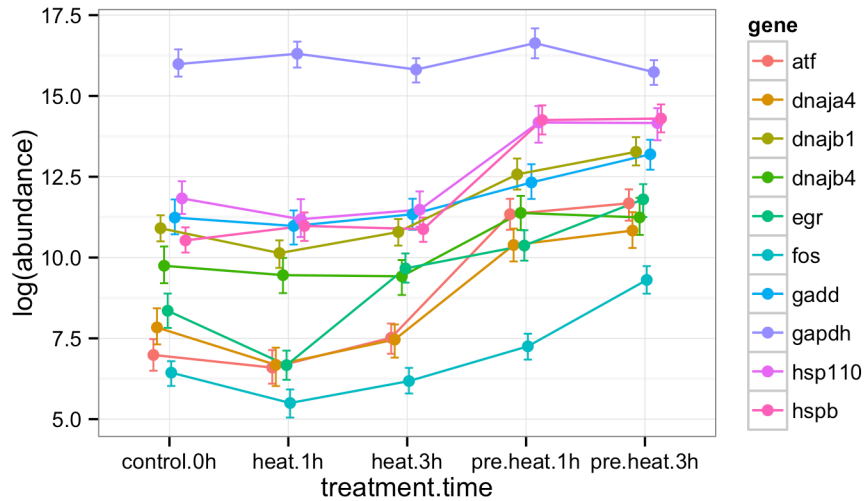


Figure 1. HPDsummary() plot of inferred transcript abundances. By default the y-axis is scaled in \log_2 units.

In most cases of qRT-PCR, however, we are interested in visualizing not the absolute transcript abundances but changes in expression in response to experimental treatments. To produce a bar graph of such changes for our case, we need to run HPDsummary() function with an additional option 'relative=TRUE', which will cause the function to display the changes relative to the control (Fig. 2):

```
s0=HPDsummary(model=naive,data=qs,relative=TRUE)
```

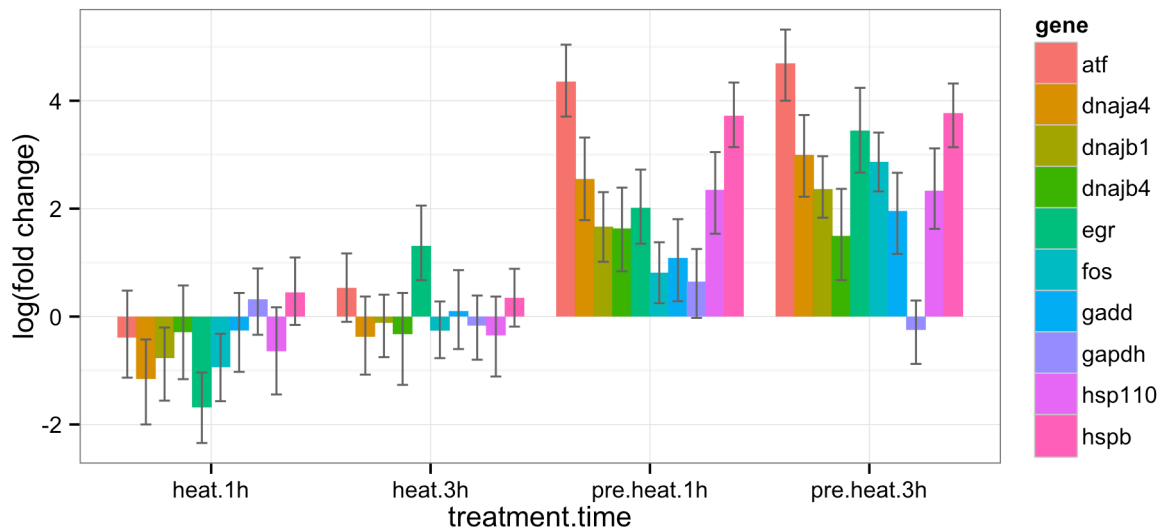


Figure 2. HPDsummary() plot of inferred \log_2 (fold changes) relative to the global control.

In addition to plotting, the function HPDsummary() returned bundles of data (we called them s1 and s0 above) containing a table where the transcript abundances (in s1) or changes relative to the control (in

s2) are listed for each gene for all treatments³, along with standard deviation of the posterior distribution and upper and lower 95% credible limits:

```
s1$summary
      gene treatment.time      mean      sd      lower      upper
1    atf   control.0h  8.966396 0.4939060  8.055152  9.613877
2    atf     heat.1h  8.569632 0.4658686  7.890858  9.308999
3    atf     heat.3h  9.916381 0.4640932  9.195763 10.658059
4    atf  pre.heat.1h 15.333001 0.3971188 14.737555 16.054843
5    atf  pre.heat.3h 15.832027 0.4036264 15.240748 16.499968
6 dnaja4   control.0h 10.182746 0.3849322  9.562955 10.771647
7 dnaja4     heat.1h  8.558357 0.3643718  7.964796  9.132464
8 dnaja4     heat.3h  9.877412 0.3783696  9.283415 10.443634
9 dnaja4  pre.heat.1h 13.940327 0.4063985 13.273199 14.520066
10 dnaja4 pre.heat.3h 14.597385 0.3195349 14.090571 15.136826
...
```

This table can be used for plotting results in a variety of ways using function `summaryPlot()` or directly using functions of the cutting-edge R graphics package, `ggplot2`, which is actually invoked by `HPDsummary()` and `summaryPlot()`.

`HPDsummary()` also calculates all the pairwise differences between treatments and their statistical significances for each gene:

```
s1$geneWise
$atf
      difference
pvalue control.0h  heat.1h  heat.3h pre.heat.1h pre.heat.3h
control.0h      NA -0.39676412 0.9499848  6.3666056  6.8656314
heat.1h      0.5720302      NA 1.3467490  6.7633697  7.2623955
heat.3h      0.1525220 0.04364789      NA 5.4166207  5.9156465
pre.heat.1h 0.0000000 0.00000000 0.0000000      NA 0.4990258
pre.heat.3h 0.0000000 0.00000000 0.0000000 0.3803415      NA

$dnaja4
      difference
pvalue control.0h  heat.1h  heat.3h pre.heat.1h pre.heat.3h
control.0h      NA -1.62438917 -3.053344e-01  3.757581  4.4146386
heat.1h  2.353268e-03      NA 1.319055e+00  5.381970  6.0390278
heat.3h  5.348679e-01 0.01553518      NA 4.062915  4.7199731
pre.heat.1h 1.528355e-11 0.00000000 4.900436e-11      NA 0.6570579
pre.heat.3h 0.000000e+00 0.00000000 0.000000e+00 0.228404      NA
...
```

The upper triangle of these matrices are \log_2 (fold-differences) and the lower triangle are the corresponding p-values (zero means less than $1e-16$). These results are directly reportable as supplementary information for a research paper.

The third object in the list returned by `HPDsummary()` is the plot object of the `ggplot2` class. In our example, it can be recalled (replotted) by saying

```
s1$ggPlot
```

This object can be replotted with different labels, backgrounds and colors using “Themes” of the `ggplot2` package (see <http://docs.ggplot2.org/current/>). Here is an example code to adjust label fonts, orientations etc:

³ In a 2-way design, all combinations of the two factors will be listed.

```
s1$ggPlot + theme(
  axis.text.x=element_text(size=12,face="bold.italic",family="serif",angle=45,hjust=1),
  axis.text.y=element_text(size=12,family="serif"),
  legend.text=element_text(family="serif",size=12),
  axis.title.x=element_text(size = 14, family="serif"),
  axis.title.y=element_text(size = 14, family="serif"),
  legend.title=element_text(face="bold",size = 14, family="serif")
)
```

Two-way design:

Two-way designs are the most common in biology, where we look for the effects of two factors (each one can have more than two levels) on their own and in combination. For the model to fit properly, all combinations of factor levels must be present in the data. To create a compatible two-way dataset out of Beckham et al data, we can simply remove the global control (timepoint “0h”):

```
subb=subset(beckham.data,time!="0h")
```

Then we create a counts dataset out of it, just like before:

```
qs2way=cq2counts(data=subb, effic=beckham.eff, genecols=c(4:13),condcols=c(1:3))
```

This is how the dataset looks:

```
head(qs2way)
  count gene sample tr time
1 3756364 gapdh    a heat  1h
2 3055707 gapdh    a heat  1h
3 2852505 gapdh    a heat  1h
4 2320441 gapdh    i heat  3h
6 2485741 gapdh    i heat  3h
7 9843782 gapdh    b heat  1h
```

There are two separate factors: treatment, or “tr” (“heat” and “pre.heat”) and “time” (“1h” and “3h”). To explore genes’s behavior in more detail than before, let’s fit a two-way naïve model with a formula “tr + time + tr:time” saying that we want to know the individual effect of each factor plus the effect of their interaction (i.e., in this case, treatment-dependent effect of time):

```
naive2=mcmc.qpcr(data=qs2way,fixed="tr+time+tr:time")
```

A typical summary plot for a two-way design is a “trellis plot” (Fig. 3), consisting of several panels where the x-axis corresponds to level of one factor (defined by xgroup argument below), and panels correspond to levels of another factor:

```
smm2=HPDsummary(naive2,qs2way,xgroup="time")
```

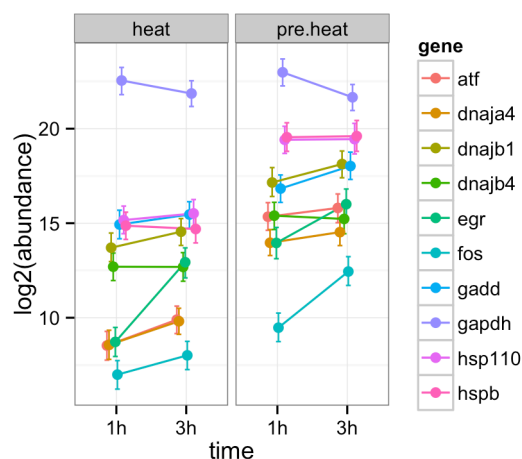


Figure 3. Trellis summary plot for a two-way design.

A more revealing plot would be to show data for each gene on the same panel. This can be done using function `trellisByGene` (Fig. 4):

```
trellisByGene(smm2, xFactor="time", groupFactor="tr")+xlab("timepoint")
```

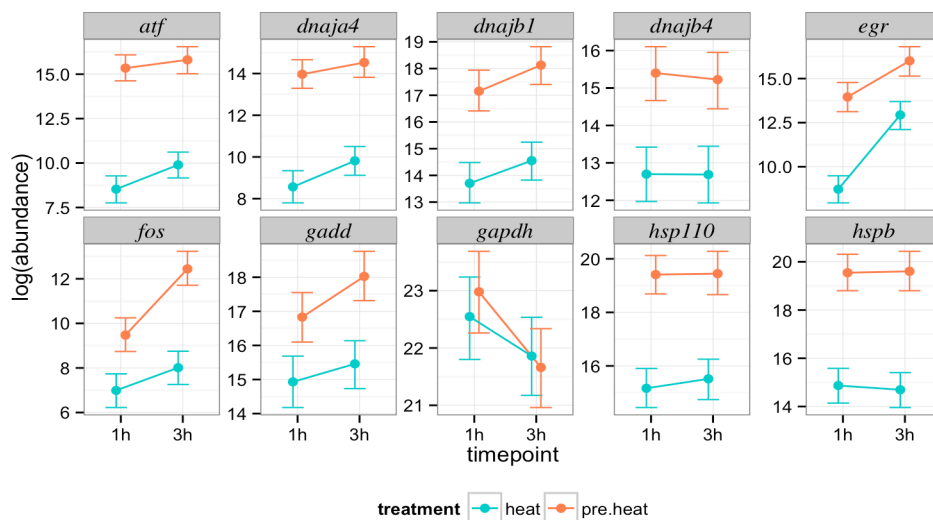


Figure 4. By-gene plot of two-way design results.

Looking at these graphs, it is immediately clear that most genes are more abundant in a pre-heated condition irrespective of time (except *gapdh*), and many of them are up-regulated at 3h compared to 1h. In addition, it appears like *egr* and *fos* appear to be regulated differently at the 3h time point depending on whether the sample was pre-heated or not: the slopes of the blue and red lines for these genes are not parallel. This implies that these genes might show significant $tr:time$ interaction. We can confirm this looking at the summary of the `naive2` model:


```
summary(naive2)
```

```
...
geneatf:time3h:trpre.heat -0.625125 -1.784476 0.627753 1000.0 0.322
genednaja4:time3h:trpre.heat -0.476287 -1.556302 0.867470 876.1 0.428
genednaja1:time3h:trpre.heat 0.089269 -1.158260 1.311152 1000.0 0.894
genednaja4:time3h:trpre.heat -0.111522 -1.260755 1.188699 901.5 0.834
geneegr:time3h:trpre.heat -1.501566 -2.755622 -0.142625 1000.0 0.024 *
genefos:time3h:trpre.heat 1.351732 0.051815 2.507756 1000.0 0.026 *
genegadd:time3h:trpre.heat 0.461193 -0.728618 1.743650 1000.0 0.442
genegapdh:time3h:trpre.heat -0.438377 -1.587533 0.743623 1000.0 0.410
genehsp110:time3h:trpre.heat -0.220222 -1.391239 1.150086 1000.0 0.692
genehspb:time3h:trpre.heat 0.160995 -1.163069 1.306889 1000.0 0.808
```

This tells us that indeed, *egr* is significantly less up-regulated whereas *fos* is significantly more up-regulated between 1h and 3h time points if the sample was pre-heated.

While the code above can be used to plot the results of any fully crossed two-way model, sometimes the designs are more complex or do not contain some combinations of factor levels (i.e., are not fully crossed). To plot the results of such models (and extract p-values) in a gene-by-gene fashion there is the package's own function `HPDplotBygeneBygroup` (pages 22-23), which plots the results directly out of the model object and allows the user to specify more specifically which factor combinations should be plotted as separate groups in the same plot.

Global effects: providing information about RNA quality/quantity

Often it is possible to obtain a measure of RNA quantity and/or quality for each sample, such as, for example, Bioanalyzer's RIN value. This could be very useful in sharpening the gene expression estimates. RNA quality/quantity would affect expression of all genes in the same way – basically diminish all genes if it is low – and therefore should be included in the model as a global, not gene-specific, effect. Such a measure should be included in the model in the form of `globalFixed` effect, which could be either continuous or categorical. Any number of scalar global effects can be specified as a vector, for example:

```
mcmc.qpcr(..., globalFixed=c("quantity","quality"))
```

If the global effect is a continuous measure (as quantity or quality would most likely be), make sure to say, after running `cq2counts` to produce `qs` dataframe:

```
qs$quality=as.numeric(as.character(qs$quality)) ,
```

to let R know that this variable should be treated as continuous.

For the sake of beauty and symmetry there is also a `globalRandom` option, although I cannot think of any specific use for it at the moment.

Extracting model-derived “normalized data” for multivariate analysis:

Sometimes trellis plots are not sufficient to convince reviewers, and/or some multivariate analysis is desirable. For this we might need the model-derived data that are free from global sample effects. This can be done in two steps:

1. Fitting the model with additional options: `random="sample"`⁴, `geneSpecRes=FALSE`, and `pr=TRUE` :

```
naive3=mcmc.qpcr(data=qs2way,fixed="tr+time+tr:time",random="sample", geneSpecRes=FALSE,  
pr=TRUE)
```

2. Extract the model predictions using the function `getNormalizedData`:

```
nd=getNormalizedData(naive3,data=qs2way)
```

The returned object (`nd`) is a list of two data frames. The first one, `nd$normData`, is the model-predicted log2-transformed transcript abundances table. It has one column per gene and one row per sample. The second data frame, `nd$conditions`, is a table of experimental conditions corresponding to the `normData` table.

Let's do principal coordinate analysis on this data. For gene expression, the most logical distance measure is Manhattan distance, since it directly corresponds to the sum of all log-fold-changes for all genes among samples. We might need to scale it down a bit by dividing the resulting scores by 100 to make sure the `pcoa` function does not complain:

```
library(vegan)  
library(ape)  
mypcoa=pcoa(vegdist(nd$normData,method="manhattan")/100)  
scores=mypcoa$vectors
```

Let's plot it, coloring by time and changing symbol types by treatment (Fig. 5)

```
plot(  
  scores[,1],scores[,2],  
  pch=as.numeric(as.factor(nd$conditions$tr)),  
  col=as.numeric(as.factor(nd$conditions$time))  
)  
ordispider(scores,nd$conditions$tr,label=T)  
ordiellipse(scores,nd$conditions$time,label=T)
```

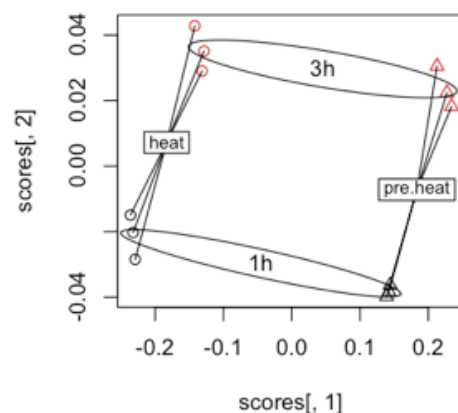


Figure 5: Principal coordinate analysis of the qPCR results.

⁴ If you already have one or more random factors (say, blocking factors or individuals in a longitudinal design) just add “sample” to them: `random=c("myFactor1", "myFactor2", "sample")`

This plot looks rather silly because there is so much difference between all combinations of factors. But for the sake of completing the task, let's run permutation-based ANOVA on this data (function `adonis`):

```
adonis(nd$normData~time*tr,data=nd$conditions,method="manhattan")
```

Call:

```
adonis(formula = nd$normData ~ time * tr, data = nd$conditions, method = "manhattan")
```

Terms added sequentially (first to last)

| | Df | SumsOfSqs | MeanSqs | F.Model | R2 | Pr(>F) | |
|-----------|----|-----------|---------|---------|----------|--------|-----|
| time | 1 | 353.0 | 353.0 | 166.35 | 0.08056 | 0.002 | ** |
| tr | 1 | 4033.0 | 4033.0 | 1900.69 | 0.92040 | 0.001 | *** |
| time:tr | 1 | -21.2 | -21.2 | -9.98 | -0.00483 | 1.000 | |
| Residuals | 8 | 17.0 | 2.1 | | 0.00387 | | |
| Total | 11 | 4381.8 | | | 1.00000 | | |

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

So according to this, both time and tr factors are super-significant, but there is no visible overall interaction. However, we have seen previously that two genes do seem to show marginally significant interaction terms (Fig. 4 and page 8).

A Very Long Tutorial ⁵

Coral stress-recovery experiment

The exercises in this tutorial are based on the dataset ‘coral.stress’, provided with the package. The experiment that generated this dataset addressed the effects of heat-light stress and subsequent recovery on gene expression in a reef-building coral *Porites astreoides* (Kenkel et al. 2011). Briefly, eight individual coral colonies were fragmented into 4 pieces each and allowed to acclimatize in common benign conditions for four days. The next morning, two fragments of each colony were placed into a stressful environment (elevated heat and light). At midday on the same day, when the stress intensity was the highest, one stressed fragment and one control fragment (remaining in the benign conditions) were sampled, representing the first sampling timepoint. In the end of the same day, the second stressed fragment was put back into the benign environment for recovery. This fragment, along with the remaining control fragment, was sampled at midday on the following day (the second timepoint, corresponding to recovery). Expression of 15 genes, 5 of which were putative control genes, was assayed by qRT-PCR on Roche LightCycler 480 instrument with SYBR detection. In the original paper (Kenkel et al. 2011), the analysis included correcting for amplification efficiencies, normalization by the 3 genes that proved to be most stable according to geNorm test (Vandesompele et al. 2002), followed by linear mixed model analysis on a gene-by-gene basis (Poletto et al. 2006).

This dataset is interesting from the analytical standpoint because of three reasons. First, one of the main effects of interest is the interaction term, Condition:Timepoint, describing the gene regulation in coral fragments that were first stressed and then allowed to recover. Evaluation of the interaction term necessitates the use of linear models or ANOVA rather than non-parametric methods (Steibel et al. 2009). Second, the dataset includes an important random effect, the identity of the individual coral colony, potentially affecting the baseline level of expression of some genes, which prompts the use of a linear mixed model rather than a simple linear model. Finally, several genes were so down-regulated that they became undetectable by qRT-PCR in a considerable number of trials, precluding a straightforward use of log-transformation typical of qRT-PCR analysis (Vandesompele et al. 2002; Luu-The et al. 2005).

Cq data format

The main input is the table of raw Cq (“cycle of quantification” values, which may be called ‘Ct’ depending on the kind of qPCR instrument) containing columns of Cq values (one column per gene) and columns of conditions (fixed and random factors). Gene and condition names should be given as column titles. In addition to normal Cq values, the Cq columns may contain entries ‘NA’ (missing data, which might be entered because the observed amplification product did not have the expected melting peak) and ‘-1’ (no amplification - presumably because there was not a single target molecule in the analyzed aliquot). Technical replicates should not be averaged but instead listed as separate rows. To view the format, use head() to print out the first ten lines of the ‘coral.stress’ dataset:

```
library(MCMC.qpcr)
data(coral.stress)
head(coral.stress)
```

| | sample | individual | condition | timepoint | hsp16 | actin | adk | c3 | chrom | clect | eif3h |
|---|--------|------------|-----------|-----------|-------|-------|-------|-------|-------|-------|-------|
| 1 | 1 | s1 | control | one | 36.62 | 22.44 | 31.54 | 29.57 | NA | 33.93 | 31.69 |
| 2 | 1 | s1 | control | one | -1.00 | 22.42 | 31.24 | 28.83 | 37.76 | 32.99 | 32.02 |
| 3 | 2 | s1 | heat | one | 26.89 | 23.27 | 30.92 | 27.98 | 30.70 | 34.74 | 29.65 |
| 4 | 2 | s1 | heat | one | 27.08 | 23.34 | 31.71 | 28.06 | 31.28 | 33.95 | 29.73 |
| 5 | 3 | s2 | control | one | NA | 23.24 | 33.22 | 27.08 | 34.95 | NA | 31.41 |
| 6 | 3 | s2 | control | one | -1.00 | 23.94 | 33.13 | 27.73 | 34.70 | -1.00 | 32.90 |

⁵ The numbering of figures restarts here...

Here, the first four columns denote random and fixed factors. Rows with exact same entries in these four columns are technical replicates (two per sample in this case). It is OK to have occasional dropouts of technical replicates, as long as the dropout rate is not correlated with any of the factors.

One critical random factor for the analysis is ‘sample’, denoting individual cDNA preparations. This factor will be used to infer different template loadings in qPCR reactions, which serves as a functional equivalent of normalization in qRT-PCR. The ‘sample’ column must be present in the table, does not matter in which position.

Other random factors would typically be grouping factors, such as block, plot, tank, cage, genotype, etc. In this case, the ‘individual’ random effect denotes the coral colony that was fragmented into clonal pieces that were subject to treatments.

Finally, the experimental design includes two fixed effects, ‘condition’ (‘control’ or ‘heat’) and ‘timepoint’ (‘one’ corresponding to the day of stress, ‘two’ corresponding to the following day when the corals were allowed to recover).

Such a table can be assembled in spreadsheet editor software, such as MS Excel, from raw Cq data exported by the qPCR instrument. While naming the factors and genes, remember that in R the column names cannot start with a number and cannot contain spaces (or rather, spaces will be converted to full stops, ‘.’). Save the table as “comma-delimited values” (with the extension .csv), and use R function read.csv() to import it into R:

```
mydata=read.csv("name-of-my-file.csv")
head(mydata)      # to see if the dataset was imported correctly
```

Amplification efficiencies

The second input is a two-column table of qPCR efficiencies for each gene. The efficiency (E) is the amplification factor per PCR cycle, and is needed for proper Cq to counts conversion. To estimate E , we recommend the dilution series method (Pfaffl 2001), where a series of 8-10 2-fold template dilutions is analyzed by qPCR. The template should be a previously amplified fragment, pre-diluted 100,000-fold to make Cq values fall within the realistic range. The package contains a dataset of dilution series results called ‘dilutions’ and a function PrimEff() that would calculate amplification efficiencies, plot the regressions (Fig. 1) and summarize the results in a form of a table:

```
data(dilutions)
dilutions
```

| | dna | cq | gene |
|-----|-------------|-------|-------|
| 1 | 1.000000000 | 19.80 | eif3h |
| 2 | 1.000000000 | 19.75 | eif3h |
| 3 | 1.000000000 | 19.99 | eif3h |
| 4 | 1.000000000 | 19.99 | eif3h |
| 5 | 1.000000000 | 19.78 | eif3h |
| 6 | 1.000000000 | 20.06 | eif3h |
| 7 | 0.250000000 | 21.73 | eif3h |
| 8 | 0.250000000 | 21.88 | eif3h |
| 9 | 0.250000000 | 21.82 | eif3h |
| 10 | 0.250000000 | 21.78 | eif3h |
| 11 | 0.250000000 | 22.01 | eif3h |
| 12 | 0.250000000 | 21.80 | eif3h |
| 13 | 0.062500000 | 24.10 | eif3h |
| 14 | 0.062500000 | 23.92 | eif3h |
| 15 | 0.062500000 | 24.18 | eif3h |
| 16 | 0.062500000 | 24.27 | eif3h |
| ... | | | |

PrimEff(dilutions) # Fig. 1

| | gene | E | E.minus.sd | E.plus.sd | intercept |
|---|-------|-------|------------|-----------|-----------|
| 1 | chrom | 2.017 | 2.00 | 2.03 | 18.6 |
| 2 | eif3h | 1.900 | 1.89 | 1.91 | 19.8 |

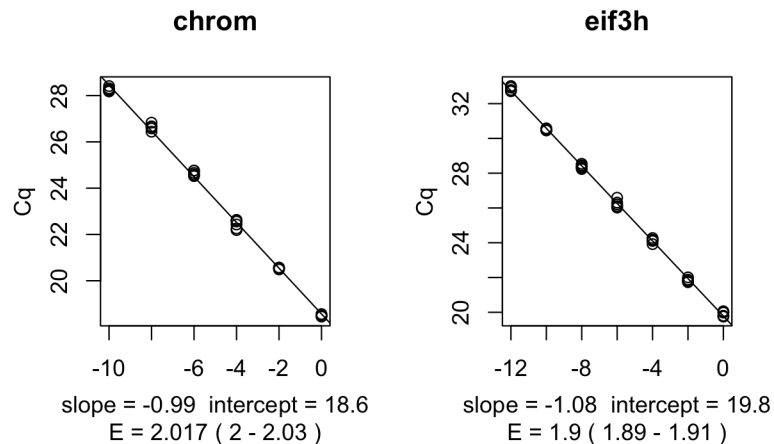


Figure 1. PrimEff() plots of regression slopes and PCR efficiencies based on dilution series.

The input table for this analysis can once again be created in Excel, and should have the same order of the columns as the 'dilutions' example: first is RNA concentration (which may be arbitrary, 1/[dilution factor], as it is here), second is Cq (or Ct), third is gene name. Names of the columns do not matter as long as their order is the same. The input may contain concatenated data for several genes.

When all the gene targets are analyzed for qPCR efficiency, the results should be put together in a table that will be used by MCMC.qpcr analysis:

```
data(amp.eff)
amp.eff
  gene efficiency Cq1
1 hsp16      1.90  NA
2 actin      1.95 36.5
3 adk        1.99 36.8
4 c3         1.99  NA
5 chrom      1.98 36.5
6 eif3h      1.90 38.0
7 g3pdh      1.85 39.2
8 gsp2       1.96 36.7
9 hsp60      1.93 37.3
10 hsp90     1.91 38.2
11 nd5       1.97 36.2
12 rpl11     1.95 37.8
13 spon2     2.00 36.5
14 ubl3      2.00  NA
15 tgoln     2.00  NA
16 r18s      1.93  NA
17 clect     2.00  NA
```

There are two obligatory columns: gene name should appear in the first column, while E should be in the second column (the column names don't matter). The third column is optional and contains an experimentally estimated Cq of a single molecule of the target. The table should contain all the genes that feature in the main Cq table. It is perhaps needless to say that the gene names must be spelled

exactly the same way in both tables (remember that R is case-sensitive).

Cq to counts conversion

This is the key transformation in the whole methodology, which makes it possible to apply generalized linear model to account for higher variation at the lower end of target abundances, and also to properly derive information from empty qPCR trials.

The conversion to approximate counts uses a simple formula:

$$\text{Count} = E^{(Cq1 - Cq)}, \text{ rounded to integer,} \quad (1)$$

where E is the efficiency of amplification and $Cq1$ is the the number of qPCR cycles required to detect a single target molecule. $Cq1$ is the feature of the qPCR assay when run on a particular instrument, and its exact determination requires considerable effort. Fortunately, at least the 11 genes that we examined in detail turned out to have very similar $Cq1$, within 36-39 range, and we were able to demonstrate that the choice of $Cq1$ does not affect the results of relative quantification much as long as it is within this range. Assuming the same average-size $Cq1 = 37$ for all genes resulted in good model fit and exactly the same results as the analysis with more accurately approximated $Cq1$. We therefore believe that $Cq1 = 37$ will work well for most tasks, as long as the goal is relative rather than absolute quantification. A more sophisticated way of specifying $Cq1$ is to approximate it based on the efficiency (E) using empirical formula $Cq1 = 79 - 21.5E$, but we cannot guarantee that the formula, which we developed for LightCycler 480, would be applicable to other instruments.

The function that performs the conversion is `cq2counts()`. In addition to the names of the main Cq dataset ('data' argument) and the name of amplification efficiencies dataset ('effic' argument), it also needs to be told which columns contain Cq values ('genecols' argument) and which columns correspond to conditions ('condcols' argument). The method of $Cq1$ setting is determined by 'Cq1' parameter ("table" for experimentally estimated $Cq1$ listed as the third column in the efficiency table, "formula" for formula-based approximation, and any number to fix $Cq1$ for all genes at this value). We will specify $Cq1 = 37$:

```
data(coral.stress)
data(amp.eff)
dd=cq2counts(
  data=coral.stress,
  genecols=c(5:19), # where the Cq data are in the data table
  condcols=c(1:4),  # which columns contain factors
  effic=amp.eff,
  Cq1=37
)
head(dd)
```

| | count | gene | sample | individual | condition | timepoint |
|----|-------|-------|--------|------------|-----------|-----------|
| 1 | 1 | hsp16 | 1 | s1 | control | one |
| 2 | 0 | hsp16 | 1 | s1 | control | one |
| 3 | 658 | hsp16 | 2 | s1 | heat | one |
| 4 | 582 | hsp16 | 2 | s1 | heat | one |
| 5 | NA | hsp16 | 3 | s2 | control | one |
| 6 | 0 | hsp16 | 3 | s2 | control | one |
| 7 | 160 | hsp16 | 4 | s2 | heat | one |
| 8 | 142 | hsp16 | 4 | s2 | heat | one |
| 9 | 7 | hsp16 | 5 | s4 | control | one |
| 10 | 4 | hsp16 | 5 | s4 | control | one |

The resulting data frame (dd) has the raw Cq values efficiency-corrected and transformed into counts based on $Cq1 = 37$, also have all the counts "stacked" so they all are now in a single column.

The qRT-PCR model

Below I use the coral example to explain, in colloquial terms, how the qRT-PCR model is constructed. A reader inclined towards more statistically rigorous notation and language is encouraged to study our original paper introducing the method (Matz, Wright, and Scott, 2013). The model has a single response variable, the natural logarithm of transcript counting rate. The most basic explanatory variable in the model is ‘gene’, which accounts for different levels of expression between genes:

$$\ln(\text{rate}) \sim \text{gene} .$$

Such a primitive model, however, would be of little value since in qRT-PCR we are typically not interested in difference in expression between genes, but want to learn how the expression of each gene varies depending on the experimental treatments. To find this out, we augment our model with a series of terms describing gene-specific effects of experimental treatments. In our coral experiment, we have two treatments (or, using linear modeling terminology, factors): Condition with levels “control” and “heat” and Timepoint with levels “one” and “two”, plus their interaction (i.e., we suspect that there might be some Timepoint-specific effects of Condition). This experimental design is incorporated into the model as follows:

$$\ln(\text{rate}) \sim \text{gene} + \text{gene:Condition} + \text{gene:Timepoint} + \text{gene:Timepoint:Condition} ,$$

where the colon indicates interaction, essentially standing for “-specific effect of “. The model is fully flexible, not being limited to a particular number of factors, number of levels within each factor, or presence-absence of interactions.

Even though our model specification now seems to contain all the terms we want to estimate, we must take care of other important sources of variation that, while being of no real interest to us, must be taken into account to ensure that the model is accurate and powerful. The most important of these is the random effect of the biological replicate (i.e., an individual RNA sample), accounting for the variation in quality and/or quantity of biological material among samples. The designation “random effect” implies that we are not interested in actual estimates of each sample’s quality or quantity, but simply want to partition out the corresponding variance. Random effects are imagined as random variables drawn from an underlying distribution the variance of which the model will estimate. In the simplified notation that we use throughout this section, we will italicize the names of random factors, to discriminate them from the factors of primary interest (“fixed factors”) that we discussed before:

$$\ln(\text{rate}) \sim \text{gene} + \text{gene:Condition} + \text{gene:Timepoint} + \text{gene:Timepoint:Condition} + \textit{sample} .$$

Note that, since the variation in cDNA quality and/or quantity affects all genes in a sample in the same way, this random factor is not gene-specific. The introduction of this random factor into the qRT-PCR model was perhaps the most important innovation in the model of Steibel et al (2009).

The experimental design might have involved additional “grouping factors” that are not directly related to the experimental treatments being studied but still might be responsible for a considerable proportion of variation and must be accounted for to achieve more accurate predictions. For example, the experiment might have involved repeated measurements of participating individuals, partitioning of the experimental subjects between several blocks (plots, tanks) for technical reasons, or measurements of all the effects of interest on different genotypes. The latter is the case in our coral example, where we used 8 coral colonies (“individuals”) each split into four clonal fragments that were exposed to our experimental treatments. The grouping factors can be specified in the model as additional random factors; however, in contrast to the *sample* factor, these would be gene-specific since different genes

might be affected by the grouping factors differently. In our case, we want to account for possible differences in baseline level of expression of each of our genes between 8 colonies, and we augment our model as follows:

$$\ln(\text{rate}) \sim \text{gene} + \text{gene:Condition} + \text{gene:Timepoint} + \text{gene:Timepoint:Condition} + \text{sample} + \text{gene:individual}.$$

Once again, the model is flexible in the number of grouping factors that could be included.

The remaining term that we still need to add is the error term, accounting for the residual variation that remained unexplained. In the early version of this package the error term has been split into two, which tended to created problems within the MCMC process. We now leave just a single error term, *gene:residual*, accounting for gene-specific residual variance:

$$\ln(\text{rate}) \sim \text{gene} + \text{gene:Condition} + \text{gene:Timepoint} + \text{gene:Timepoint:Condition} + \text{sample} + \text{gene:individual} + \text{gene:residual}. \quad (2)$$

There is one last, but by no means the least, piece to the model formulation. We will assume additional variability due to Poisson process on top of all these sources of variation: the observed count is assumed to be a sample drawn from the Poisson distribution with the mean equal to the predicted count. This accounts for the increase in variance due to “shot noise” that might accompany down-regulations of low- and medium-abundant genes and allows for zero counts in the data. Note that the model does not assume that Poisson variation is the only source of residual variation: the error term *gene:residual* within the model (2) captures any additional variation, and therefore account for the over-dispersion of the data.

Fitting the model: function `mcmc.qpcr()`

The model (2) may look quite complicated, but since many of its terms are universal to any qRT-PCR analysis, the syntax for the actual function call can be substantially simplified. To specify the model, construct appropriate priors, and fit it to the data without (at the moment) specifying any control genes, the function `mcmc.qpcr()` only requires the following:

```
mm=mcmc.qpcr(
  fixed="condition+timepoint+condition:timepoint",
  random="individual",
  data=dd
)
```

As the function starts to run, it prints out constructed priors and MCMCglmm-aimed formulas for fixed and random effects (as a basic “sanity check”), and then proceeds to the MCMC chain reporting the number of iterations done and one useful value called “Acceptance ratio for latent scores”. This value tells us whether the MCMC chain is still searching for a best-fit patch of parameters (smaller values at the beginning of the chain) or has reached it and is now sampling all the compatible parameter combinations (the values become more or less stable). By default, the chain does 12000 iterations (`nitt=12000`) and discards the first 2000 of them (`burnin=2000`). If the plateau of the acceptance ratios is reached later than iteration 2000, we will need to adjust these parameters a bit. If, for example, the plateau is reached at iteration 4000, we will need to specify `burnin=4000` and also increase the total number of iterations proportionally (by 4000-2000 in our case) to obtain the same number of parameter samples, which comes to `nitt=14000`.

The object returned by the function ('mm') is of the MCMCglmm class, containing all the parameter values and deviances sampled during the progress of the MCMC chain. To appreciate the complexity of the actually fitted model, let's summarize it and see how many terms and interactions were involved. Below is the truncated result (omitting 11 genes out of 15), with annotations explaining the entries:

```
summary(mm)
  Iterations = 3001:12991
  Thinning interval = 10
  Sample size = 1000 # 1000 samples of parameter sets and deviances were stored

DIC: 6479.916 # Deviance Information Criterion

G-structure: ~sample # variance due to unequal template loading between samples

      post.mean l-95% CI u-95% CI eff.samp
sample      1.493    0.7976    2.442    1000

      ~idh(gene):individual # gene-specific variance between individual corals

            post.mean l-95% CI u-95% CI eff.samp
actin.individual 0.0041456 8.862e-17 2.185e-02 103.85
adk.individual   0.0006856 3.992e-17 3.379e-05 301.57
... # omitting entries for 11 genes
spon2.individual 6.3975206 1.183e+00 1.521e+01 1000.00
ubl3.individual  0.0571330 5.994e-17 2.996e-01 41.49

      ~idh(gene):sample # gene-specific variance between samples

            post.mean l-95% CI u-95% CI eff.samp
actin.sample 0.2156528 9.914e-02 0.374336 512.84
adk.sample   0.5445622 1.785e-01 0.961275 282.26
...
spon2.sample 0.7653844 2.902e-01 1.421424 222.94
ubl3.sample  0.2851004 6.560e-02 0.547365 113.78

R-structure: ~idh(gene):units # gene-specific variance in measurement precision

            post.mean l-95% CI u-95% CI eff.samp
actin.units 0.0650145 3.483e-02 0.098712 1000.00
adk.units   0.0710713 1.693e-02 0.145826 386.69
...
spon2.units 0.0292340 6.446e-03 0.061818 311.44
ubl3.units  0.0303894 6.487e-04 0.083863 79.43
Location effects: count ~ 0 + gene + gene:condition + gene:timepoint + gene:condition:timepoint

            post.mean l-95% CI u-95% CI eff.samp pMCMC
# First, gene-specific intercepts, reflecting how abundant each gene is on average.
# These are of no interest to us.
geneactin      9.35429  8.37311 10.16611 1134.68 <0.001 ***
geneadk        2.33339  1.21747  3.28453 1100.97 <0.001 ***
...
genespon2      3.40589  1.30645  5.43524 1000.00 0.002 **
geneubl3       2.67307  1.72603  3.63866 1000.00 <0.001 ***
# expression changes due to exposure to heat stress:
geneactin:conditionheat -1.29628 -2.49431 -0.01555 1000.00 0.046 *
geneadk:conditionheat   0.37930 -1.02631  1.83121 1000.00 0.574
...
genespon2:conditionheat 1.11408 -0.21414  2.69422 1000.00 0.124
geneubl3:conditionheat  0.51200 -0.70768  1.99122 1000.00 0.434
```

```

# expression changes between two timepoints:
geneactin:timepointtwo      -0.96082 -2.15698  0.49938 1000.00  0.148
geneadk:timepointtwo        -1.29126 -2.75501  0.17560  549.28  0.094 .
...
genespon2:timepointtwo      -1.57614 -2.98161  0.04681  669.22  0.044 *
geneubl3:timepointtwo       -1.94519 -3.27265 -0.62660  749.12  0.008 **
# additional expression changes between two timepoints if a coral was heat-stressed at first:
geneactin:conditionheat:timepointtwo  1.85779 -0.08222  3.62050 1000.00  0.050 .
geneadk:conditionheat:timepointtwo    1.08814 -1.01211  2.94039 1000.00  0.302
...
genespon2:conditionheat:timepointtwo   0.29039 -2.00639  2.15243  775.15  0.780
geneubl3:conditionheat:timepointtwo    0.54378 -1.33804  2.31208  876.90  0.562
---
```

The results may be ever so slightly different in each case of model fitting, because of the randomness in MCMC process. Note that the summary lists 95% credible intervals and MCMC-based p-values for each of the estimated parameters. A credible interval is a Bayesian analog of a confidence interval in frequentist statistics. Although a confidence interval may sound more familiar, the credible interval has a more intuitive interpretation, being the interval containing the true value of the parameter with a set probability (for example 0.95) given the data and the priors, whereas the confidence interval would be the range that includes the true parameter value in 95% of the independent re-runs of the experiment. The “location effects” (= fixed effects) will be of our primary interest. They are expressed as natural logarithms of fold-changes. qPCR practitioners might be more comfortable with the fold-changes on \log_2 scale (divide the listed values by $\ln(2)$), since it would be just like the difference in number of qPCR cycles. We will later see how these values can be combined to calculate the difference between conditions of interest.

Also note that the summary for random effects does not show point-estimates (for example, for `~idh(gene):individual`, there is no value giving the expression of actin in the individual s1), only the variances attributable to each gene. Although it is possible to make the function save these estimates, they are of little practical value.

Diagnostic plots

There are three main criteria that can tell us whether our linear modeling approach is valid in application to the dataset at hand. First, the residuals of the model should not show a trend depending on the predicted value; if this is violated, then the data are not actually linear. Second, the size of the residuals should not change depending on the predicted value. This is the test for equal variances across the modeled range (homoscedasticity). Third, the residuals should be approximately normally distributed. For intricate statistical procedures such as linear mixed modeling, these assumptions are best tested graphically using three diagnostic plots: residuals plotted against predicted value to verify linearity, “scale-location” plot of the square root of absolute value of the residuals (i.e., the size of residuals) to test for homoscedasticity, and quantile-quantile plot of residuals against normal distribution to test for normality. The latter is simply a plot of ranked standardized (divided by their standard deviation) residuals against ranked normally-distributed variable, which is simulated. In our case, the criteria should apply to the lognormal residuals e_{gijk} from formula [2] (remember that we also have Poisson residuals on top of these). The MCMC.qpcr package includes a function *diagnostic.mcmc* that produces these plots; however, we first need to run the model with two additional options (`pr=T, pl=T`) to be able to extract the residuals:

```

mmd=mcmc.qpcr(
  fixed="condition+timepoint+condition:timepoint",
  random="individual",
  data=dd,
  pr=T,
  pl=T,
```

```
pl=T
)
```

Then we can see whether our data fit the linear model assumptions reasonably well (Fig.2):

```
diagnostic.mcmc(
  model=mmd,
  col="grey50",
  cex=0.8
)
```

(the arguments and 'col' and 'cex' here are not essential, they adjust the color and the size of the points on the plots)

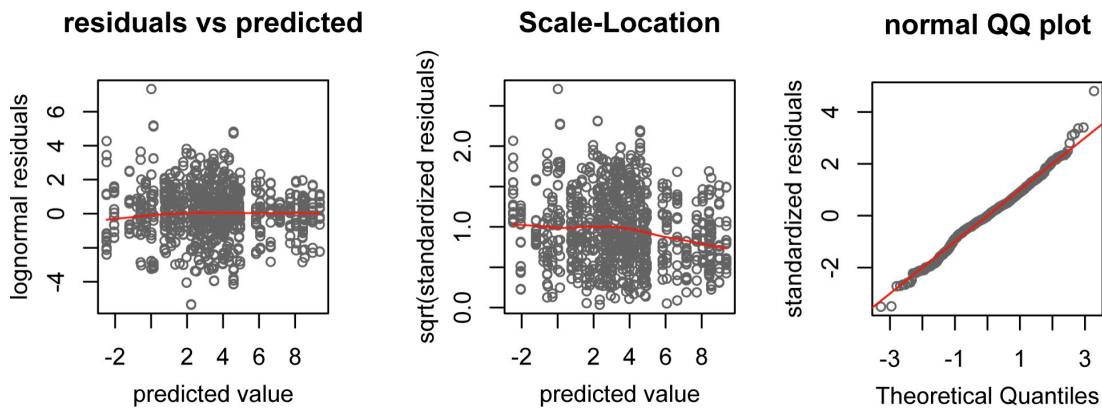


Figure 2. Diagnostic plots produced by the function `diagnostic.mcmc()`.

Extracting and visualizing results

NOTE: This section has been written prior to version 1.0.3. It is all still valid; however, if your experimental design involves a single multilevel factor or two fully crossed multilevel factors, your best bet in extracting and plotting the results is functions `HPDsummary()` and `summaryPlot()`, described in the Very Short tutorial above.

One great advantage of the MCMC-based model fitting is that the estimates as well as credible intervals for any modeled effects (or their combinations) can be computed directly from the results of MCMC sampling.

Determining exactly which combination of factors corresponds to the contrasts of interest can be confusing for someone who is new to linear modeling, so I will briefly walk through the logic using our coral example. We want to know how coral genes are regulated in response to heat stress, and how they are then regulated after the coral is allowed to recover. So we want to find the combinations of fixed effects which would describe (i) the difference between stressed and unstressed coral on the first day, and (ii) the difference between recovering coral and its earlier stressed condition. Let's call the first contrast "stress", and the second one "recovery". To see which combinations of effects describe these contrasts, it is also important to remember that all the effects listed in our model's summary are differences with respect to one particular combination of factor levels. Which one? The one that does not appear in the list of fixed effects in the summary. Conveniently, it seems to be the control condition at timepoint one; R chose it simply because 'control' and 'one' come alphabetically before 'heat' and 'two' (generally, any combination of factor levels can be specified as a reference using the generic `relevel()` function). Therefore, the "stress" contrast directly corresponds to 'conditionheat' effect. The mean

expression change for any particular gene, for example, actin, due to “stress” is thus given by the mean of the MCMC sample of the `geneactin:conditionheat` parameter, while its 95% credible interval is the range excluding top and bottom 2.5% of all sampled values. The means and credible intervals for such directly reportable effects are given in the model’s summary:

```
...
               post.mean l-95% CI u-95% CI eff.samp  pMCMC
geneactin:conditionheat -1.29628 -2.49431 -0.01555  1000.00  0.046 *
```

‘pMCMC’ here is a two-tailed p-value, which is twice the fraction of all sampled values (out of ‘eff.samp’, 1000) that cross zero with respect to the mean. Note that, under this model, the actin down-regulation due to stress is significant at the 0.05 level.

“Recovery” is a trickier contrast: it is a compound effect, involving a combination of several directly reported effects. To compute it, remember that the expression of a gene in a stressed coral on the day of stress is, as we just discussed,

$$E_S = [\text{reference condition}] + \text{conditionheat} ,$$

while expression of a gene in a previously stressed coral on the day of recovery (timepoint ‘two’) is

$$E_R = [\text{reference condition}] + \text{conditionheat} + \text{timepointtwo} + \text{conditionheat:timepointtwo} .$$

Therefore, the difference in expression between these two conditions, representing gene regulation due to recovery from stress, is

$$E_R - E_S = \text{timepointtwo} + \text{conditionheat:timepointtwo} .$$

So, to compute the “recovery” effect for a gene, we have to sum up its ‘timepointtwo’ and ‘conditionheat:timepointtwo’ effects within each sampled iteration. These sums will then constitute a new MCMC sample for which the mean and credible interval can be computed in the same manner as for the directly reported effects.

Manually extracting and manipulating gene-specific effects from MCMC results can be tedious, to say the least. Function `HPDplot()` has been developed to streamline this processes and plot the results. It also converts the estimates from natural logarithm to \log_2 .

The following will generate two separate point-and-whiskers plots for the “stress” and “recovery” effects across all genes (Fig. 3):

```
HPDplot(
  model=mm,
  factors="conditionheat",
  main="stress"
)
HPDplot(
  model=mm,
  factors=c(
    "timepointtwo",
    "conditionheat:timepointtwo"
  ),
  main="recovery"
)
```

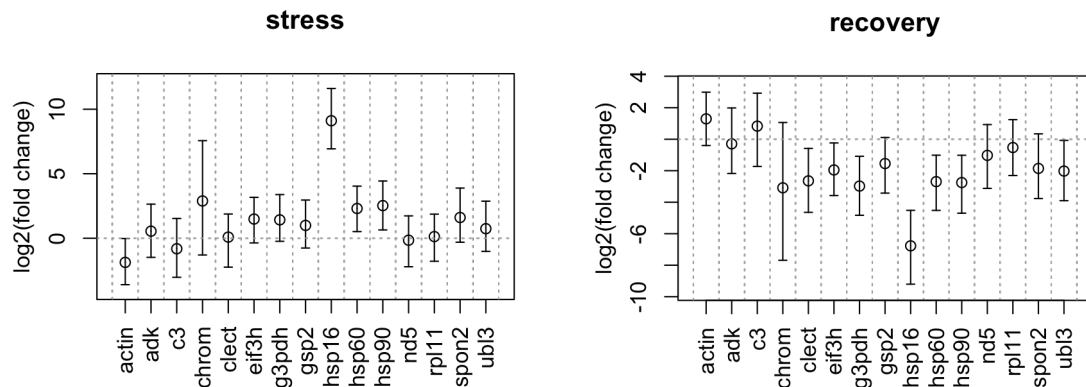


Figure 3. Fixed effects of stress and recovery according to the naïve model (no control genes specified). The points are posterior means, the whiskers denote 95% credible intervals. The figure is plotted with `HPDplot()`.

The argument ‘`factors`’ here specifies the factors which need to be plotted. If more than one factor is listed, such as `c("timepointtwo", "conditionheat:timepointtwo")`, these factors will be summed up – this is how compound effects, such as our “recovery”, can be calculated. The argument “`main`” simply gives a title to the plot.

The fixed effects math goes just one step further. In models with fixed factors with more than two levels, to perform Tukey-style pairwise comparisons we might wish to subtract one type of effect from another, or, in a more general case, subtract one sum of effects from another sum of effects. To do this, the function `HPDplot()` can be provided with an additional argument, ‘`factors2`’, which will specify the sum of effects to be subtracted from the one specified by ‘`factors`’.

Visually, it would be easier to compare the “stress” changes to “recovery changes if they were plotted on the same plot. This can be done with just a couple extra arguments (Fig. 4):

```
HPDplot(
  model=mm,
  factors="conditionheat",
  main="stress / recovery",
  jitter=-0.15,
  ylim=c(-10,12)
)
HPDpoints(
  model=mm,
  factors=c(
    "timepointtwo",
    "conditionheat:timepointtwo"
  ),
  jitter=0.15,
  col="orange2",
  pch=17
)
```

Note that the second function call is now to ‘`HPDpoints`’, which adds to an existing plot rather than creates a new one. The parameter ‘`jitter`’ shifts the dot-whiskers to the left if negative and to the right if positive, so the combined graphs would not overlap. ‘`ylim`’ in the call to ‘`HPDplot`’ sets the y-axis range, to make sure both graphs will fit. Finally, ‘`pch`’ in the second call changes the type of symbol (see

<http://www.endmemo.com/program/R/pchsymbols.php> for the chart of what's available) and 'col' changes the color of the added graph (R colors: <http://www.stat.columbia.edu/~tzheng/files/Rcolor.pdf>).

A finishing touch is to add legend to the plot:

```
legend(11,12,"stress",lty=1,pch=1,bty="n")
legend(11,10,"recovery",lty=1,pch=17,col="orange2",bty="n")
```

Try ?legend to see details about this basic R function. Briefly, it needs to be told the coordinates on the plot where to put the label (the first two numbers are x,y), type of line (if any), type of symbol (if any), color (black by default), and whether it should be in the box.

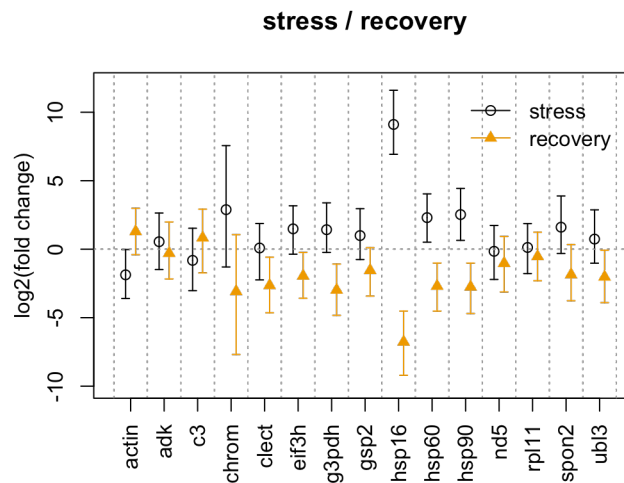


Figure 4. Fixed effects of stress and recovery according to naïve model (no control genes specified). The points are posterior means, the whiskers (left) or dashed lines (right) denote 95% credible intervals. The figure is plotted with HPDplot(), HPDpoints(), and legend().

An alternative representation of the results is to plot them gene by gene for all conditions of interest. The function HPDplotBygene() does that, but first we need to create a 'list' object describing what are the conditions we are looking to plot and which factor combinations they correspond to. Similarly to HPDplot() function, each condition can be described by two groups of fixed effects, 'factors' and 'factors2'. The effects within each group will be summed up, and then the sum for 'factors2' will be subtracted from the sum for 'factors'. In the vast majority of cases, a single group of effects ('factors') would be sufficient to describe conditions of interest. The groups may include the gene-specific intercept (which should be denoted by '0' among 'factors'), corresponding to the gene expression level under 'reference' condition (see page 10).

First, we create the condition-defining list (review page 10 if you are still unsure how different conditions are described by sums of fixed effects):

```
cds=list(
  control=list(factors=0), # this is the gene-specific intercept, i.e., our reference condition
  stress=list(factors=c(0,"conditionheat")),
  recovery=list(factors=c(0,"conditionheat","timepointtwo","conditionheat:timepointtwo"))
)
```

Now we can plot abundances of any gene under these conditions. Let's plot three most responsive genes, actin, hsp60 and hsp16. We will do it gene by gene, creating a plot panel with y-limits when plotting the first gene and then adding more graphs to the same plot, jittering them a little so they don't overlap:

```
HPDplotBygene(
  model=mm,
  gene="actin",
  conditions=cds,
  col="cyan3",
  jitter=-0.15,
  ylim=c(-3.5,15),
  pval="z"
)
HPDplotBygene(
  model=mm,
  gene="hsp60",
  conditions=cds,
  newplot=FALSE,
  col="grey50",
  pval="z"
)
HPDplotBygene(
  model=mm,
  gene="hsp16",
  conditions=cds,
  newplot=FALSE,
  col="coral",
  jitter=0.15,
  pval="z"
)
```

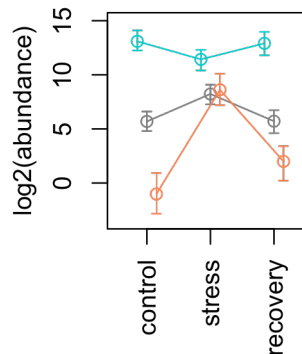


Figure 5. Abundances of actin (blue), hsp60 (grey) and hsp16 (red) across experimental conditions, plotted using HPDplotBygene(). The whiskers denote 95% credible intervals.

Note that in addition to the plot (Fig. 5), the function HPDplotBygene outputs the matrix of mean pairwise differences (log2-transformed fold changes, think of them as the difference in number of PCR cycles) and the matrix of pairwise *p*-values, like shown here for the last call to HPDplotBygene (for hsp16):

```
$mean.pairwise.differences
      control  stress  recovery
control      0 6.678398  2.089490
stress       0 0.000000 -4.588908
recovery     0 0.000000  0.000000

$pvalues
      control  stress      recovery
control      0      0 9.056390e-03
stress       0      0 3.904765e-11
recovery     0      0 0.000000e+00
```

Only the top triangles of the matrices are meaningful.

The *p*-values listed in this case are based on Bayesian z-score by specifying *pval*="z" among arguments, to approximate very small *p*-values from the limited MCMC sample size. See "Estimating statistical significance" section below for details on that.

If the experiment contains more than one grouping factor, function HPDplotBygeneBygroup() can plot up to three different groups on the same plot. For example, in another coral-related experiment that we recently performed, we heat-stressed corals from two different populations, 'offshore' and 'inshore'. Fig. 6 shows the plot produced by HPDplotBygeneBygroup() for one of the genes that we assayed (*coll*, collagen), split by the population of origin, across three coral conditions: normal, pale and bleached. The

function takes two or three lists of conditions that define the groups to be plotted (note: the following commands will not work with the demo dataset):

```
inshore=list(
  normal=list(factors=c(0)),
  pale=list(factors=c(0,"statuspale")),
  bleached=list(factors=c(0,"statusbleach"))
)
offshore=list(
  normal=list(factors=c(0,"originoffshore")),
  pale=list(factors=c(0,"statuspale","originoffshore","originoffshore:statuspale")),
  bleached=list(factors=c(0,"statusbleach","originoffshore","originoffshore:statusbleach"))
)

HPDplotBygeneBygroup(
  model=mm,
  gene="coll",
  group1=inshore,
  group2=offshore
)
```

Incorporating information about control genes

Now it is time to remember that all the results we have seen thus far were obtained without telling the model which genes are expected to be stable. This is actually not required for the model to work correctly, even when there are only a few genes with very unbalanced pattern of changes (Matz, Wright, and Scott, 2013). This highlights the advantage of linear mixed model analysis, which makes the model “self-normalizing” by correctly inferring the variation due to unequal template loading, at least as long as the number of biological samples in the experiment is relatively large. Still, incorporating control genes into the analysis is a venerable tradition in qRT-PCR, and indeed this information helps to increase the power (i.e., narrow down credible intervals) and might adjust the point estimates slightly, as we will see. More importantly, stable genes can be used to make sure that the model behaves reasonably: they should appear more or less unchanged even if the model is fitted without using them as priors, as we have done before in this tutorial.

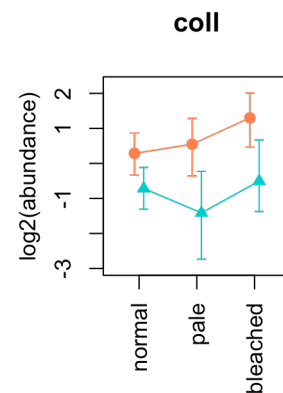


Figure 6. Relative abundances of *coll* across conditions in inshore (red circles) and offshore (blue triangles) corals. The whiskers denote 95% credible intervals. Plotted using HPDplotBygeneBygroup().

The three control genes that were used in the published analysis of the coral.stress dataset (Kenkel et al. 2011) were *rp111*, *nd5*, and *eif3h*. Looking at the plots of fixed effects from the ‘naïve’ model (Fig. 4), we can see that *nd5* and *rp111* indeed appear more or less stable, while *eif3h* tends to come up under stress and down during recovery. We therefore choose to use only *rp111* and *nd5* as control genes. Generally, the naïve model is a good way to identify potential control genes in the first place.

It must be emphasized, however, that inferring control genes from an experimental dataset and then using them to analyze the same dataset may lead to erroneous inference due to circularity. Ideally, control genes should be selected based on an independent experiment or other supporting data. If there is no such prior information, at the very least an alternative method of control gene selection should be used, such as non-parametric geNorm (Vandesompele et al, 2002). The MCMC.qpcr package includes a function *cq2genorm*, which reformats the data into log-transformed relative expression values and

outputs the data in the form that may be directly fed into `selectHKgenes` function of `SLqPCR` package, which is the R implementation of `geNorm` algorithm. Try `?cq2genorm` for more details.

To fit the ‘informed’ model using these two control genes, we must tell the model not only what are our controls, but also how stable we expect them to be. We actually don’t have to assume that the specified controls are fully stable, which is a particularly nice touch in Bayesian analysis. In the syntax of `mcmc.qpcr()` function, the control genes’ stability is specified using `m.fix` and `v.fix` parameters, which correspond to the average allowed fold change in response to fixed and random factors, respectively. The default values of `m.fix` is 1.2 (and of `v.fix` is `NULL`, no fixation) but it can be increased to reflect greater uncertainty about the stability of control genes, or lowered all the way down to 1, which would mean that the control genes are required to be perfectly stable (hardly ever a realistic assumption, Thellin et al. 1999). The parameter that has the most effect on the estimates is `m.fix`, we are only keeping `v.fix` because it seems reasonable and does not hurt.

Let’s fit the ‘informed’ model with `rpl11` and `nd5` as control genes and `m.fix=1.2` to the `dd` data and compare the results to the ‘naïve’ model. But first, we will re-fit the naïve model with the arguments that tell the model what the control genes are but do not let the model use them (`‘include=0’`). The estimates will not change, but the order of the genes in the output will be the same as in the informed model, so their results can be compared on the same plot.

```
naive=mcmc.qpcr(
  fixed="condition+timepoint+condition:timepoint",
  random="individual",
  data=dd,
  controls=c("rpl11","nd5"),
  include=0
)
informed=mcmc.qpcr(
  fixed="condition+timepoint+condition:timepoint",
  random="individual",
  data=dd,
  controls=c("rpl11","nd5"),
  m.fix=1.2
)
```

Plotting “stress” effects (Fig. 7, left panel):

```
HPDplot(
  model=naive,
  factors="conditionheat",
  main="stress",
  hpdtype="l"
)
HPDpoints(
  model=informed,
  factors="conditionheat",
  hpdtype="l",
  col="coral"
)
```

Plotting “recovery” effects (Fig. 7, right panel):

```
HPDplot(
  model=naive,
  factors=c("timepointtwo","conditionheat:timepointtwo"),
  main="recovery",
  hpdtype="l"
)
```

```
HPDpoints(
  model=informed,
  factors=c("timepointtwo", "conditionheat:timepointtwo"),
  hpdtype="l",
  col="coral"
)
```

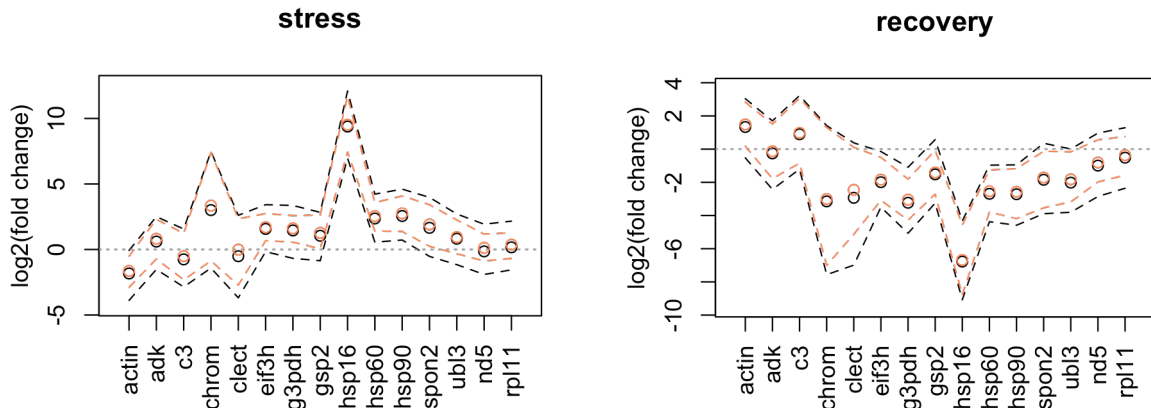


Figure 7. Comparison of the informed (orange) and naïve (black) models. The informed model used two control genes, *rp111* and *nd5*, with *m.fix* (average allowed fold-change) =1.2; the naïve model did not use any control gene information. The points are posterior means, the dashed lines denote 95% credible intervals. The figure is plotted with `HPDplot()` and `HPDpoints()` with the option ‘`hpdtype=”l”`’.

This time, to better evaluate the changes in the width of credible intervals, we used the option ‘`hpdtype=”l”`’ for `HPDplot()` and `HPDpoints()`. It makes the functions draw dashed lines across upper and lower 95% credible interval limits of all genes.

We can see (Fig. 7) that informing the model about control genes and allowing them to be regulated 1.2 fold on average has virtually no effect on the point estimates, but noticeably narrows the credible intervals, so the informed model is more powerful. In fact, almost the same increase in power is already provided by including a single control gene.

Estimating statistical significance

Significant (at the $\alpha = 0.05$) fixed effects are the ones in which the 95% credible interval does not include zero, such as, for example, *hsp16*, *hsp70*, or *hsp90* on Fig. 4. However, we are typically performing multiple comparisons of this kind within a qRT-PCR experiment, and so the resulting significances must be corrected accordingly. The solution provided within the `MCMC.qpcr` package is to calculate p-values for all the effects of potential interest (i.e., all of those which were given a chance to become significant) and correct them for multiple testing using one of the established methods. The p-values can be obtained in two ways. For large MCMC samples it is practical to use a Bayesian two-sided p-value, which is twice the fraction of all sampled values that crosses zero with respect to the mean. The lowest p-value that can be thus obtained is 2 divided by the size of MCMC sample; so for the default set of MCMC chain parameters that results in 1,000 samples it cannot be lower than 0.002. To approximate lower p-values based on a limited MCMC sample size, we assume that the posterior distributions of a parameter can be represented by a normal distribution, calculate a Bayesian z-score (the mean of the posterior divided by its standard deviation) and perform a standard z-test to derive a two-tailed p-value. The z-score based p-values agree with MCMC-based ones very well and are distributed uniformly under the null hypothesis (Matz, Wright, and Scott, 2013).

To obtain point-estimates of posterior modes, means, 95% credible intervals, and uncorrected p-values for fixed effects from our informed model, we will run the function `HPDplot()` with a flag `'plot=FALSE'`:

```
stress=HPDplot(
  model=informed,
  factors="conditionheat",
  plot=FALSE
)
stress
```

| | mode | mean | lower | upper | pval.z | pval.mcmc |
|-------------------------|------------|-------------|-------------|------------|--------------|-----------|
| geneactin:conditionheat | -1.5269197 | -1.63992250 | -2.89236066 | -0.5189583 | 6.801355e-03 | 0.006 |
| geneadk:conditionheat | 0.8814979 | 0.81502759 | -0.72771887 | 2.3017463 | 2.906479e-01 | 0.270 |
| ... | | | | | | |
| genehsp60:conditionheat | 2.7582144 | 2.54611536 | 1.40805668 | 3.5734072 | 3.178015e-06 | 0.002 |
| genehsp90:conditionheat | 2.6241394 | 2.75244674 | 1.37413737 | 4.0876553 | 5.664635e-05 | 0.002 |
| ... | | | | | | |
| genend5:conditionheat | 0.1592772 | 0.12640394 | -0.87753846 | 1.1750965 | 8.113947e-01 | 0.814 |
| generpl11:conditionheat | 0.3852459 | 0.36824375 | -0.68370549 | 1.2741158 | 4.703683e-01 | 0.494 |

This was for the effects of “stress”, let’s obtain the “recovery” estimates, too:

```
recovery=HPDplot(
  model=informed,
  factors=c("timepointtwo", "conditionheat:timepointtwo"),
  plot=FALSE
)
recovery
```

| | mode | mean | lower | upper | pval.z | pval.mcmc |
|---------------|-------------|------------|------------|-------------|--------------|-----------|
| geneactin ... | 1.52610996 | 1.4851758 | 0.1752831 | 2.83182731 | 3.190544e-02 | 0.024 |
| geneadk ... | 0.06651484 | -0.1314239 | -1.7749815 | 1.50854783 | 8.766451e-01 | 0.898 |
| ... | | | | | | |
| genehsp60 ... | -2.35357919 | -2.5368612 | -3.7839781 | -1.25969779 | 8.798320e-05 | 0.002 |
| genehsp90 ... | -2.36500390 | -2.5724855 | -4.1916809 | -1.17988543 | 8.776660e-04 | 0.002 |
| ... | | | | | | |
| genend5 ... | -0.79335215 | -0.8088653 | -1.9794449 | 0.55651985 | 2.186604e-01 | 0.208 |
| generpl11 ... | -0.35166553 | -0.3625902 | -1.5735637 | 0.75848378 | 5.511591e-01 | 0.550 |

(The names of the effects in this case have been truncated to fit the table into page.)

Note that the control genes ("rpl11", "nd5") are still there, appearing in the end of each list.

Now, we will concatenate these results into a single table `all.effects` and correct the p-values for multiple testing using Benjamini-Hochberg method (Benjamini, Hochberg 1995), while disregarding the entries corresponding to the control genes since these are not among our effects of interest:

```
all.effects=rbind(stress,recovery)
padj.qpcr(all.effects, controls=c("rpl11","nd5"))
      pval.z  pval.mcmc      padj.z  padj.mcmc
# stress:
geneactin ... 6.801355e-03  0.006 1.607593e-02 0.014181818
geneadk ...  2.906479e-01  0.270 3.434930e-01 0.319090909
...
genehsp60 ... 3.178015e-06  0.002 2.065710e-05 0.005777778
genehsp90 ... 5.664635e-05  0.002 2.945610e-04 0.005777778
...
genend5 ...   NA      NA      NA      NA
generpl11 ... NA      NA      NA      NA
```

```

# recovery:
geneactin ... 3.190544e-02 0.024 5.925296e-02 0.044571429
geneadk ... 8.766451e-01 0.898 9.117109e-01 0.933920000
...
genend5 ... NA NA NA NA
generpl11 ... NA NA NA NA

```

The output of `padj.qpcr()` actually has full names of effects and contains all the original columns (including mean, mode, and credible interval). Now the p-values for the control genes are dropped from consideration.

Lognormal model for higher-abundance data

In datasets where all the targets always remain relatively abundant, there will be little or no Poisson-induced variation. In such cases, it is possible to perform the Bayesian analysis described here based on the lognormal model without the Poisson component, thus sidestepping the need to make assumptions concerning Cq_1 . MCMC.qpcr package implements this model as function `mcmc.qpcr.lognormal`. The data for this function must be prepared using the function `cq2log`, which is analogous to `cq2counts` but converts the Cq values into natural logarithms of relative abundances (Ra) while correcting for the efficiency of amplification using the following formula (Steibel et al, 2009; Kenkel et al, 2011):

$$Ra = - Cq \cdot \ln (E) . \quad (4)$$

These values are processed using the same model but lacking the Poisson component, with the same possibilities for specifying control genes as priors as well as for downstream statistical analysis and visualization. The model is expected to generate the same or very similar results as the Poisson-lognormal model for datasets that do not have Cq values exceeding 32. It is important to remember that, since the lognormal model cannot adequately deal with the instances of no amplification, such datapoints must be excluded from the analysis or replaced by some arbitrarily high Cq value (for example, 38), which may bias the inference if such instances are frequent – so use the Poisson-lognormal model for such cases.

For high-abundance data, the results of lognormal model will be identical to the basic `mcmc.qpcr` model irrespective of the choice of Cq_1 , so there is really no particular reason to use it.

“Soft normalization”

One of the key assumptions of the MCMC.qpcr model is that the template loadings, which reflect the amount and quality of RNA across samples, are drawn from the same gaussian distribution irrespective of the condition. In other words, even though RNA quantity and quality is allowed to vary between samples, it is assumed to vary in the same way under all conditions. If under some condition the RNA samples are consistently of lower concentration and/or poorer quality, the model will infer down-regulation of all genes under this condition – in other words, this condition will appear to have a global effect affecting all genes in the same way. Note that the presence of such a global effect does not necessarily mean it is not really there: all genes can indeed be co-regulated together. If there is a good reason to suspect that global effect is an artifact - for example, when RNA concentration or integrity was correlated with condition, and/or several highly respectable control genes change their expression together with everybody else - there is a way to account for such a bias, which would unavoidably require falling back to reliance on control genes for normalization. The option `normalize=TRUE` in combination with specifying control genes (ideally, 3 or more) in a call to `mcmc.qpcr()` will result in “soft normalization” without losing the GLM advantages (i.e., low-abundant targets affected by Poisson noise and occasional lack of amplification will still be properly modeled). Under soft normalization, a

fake control gene is created representing geometric average of the specified control genes and is used as a tracker of global effects, which will be subtracted by functions `HPDsummary()` and `HPDplot()`.

In our coral stress dataset, we seem to have a global effect problem at time point two, where all genes appear to be slightly down-regulated (Fig. 8):

```
data(coral.stress)
data(amp.eff)
dd=cq2counts(coral.stress,genecols=c(5:19),condcols=c(1:4),effic=amp.eff)

naive=mcmc.qpcr(
  fixed="condition+timepoint+condition:timepoint",
  random="individual",
  data=dd
)
smm.naive=HPDsummary(naive,dd,relative=T)
```

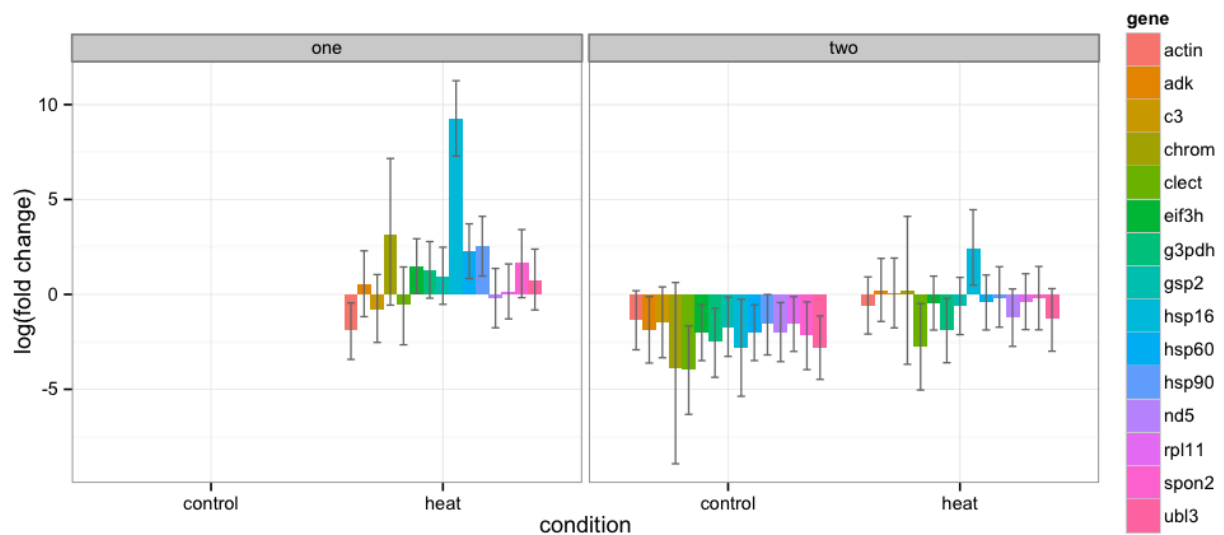


Figure 8. HPDsummary of the full two-factorial naïve model for the coral.stress dataset.

Let's see if we can fix this with soft normalization using nd5 and rpl11 as controls (Fig. 9):

```
norms=mcmc.qpcr(
  fixed="condition+timepoint+condition:timepoint",
  random="individual",
  data=dd,
  controls=c("nd5", "rpl11"),
  normalize=TRUE
)
smm.norms=HPDsummary(norms,dd,relative=T)
```

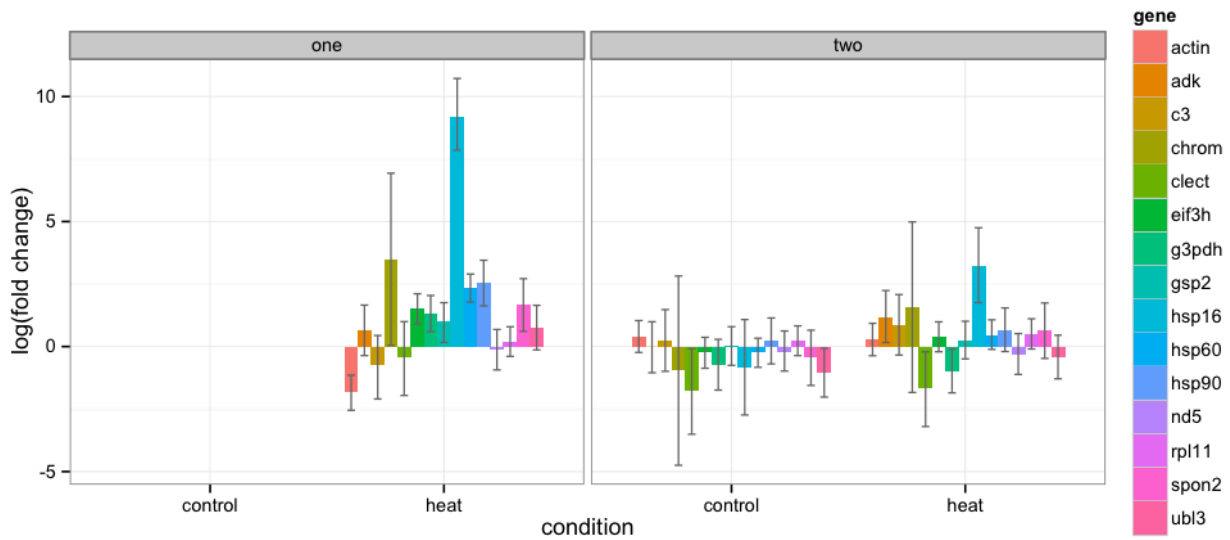


Figure 9. HPDsummary of the “soft-normalized” model (with nd5 and rpl11 as control genes) for the coral.stress dataset. The genes at timepoint two are now well-behaved (compare to Fig. 8).

The “classic” model

For the old times sake and for the cases when targets remain relatively abundant not to worry about Poisson noise (the majority of the Cq values are below 30 and none of them are higher than 32), the package implements the “classic” approach that starts with the log-transformed relative abundances (Ra , formula 4) produced by the `cq2logC` function, performs multigene normalization (Vandesompele et al, 2002), and then analyzes all the genes jointly within a single linear mixed model fitted by MCMC. We call this model “classic” since it is mostly based on earlier developments and lacks the main advancements implemented within the `MCMC.qpcr` package, such as the use of generalized linear modeling to account for higher variance of low-abundant targets and the possibility to analyze the data without using control genes. The one innovation the “classic” model offers, however, is a single-model rather than gene-by-gene analysis, which boosts the power considerably since the model draws evidence from all genes simultaneously. The “classic” model uses the same formula (2), only omitting the sample-specific variance and Poisson components. The function `mcmc.qpcr.classic()`, implementing this model, uses default uninformative priors of the `MCMCglmm` function, which results in estimates corresponding to maximum likelihood analysis.

To analyze the coral stress data using the “classic” model, we first must create a log-transformed dataset (this command uses very similar syntax as `cq2counts`, see page 10):

```
d1=cq2logC(
  data=coral.stress,
  genecols=c(5:19), # where the Cq data are in the data table
  condcols=c(1:4),  # which columns contain factors
  effic=amp.eff,
  noamp=38
)
```

There were 11 warnings (use `warnings()` to see them)

The warnings are produced because the instances on no-amplification, coded as -1, were encountered in the data. They were replaced by the value specified as ‘noamp’ argument: 38 (the default) is an arbitrarily

low, but not too low, value corresponding slightly less than one molecule per amplification trial. Use 'noamp=NA' to disregard such instances completely. Technically, such low-abundance datasets should be analyzed using Poisson-lognormal model.

Let's fit the "classic" model with `pl=T, pr=T` options for us to be able to plot the diagnostic plots using `diagnostic.mcmc()`:

```
classic=mcmc.qpcr.classic(
  fixed="condition+timepoint+condition:timepoint",
  random="individual",
  data=d1,
  controls=c("nd5", "rpl11"),
  pr=T,
  pl=T
)
diagnostic.mcmc(
  model=classic,
  col="grey50",
  cex=0.8
)
```

The arguments and 'col' and 'cex' here are not essential, they adjust the color and the size of the points on the plots.

The plots (Fig. 10) show that the "classic" model satisfies the linearity ("residuals vs predicted" plot) and homoscedasticity ("Scale-Location" plot) criteria reasonably well, although its residuals do not fully conform to the normal distribution ("normal Q-Q plot"). This is most likely the result of Poisson variation existing in the data as well as no-amplification instances, since the residuals of the Poisson-lognormal model were much closer to normal (see Fig. 2).

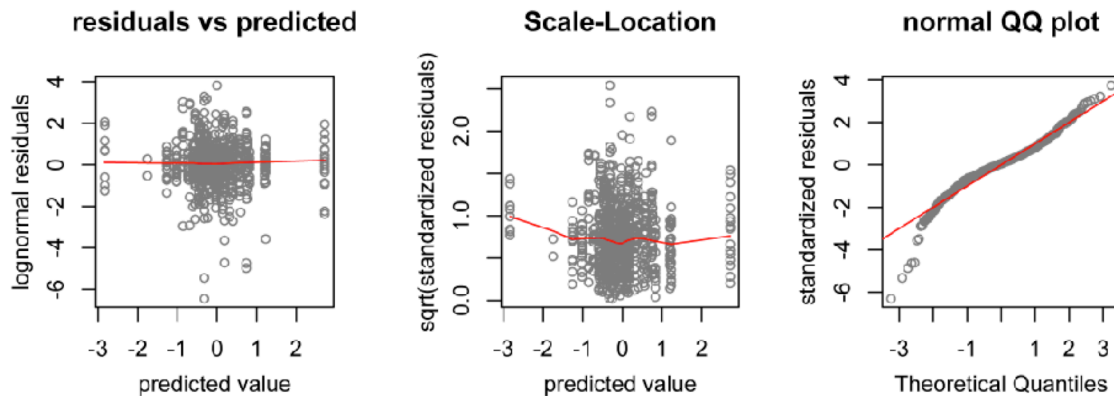


Figure 10. Diagnostic plots for the "classic" (normalizing) model (compare to Fig. 2)

Let's compare the inference of the "classic" model to our full-Bayesian informed model (Fig. 11):

```
HPDplot(
  model=informed,
  factors="conditionheat",
  pch=19,
  col="cyan3",
  jitter=-0.15,
  main="stress"
)
HPDpoints(
```



```

model=classic,
factors="conditionheat",
pch=19,
col="coral",
jitter=0.15,
)
legend(11,10.5,"informed",bty="n",pch=19,col="cyan3")
legend(11,9,"\"classic\"",bty="n",pch=19,col="coral")

```

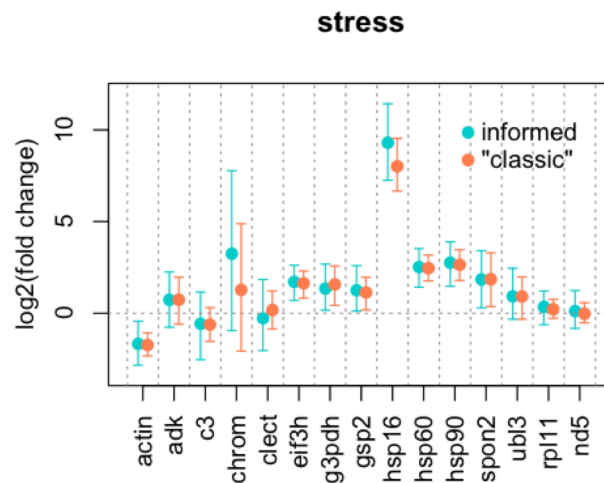


Figure 11. Comparison of the predictions of the informed model with two control genes and “classic” (normalizing) model. Credible intervals of the “classic” model are typically narrower, so the model is more powerful as long as the average stability of the control genes can be fully trusted.

See page 18 for explanations of the ‘beautifying’ tricks used here, such as options `pch`, `col`, and `jitter`, and the `legend()` function.

We can see that the “classic” model infers virtually the same fold-changes as the full-Bayesian informed model, but does it with higher confidence since the credible intervals are typically narrower. The “classic” model therefore represents a powerful alternative to the GLM-based analysis when the expression levels remain relatively high and control genes can be trusted.

Detecting outlier samples

As an optional step during the preliminary data analysis we might wish to detect and exclude samples that have too little amplifiable material. The function `outlierSamples()` will return a vector of sample names that have model-inferred template loadings less than a specified number of standard deviations (by default, 2) below the mean. The function takes as arguments the model produced by `mcmc.qpcr()` or `mcmc.qpcr.lognormal()` (the choice of naïve model feels natural here) and the dataset that was used to fit the model. Here is an example based on the coral stress dataset. Note that the function `mcmc.qpcr()` is invoked with an additional option `pr=TRUE` to enable model predictions.

```
library(MCMC.qpcr)
data(coral.stress)
str(coral.stress)
data(amp.eff)
genecolumns=c(5:19) # specifying where the Ct data are in the data table
condcols=c(1:4) # specifying data table columns containing factors
# converting to counts and reformatting:
dd=cq2counts(data=coral.stress,genecols=genecolumns,condcols=condcols,effic=amp.eff)

# Fitting naive model with pr=TRUE to enable predictions
naive=mcmc.qpcr(
  fixed="condition+timepoint+condition:timepoint",
  random="individual",
  data=dd,
  pr=TRUE
)

# detecting outlier samples
outs=outlierSamples(naive,dd)
outs # "14" "26"
# excluding outlier samples
dd=dd[!(dd$sample %in% outs),]
```

References

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