Modelling behavioural data

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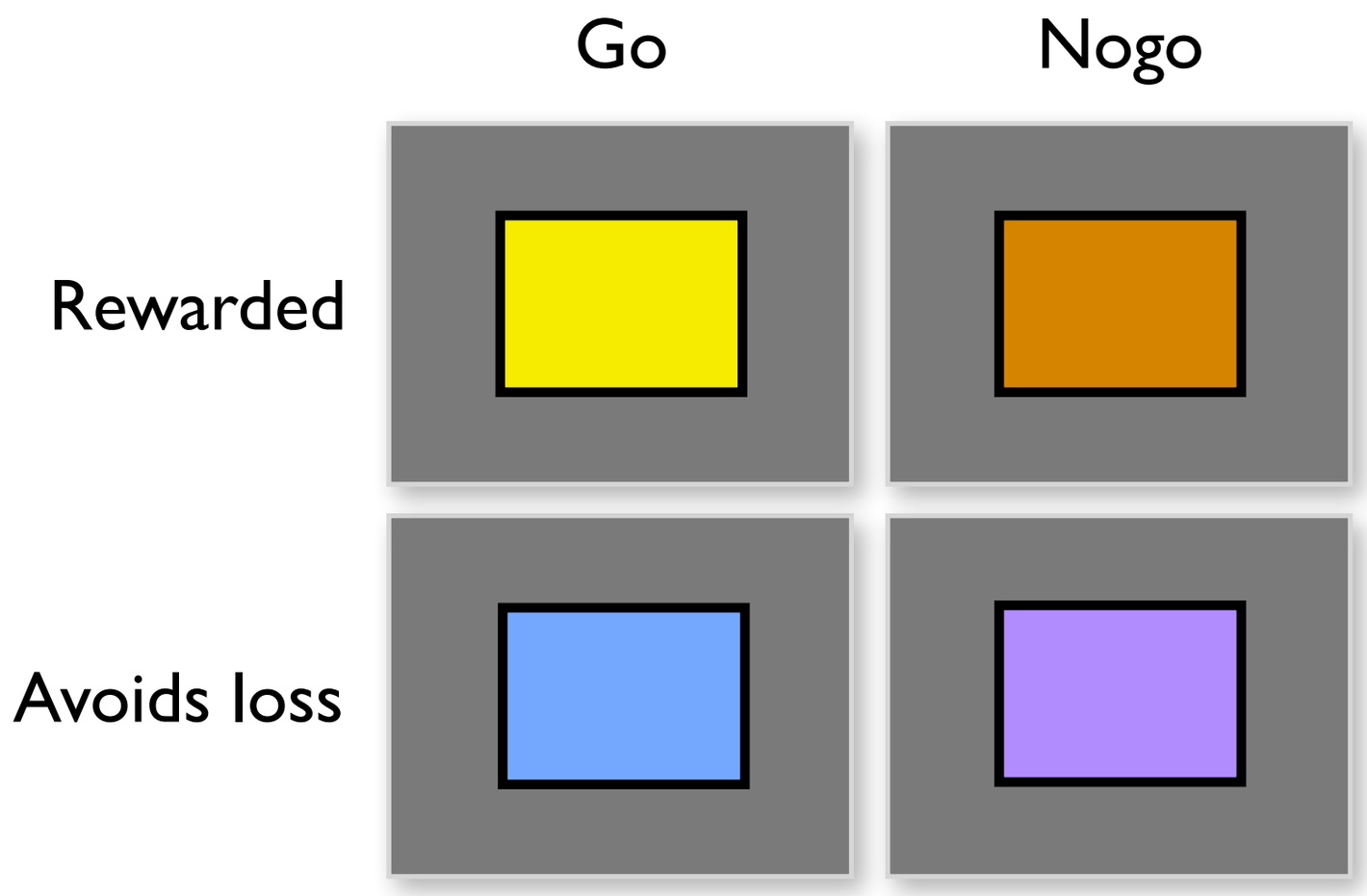
Outline

- Why build models? What is a model
- Fitting models
- Validating & comparing models
- Model comparison issues in psychiatry

Example task



Guitart-Masip, Huys et al. *2012*

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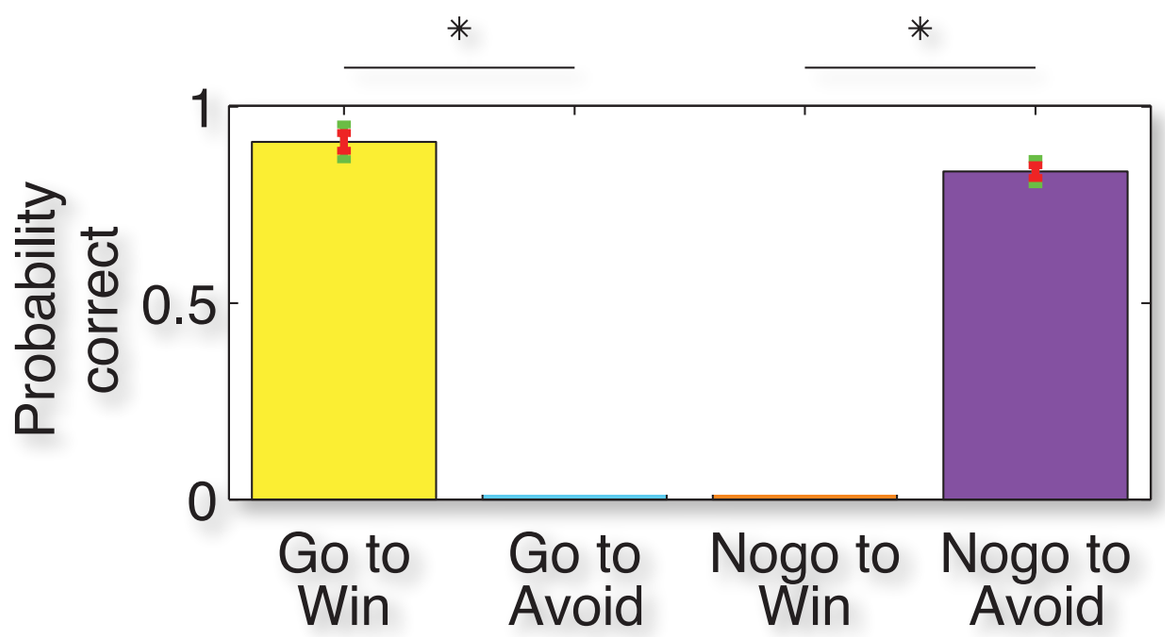

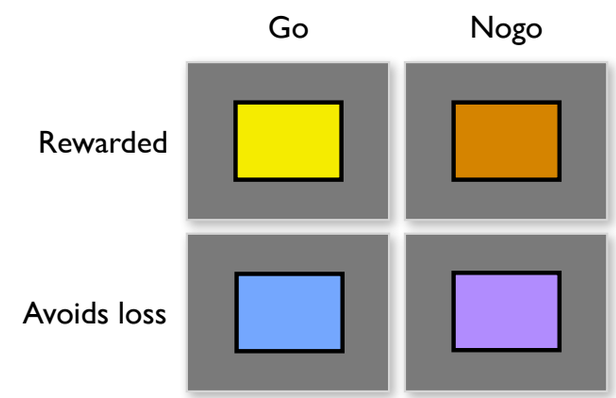

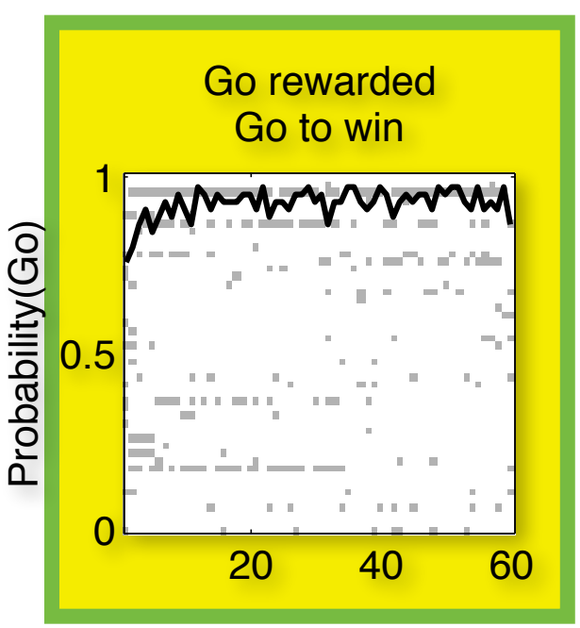

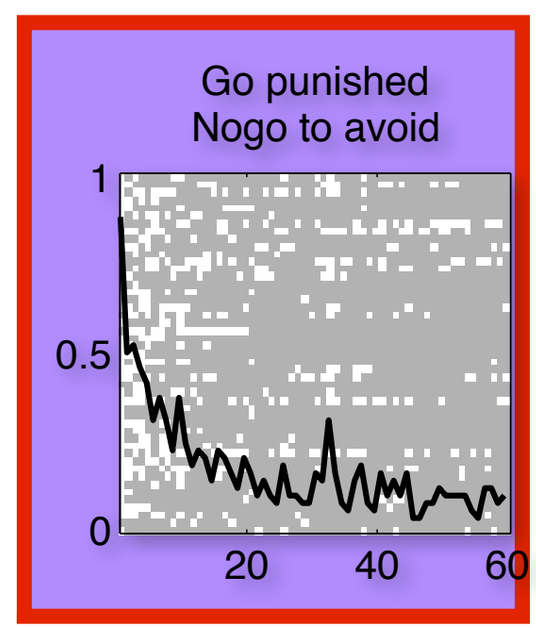

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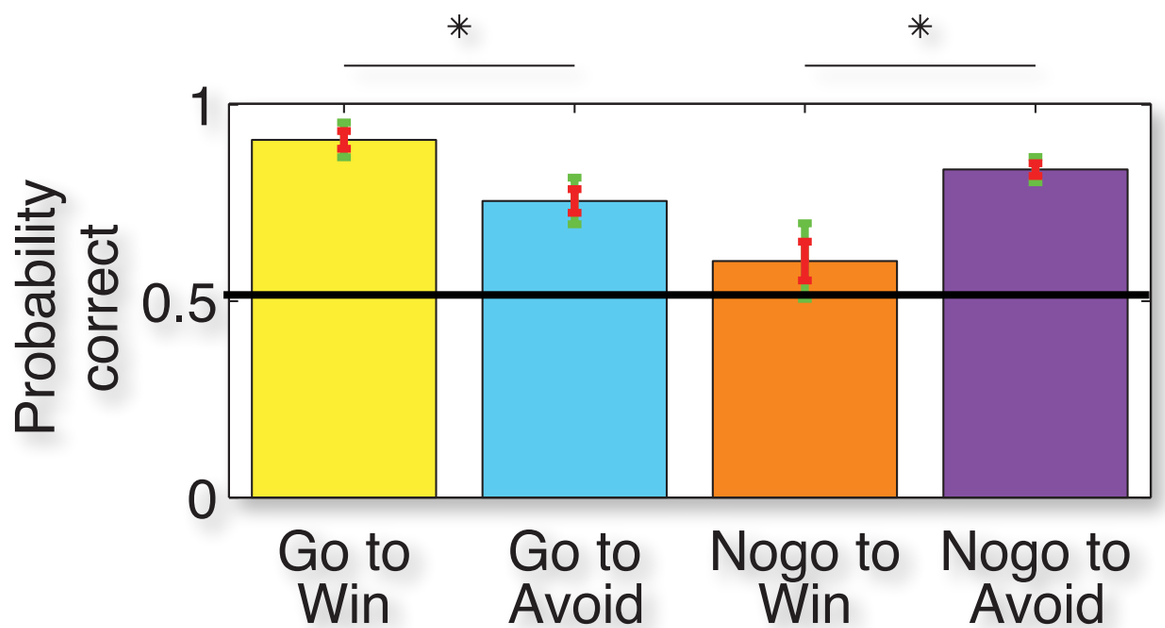

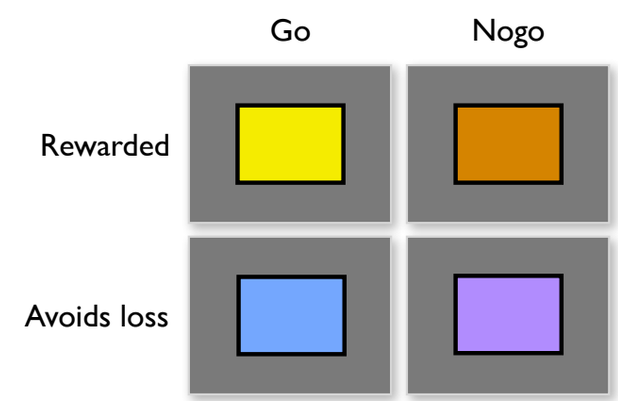

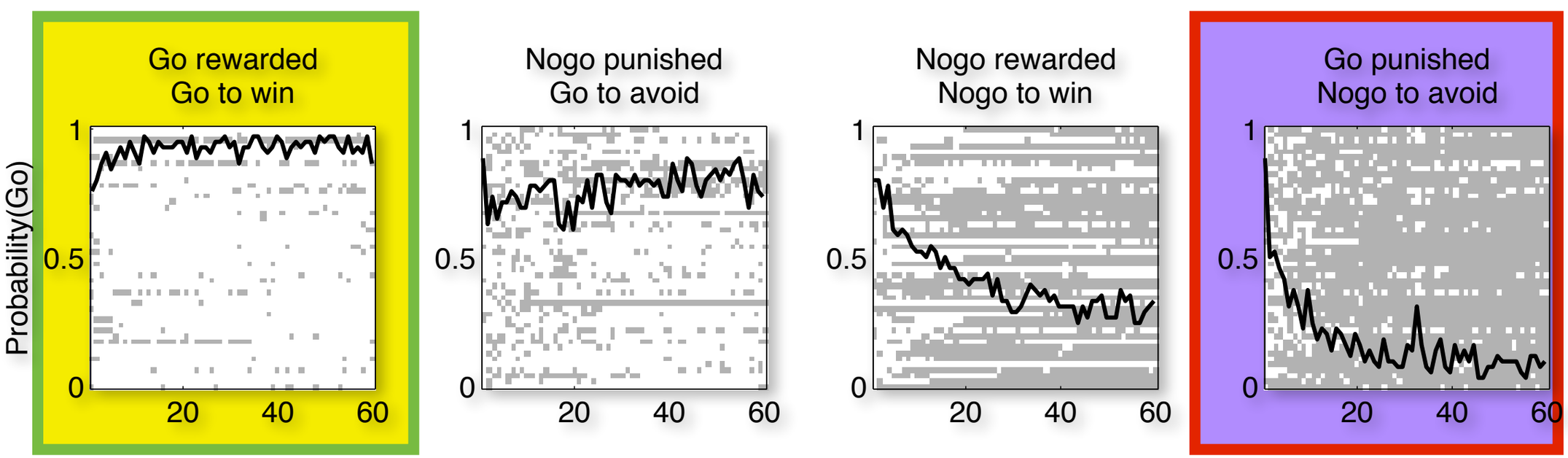

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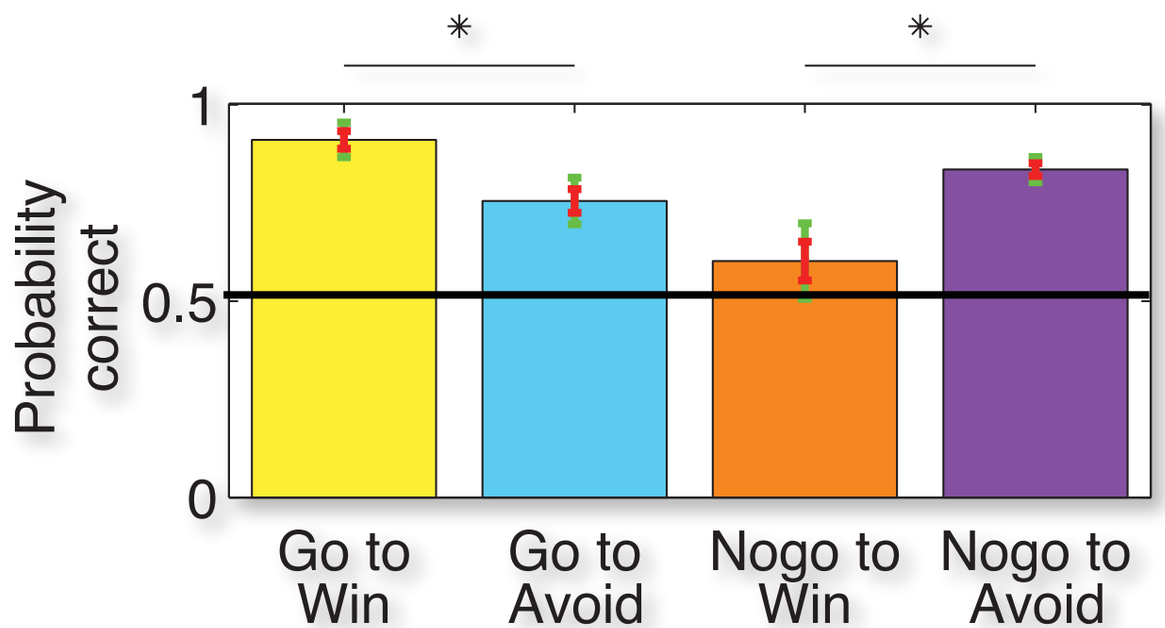

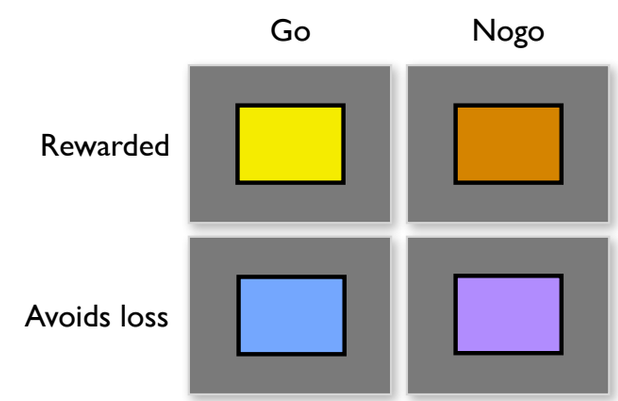

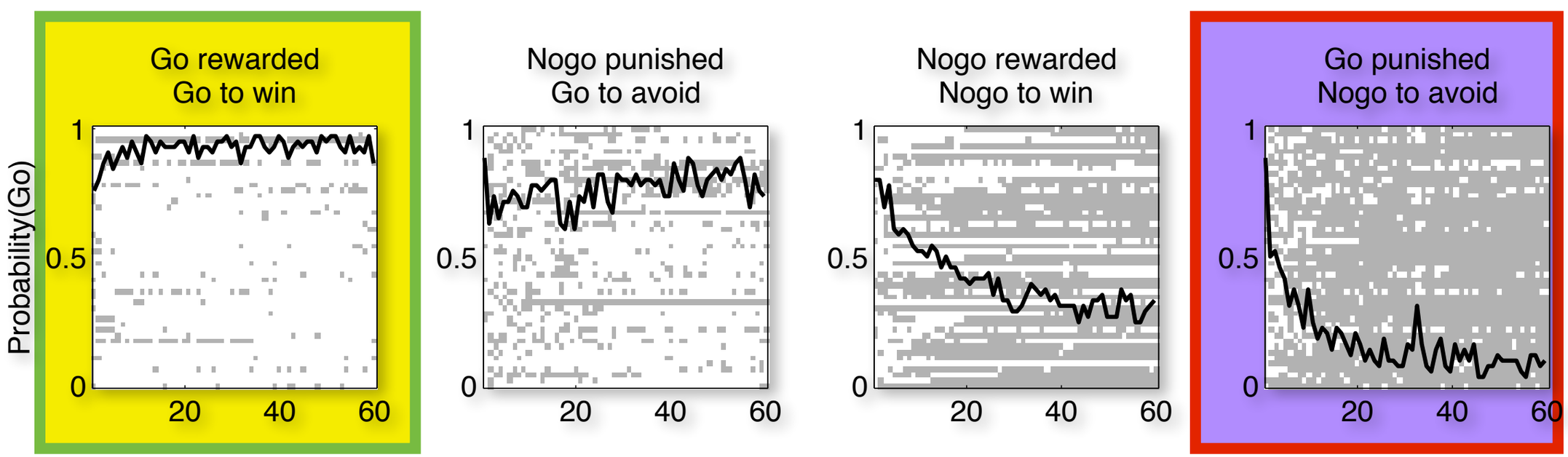

Think of it as four separate two-armed bandit tasks

Guitart-Masip, Huys et al. *2012*

Analysing behaviour

- Standard approach:
  - Decide which feature of the data you care about
  - Run descriptive statistical tests, e.g. ANOVA

- Many strengths
- Weakness
  - Piecemeal, not holistic / global
  - Descriptive, not generative
  - No internal variables

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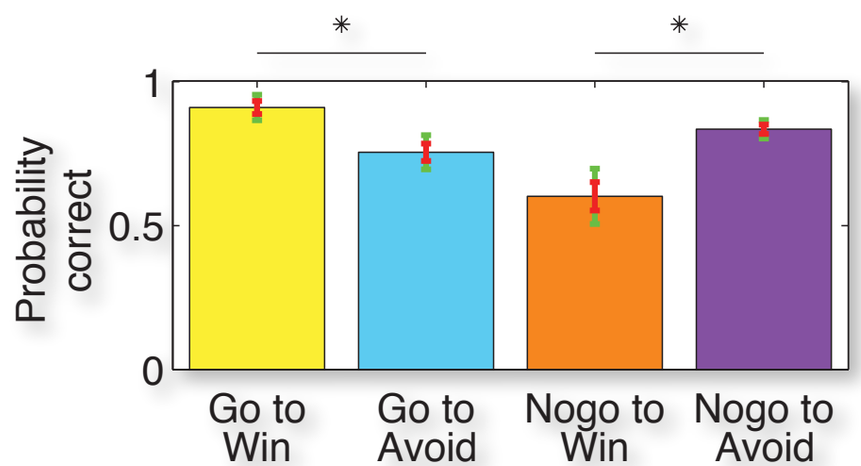

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Models

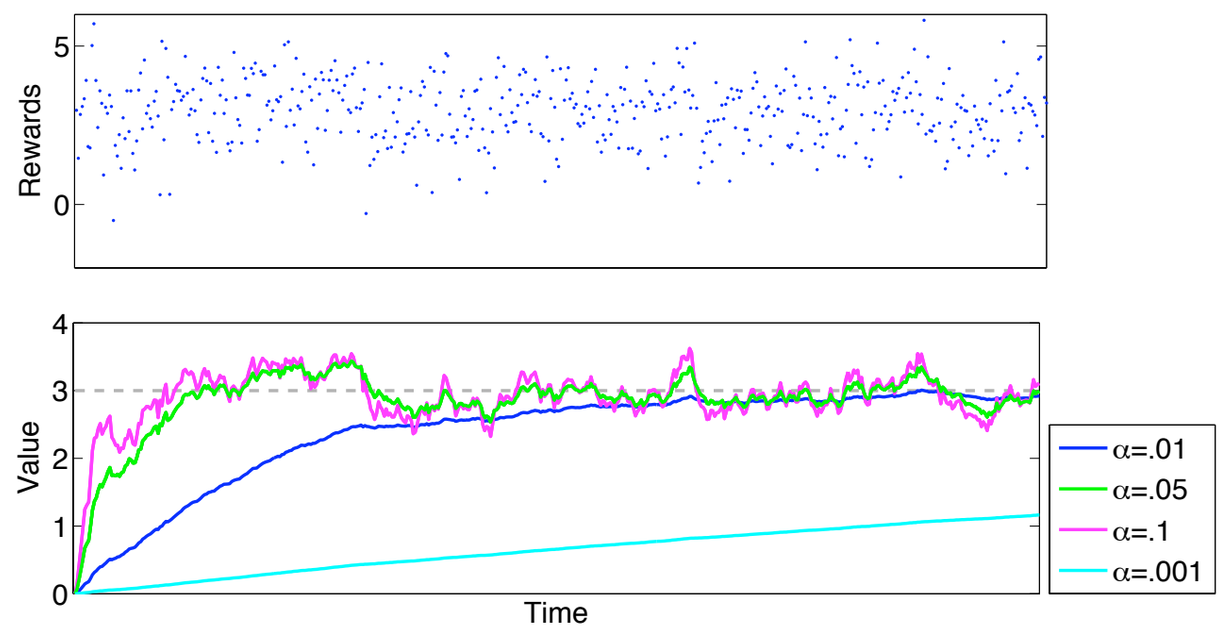
- Holistic
  - Aim to model the process by which the data came about in its "entirety"
- Generative
  - They can be run on the task to generate data as if a subject had done the task
- Inference process
  - Capture the inference process subjects have to make to perform the task.
  - Do this in sufficient detail to replicate the data.
- Parameters
  - replace test statistics
  - their meaning is explicit in the model
  - their contribution to the data is assessed in a holistic manner

A simple Rescorla-Wagner model

- Q values

$$\mathcal{Q}_t(a_t, s_t) = \mathcal{Q}_{t-1}(a_t, s_t) + \epsilon(r_t - \mathcal{Q}_{t-1}(a_t, s_t))$$

a_t action on trial t; can be either 'go' or 'logo'
s_t stimulus presented on trial t
ϵ learning rate



- Key points:
  - Q is the key part of the hypothesis
  - formally states the learning process in quantitative detail
  - formalizes internal quantities that are used in the task

Actions

- Q values

$$\mathcal{Q}_t(a_t, s_t) = \mathcal{Q}_{t-1}(a_t, s_t) + \epsilon(r_t - \mathcal{Q}_{t-1}(a_t, s_t))$$

- Action probabilities: "softmax" of Q value

$$\begin{aligned} p(a_t|s_t, h_t, \beta) &= p(a_t|\mathcal{Q}(a_t, s_t), \beta) \\ &= \frac{e^{\beta \mathcal{Q}(a_t, s_t)}}{\sum_{a'} e^{\beta \mathcal{Q}(a', s_t)}} \end{aligned}$$

- Features:

$$p(a_t|s_t) \propto \mathcal{Q}(a_t, s_t)$$

$$0 \leq p(a) \leq 1$$

- links learning process and observations
  - choices, RTs, or any other data
  - link function in GLMs
  - man other forms

Fitting models I

- Maximum likelihood (ML) parameters

$$\hat{\theta} = \underset{\theta}{\operatorname{argmax}}\, \mathcal{L}(\theta)$$

- where the likelihood of all choices is:

$$\begin{aligned}
\mathcal{L}(\theta) &= \log p(\{a_t\}_{t=1}^T | \{s_t\}_{t=1}^T, \{r_t\}_{t=1}^T, \underbrace{\theta}_{\beta,\epsilon}) \\
&= \log p(\{a_t\}_{t=1}^T | \{\mathcal{Q}(s_t, a_t; \epsilon)\}_{t=1}^T, \beta) \\
&= \log \prod_{t=1}^T p(a_t | \mathcal{Q}(s_t, a_t; \epsilon), \beta) \\
&= \sum_{t=1}^T \log p(a_t | \mathcal{Q}(s_t, a_t; \epsilon), \beta)
\end{aligned}$$

Fitting models II

- No closed form
- Use your favourite method
  - gradients
  - fminunc / fmincon...
- Gradients for RW model

$$
\begin{aligned}
\frac{d\mathcal{L}(\theta)}{d\theta} &= \frac{d}{d\theta}\sum_t \log p(a_t|\mathcal{Q}_t(a_t,s_t;\epsilon),\beta) \\
&= \sum_t \frac{d}{d\theta}\beta\mathcal{Q}_t(a_t,s_t;\epsilon) - \sum_{a'} p(a'|\mathcal{Q}_t(a',s_t;\epsilon),\beta)\frac{d}{d\theta}\beta\mathcal{Q}_t(a',s_t;\epsilon) \\
\frac{d\mathcal{Q}_t(a_t,s_t;\epsilon)}{d\epsilon} &= (1-\epsilon)\frac{d\mathcal{Q}_{t-1}(a_t,s_t;\epsilon)}{d\epsilon} + (r_t - \mathcal{Q}_{t-1}(a_t,s_t;\epsilon))
\end{aligned}
$$

Little tricks

- Transform your variables

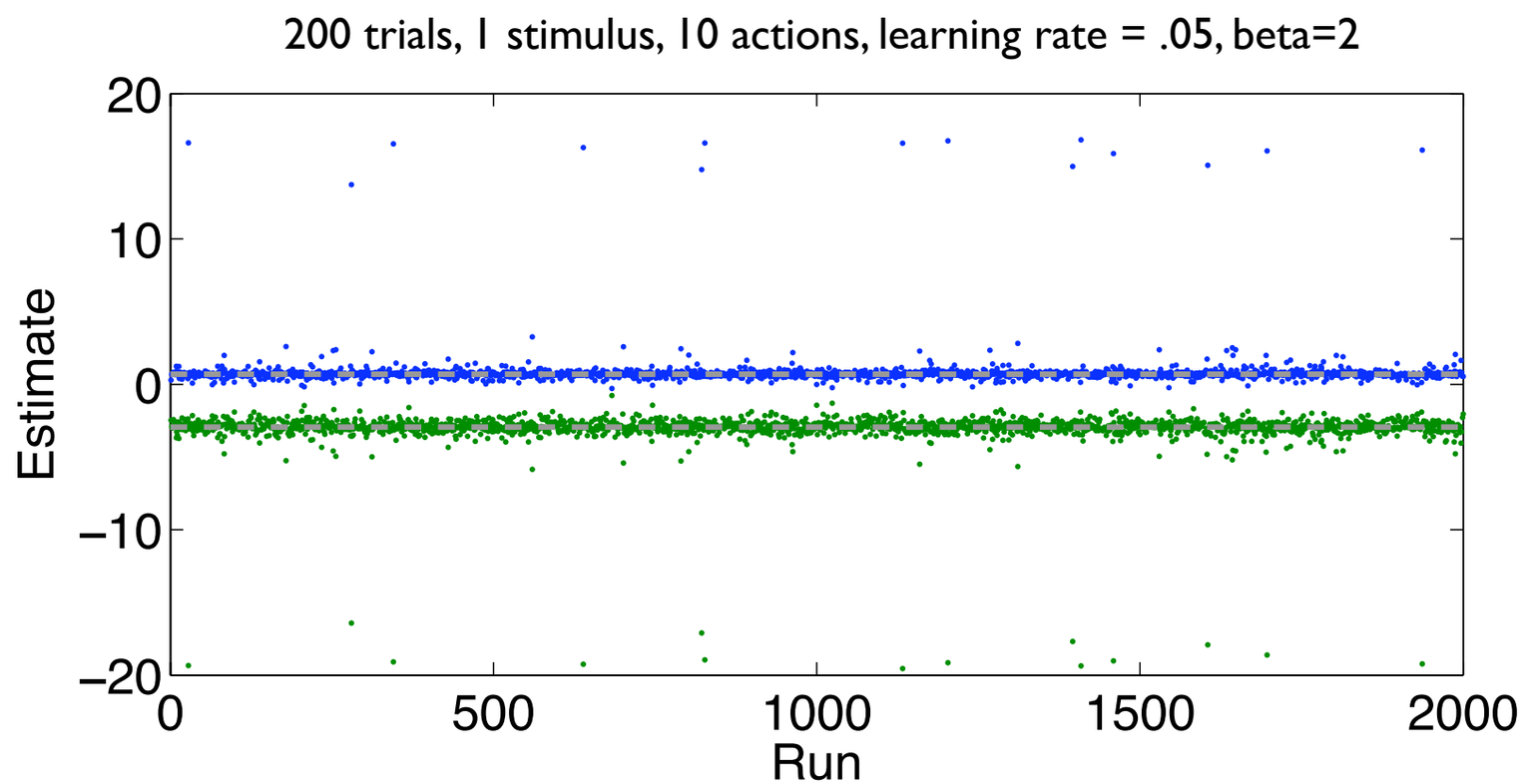
$$\begin{aligned}\beta &= e^{\beta'} \\ &\Rightarrow \beta' = \log(\beta) \\ \epsilon &= \frac{1}{1+e^{-\epsilon'}} \\ &\Rightarrow \epsilon' = \log\left(\frac{\epsilon}{1-\epsilon}\right)\end{aligned}$$

$$\frac{d\log\mathcal{L}(\theta')}{d\theta'}$$

- Avoid over/underflow

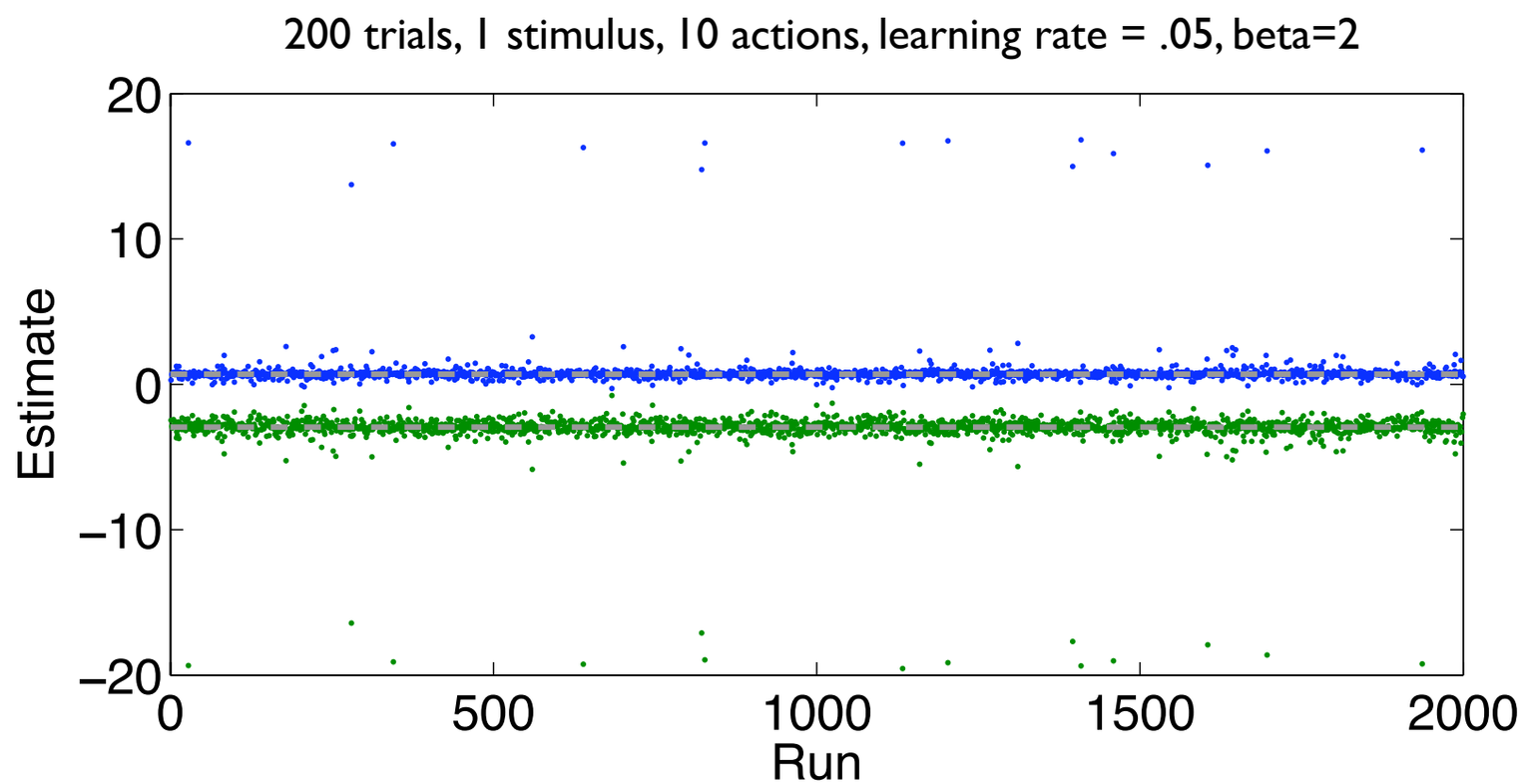
$$\begin{aligned}y(a) &= \beta\mathcal{Q}(a) \\ y_m &= \max_a y(a) \\ p &= \frac{e^{y(a)}}{\sum_b e^{y(b)}} = \frac{e^{y(a)-y_m}}{\sum_b e^{y(b)-y_m}}\end{aligned}$$

ML characteristics



ML characteristics

- ML is asymptotically consistent, but variance high
  - 10-armed bandit, infer beta and epsilon



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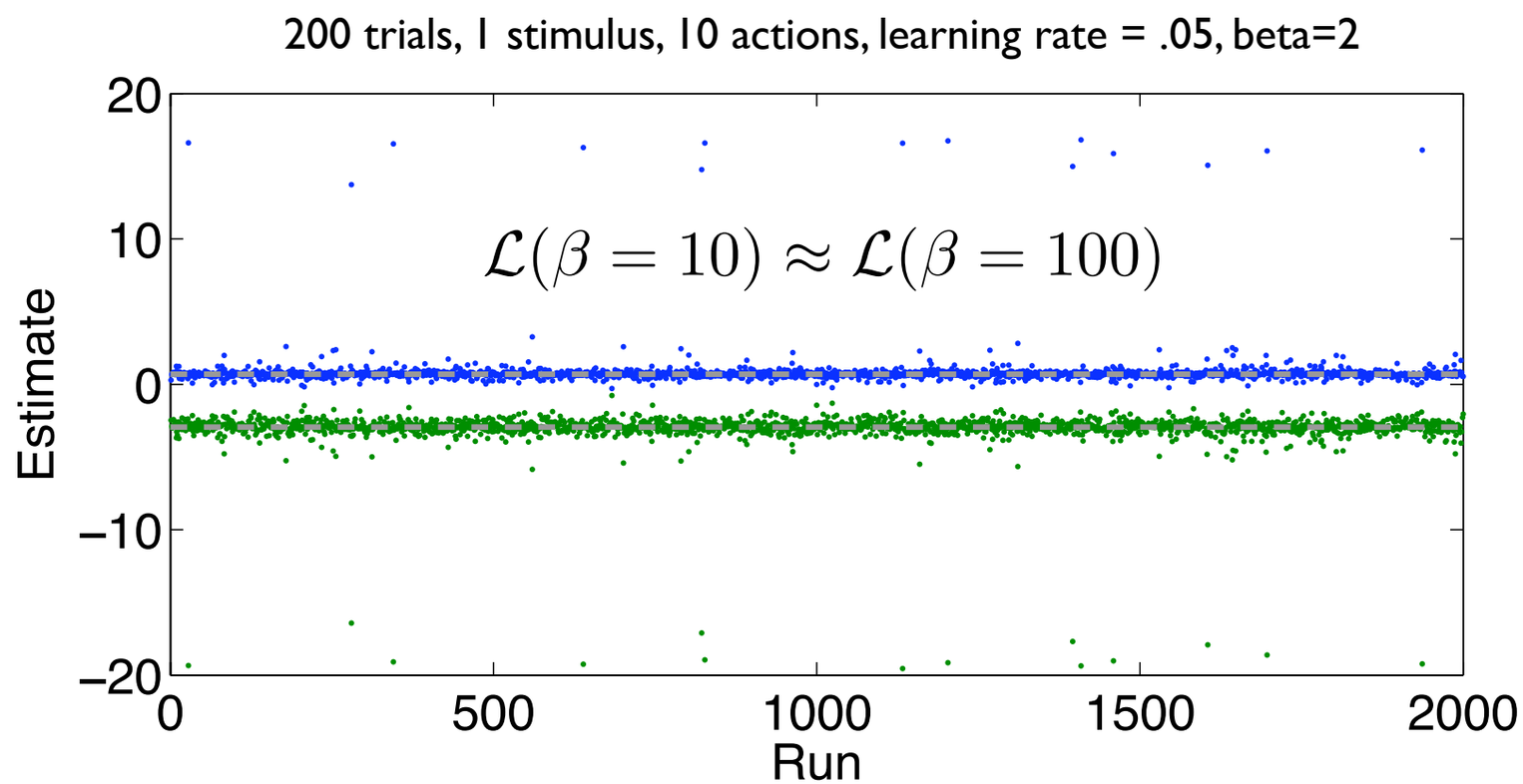
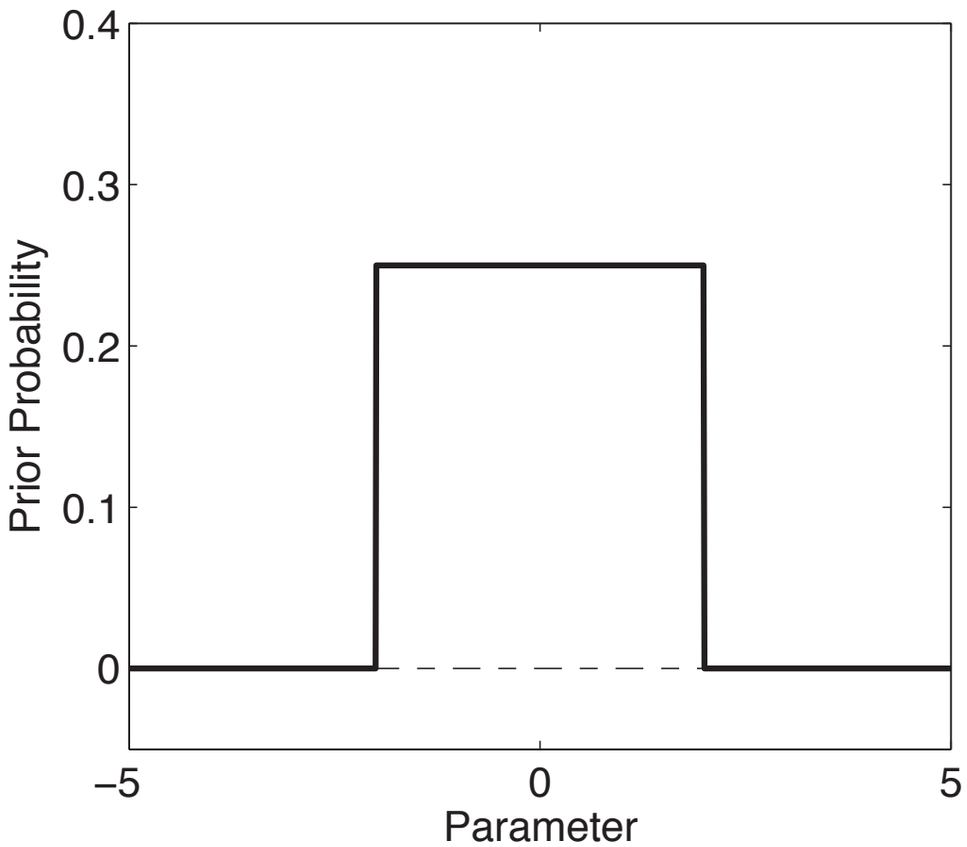


Priors

Not so smooth



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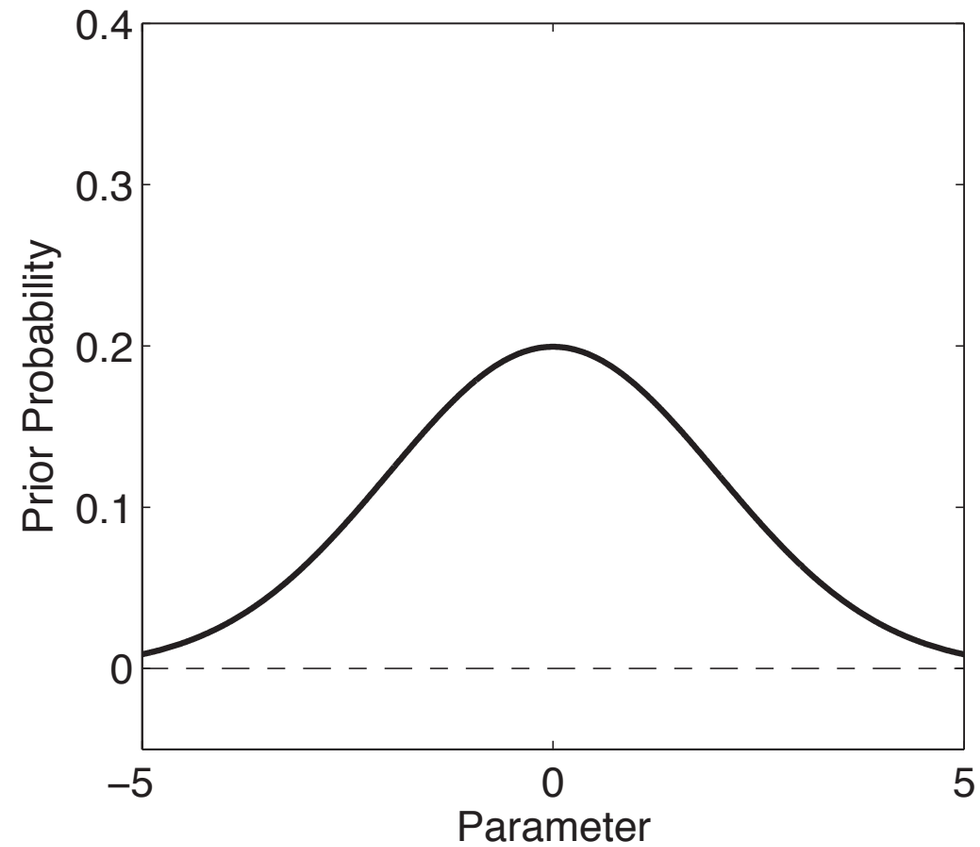

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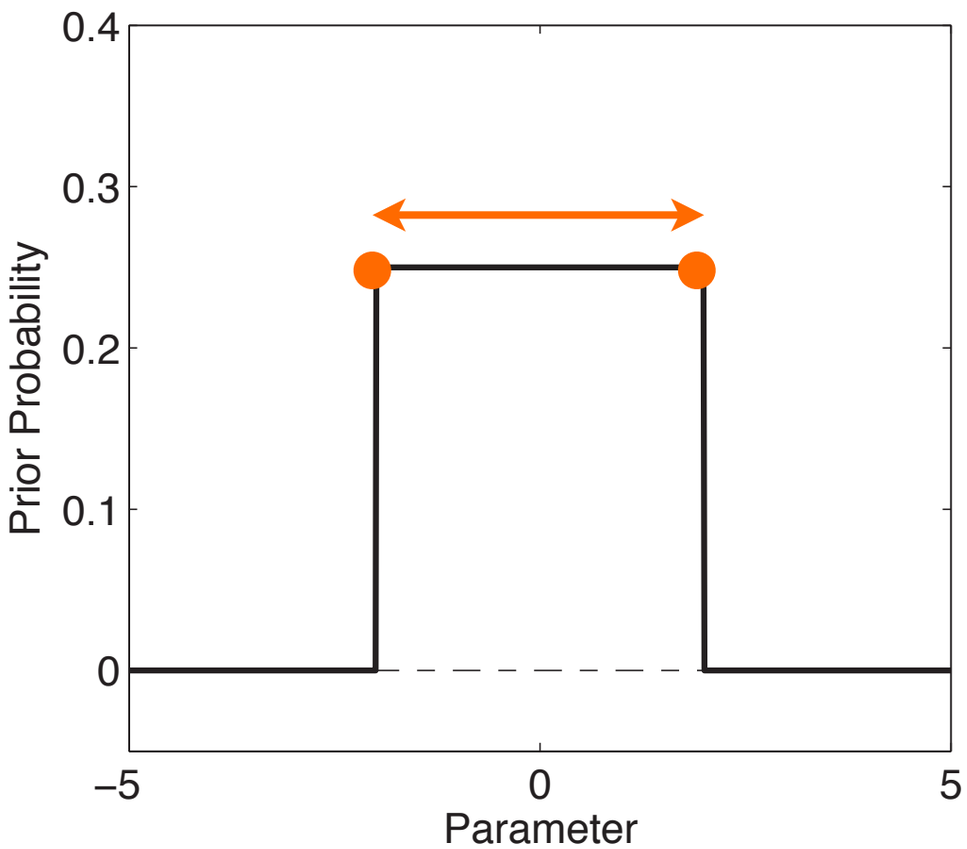

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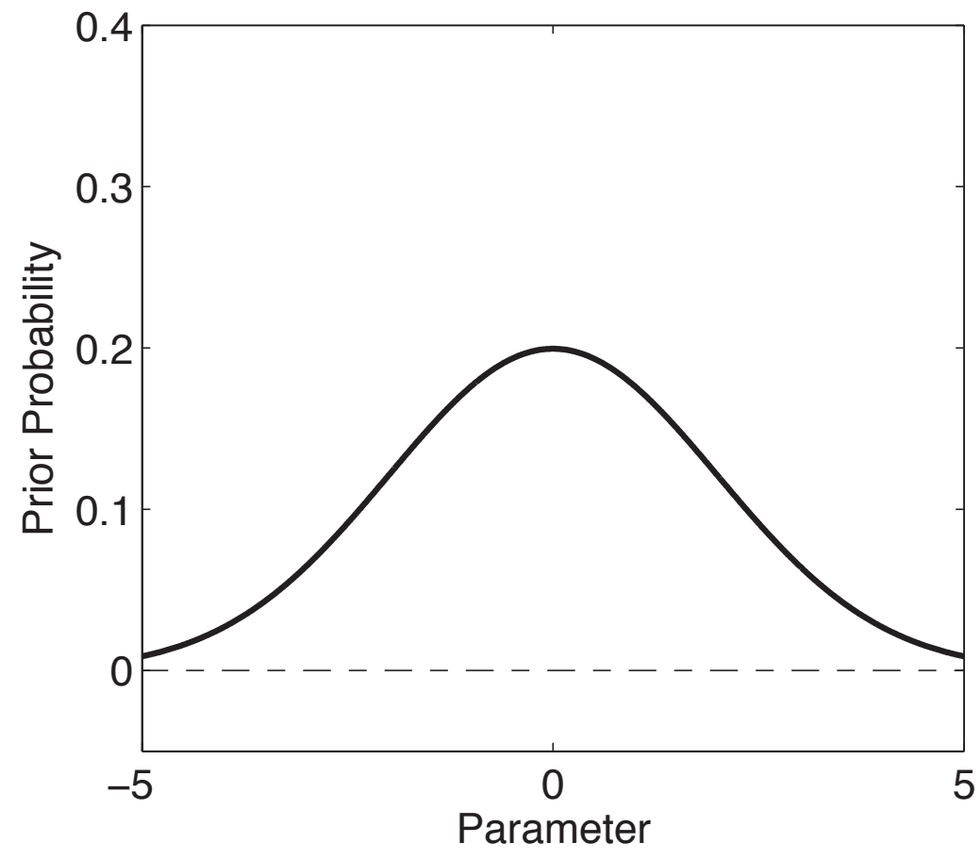

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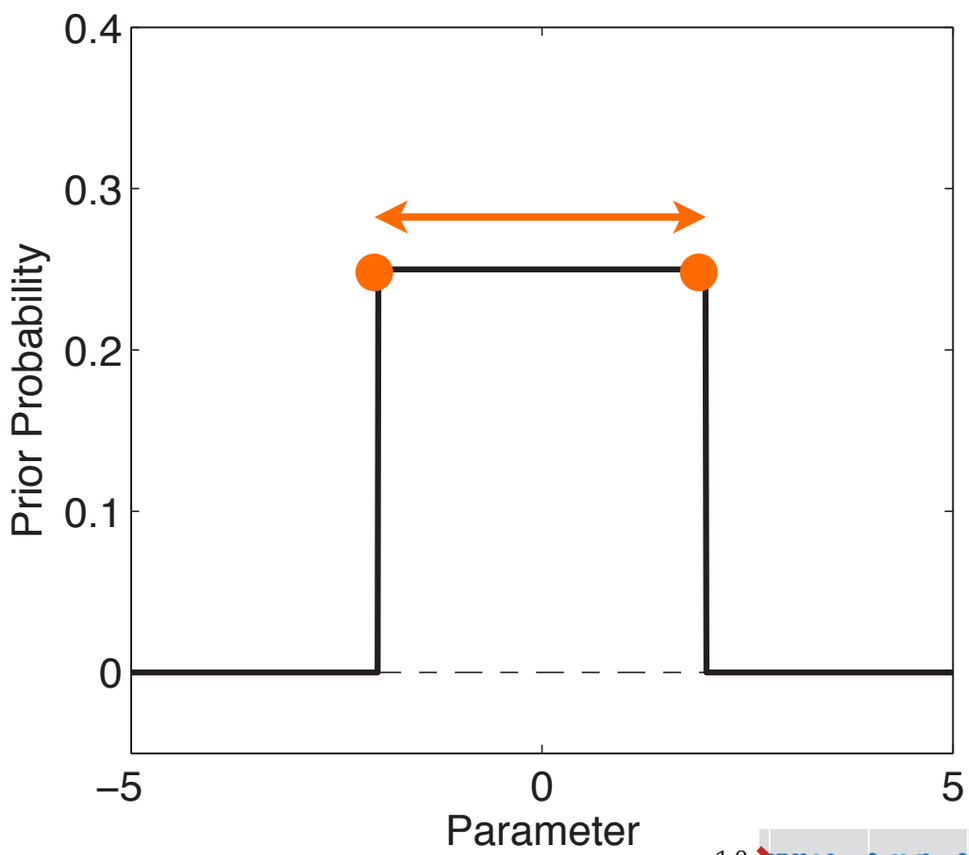

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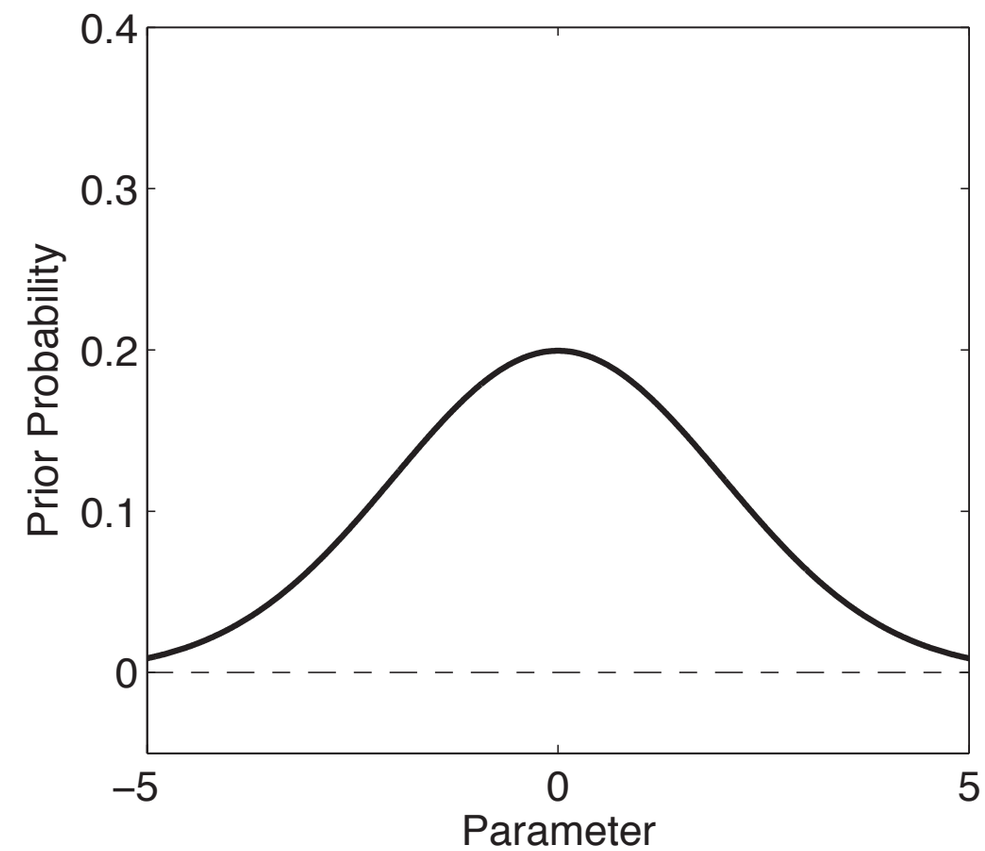
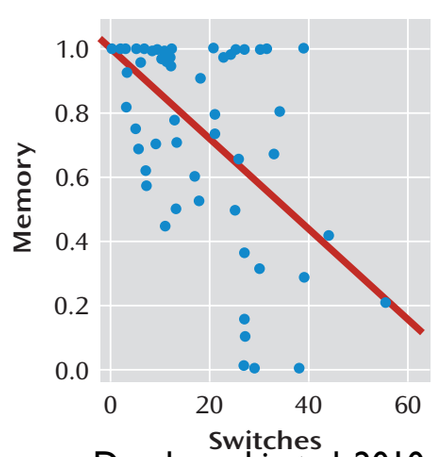




Dombrovski et al. 2010

Maximum a posteriori estimate

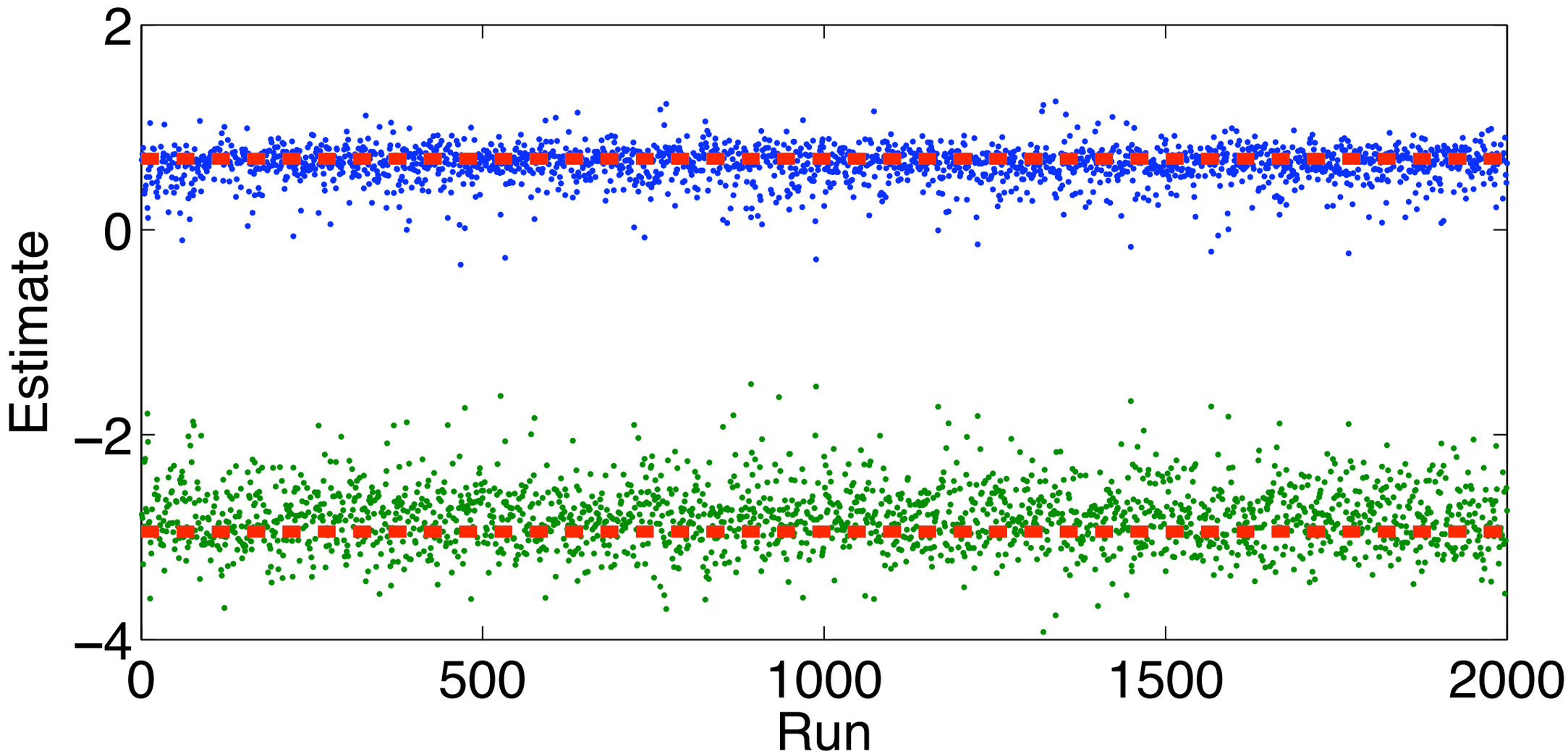
$$\mathcal{P}(\theta) = p(\theta|a_{1...T}) = \frac{p(a_{1...T}|\theta)p(\theta)}{\int d\theta p(\theta|a_{1...T})p(\theta)}$$

$$\log \mathcal{P}(\theta) = \sum_{t=1}^{T} \log p(a_t|\theta) + \log p(\theta) + const.$$

$$\frac{\log \mathcal{P}(\theta)}{d\alpha} = \frac{\log \mathcal{L}(\theta)}{d\alpha} + \frac{d\,p(\theta)}{d\theta}$$

- If likelihood is strong, prior will have little effect
  - mainly has influence on poorly constrained parameters
  - if a parameter is strongly constrained to be outside the typical range of the prior, then it will win over the prior

Maximum a posteriori estimate



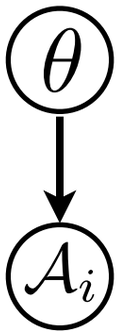
200 trials, 1 stimulus, 10 actions, learning rate = .05, beta=2

m_{beta}=0, m_{eps}=-3, n=1

But

What prior parameters should I use?

Hierarchical estimation - “random” effects



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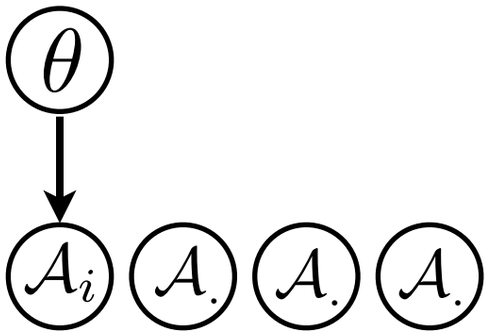

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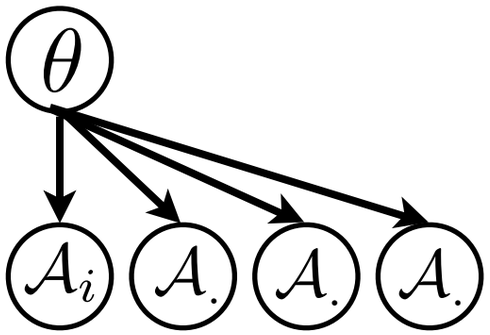

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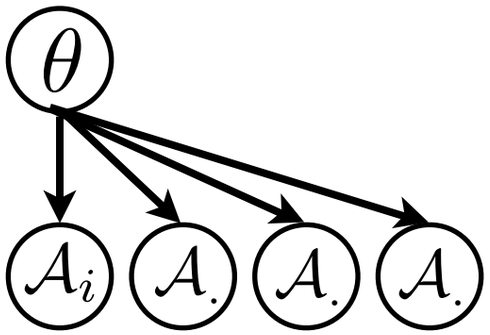

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  - need to adapt model

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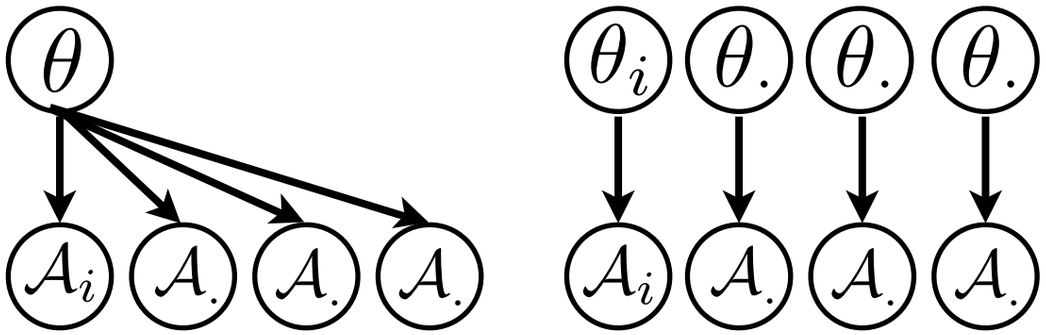

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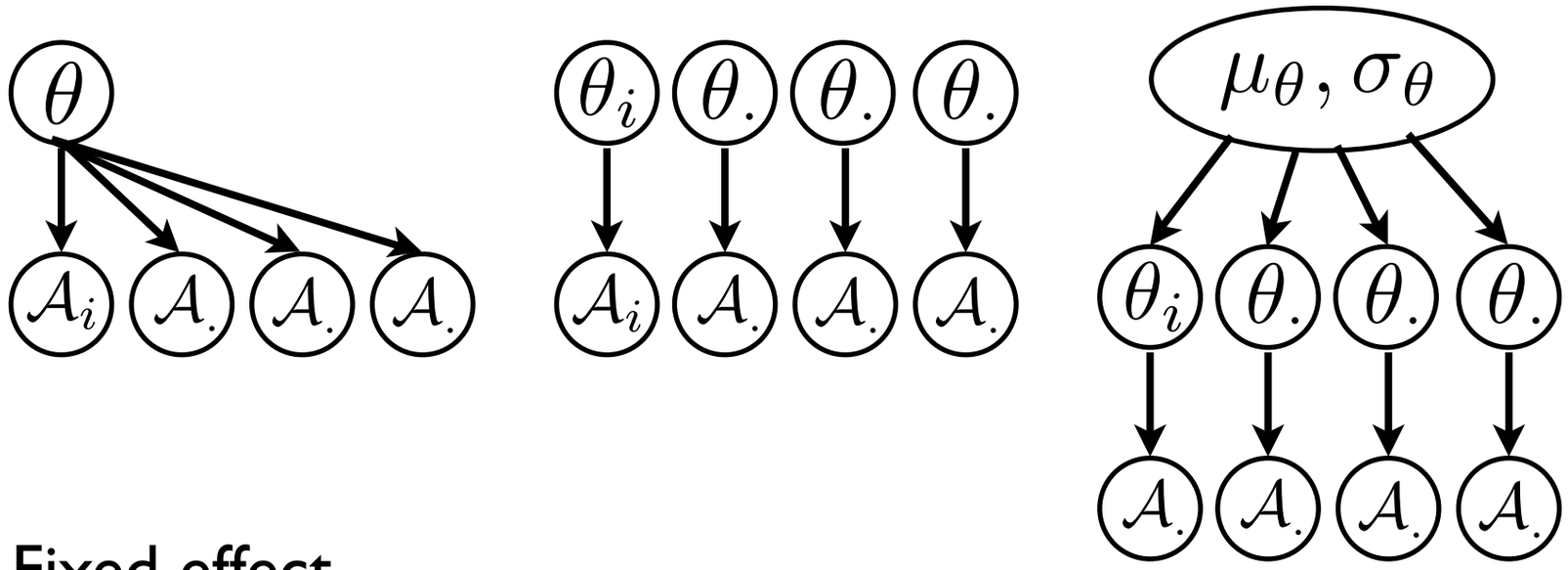

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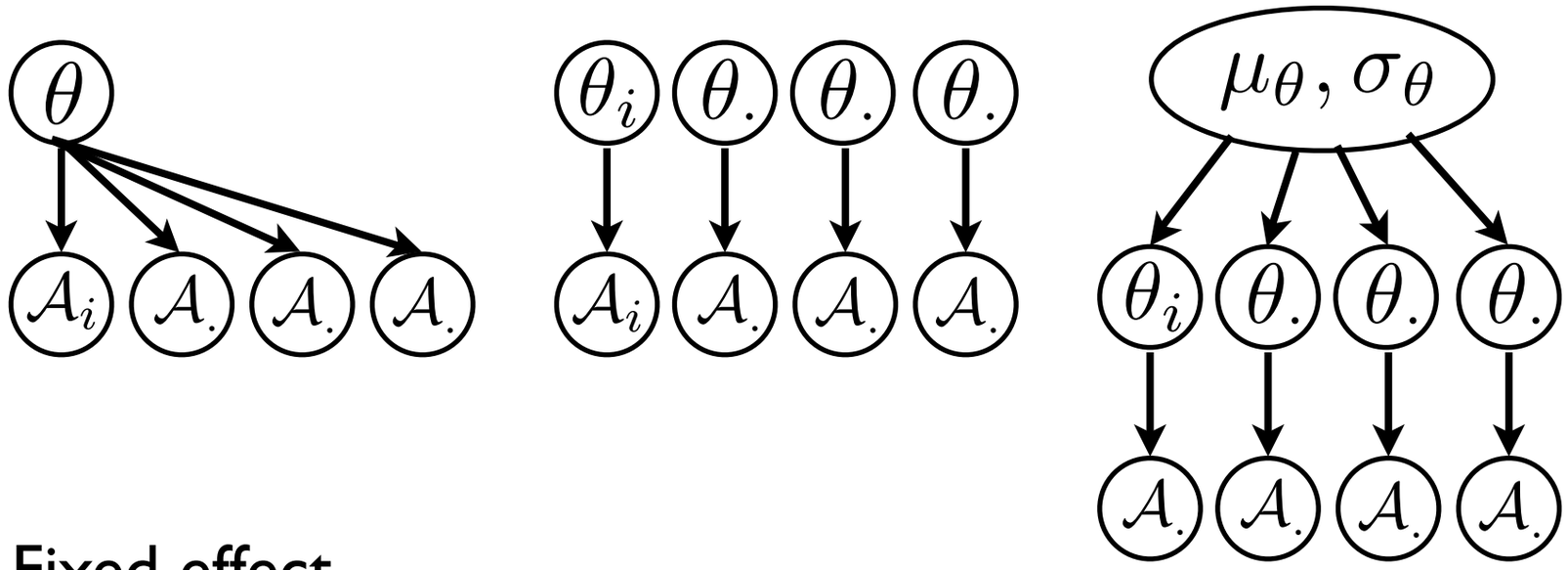

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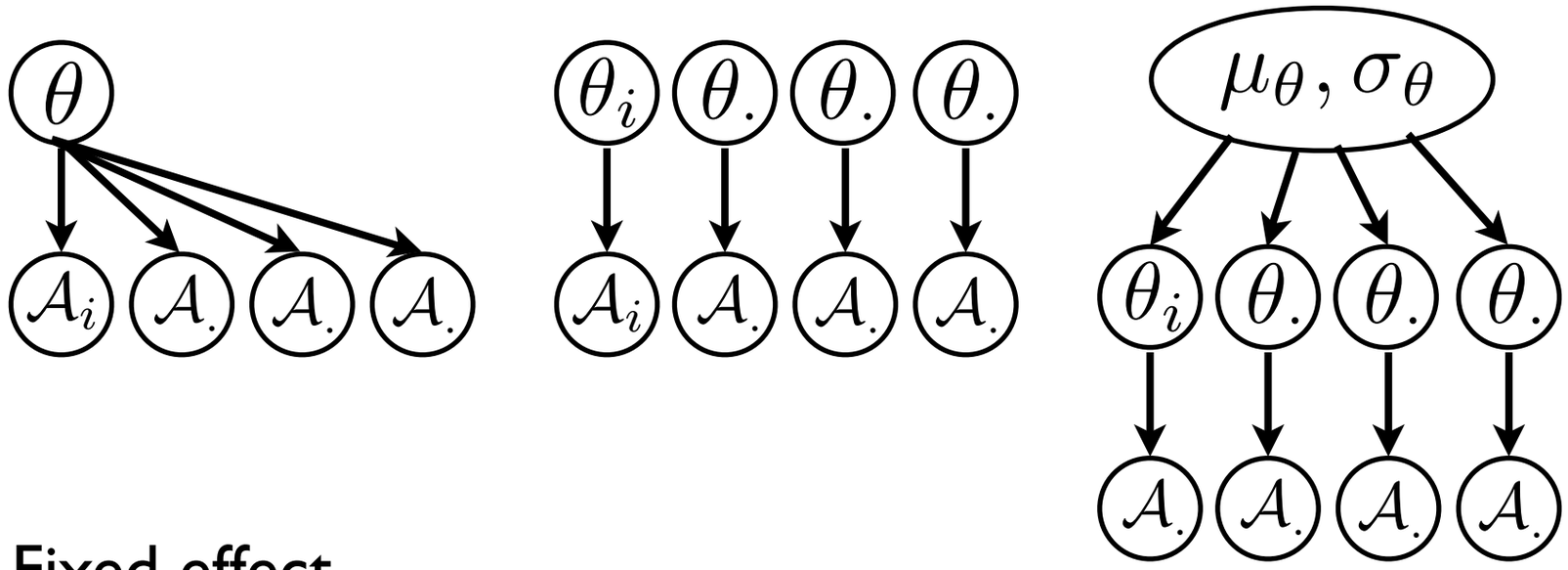

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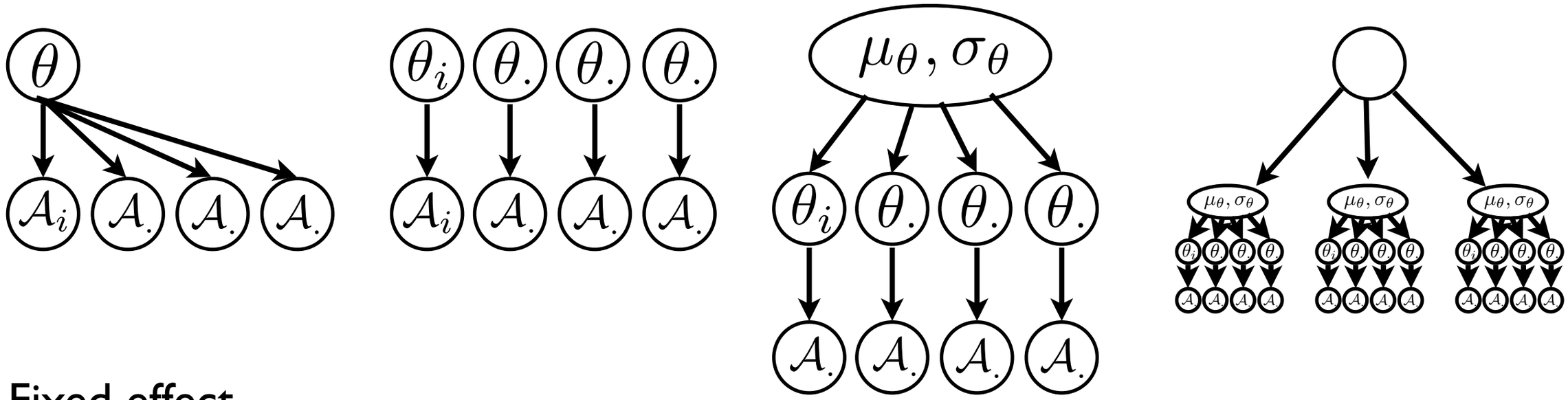

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Estimating the hyperparameters

- MAP

$$\log \mathcal{P}(\theta) = \mathcal{L}(\theta) + \log \underbrace{p(\theta)}_{=p(\theta|\zeta)} + const.$$

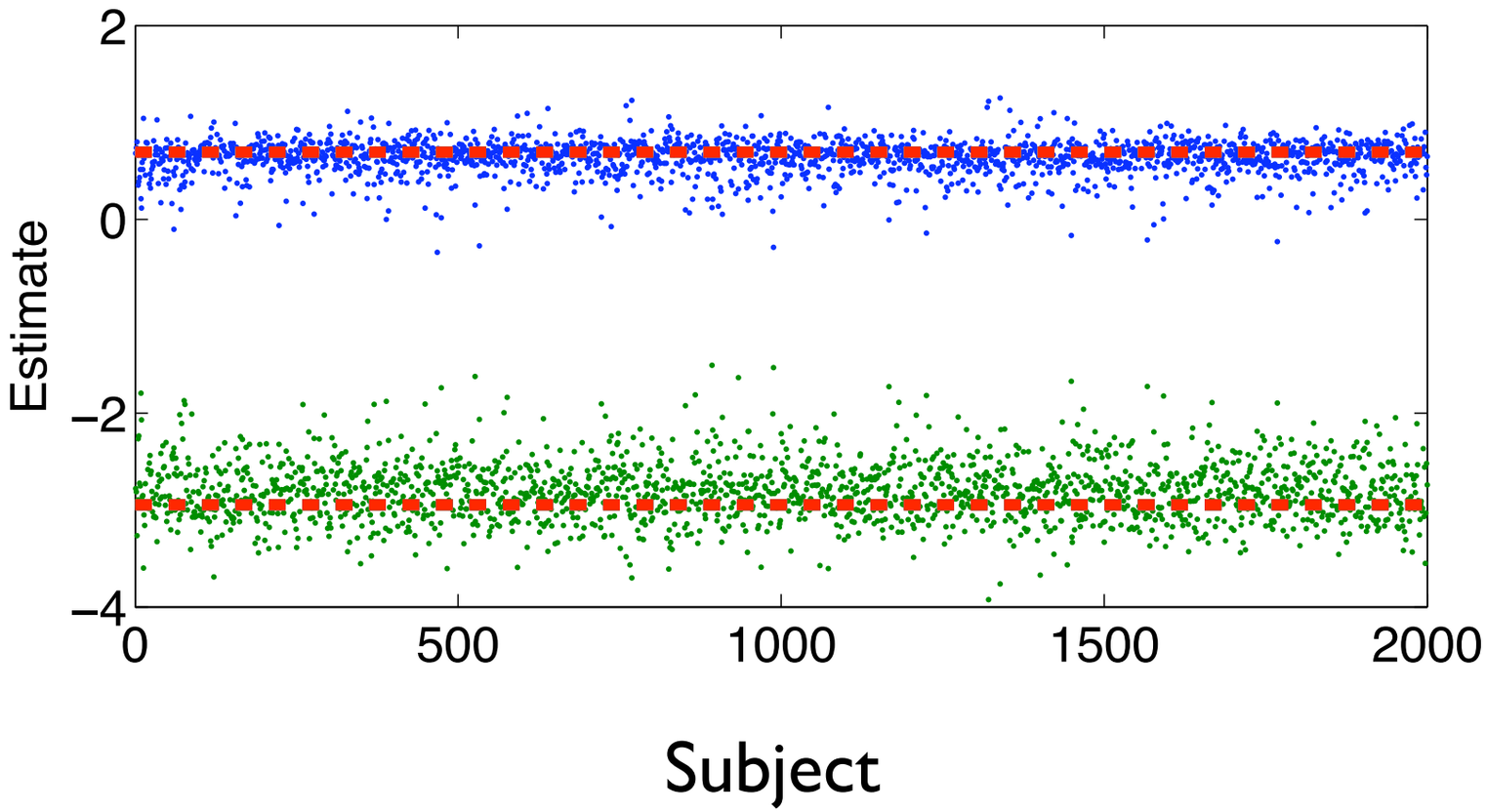
- Empirical Bayes: set them to ML estimate

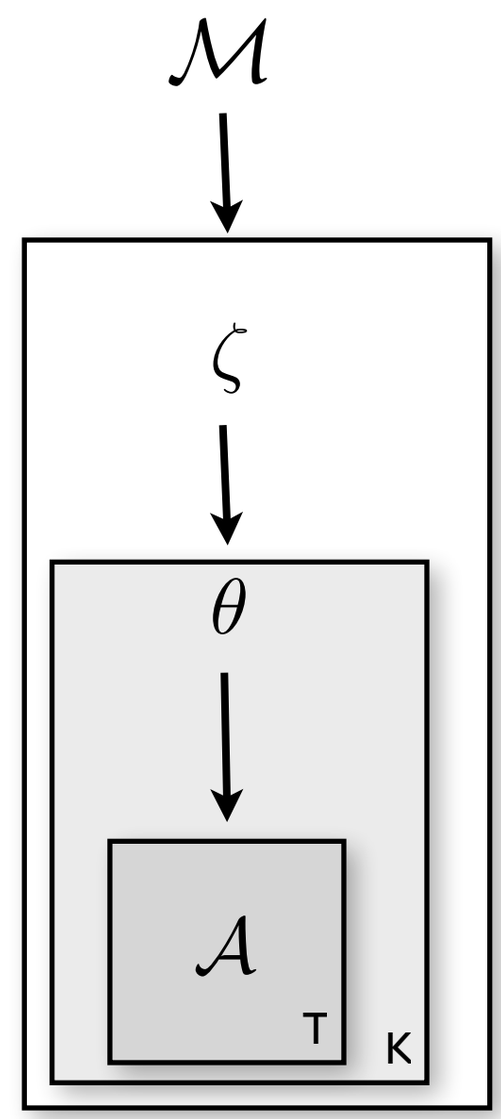
$$\hat{\zeta} = \underset{\zeta}{\operatorname{argmax}}\, p(\mathcal{A}|\zeta)$$

- where we use all the actions by all the *k* subjects

$$\mathcal{A} = \{a^k_{1\ldots T}\}_{k=1}^K$$

ML estimate of top-level parameters





$$\hat{\zeta} = \underset{\zeta}{\operatorname{argmax}}\, p(\mathcal{A}|\zeta)$$

Estimating the hyperparameters

- Effectively we now want to do gradient ascent on:

$$\frac{d}{d\zeta} p(\mathcal{A}|\zeta)$$

- But this contains an integral over individual parameters:

$$p(\mathcal{A}|\zeta) = \int d\theta p(\mathcal{A}|\theta)\, p(\theta|\zeta)$$

- So we need to:

$$\begin{aligned} \hat{\zeta} &= \underset{\zeta}{\operatorname{argmax}}\, p(\mathcal{A}|\zeta) \\ &= \underset{\zeta}{\operatorname{argmax}} \int d\,\theta p(\mathcal{A}|\theta)\, p(\theta|\zeta) \end{aligned}$$

Integrating the integral

$$\begin{aligned}\hat{\zeta} &= \underset{\zeta}{\operatorname{argmax}}\, p(\mathcal{A}|\zeta) \\ &= \underset{\zeta}{\operatorname{argmax}} \int d\,\theta p(\mathcal{A}|\theta)\, p(\theta|\zeta)\end{aligned}$$

- analytical - rare
- brute force - for simple problems
- Expectation Maximisation - approximate, easy
- Variational Bayes
- Sampling / MCMC

EM with Laplace approximation

- Next update the prior

Prior mean = mean of MAP estimates

$$\text{M step:} \qquad \zeta_\mu^{(i+1)} = \frac{1}{K}\sum_k \mathbf{m}_k$$

$$\zeta_{\nu^2}^{(i+1)} = \frac{1}{N}\sum_i \left[(\mathbf{m}_k)^2 + \mathbf{S}_k\right] - (\zeta_\mu^{(i+1)})^2$$

Prior variance depends on inverse Hessian S and variance of MAP estimates

Take uncertainty of estimates into account

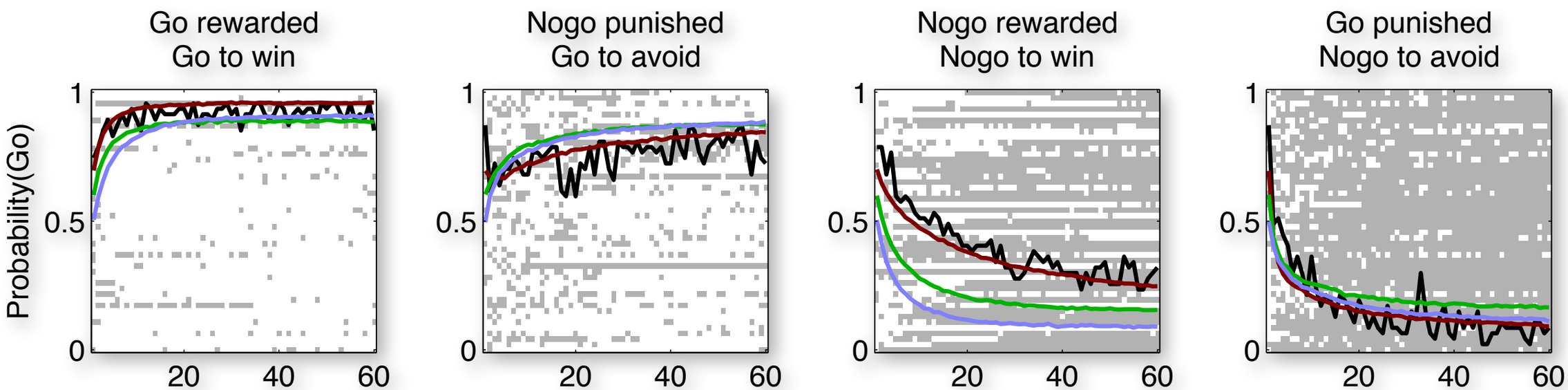
- And now iterate until convergence

Model comparison

- A fit by itself is not meaningful
- Generative test
  - qualitative
- Comparisons
  - vs random
  - vs other model -> test specific hypotheses and isolate particular effects in a generative setting

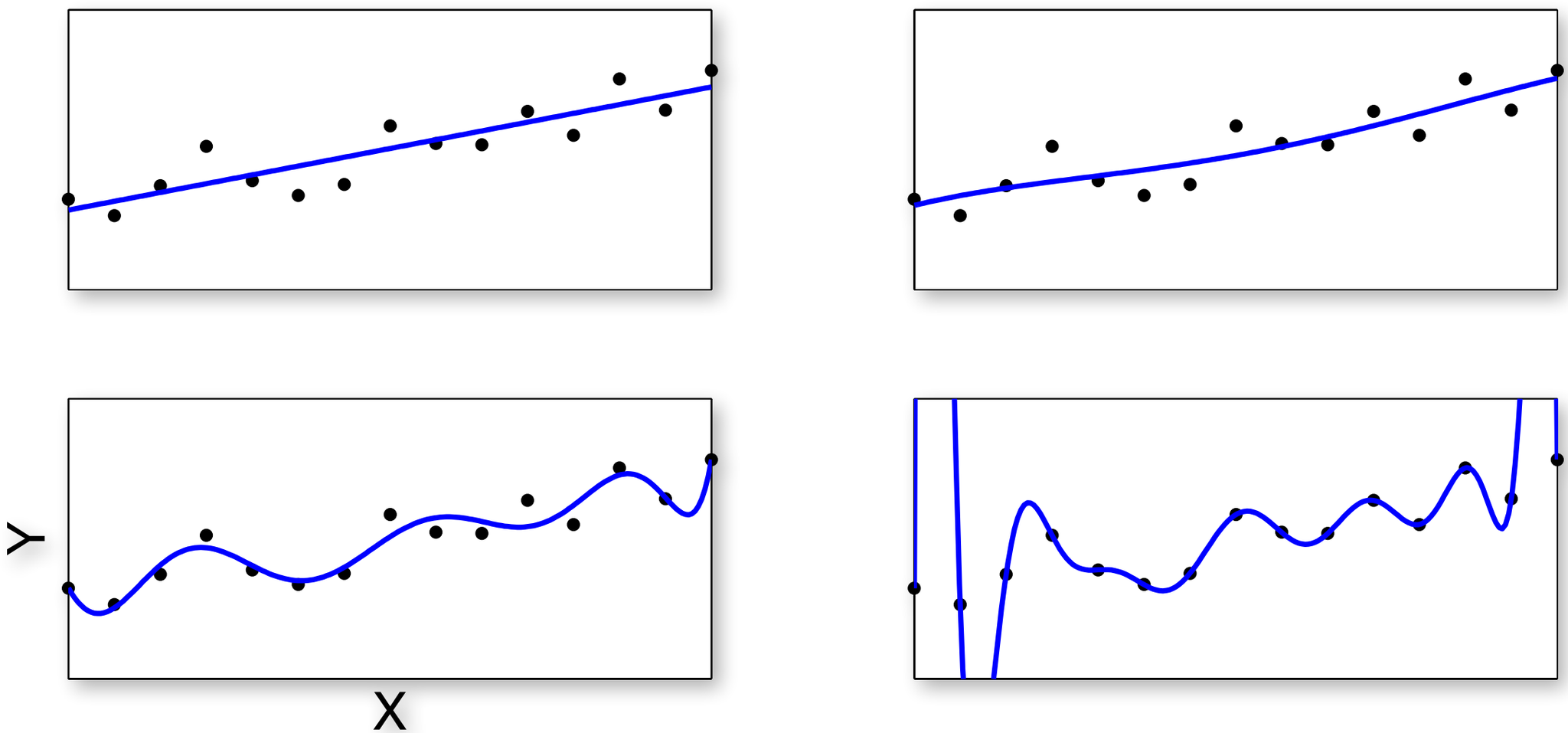
Generative test

- Model: probability(actions)
  - simply draw from this distribution, and see what happens



- Critical sanity test: is the model meaningful?
- Caveat: overfitting

Overfitting



Model comparison

- Averaged over its parameter settings, how well does the model fit the data?

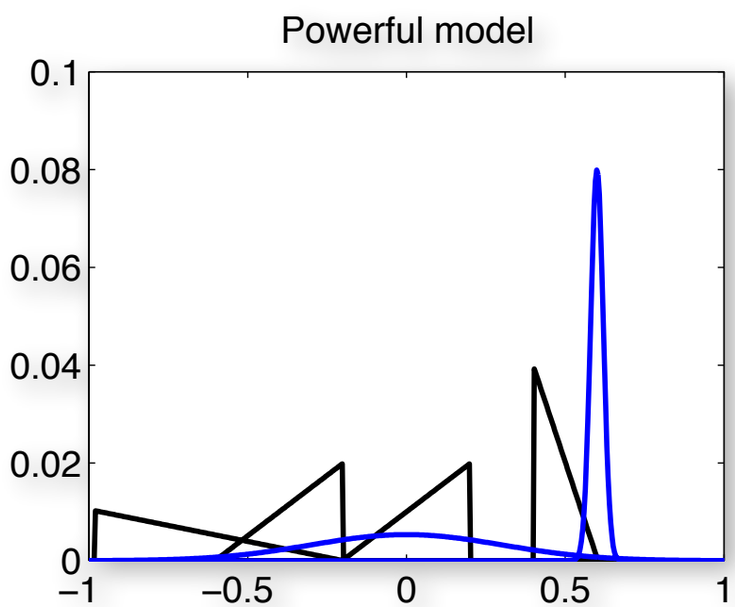
$$p(\mathcal{A}|\mathcal{M}) = \int d\theta \, p(\mathcal{A}|\theta) \, p(\theta|\mathcal{M})$$

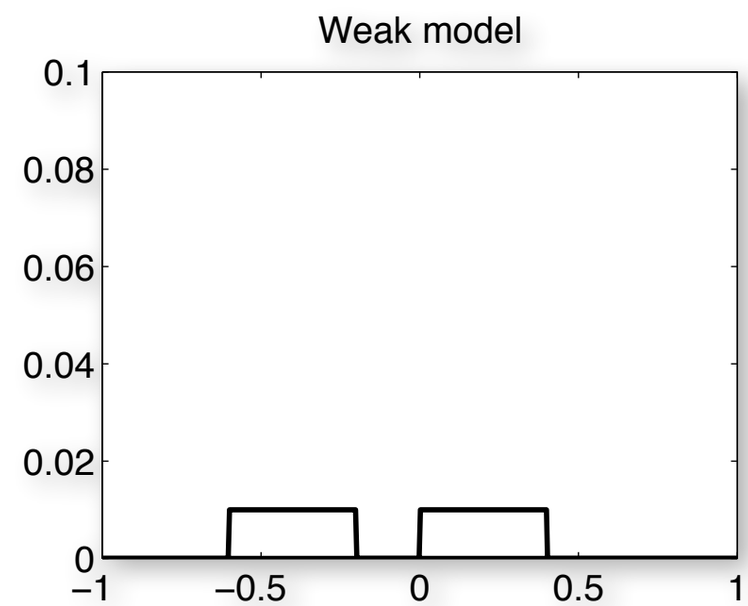
- Model comparison: Bayes factors

$$BF = \frac{p(\mathcal{A}|\mathcal{M}_1)}{p(\mathcal{A}|\mathcal{M}_2)}$$

- Problem:
  - integral rarely solvable
  - approximation: Laplace, sampling, variational...

Why integrals? The God Almighty test





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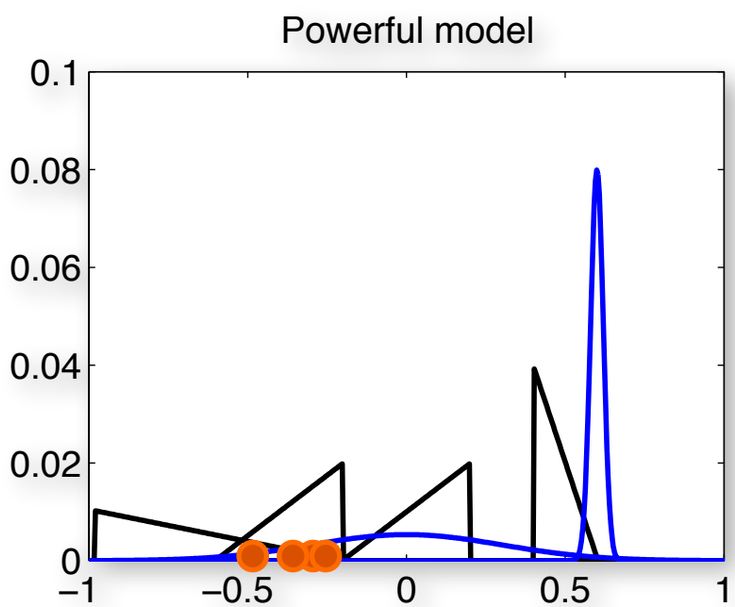
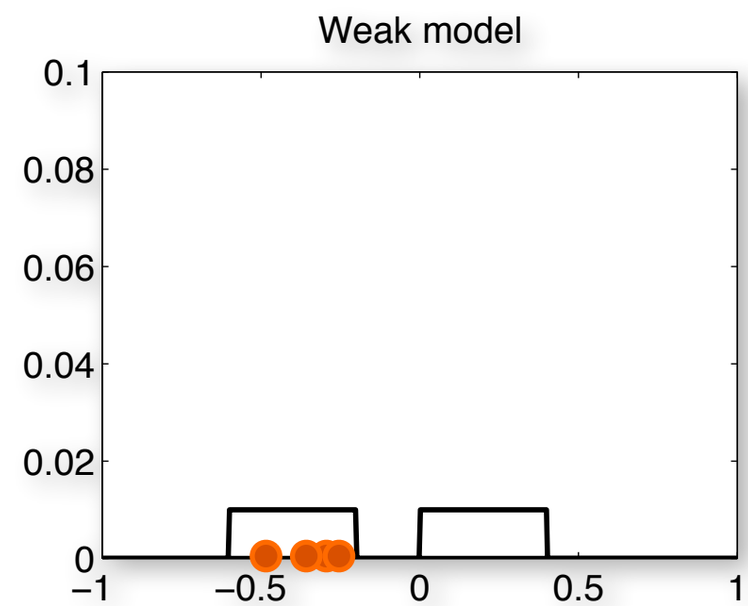
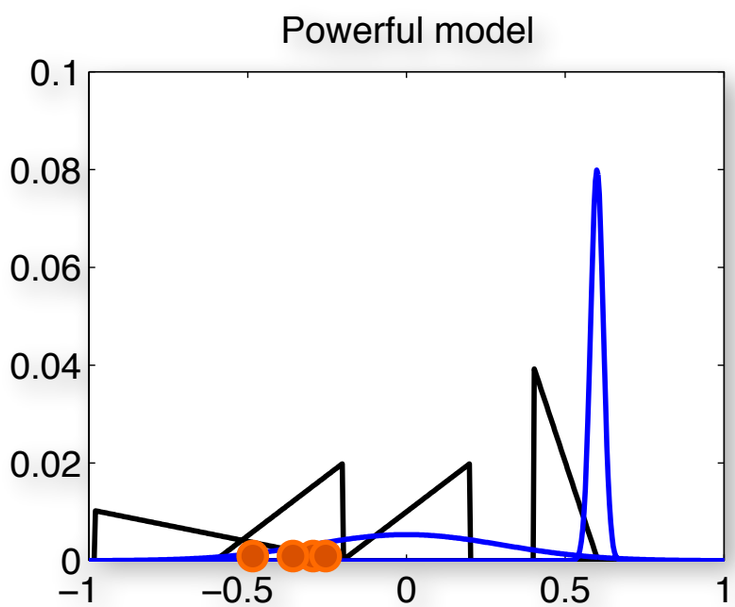
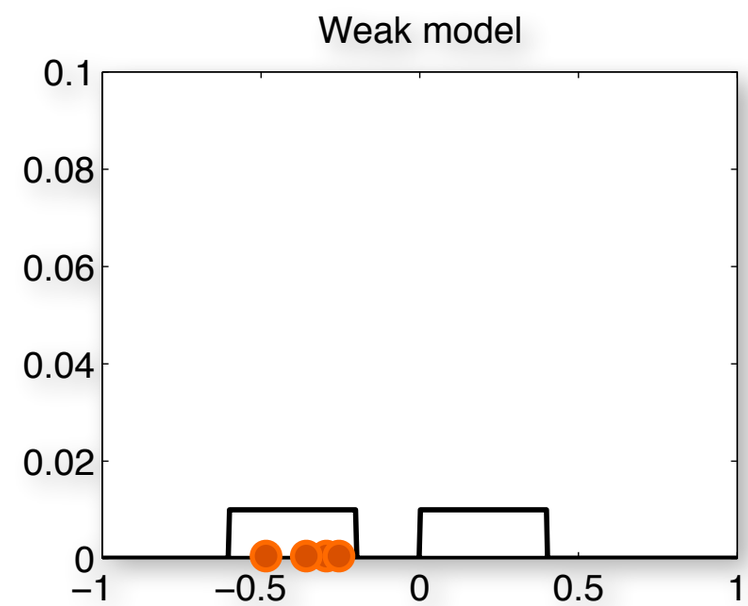




Why integrals? The God Almighty test



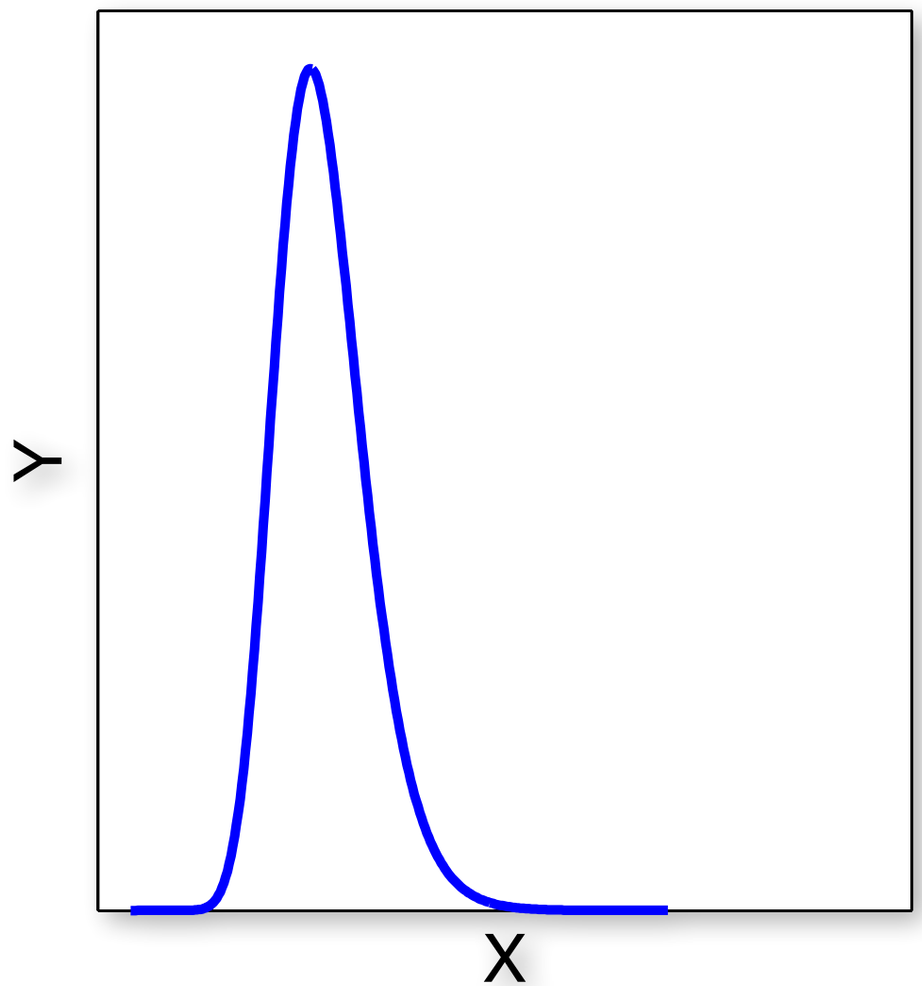


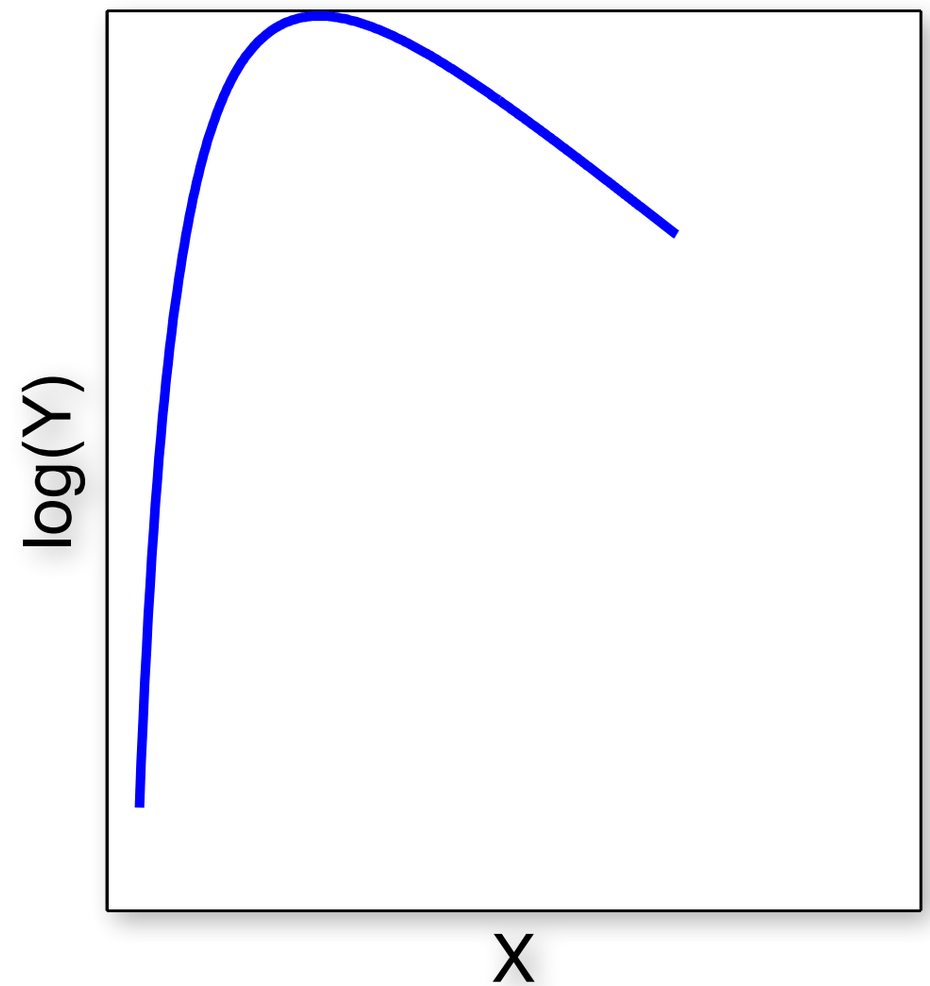
$$\frac{1}{N}\left(\mathbf{p}(\mathbf{X}|\boldsymbol{\theta_1}) + p(X|\theta_2) + \cdots\right)$$

These two factors fight it out
Model complexity vs model fit

Bayesian Information Criterion

- Laplace's approximation (saddle-point method)





Bayesian Information Criterion

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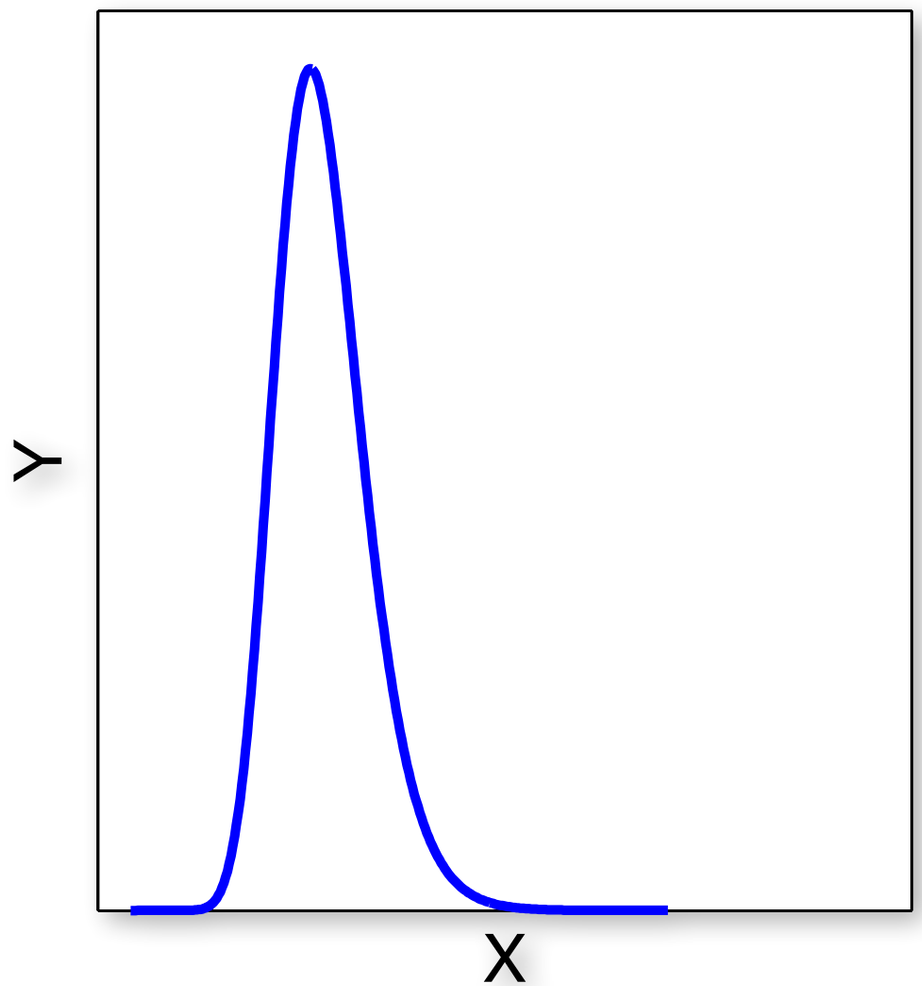

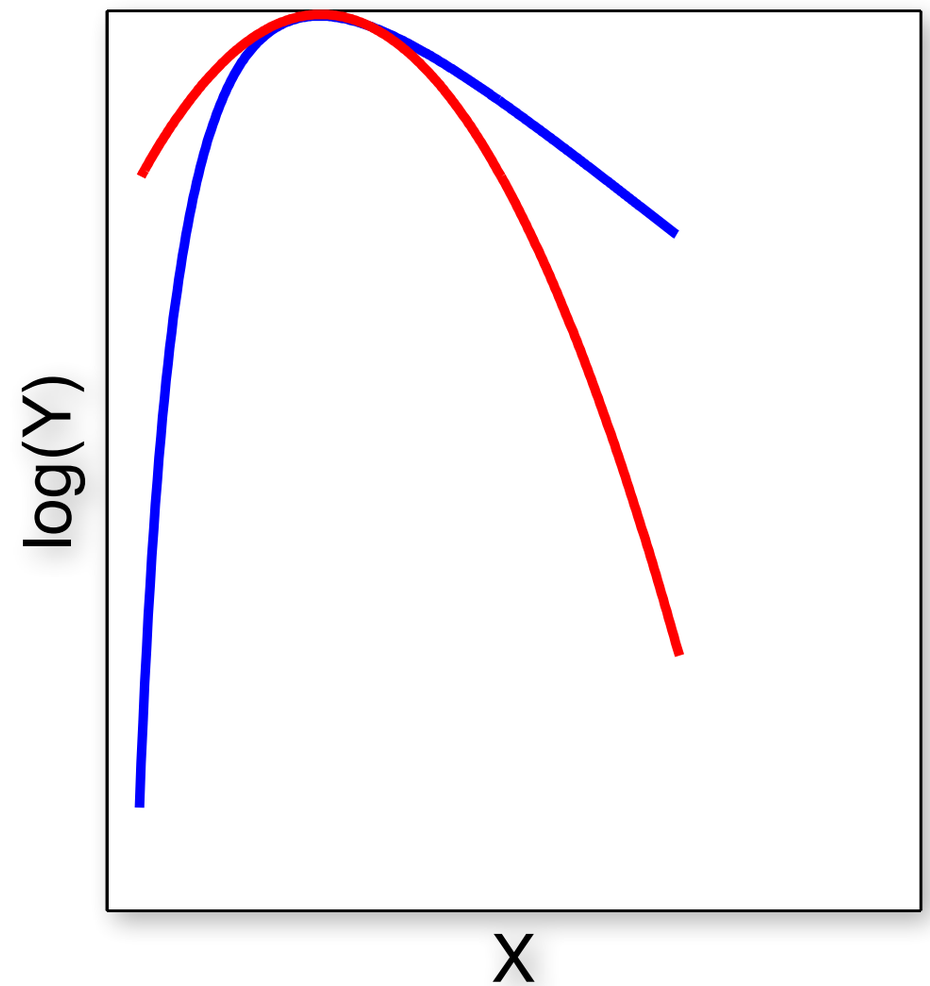

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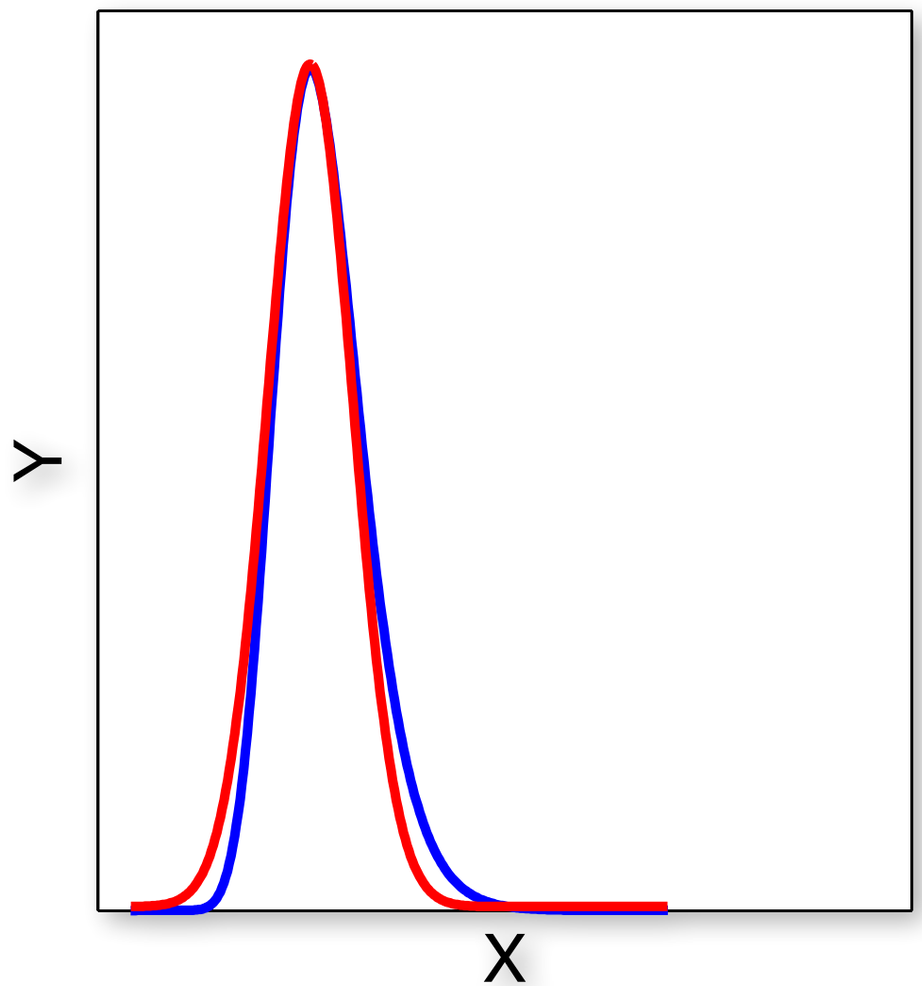

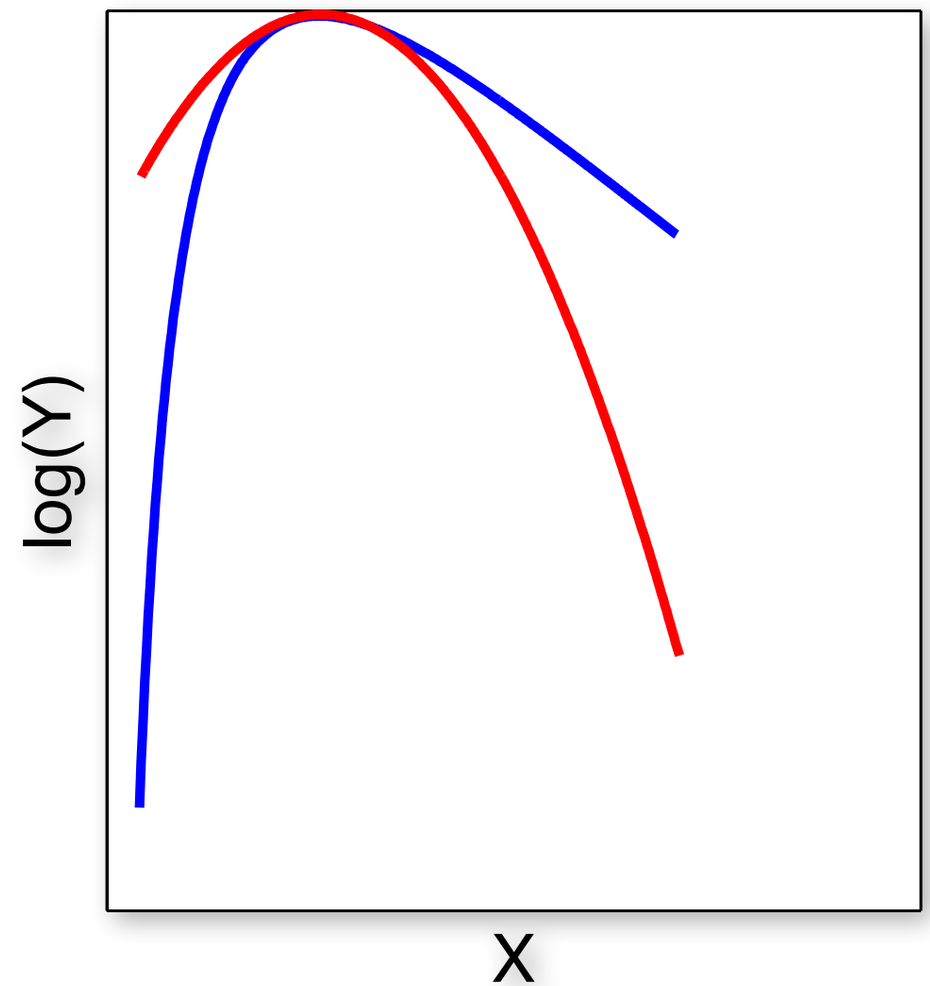

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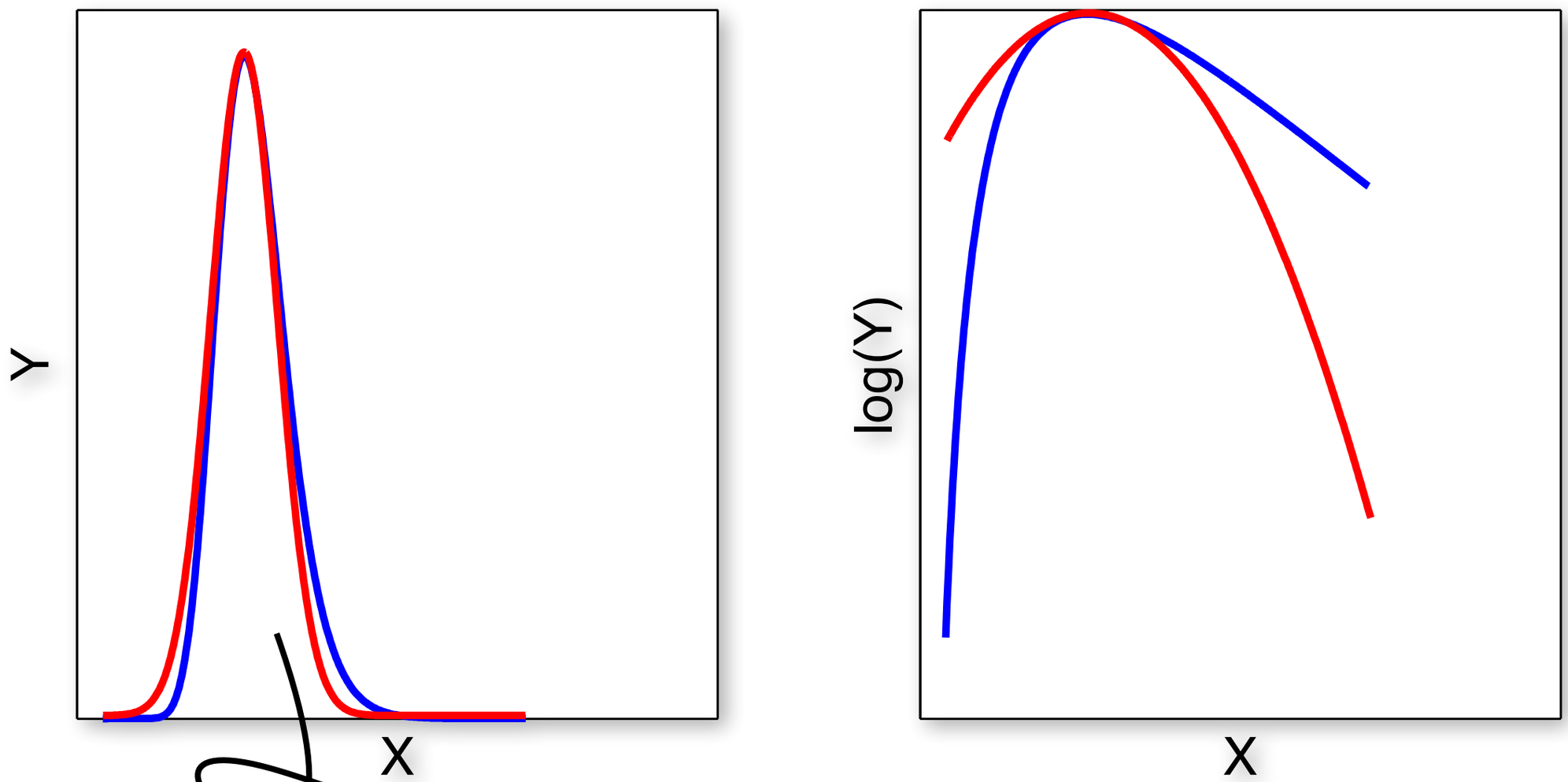

Just a Gaussian

$$\int dx\, f(x) \approx f^*(x_0)\sqrt{2\pi\sigma^2}$$

Bayesian Information Criterion: one subject

$$p(\mathcal{A}|\mathcal{M}) \quad = \quad \int d\theta \, p(\mathcal{A}|\theta, \mathcal{M}) \; p(\theta|\mathcal{M})$$

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is propto Gaussian

Bayesian Information Criterion: one subject

$p(\mathcal{A}|\theta)\ p(\theta|\mathcal{M})$
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$$
\begin{aligned}
p(\mathcal{A}|\mathcal{M}) &= \int d\theta\, p(\mathcal{A}|\theta,\mathcal{M})\ p(\theta|\mathcal{M}) \\
&\approx p(\mathcal{A}|\theta^{ML},\mathcal{M})p(\theta^{ML}|\mathcal{M}) \times \sqrt{(2\pi)^N|\Sigma|}
\end{aligned}
$$

Bayesian Information Criterion: one subject

$p(\mathcal{A}|\theta)\ p(\theta|\mathcal{M})$
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$p(\theta|\mathcal{M}) = \text{const.}$
Model doesn't prefer particular

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Laplacian approximation

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Laplacian approximation

$$
\Sigma_{ii} \propto \frac{1}{T} \Rightarrow \frac{1}{2}\log(|\Sigma|) \approx -\tfrac{N}{2}\log(T)
$$

Bayesian Information Criterion (BIC)

$$
\approx -N
$$

Akaike Information Criterion (AIC)

Bayesian Information Criterion: one subject

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Akaike Information Criterion (AIC)

Model fit vs Model complexity

Group data

- Multiple subjects
- Multiple models
  - do they use the same model? If not parameters are not comparable
  - which model best accounts for all of them?
- Multiple groups
  - difference in models?
  - difference in parameters?
  - 2^k possible model comparisons
- Multiple parameters
  - 2^k possible correlations with any one psychometric measure

Group data - approaches

- Summary statistic
  - Treat individual model comparison measure as summary statistics, do ANOVA or t-test
- Fixed effect analysis
  - Subject data independent

$$\begin{aligned}\log p(\mathcal{A}|\mathcal{M}) &= \sum_i \log p(\mathcal{A}_i|\mathcal{M}) \\ &= \sum_i \log \int d\theta_i \, p(\mathcal{A}_i|\theta_i) p(\theta_i|\mathcal{M}_i) \approx -\frac{1}{2} \sum_i \mathrm{BIC}_i\end{aligned}$$

- Random effects analyses
  - Hierarchical prior on group parameters

$$p(\mathcal{A}|\mathcal{M}) = \int d\zeta \int d\theta \, p(\mathcal{A}|\theta) \, p(\theta|\zeta) \, p(\zeta|\mathcal{M})$$

  - Hierarchical prior on models

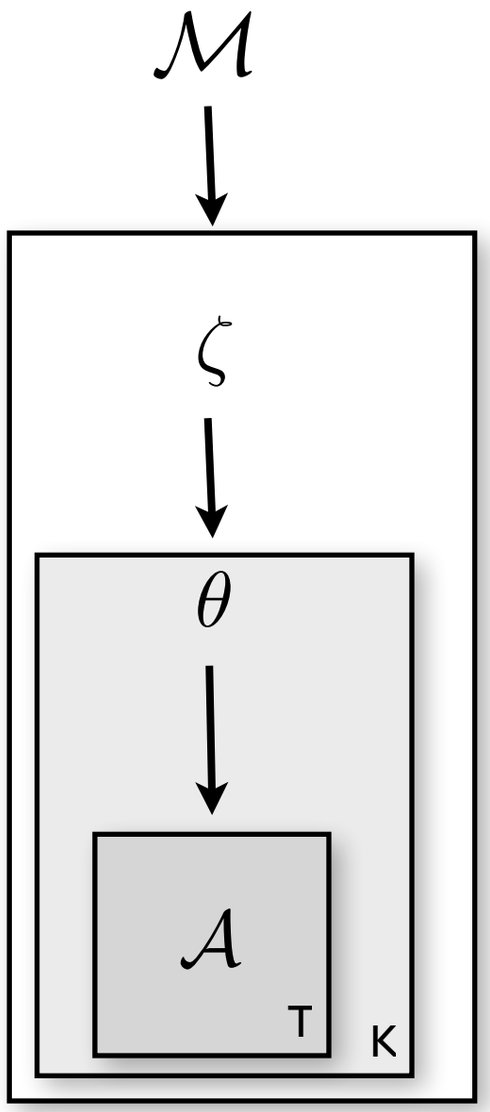
$$p(\mathcal{A}, \mathcal{M}_k, r|\alpha) = p(\mathcal{A}|\mathcal{M}_k) \, p(\mathcal{M}_k|r) \, p(r|\alpha)$$

  - Hierarchical prior on models and parameters…

Group-level likelihood

- Contains two integrals:
  - subject parameters
  - prior parameters

$$p(\mathcal{A}|\mathcal{M}) = \int d\theta\, p(\mathcal{A}|\theta,\mathcal{M}) \int d\zeta\, p(\theta|\zeta)\, p(\zeta|\mathcal{M})$$



Evaluating p(A|M)

- Two integrals
  - tricky

$$p(\mathcal{A}|\mathcal{M}) = \int d\theta\, p(\mathcal{A}|\theta,\mathcal{M}) \int d\zeta\, p(\theta|\zeta)\, p(\zeta|\mathcal{M})$$

- Step by step: approximating levels separately
  - Approximate at the top level

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Model doesn't prefer particular ζ

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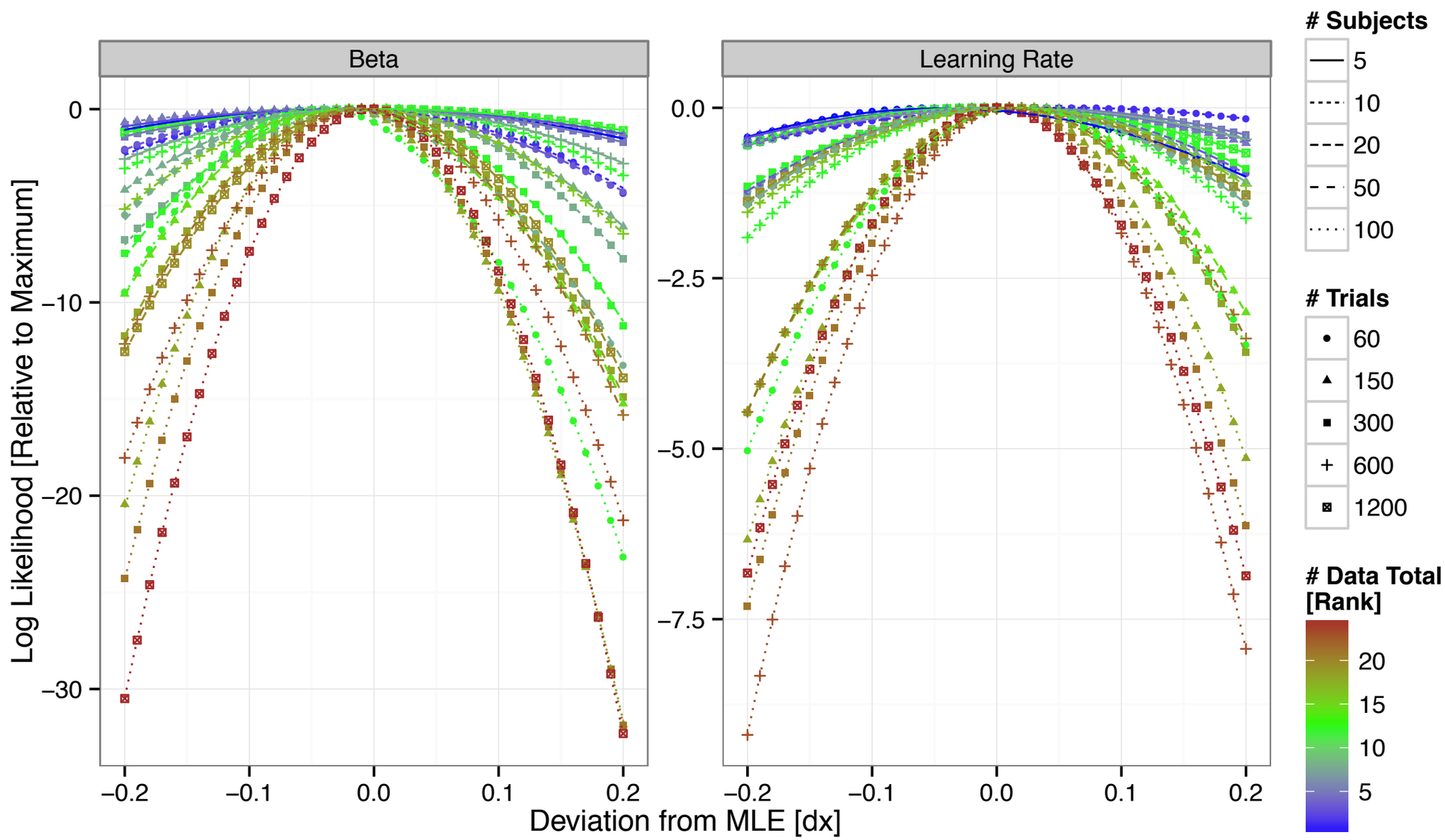
Model doesn't prefer particular ζ

just as before, top-level BIC

Is this reasonable?



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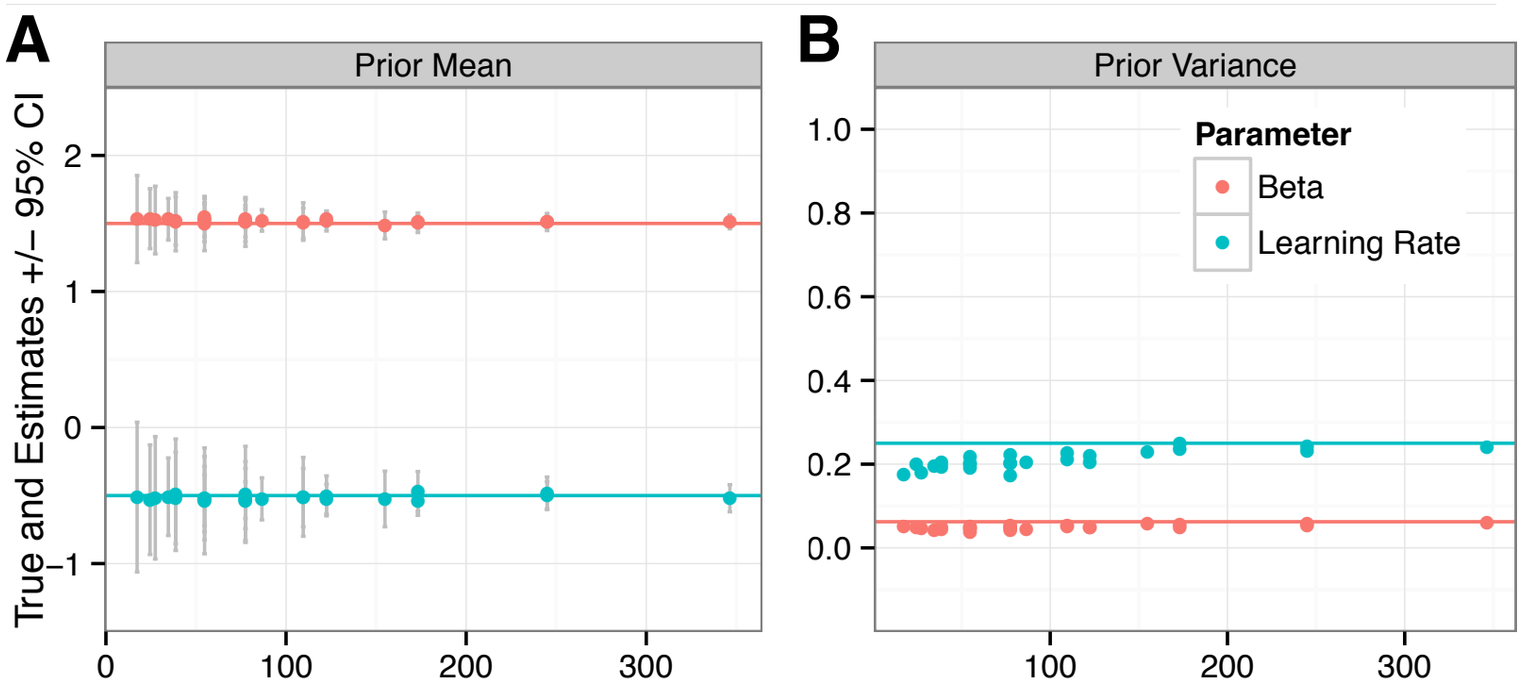
Group level errors



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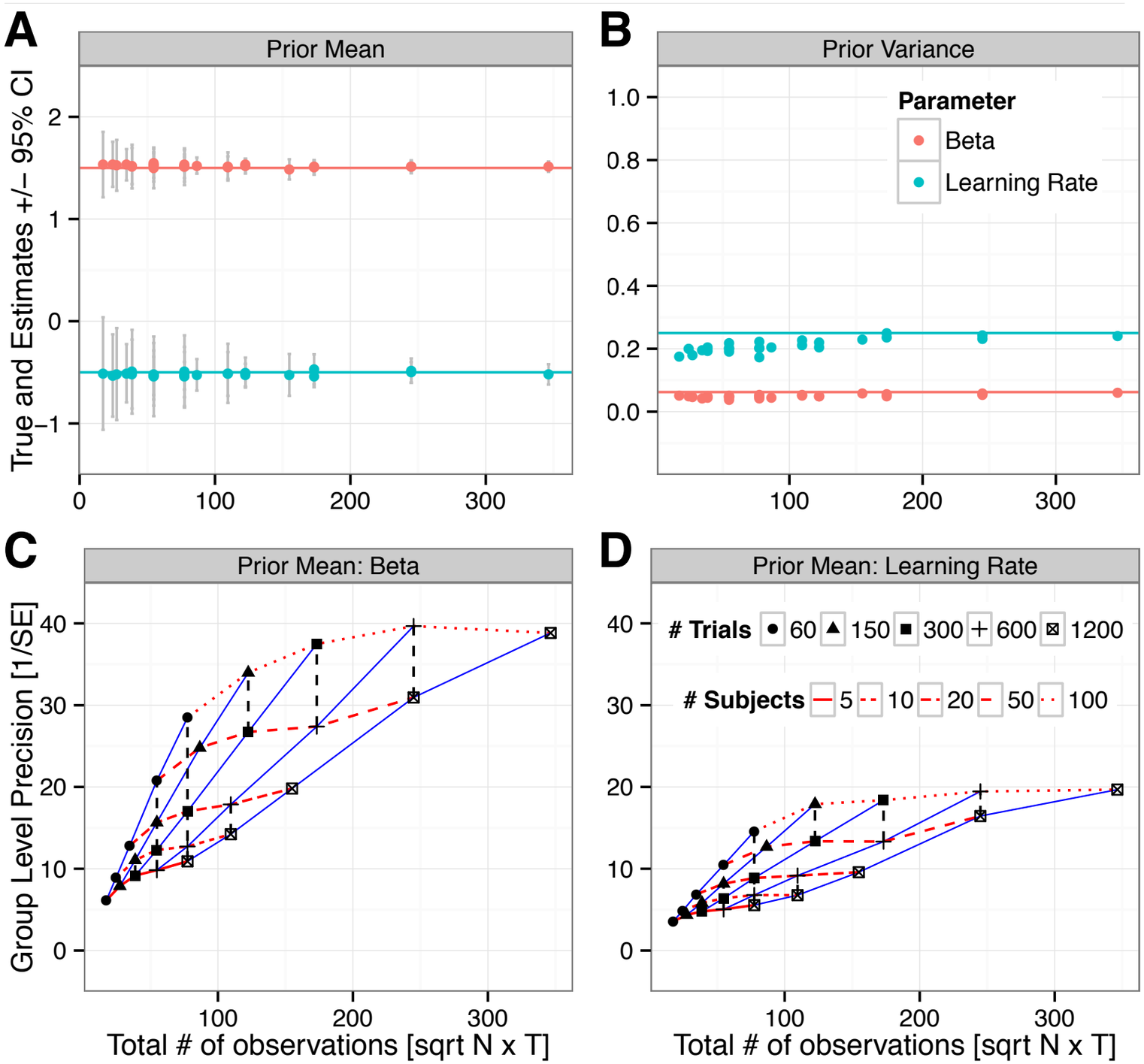

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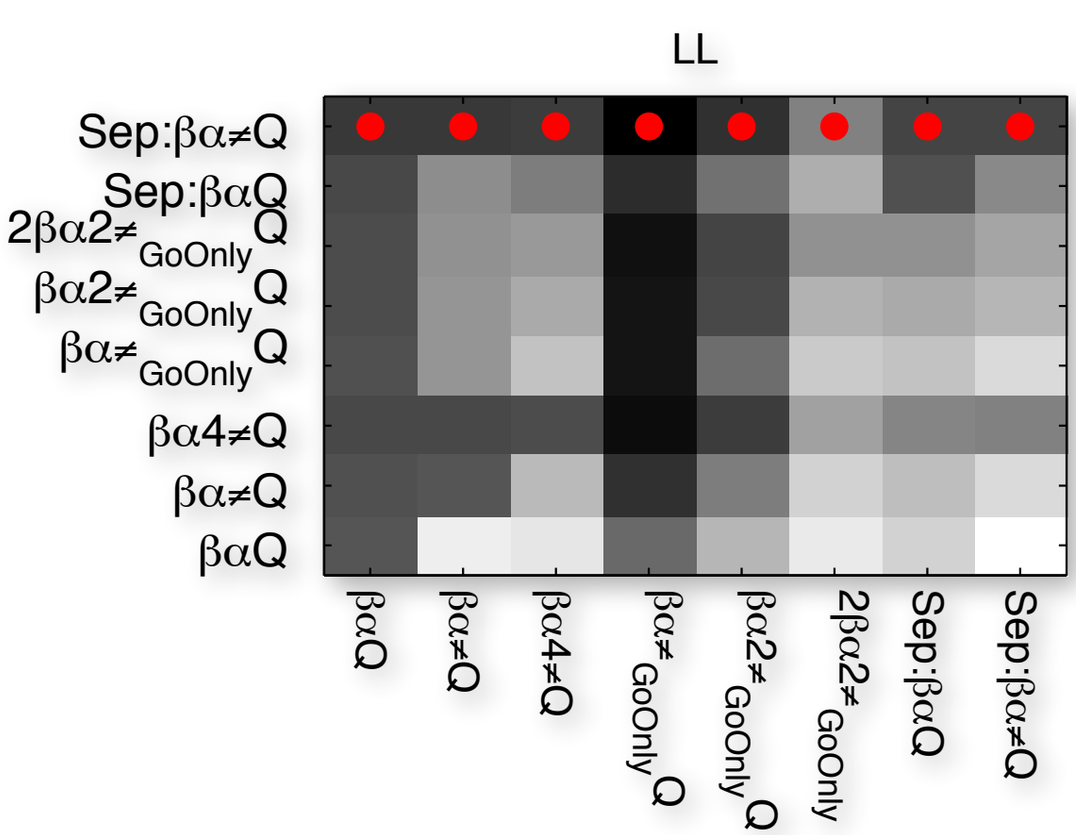
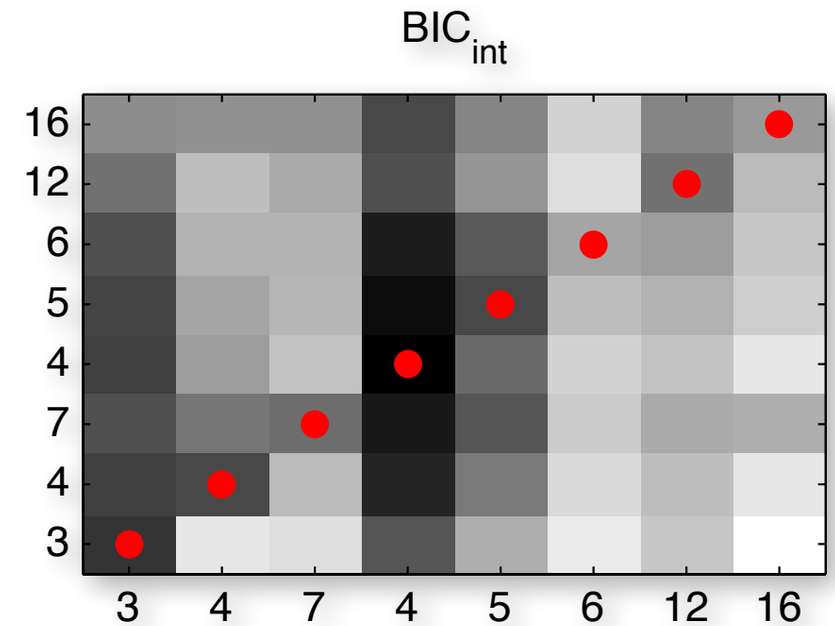
Group-level BIC

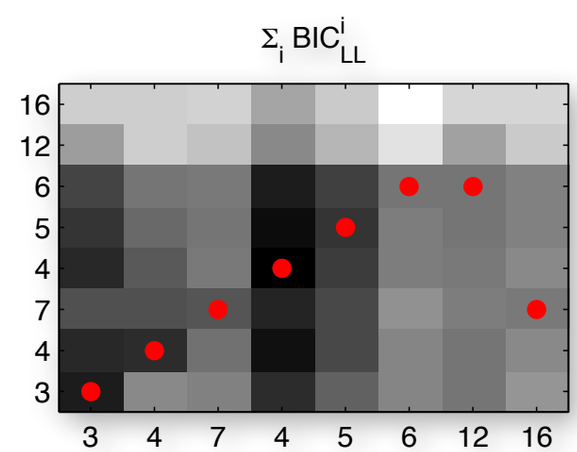
$$
\begin{aligned}
\log p(\mathcal{A}|\mathcal{M}) &= \int d\boldsymbol{\zeta}\, p(\mathcal{A}|\boldsymbol{\zeta})\, p(\boldsymbol{\zeta}|\mathcal{M}) \\
&\approx -\frac{1}{2}\mathsf{BIC}_{\mathsf{int}} \\
&= \log \hat{p}(\mathcal{A}|\hat{\boldsymbol{\zeta}}^{ML}) - \frac{1}{2}|\mathcal{M}| \log(|\mathcal{A}|)
\end{aligned}
$$

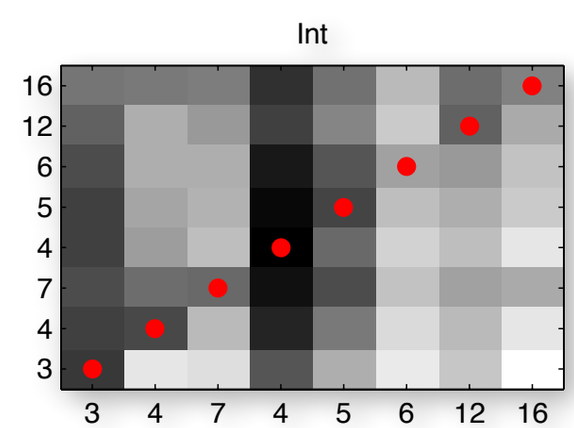
- Very simple
  - 1) EM to estimate group prior mean & variance
    - simply done using fminunc, which provides Hessians
  - 2) Sample from estimated priors
  - 3) Average

How does it do?









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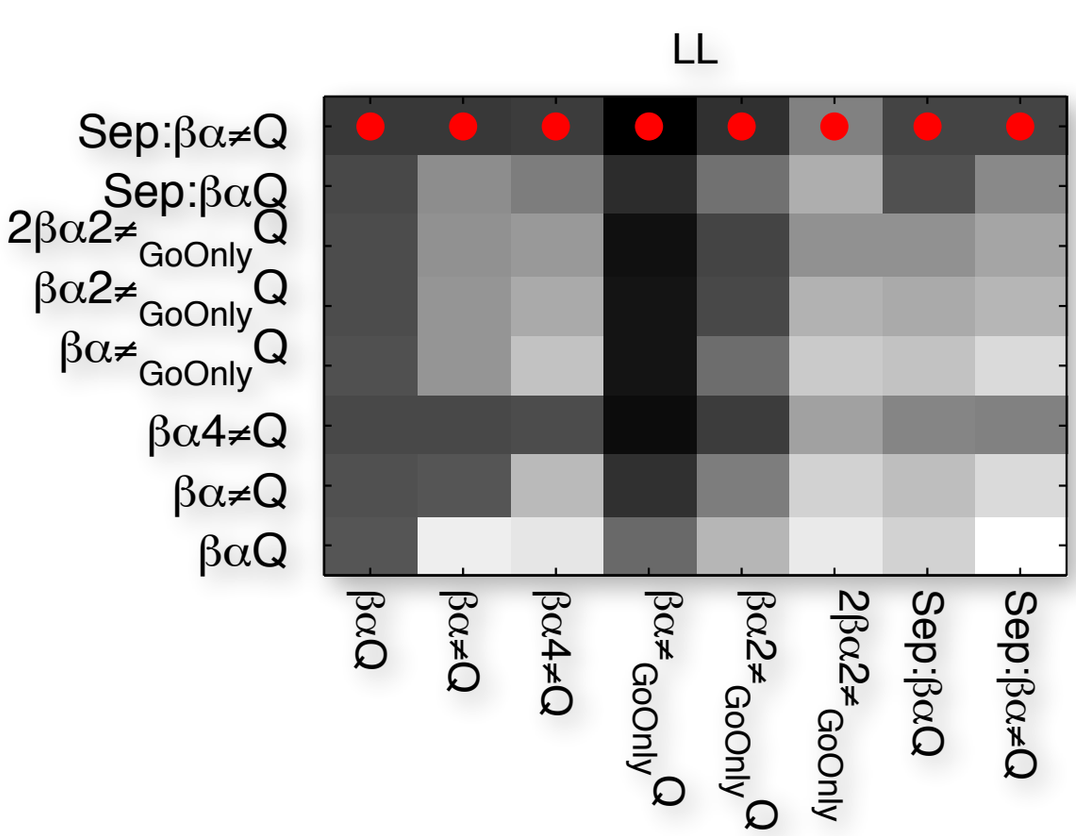
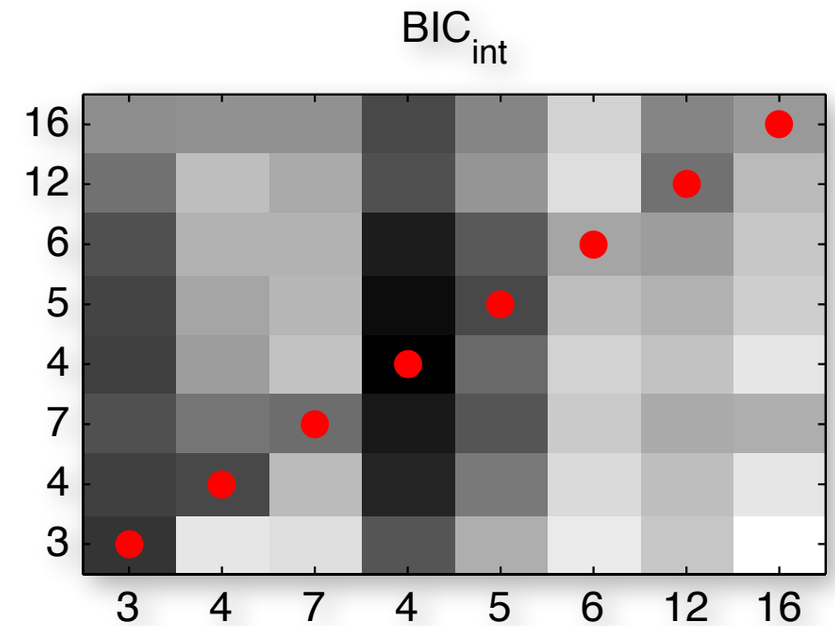
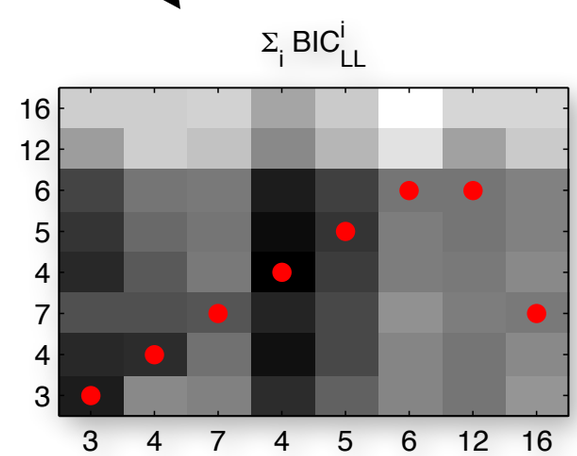
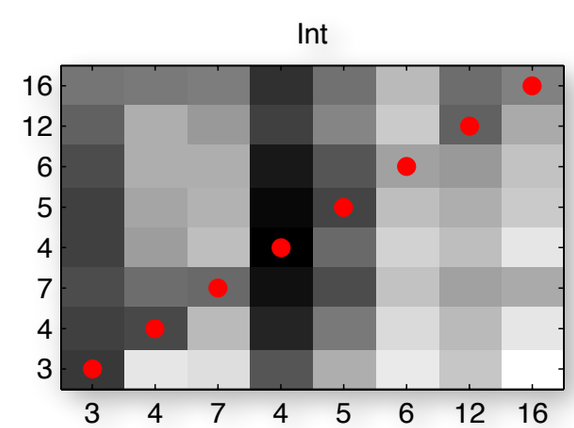




Fitted by EM...
too nice?





iBIC in simulation 2

Generating Model	Fitted model					
	m2b2alr	mr	2b2alr	m2b2al	m	2b2al
m2b2alr	0	337	49	441	1297	531
mr	42	0	428	800	801	1490
2b2alr	12	841	0	280	2678	271
m2b2al	6	452	95	0	514	83
m	40	21	408	45	0	436
2b2al	16	1391	5	18	2271	0

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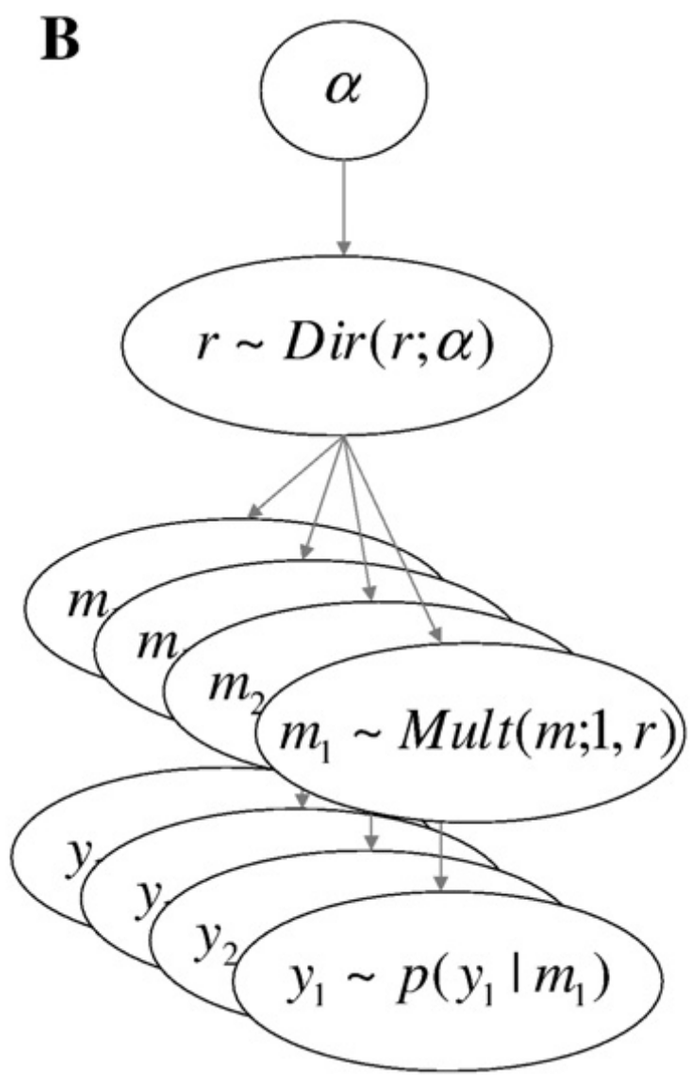
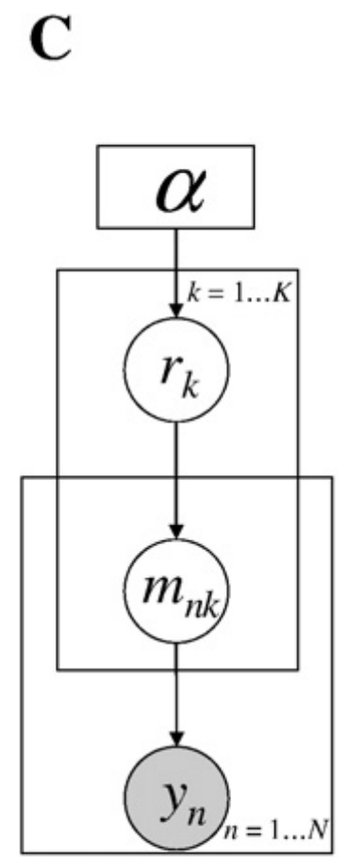
Posterior distribution on models

- Generative model for models





Stephan et al. 2009

Bayesian model selection - equations

- Write down joint distribution of generative model
- Variational approximations lead to set of very simple update equations
  - start with flat prior over model probabilities

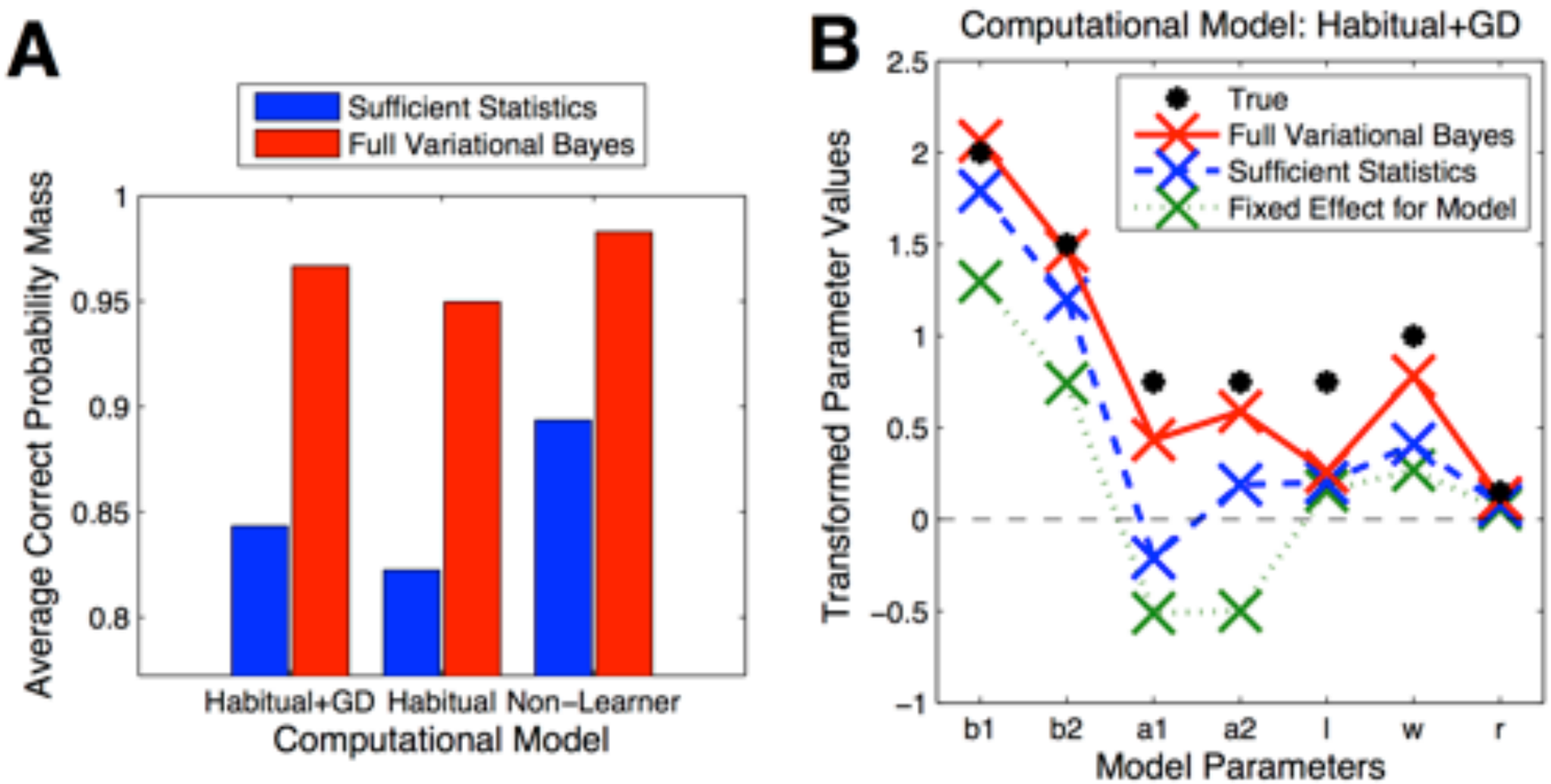
$$\alpha = \alpha_0$$

  - then update

$$u_k^i = \left(\int d\theta_i \, p(\mathcal{A}_i, \theta_i | \mathcal{M}_k) \right) \exp\left(\Psi(\alpha_k) - \Psi\left(\sum_k \alpha_k \right) \right)$$

$$\alpha_k \leftarrow \alpha_{0,k} + \sum_i \frac{u_k^i}{\sum_k u_k^i}$$

Random effects model & parameter



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Group Model selection

Integrate out your parameters

Questions in psychiatry I: regression

- Parametric relationship with other variables ψ
  - do standard second level analyses
  - can use Hessians to determine weights
  - better: compare two models

$$
\begin{aligned}
\text{Model 1:} \quad & \prod_i p(\mathcal{A}_i|\theta_i)\, p(\theta_i|\mu_0, \sigma) \\
\text{i.e.} \quad & \theta_i \sim \mathcal{N}(\mu_0, \sigma) \\
\text{Model 2:} \quad & \prod_i p(\mathcal{A}_i|\theta_i)\, p(\theta_i|\mu_0, c, \sigma, \psi_i) \\
\text{i.e.} \quad & \theta_i \sim \mathcal{N}(\mu_0 + c\psi_i, \sigma)
\end{aligned}
$$

Regression

- Standard regression analysis:

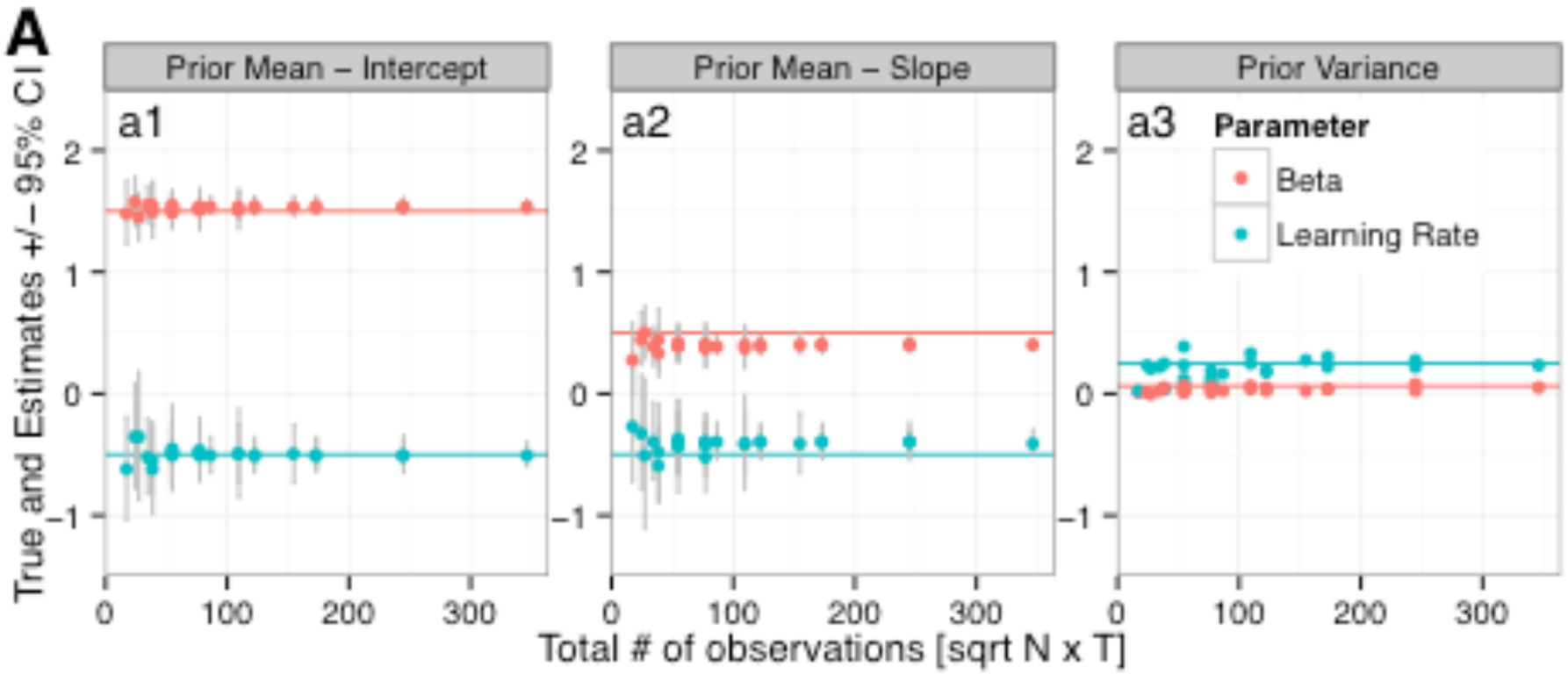
$$\mathbf{m}_i = \mathbf{C}\mathbf{r}_i + \Sigma^{1/2}\boldsymbol{\eta} \qquad \forall i$$

- Including uncertainty about each subject's inferred parameters

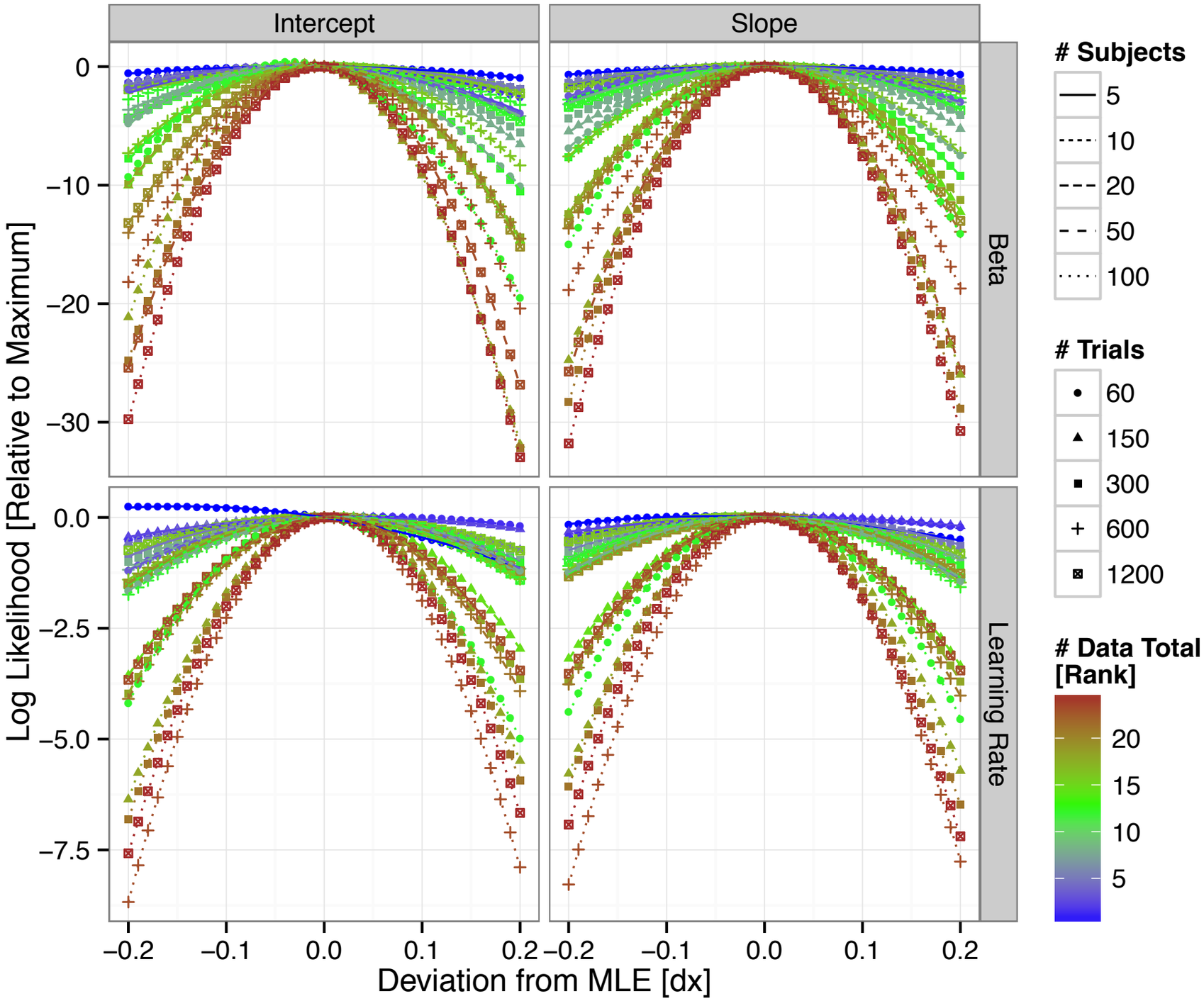
$$\mathbf{m}_i = \mathbf{C}\mathbf{r}_i + (\Sigma^{1/2} + \mathbf{S}_i^{1/2})\boldsymbol{\eta} \qquad \forall i$$

- Careful: Finite difference estimates S can be noisy!
  - regularize...

GLMs for behaviour

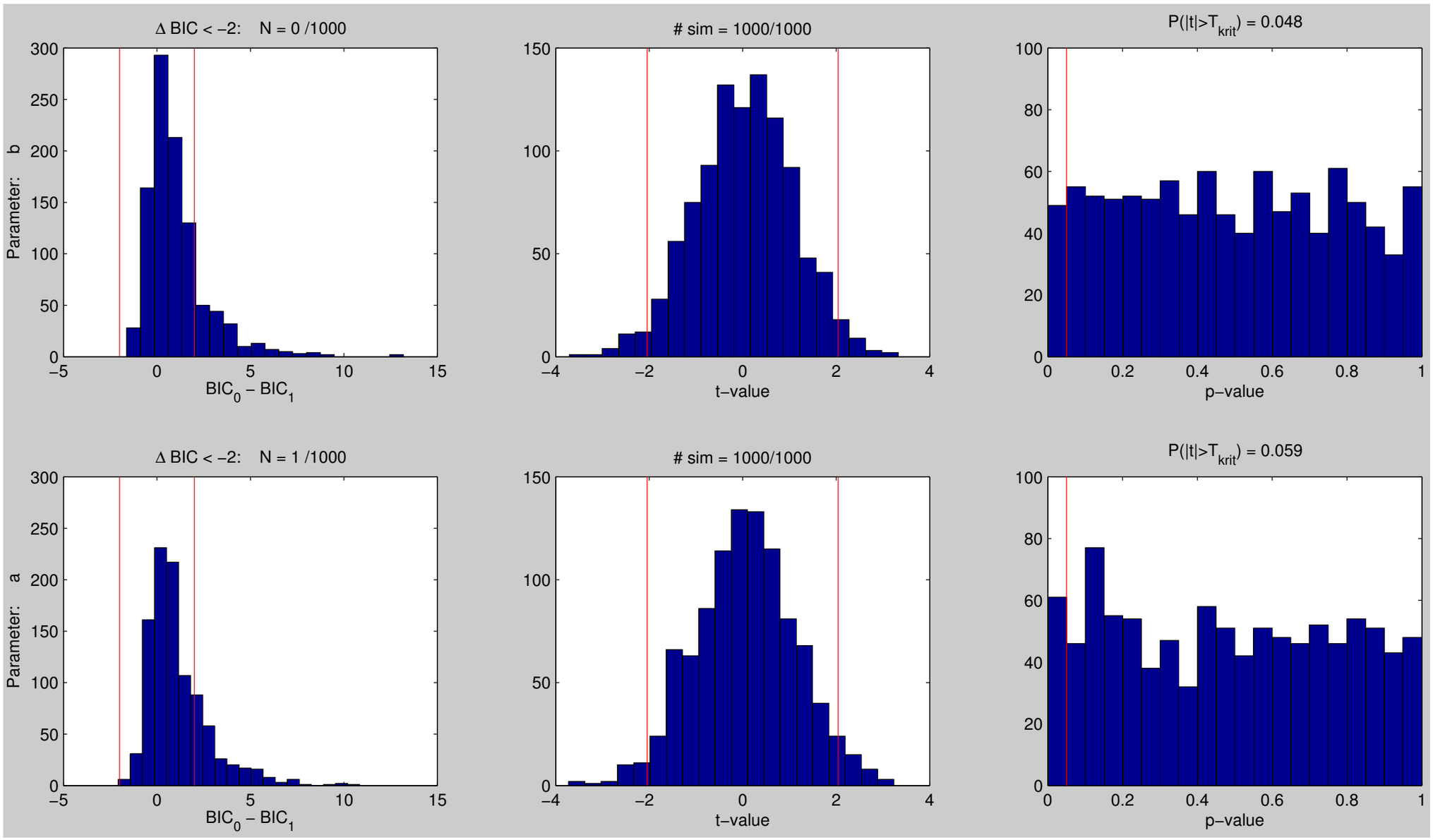


GLMs for behaviour



Is there a correlation or not?

- GLM regression coefficients and Model comparison



Questions in psychiatry II: group differences

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- Compare parameters across different models with care
  - even very similar parameters can account for different effects, and thus 'mean' something else
  - Bayesian model averaging
    - Best if do full random effects inference
    - Dominated by few subjects?

Questions in psychiatry II: group differences

- Compare parameters across different models with care
  - even very similar parameters can account for different effects, and thus 'mean' something else
  - Bayesian model averaging
    - Best if do full random effects inference
    - Dominated by few subjects?
- Within model - as model comparisons?
  - Can't compare parameters estimated with different priors
    - Fit all with one and the same prior, do t-tests
    - But: only models the variance in parameters, not data
  - Compare models with separate priors
    - For models with k parameters, there are 2^k-1 possible comparisons
    - multiple comparisons?

Questions in psychiatry II: group differences

Model 1	ε	β
Model 2	ε	β

- Within model - as model comparisons?
  - Can't compare parameters estimated with different priors
    - Fit all with one and the same prior, do t-tests
    - But: only models the variance in parameters, not data
  - Compare models with separate priors
    - For models with k parameters, there are 2^k-1 possible comparisons
    - multiple comparisons?

Questions in psychiatry III: Classification

- Who belongs to which of two groups?
- How many groups are there?

Model comparison again

- What is 'significant'?

$$BF = \frac{p(\mathcal{A}|\mathcal{M}_1)}{p(\mathcal{A}|\mathcal{M}_2)}$$

$$p(\Lambda < \eta)$$

$\log_{10}(B_{10})$	B_{10}	Evidence against H_0
0 to 1/2	1 to 3.2	Not worth more than a bare mention
1/2 to 1	3.2 to 10	Substantial
1 to 2	10 to 100	Strong
>2	>100	Decisive

Kaas and Raftery 95

- Fixed vs Random effects
- "Spread of effect" in group comparisons
  - Better model does not mean a behavioural effect is concentrated in one parameter
  - Obvious raw differences spread between parameters

Behavioural data modelling

- Are no panacea
  - statistics about specific aspects of decision machinery
  - only account for part of the variance
- Model needs to match experiment
  - ensure subjects actually do the task the way you wrote it in the model
  - model comparison
- Model = Quantitative hypothesis
  - strong test
  - need to compare **models**, not **parameters**
  - includes all consequences of a hypothesis for choice

Modelling in psychiatry

- Hypothesis testing
  - otherwise untestable hypotheses
  - internal processes
- Limited by data quality
  - Look for strong behaviours, not noisy
- “Holistic” testing of hypotheses
- Marr’s levels
  - physical
  - algorithm
  - computational