

Modelling the Predictive Brain II

Predictive coding examples / Mean updating / HGF / Active Inference

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12-13 July 2018

What do you see here?

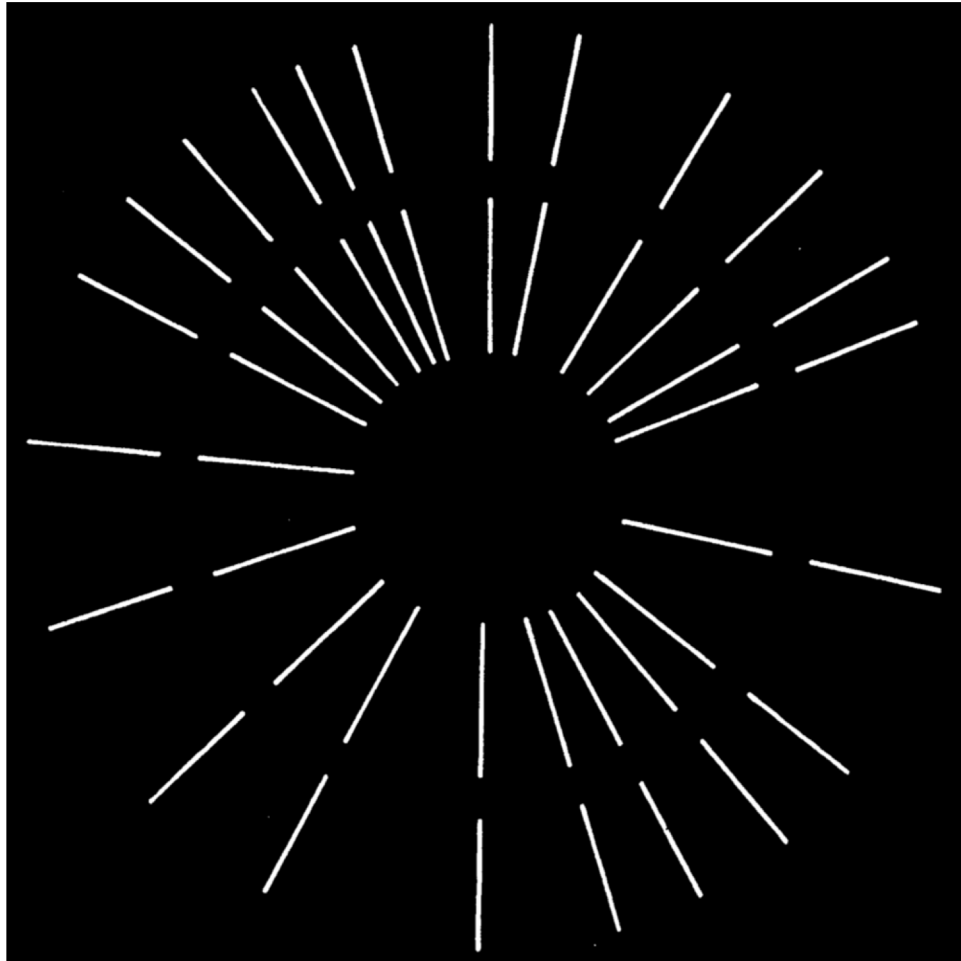


FIGURE 2. Illusory contours and regions of modified brightness seem to be postulates of nearer eclipsing objects, to 'explain' unlikely gaps. It seems that an essentially Bayesian strategy is responsible.

What do you see here?

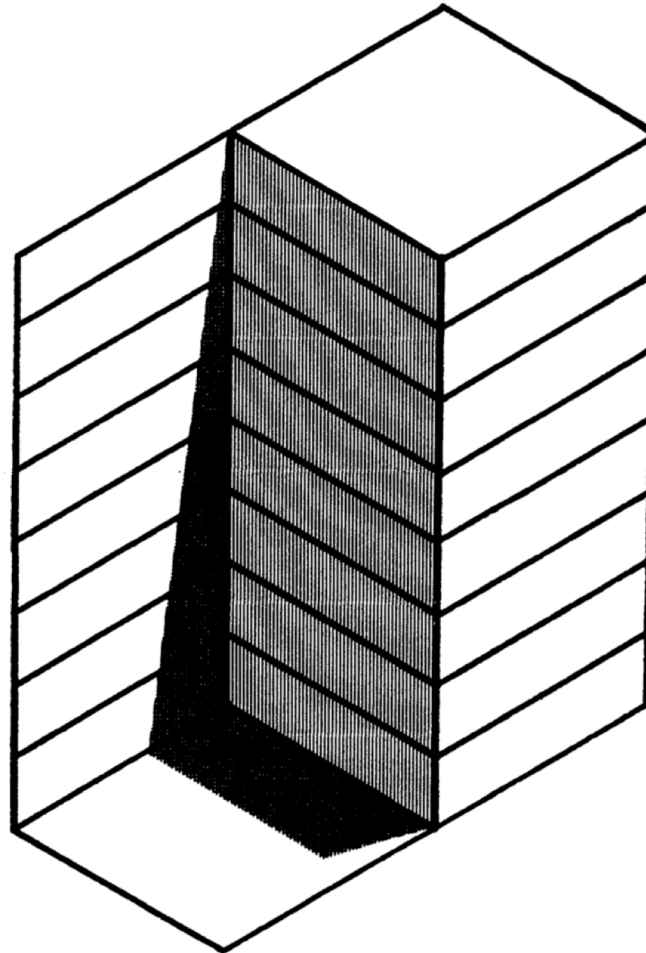


FIGURE 3. In this depth-ambiguous figure the grey rectangular region changes in brightness for most observers according to whether this area is a probable shadow. The systematic brightness change with depth-reversal is, clearly, centrally initiated and is a 'downwards' effect.

D. Mumford

Mathematics Department, Harvard University, 1 Oxford Street, Cambridge, MA 02138, USA

Biol. Cybern. 66, 241–251 (1992)

What do you see here?



Fig. 2. Top down processing reveals the dalmation dog (Rock 1984)

What do you see here?

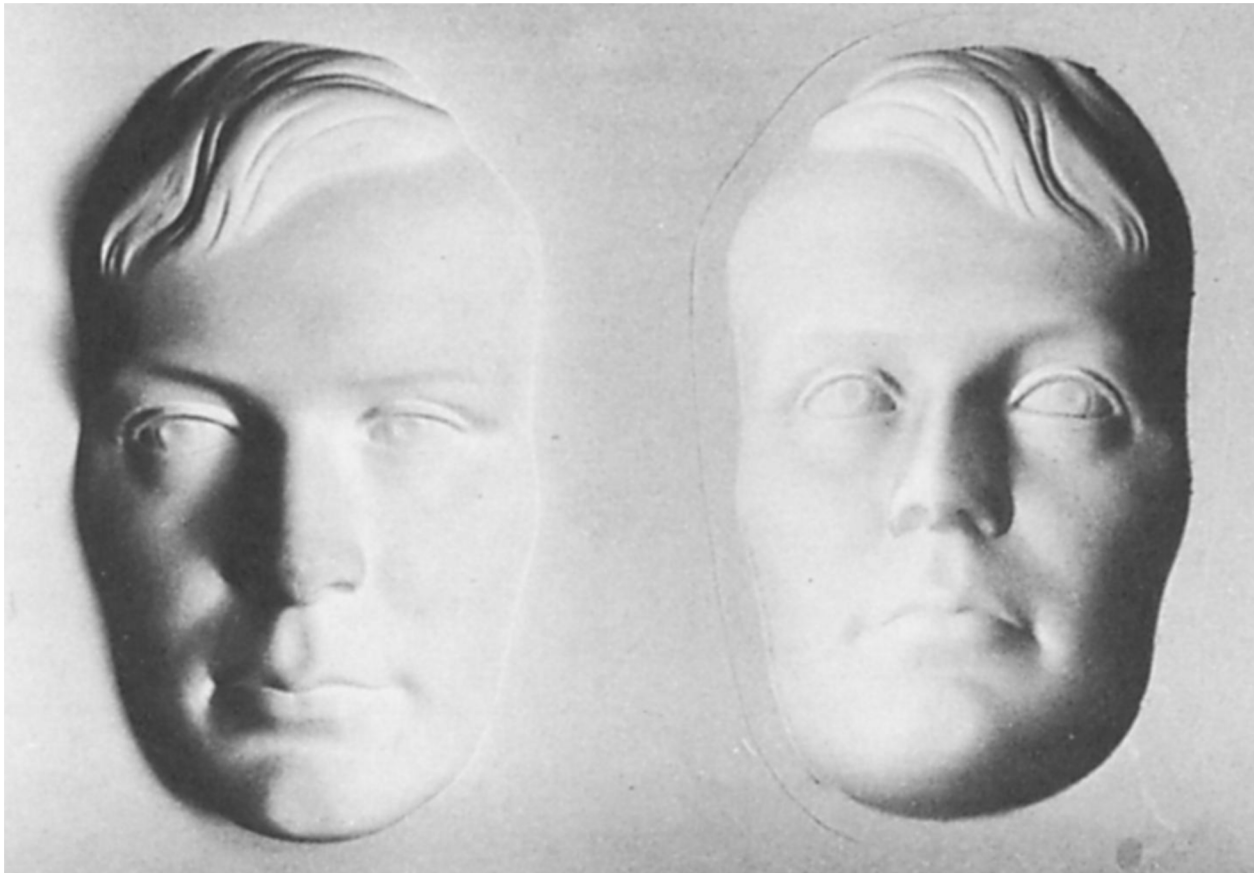


FIGURE 6. The 'face' on the right is in fact the hollow mould of the face on the left. Though hollow, the mould appears as a normal face. Texture and even stereoscopic counter-information are rejected to maintain this highly probable (but incorrect) hypothesis.

More on this:

<https://www.youtube.com/watch?v=ORoTCBrCKIQ>

<https://www.youtube.com/watch?v=6YIPtJlCbIA>

Reduction of Bayesian inference to mean updating

Reminder: updates in a simple Gaussian model

Think boat, lighthouse, etc., again, but now we're doing Bayesian inference.

Before we make the next observation, our belief about the true value of the parameter ϑ can be described by a Gaussian prior:

$$p(\vartheta) \sim \mathcal{N}(\mu_{\vartheta}, \pi_{\vartheta}^{-1})$$

The likelihood of an observation x is also Gaussian, with precision π_{ε} :

$$p(x|\vartheta) \sim \mathcal{N}(\vartheta, \pi_{\varepsilon}^{-1})$$

Bayes' rule now tells us that the posterior is Gaussian again:

$$p(\vartheta|x) = \frac{p(x|\vartheta)p(\vartheta)}{\int p(x|\vartheta')p(\vartheta')d\vartheta'} \sim \mathcal{N}(\mu_{\vartheta|x}, \pi_{\vartheta|x}^{-1})$$

Reminder: updates in a simple Gaussian model

Here's how the updates to the sufficient statistics μ and π describing our belief look like:

$$\pi_{\vartheta|x} = \pi_{\vartheta} + \pi_{\varepsilon}$$
$$\mu_{\vartheta|x} = \mu_{\vartheta} + \frac{\pi_{\varepsilon}}{\pi_{\vartheta|x}} (x - \mu_{\vartheta})$$

The diagram illustrates the update equation for the mean $\mu_{\vartheta|x}$. It shows the prior mean μ_{ϑ} being updated by a weighted prediction error. A red arrow points from the text 'prediction' to μ_{ϑ} . A blue arrow points from the text 'weight (learning rate)' to the fraction $\frac{\pi_{\varepsilon}}{\pi_{\vartheta|x}}$. A purple oval highlights the term $(x - \mu_{\vartheta})$, with a blue arrow pointing from the text 'prediction error' to it. To the right, a blue equation defines the weight: $\text{weight (learning rate)} = \frac{\text{how much we're learning here}}{\text{how much we already know}}$.

The mean is updated by an uncertainty-weighted (more specifically: precision-weighted) prediction error.

The size of the update is proportional to the likelihood precision and inversely proportional to the posterior precision.

This pattern is not specific to the univariate Gaussian case, but generalizes to Bayesian updates for all exponential families of likelihood distributions with conjugate priors (i.e., to all formal descriptions of inference you are ever likely to need).

Reminder: reduction to mean updating

Reminder (Gaussian update):

$$\mu_{\vartheta|x} = \mu_{\vartheta} + \frac{\pi_{\varepsilon}}{\pi_{\vartheta|x}}(x - \mu_{\vartheta}) = \mu_{\vartheta} + \frac{\pi_{\varepsilon}}{\pi_{\vartheta} + \pi_{\varepsilon}}(x - \mu_{\vartheta})$$

Reducing by π_{ε} the fraction of precisions that make the learning rate, we get

$$\mu_{\vartheta|x} = \mu_{\vartheta} + \frac{1}{\frac{\pi_{\vartheta}}{\pi_{\varepsilon}} + 1}(x - \mu_{\vartheta})$$

As we shall see, this is the equation for updating an arithmetic mean, but with the number of observations n replaced by $\frac{\pi_{\vartheta}}{\pi_{\varepsilon}}$.

This shows that Bayesian inference on the mean of a Gaussian distribution entails nothing more than updating the arithmetic mean of observations with $\frac{\pi_{\vartheta}}{\pi_{\varepsilon}} =: \nu$ as a proxy for the number of prior observations, i.e. for the **weight of the prior relative to the observation**.

Reminder: generalization to all exponential families of distributions

Many of the most widely used probability distributions are families of exponential distributions.

For example, the Gaussian distribution is an exponential family of distributions (and so are the beta, gamma, binomial, Bernoulli, multinomial, categorical, Dirichlet, Wishart, Gaussian-gamma, log-Gaussian, multivariate Gaussian, Poisson, and exponential distributions, among others). This means it can be written the following way:

$$p(\mathbf{x}|\boldsymbol{\vartheta}) = h(\mathbf{x}) \exp(\boldsymbol{\eta}(\boldsymbol{\vartheta}) \cdot \mathbf{T}(\mathbf{x}) - A(\boldsymbol{\vartheta})) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left(-\frac{(x - \mu)^2}{2\sigma}\right)$$

with

$$\mathbf{x} = x, \quad \boldsymbol{\vartheta} = (\mu, \sigma)^T, \quad h(\mathbf{x}) = \frac{1}{\sqrt{2\pi}}, \quad \boldsymbol{\eta}(\boldsymbol{\vartheta}) = \left(\frac{\mu}{\sigma}, -\frac{1}{2\sigma}\right)^T, \quad \mathbf{T}(\mathbf{x}) = (x, x^2)^T, \quad A(\boldsymbol{\vartheta}) = \frac{\mu^2}{\sigma} + \frac{\ln \sigma}{2}$$

This allows us to look at Bayesian belief updating in a very general way for all exponential families of distributions.

Reminder: generalization to all exponential families of distributions (Mathys, 2016)

Our likelihood is an exponential family in its general form:

$$p(\mathbf{x}|\boldsymbol{\vartheta}) = h(\mathbf{x}) \exp(\boldsymbol{\eta}(\boldsymbol{\vartheta}) \cdot \mathbf{T}(\mathbf{x}) - A(\boldsymbol{\vartheta}))$$

The vector $\mathbf{T}(\mathbf{x})$ (a function of the observation $\mathbf{x}$) is called the sufficient statistic.

For the prior, we may assume that we have made ν observations with sufficient statistic $\boldsymbol{\xi}$:

$$p(\boldsymbol{\vartheta}|\boldsymbol{\xi}, \nu) = z(\boldsymbol{\xi}, \nu) \exp(\nu(\boldsymbol{\eta}(\boldsymbol{\vartheta}) \cdot \boldsymbol{\xi} - A(\boldsymbol{\vartheta}))) \quad (\text{where } z(\boldsymbol{\xi}, \nu) \text{ is a normalization constant})$$

It then turns out that the posterior has the same form, but with an updated $\boldsymbol{\xi}$ and ν replaced with $\nu + 1$:

$$p(\boldsymbol{\vartheta}|\mathbf{x}, \boldsymbol{\xi}, \nu) = z(\boldsymbol{\xi}', \nu + 1) \exp((\nu + 1)(\boldsymbol{\eta}(\boldsymbol{\vartheta}) \cdot \boldsymbol{\xi}' - A(\boldsymbol{\vartheta})))$$

$$\boldsymbol{\xi}' = \boldsymbol{\xi} + \frac{1}{\nu + 1} (\mathbf{T}(\mathbf{x}) - \boldsymbol{\xi})$$

Some examples

Univariate Gaussian model with unknown mean but **known precision** (our example from the beginning):

$$\mathbf{T}(x) = x$$

This means updating beliefs about the mean simply requires tracking the mean of observations

Univariate Gaussian model with unknown mean and unknown precision:

$$\mathbf{T}(x) = (x, x^2)^T$$

Updating beliefs about both mean and precision of a Gaussian requires tracking the means of observations and squared observations; this amounts to the first and second moments by which a Gaussian distribution is fully characterized.

In the **multivariate Gaussian** case we have $\mathbf{T}(x) = (x, xx^T)^T$

Some examples

Bernoulli model (one out of two possible outcomes, coded as 0 and 1; e.g., coin flipping):

$$T(x) = x$$

The prior here turns out to be a **beta distribution** corresponding to ν pseudo-observations with mean ξ . All we need to do to get the posterior (i.e., to update our belief) is to update the mean as new observations come in.

Categorical model (one out of several possible outcomes, with the observed outcome coded as 1, the rest as 0)

$$T(x) = x$$

The prior and posterior here are **Dirichlet distributions**, and again, all we need to do to update beliefs that have a Dirichlet form is to track the means of observed successes (1) and failures (0).

Some examples

Beta model (an outcome bounded between 0 and 1):

$$\mathbf{T}(x) = (\ln x, \ln(1 - x))^T$$

Gamma model (an outcome bounded below at 0):

$$\mathbf{T}(x) = (\ln x, x)^T$$

... so in sum:

... we have dealt (among others) with beliefs about states that are

- binary (Bernoulli)
- categorical
- bounded on both sides (beta)
- bounded on one side (gamma)
- and unbounded (Gaussian)

This includes most kinds of states we can have beliefs about. Notably,

- **All Bayesian (i.e., probabilistic, rational) updates of such beliefs take the form of precision-weighted prediction errors.**
- **These prediction errors and their precision weights are easy to compute.**
- **The prediction errors are simple functions of inputs.**

Limitations

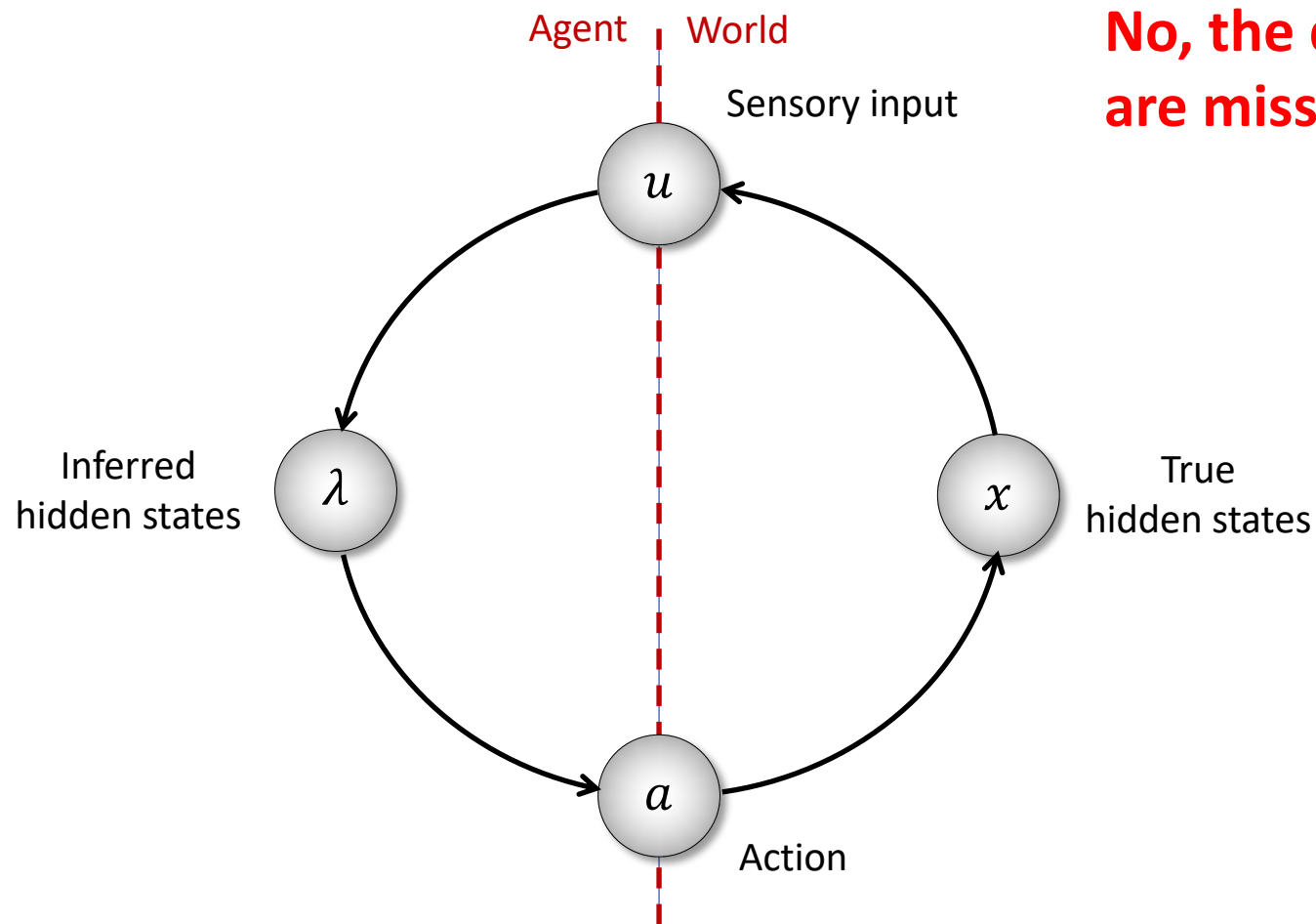
- Examples of distributions that are not exponential families: Student's t , Cauchy
- These distributions are popular because of their «fat tails». However, fat tails can also be achieved with appropriate hierarchies of Gaussians (cf. the hierarchical Gaussian filter, HGF)
- A further kind of distributions that are not exponential families are found in mixture models.
- Such models are popular because of they provide multimodal distributions. But again, appropriate hierarchies of distributions may save the day.

How to reveal the precision-weighting of prediction errors when simple exponential-family likelihoods will not do

- Formulate the problem hierarchically (i.e., imitate evolution: when it built a brain that supports a mind which is a model of its environment, it came up with a (largely) hierarchical solution)
- Separate levels using a mean-field approximation
- Derive update equations
- Example: HGF

Hierarchical Gaussian Filtering

But: does inference as we've described it adequately describe the situation of actual biological agents?



No, the dynamics are missing!

What about dynamics?

Up to now, we've only looked at inference on static quantities, but biological agents live in a continually changing world.

In our example, the boat's position changes and with it the angle to the lighthouse.

How can we take into account that old information becomes obsolete? If we don't, our learning rate becomes smaller and smaller because our equations were derived under the assumption that we're accumulating information about a stable quantity.

What's the simplest way to keep the learning rate from going too low?

Keep it constant!

So, taking the update equation for the mean of our observations as our point of departure...

$$\bar{x}_n = \bar{x}_{n-1} + \frac{1}{n}(x_n - \bar{x}_{n-1}),$$

... we simply replace $\frac{1}{n}$ with a constant α :

$$\mu_n = \mu_{n-1} + \alpha(x_n - \mu_{n-1}).$$

This is called *Rescorla-Wagner learning* [although it wasn't this line of reasoning that led Rescorla & Wagner (1972) to their formulation].

Does a constant learning rate solve our problems?

Partly: it implies a certain rate of forgetting because it amounts to taking only the $n = \frac{1}{\alpha}$ last data points into account. But...

... if the learning rate is supposed to reflect uncertainty in Bayesian inference, then how do we

(a) know that α reflects the right level of uncertainty at any one time, and

(b) account for changes in uncertainty if α is constant?

What we really need is an adaptive learning that accurately reflects uncertainty.

Needed: an adaptive learning rate that accurately reflects uncertainty

This requires us to think a bit more about what kinds of uncertainty we are dealing with.

A possible taxonomy of uncertainty is (cf. Yu & Dayan, 2003; Payzan-LeNestour & Bossaerts, 2011):

(a) **outcome uncertainty** that remains unaccounted for by the model, called *risk* by economists (π_{ε} in our Bayesian example); this uncertainty remains even when we know all parameters exactly,

(b) **informational** or *expected* uncertainty about the value of model parameters ($\pi_{\vartheta|x}$ in the Bayesian example),

(c) **environmental** or *unexpected* uncertainty owing to changes in model parameters (not accounted for in our Bayesian example, hence unexpected).

An adaptive learning rate that accurately reflects uncertainty

Various efforts have been made to come up with an adaptive learning rate:

- Kalman (1960)
- Sutton (1992)
- Nassar et al. (2010)
- Payzan-LeNestour & Bossaerts (2011)
- Mathys et al. (2011)
- Wilson et al. (2013)

The Kalman filter is optimal for linear dynamical systems, but realistic data usually require non-linear models.

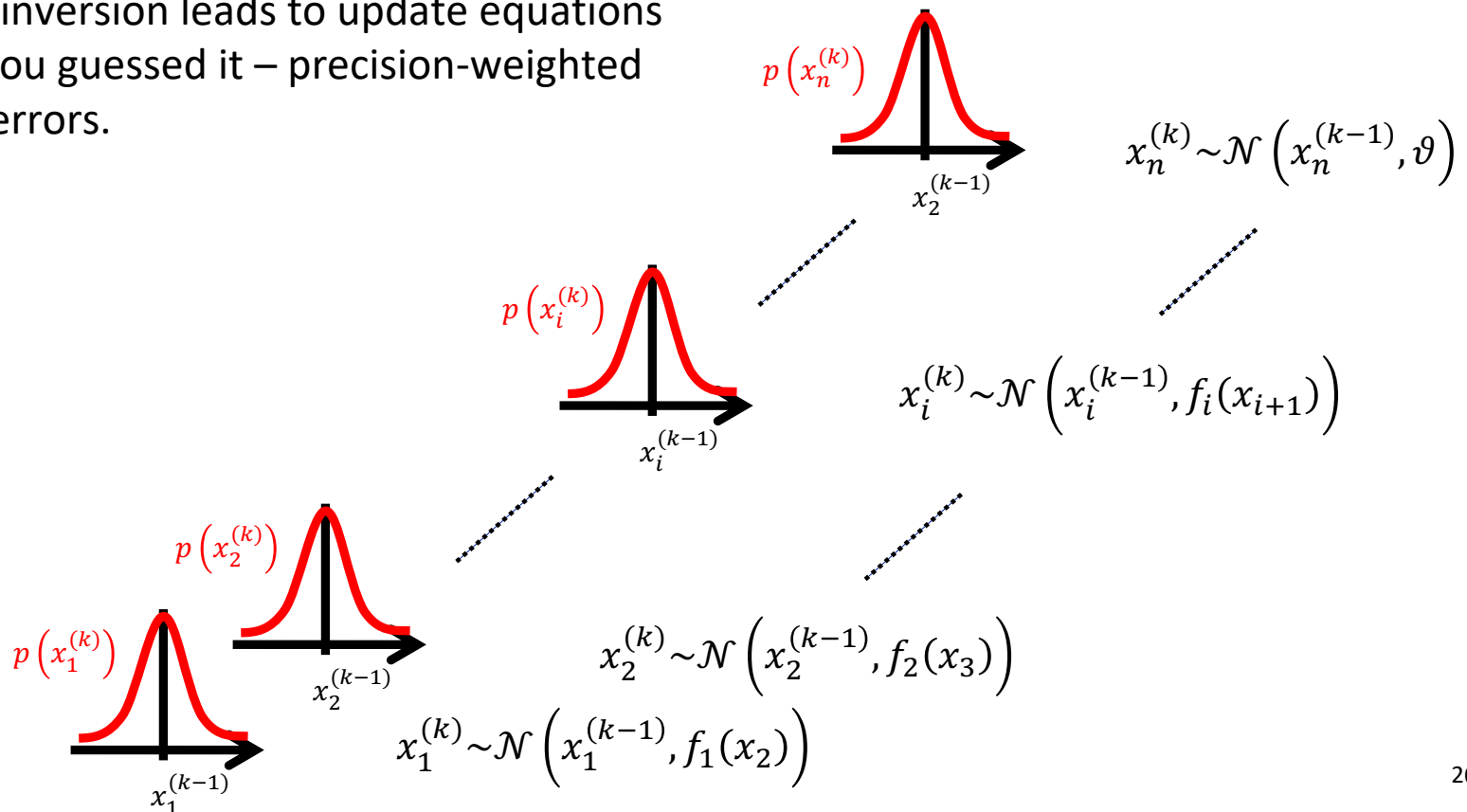
Mathys et al. use a generic non-linear hierarchical Bayesian model that allows us to derive update equations that are optimal in the sense that they minimize surprise.

The hierarchical Gaussian filter

(HGF, Mathys et al., 2011; 2014)

The HGF provides a generic solution to the problem of adapting one's learning rate in a volatile environment.

Variational inversion leads to update equations that are – you guessed it – precision-weighted prediction errors.



Coupling between levels

Since f has to be everywhere positive, we cannot approximate it by expanding in powers. Instead, we expand its logarithm.

$$f(x) > 0 \forall x \Rightarrow \exists g: f(x) = \exp(g(x)) \forall x$$

$$g(x) = g(a) + g'(a) \cdot (x - a) + O(2) = \log f(x) =$$

$$= \log f(a) + \frac{f'(a)}{f(a)} \cdot (x - a) + O(2) =$$

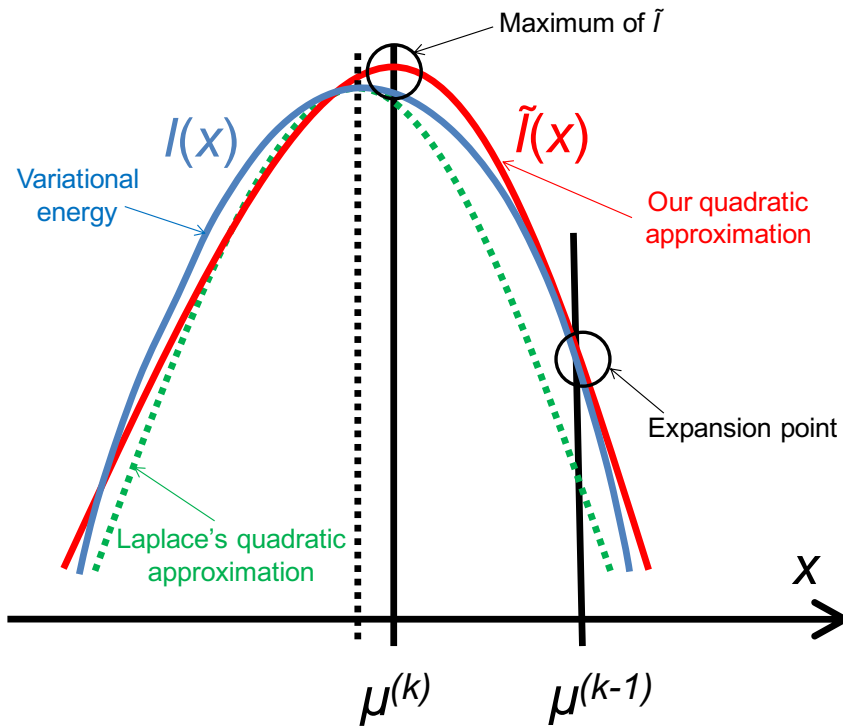
$$= \underbrace{\frac{f'(a)}{f(a)}}_{\stackrel{\text{def}}{=} \kappa} \cdot x + \underbrace{\log f(a) - a \cdot \frac{f'(a)}{f(a)}}_{\stackrel{\text{def}}{=} \omega} + O(2) =$$

$$= \kappa x + \omega + O(2)$$

$$\Rightarrow f(x) \approx \exp(\kappa x + \omega)$$

Variational inversion

- A quadratic approximation is found by expanding to second order about the expectation $\mu^{(k-1)}$.
- The update in the sufficient statistics of the approximate posterior is then performed by analytically finding the maximum of the quadratic approximation.



$$\sigma_i^{(k)} = -\frac{1}{\partial^2 I(\mu_i^{(k-1)})}$$

$$\mu_i^{(k)} = \mu_i^{(k-1)} - \frac{\partial I(\mu_i^{(k-1)})}{\partial^2 I(\mu_i^{(k-1)})} = \mu_i^{(k-1)} + \sigma_i^{(k)} \partial I(\mu_i^{(k-1)})$$

Mathys et al. (2011). *Front. Hum. Neurosci.*, 5:39.

Variational inversion and update equations

- Inversion proceeds by introducing a mean field approximation and fitting quadratic approximations to the resulting variational energies (Mathys et al., 2011).
- This leads to **simple one-step update equations** for the sufficient statistics (mean and precision) of the approximate Gaussian posteriors of the states x_i .
- The updates of the means have the same structure as value updates in Rescorla-Wagner learning:

$$\Delta\mu_i \propto \frac{\hat{\pi}_{i-1}}{\pi_i} \delta_{i-1}$$

Predictions determine learning rate

Prediction error

- Furthermore, the updates are **precision-weighted prediction errors**.

Precision-weighting of volatility updates

Comparison to the simple non-hierarchical Bayesian update:

HGF:

$$\mu_i^{(k)} = \mu_i^{(k-1)} + \frac{1}{2} \kappa_{i-1} v_{i-1}^{(k)} \cdot \frac{\hat{\pi}_{i-1}^{(k)}}{\pi_i^{(k)}} \cdot \delta_{i-1}^{(k)}$$

Precision-weighted prediction error

Simple Gaussian:

$$\mu_{\vartheta|x} = \mu_{\vartheta} + \frac{\pi_{\varepsilon}}{\pi_{\vartheta|x}} (x - \mu_{\vartheta})$$

Updates at the outcome level

At the outcome level (i.e., at the very bottom of the hierarchy), we have

$$u^{(k)} \sim \mathcal{N} \left(x_1^{(k)}, \hat{\pi}_u^{-1} \right)$$

This gives us the following update for our belief on x_1 (our quantity of interest):

$$\pi_1^{(k)} = \hat{\pi}_1^{(k)} + \hat{\pi}_u$$
$$\mu_1^{(k)} = \mu_1^{(k-1)} + \frac{\hat{\pi}_u}{\pi_1^{(k)}} \left(u^{(k)} - \mu_1^{(k-1)} \right)$$

The familiar structure again – but now with a learning rate that is responsive to all kinds of uncertainty, including environmental (unexpected) uncertainty.

The learning rate in the HGF

Unpacking the learning rate, we see:

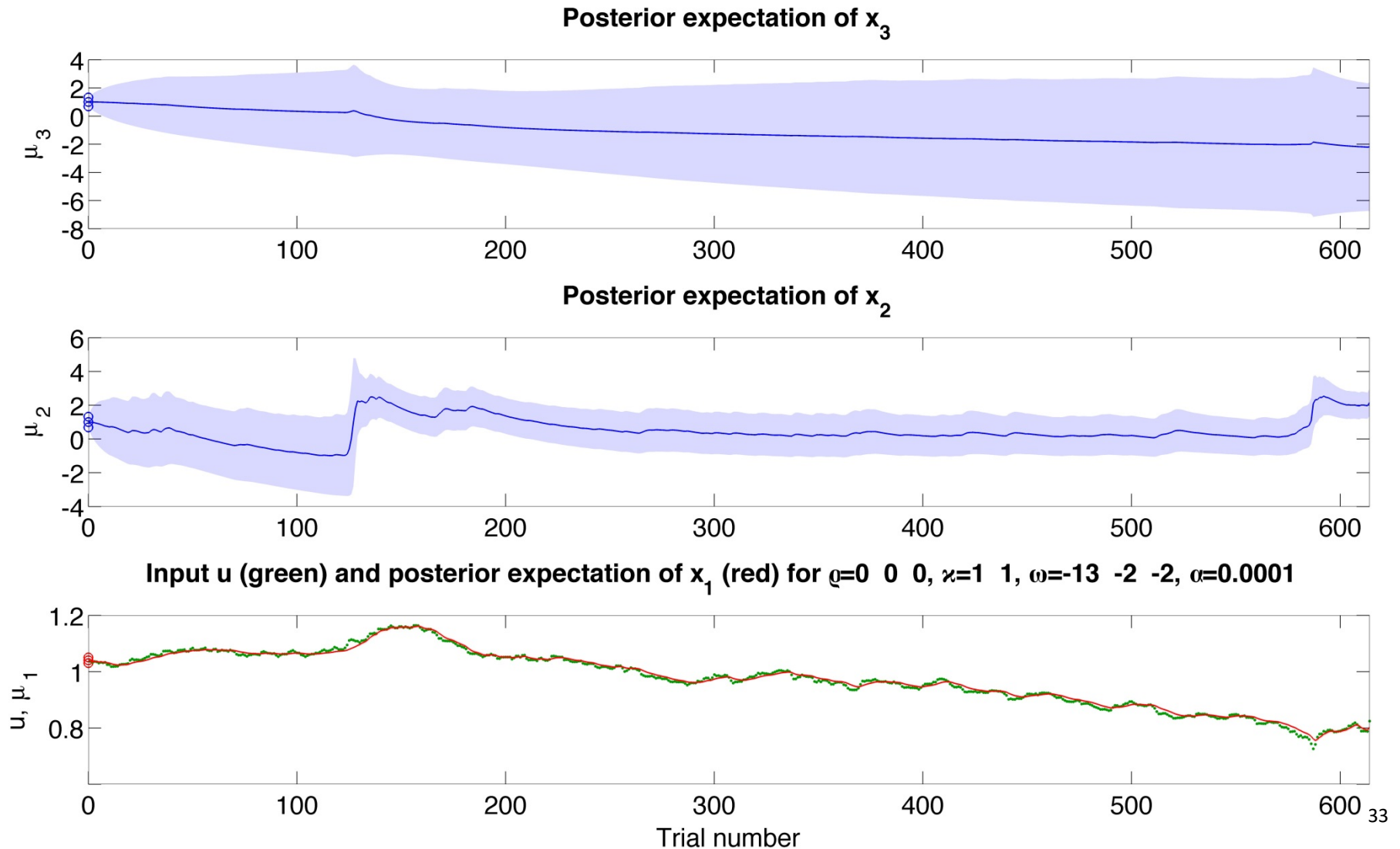
$$\frac{\hat{\pi}_u}{\pi_1^{(k)}} = \frac{\hat{\pi}_u}{\hat{\pi}_1^{(k)} + \hat{\pi}_u} = \frac{\hat{\pi}_u}{\frac{1}{\sigma_1^{(k-1)} + \exp(\kappa_1 \mu_2^{(k-1)} + \omega_1)} + \hat{\pi}_u}$$

outcome uncertainty

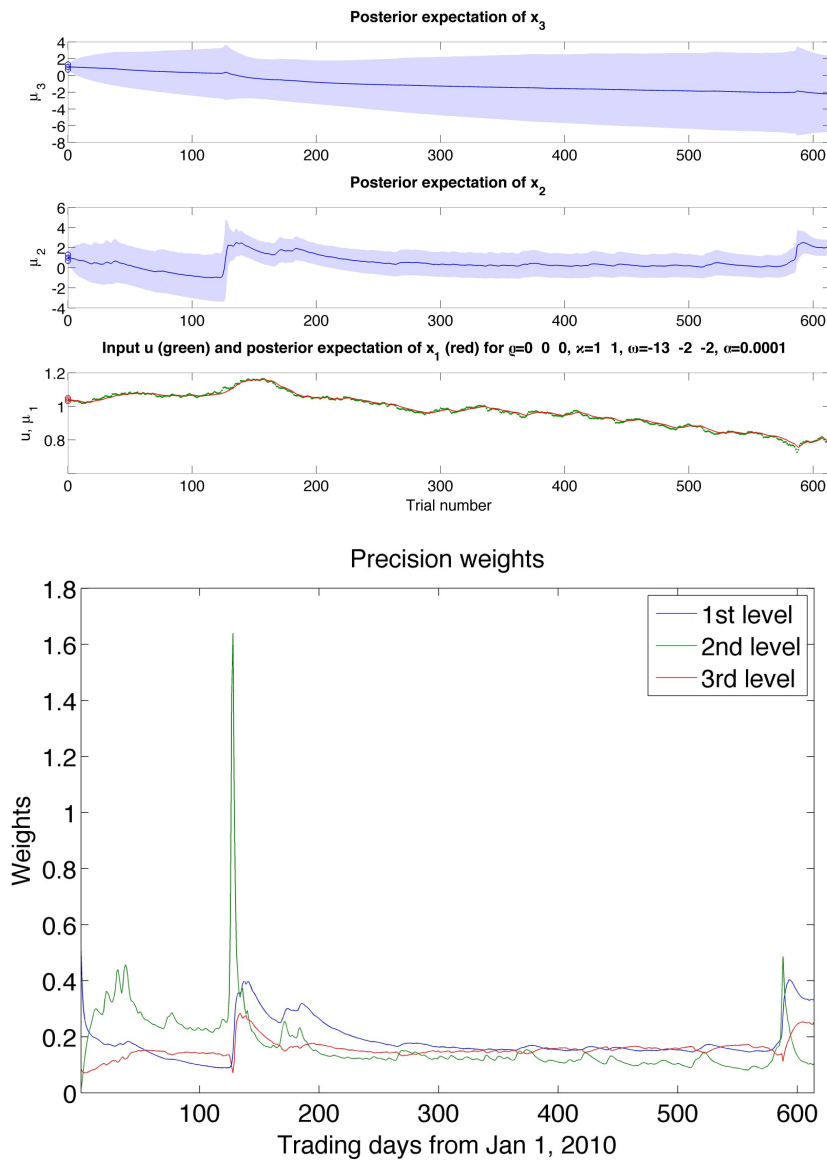
informational uncertainty

environmental uncertainty

3-level HGF for continuous observations

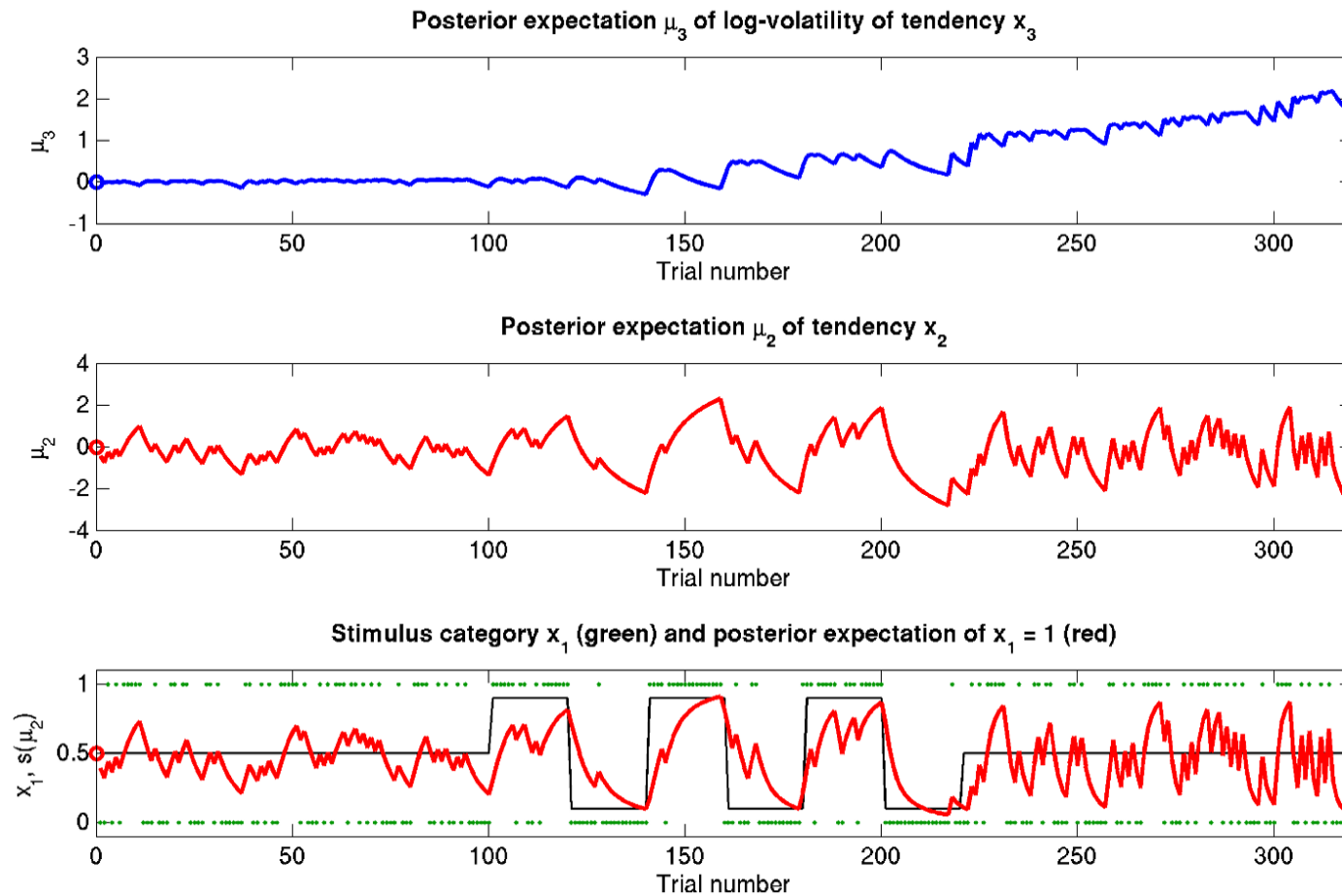


Example of precision weight trajectory

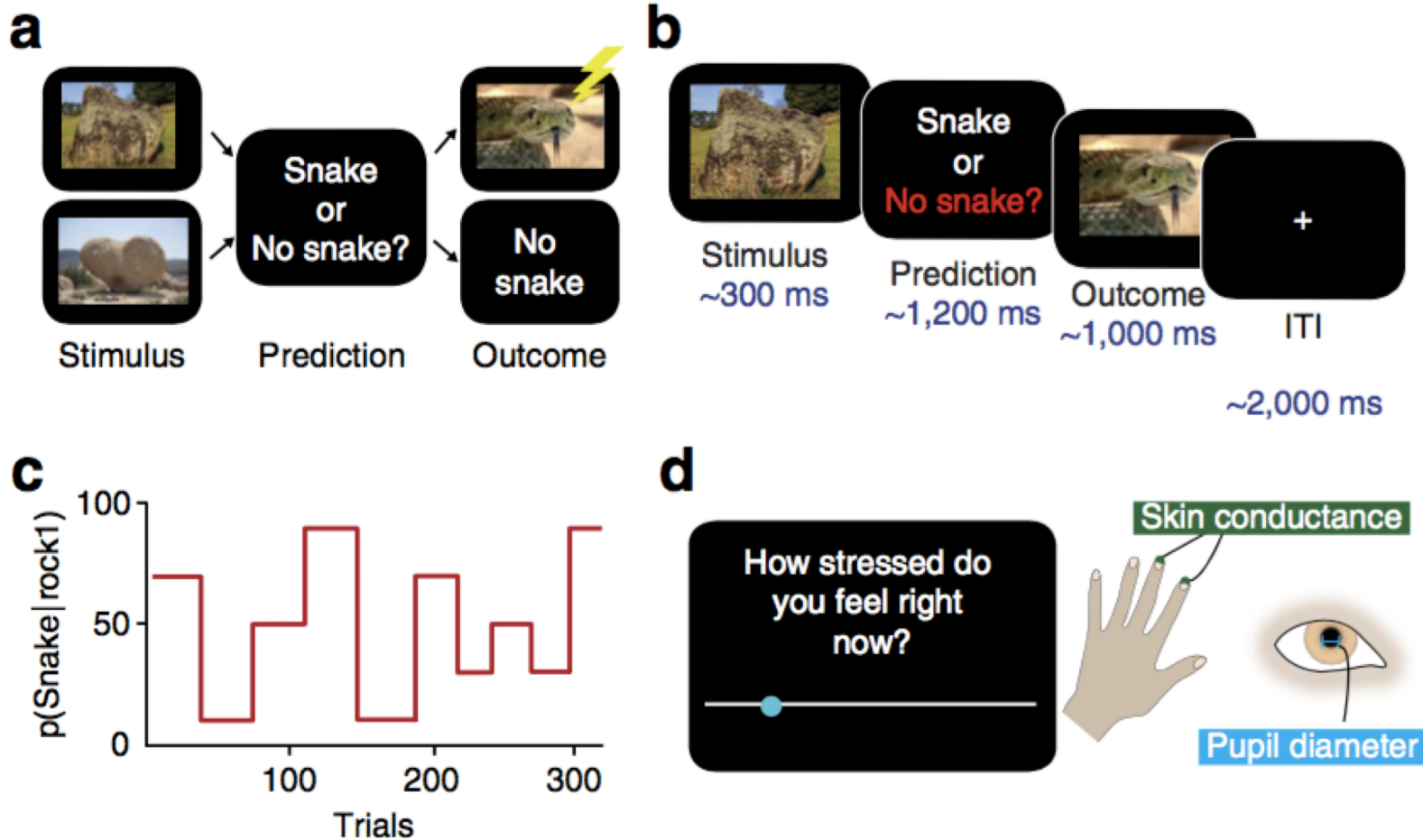


Context effects on the learning rate

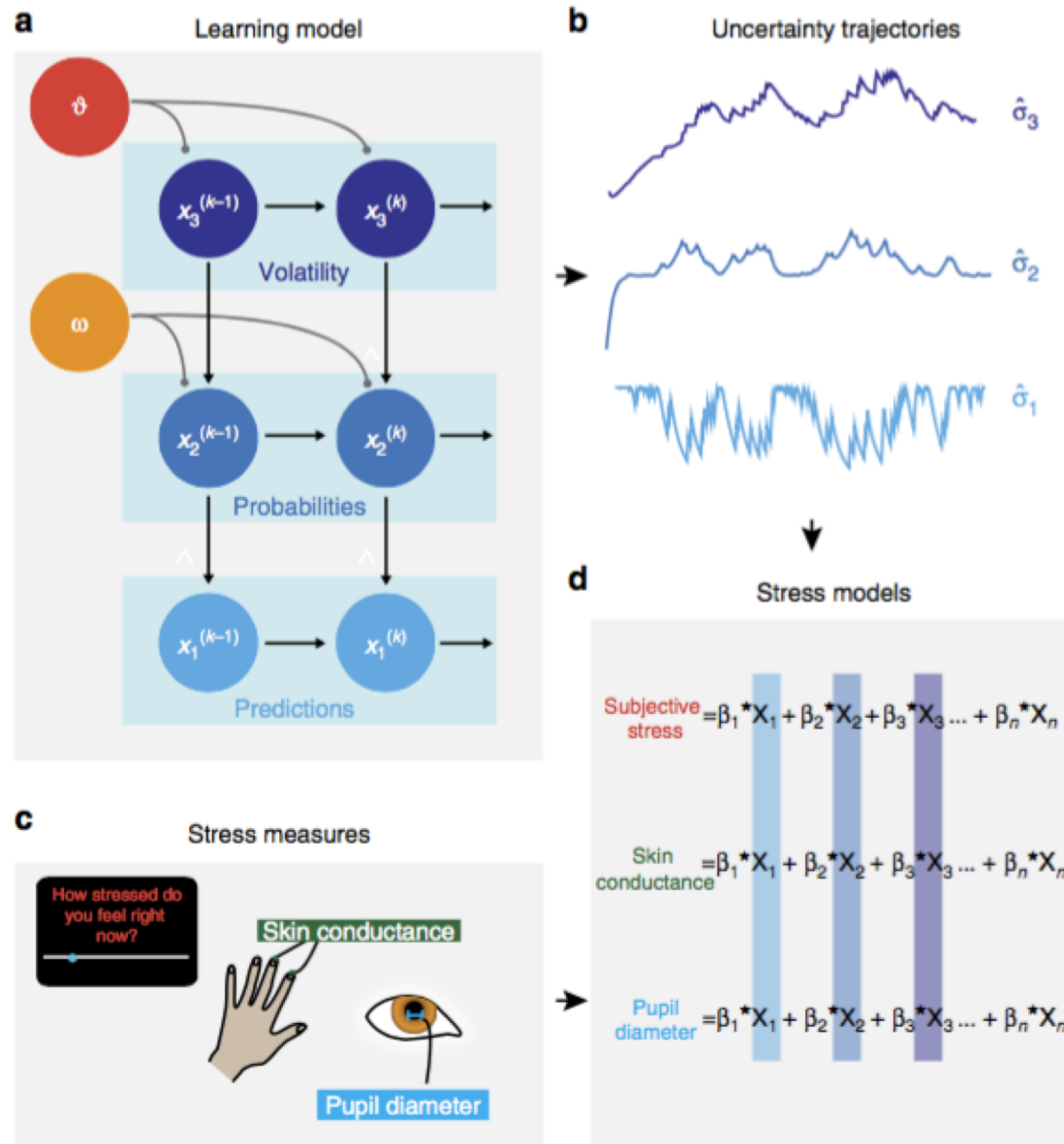
Simulation: $\mathcal{G} = 0.5$, $\omega = -2.2$, $\kappa = 1.4$



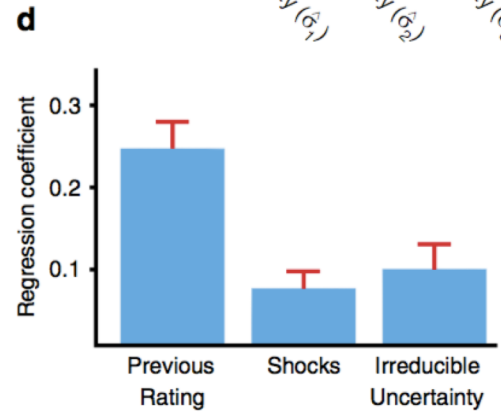
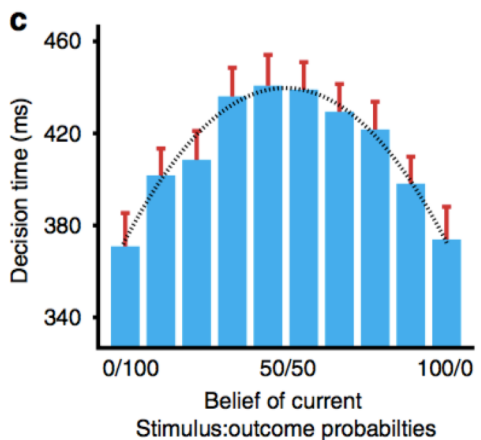
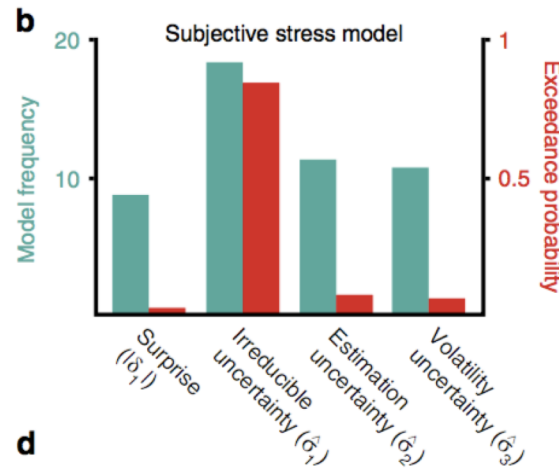
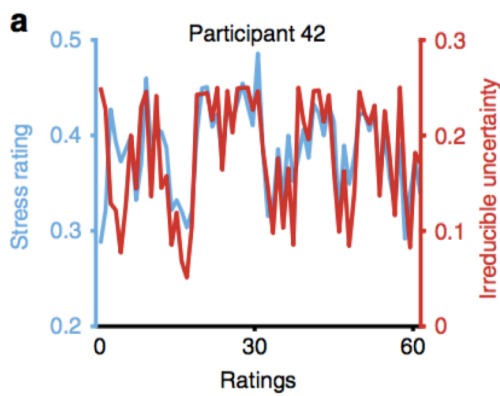
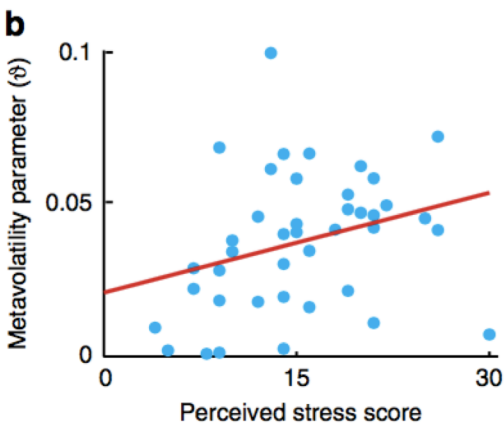
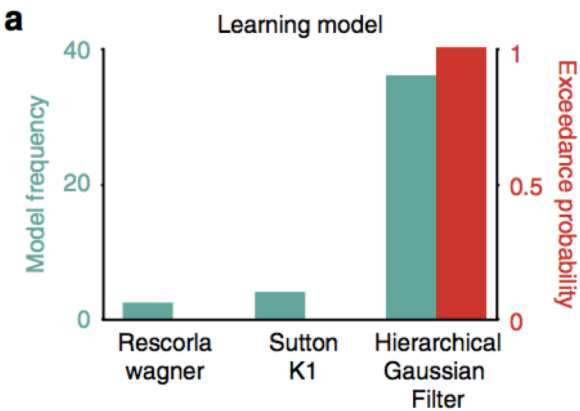
HGF: empirical evidence (De Berker et al, Nature Comms, 2016)



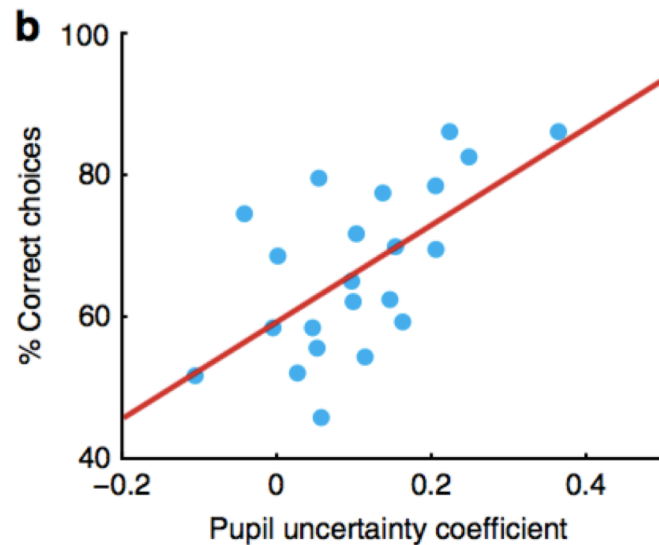
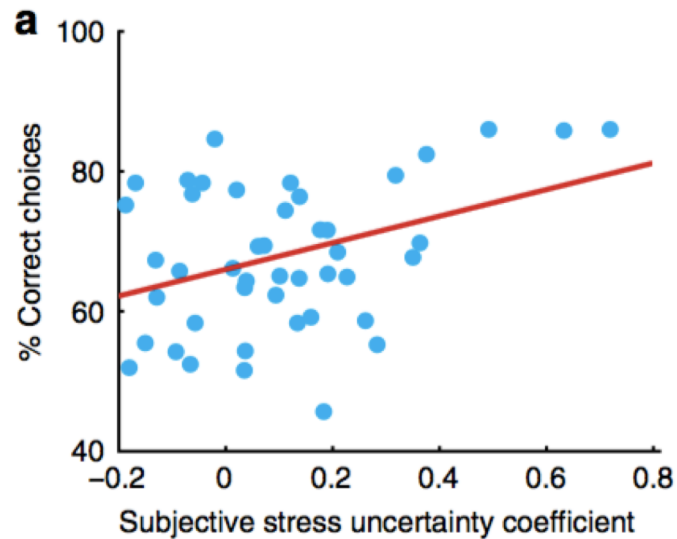
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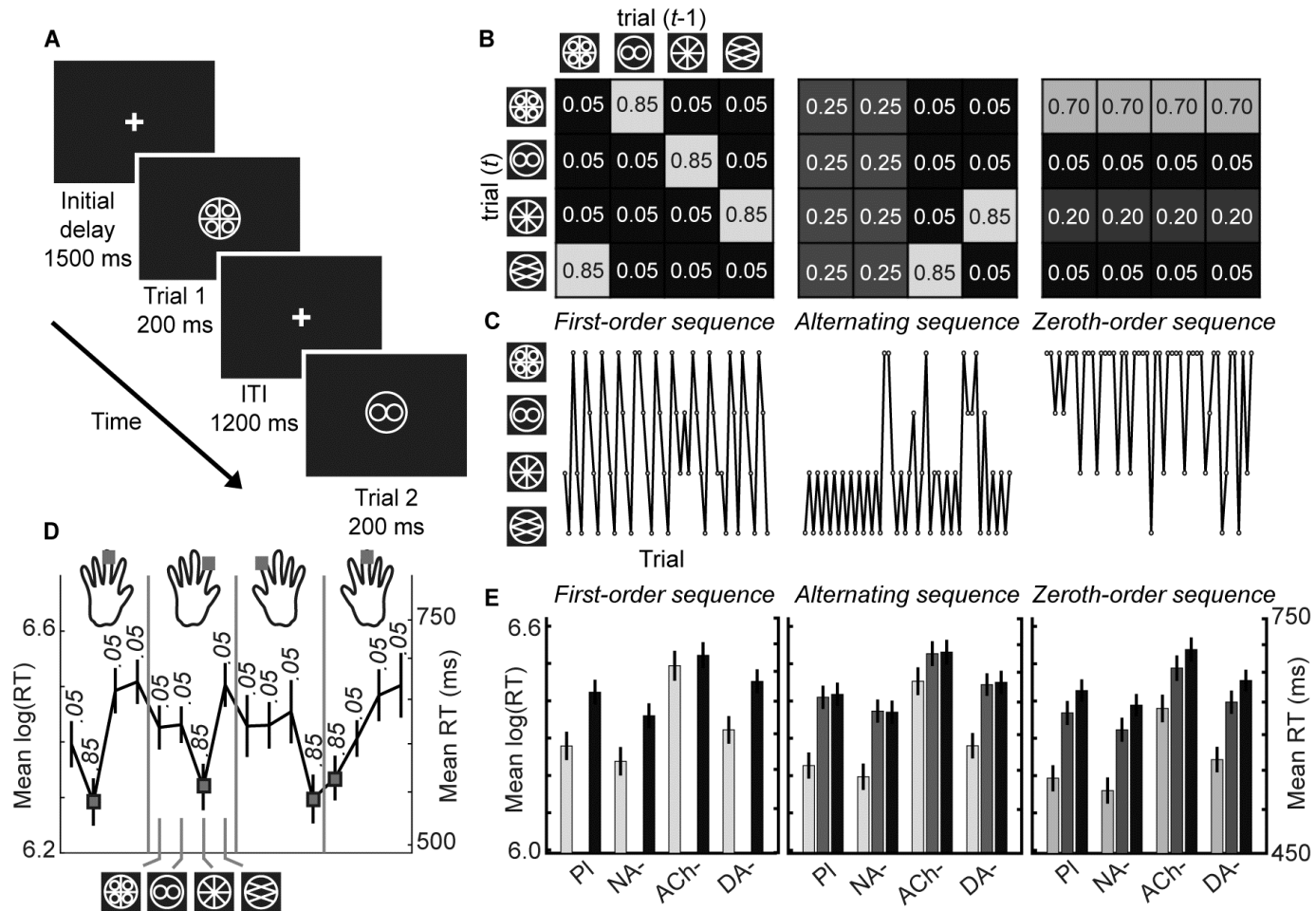
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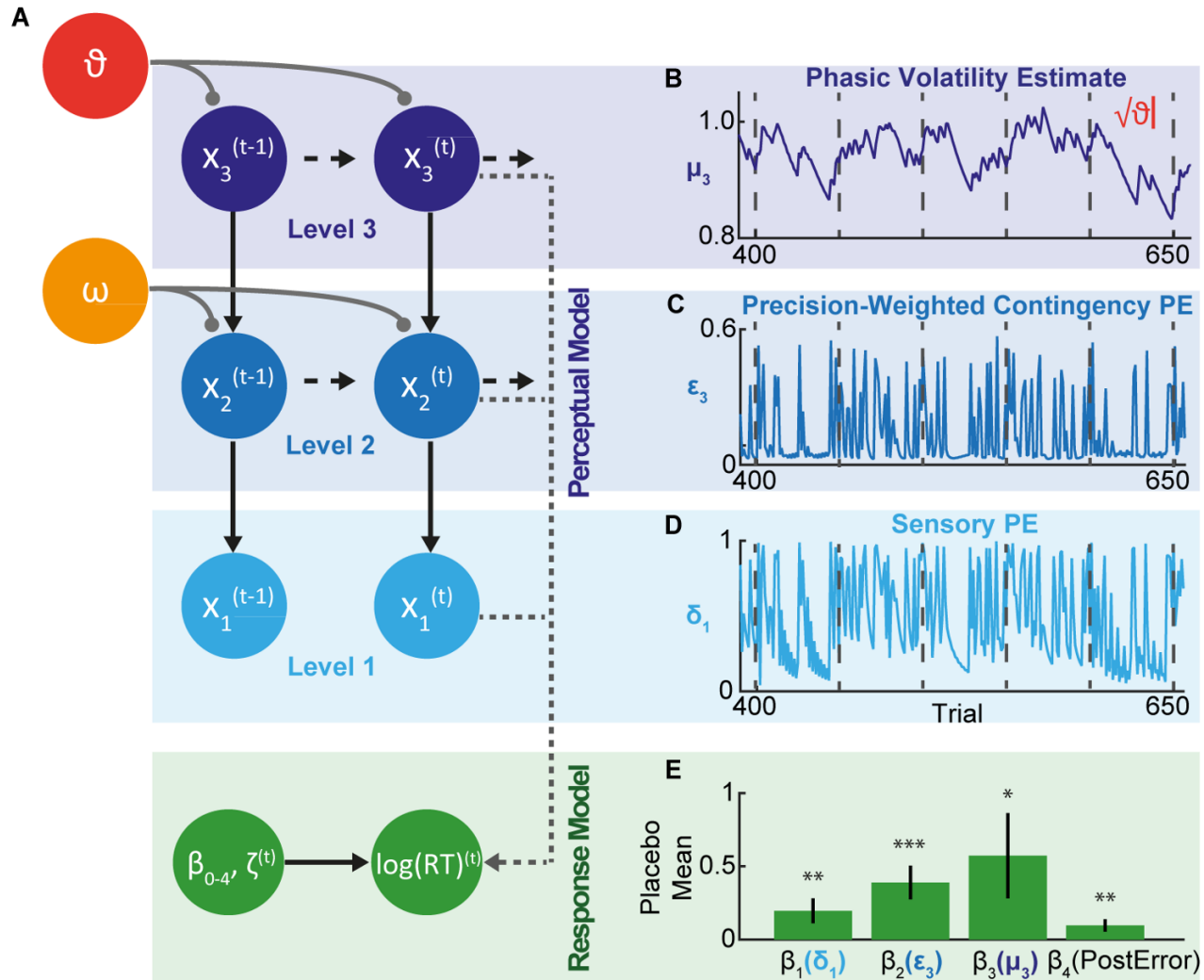
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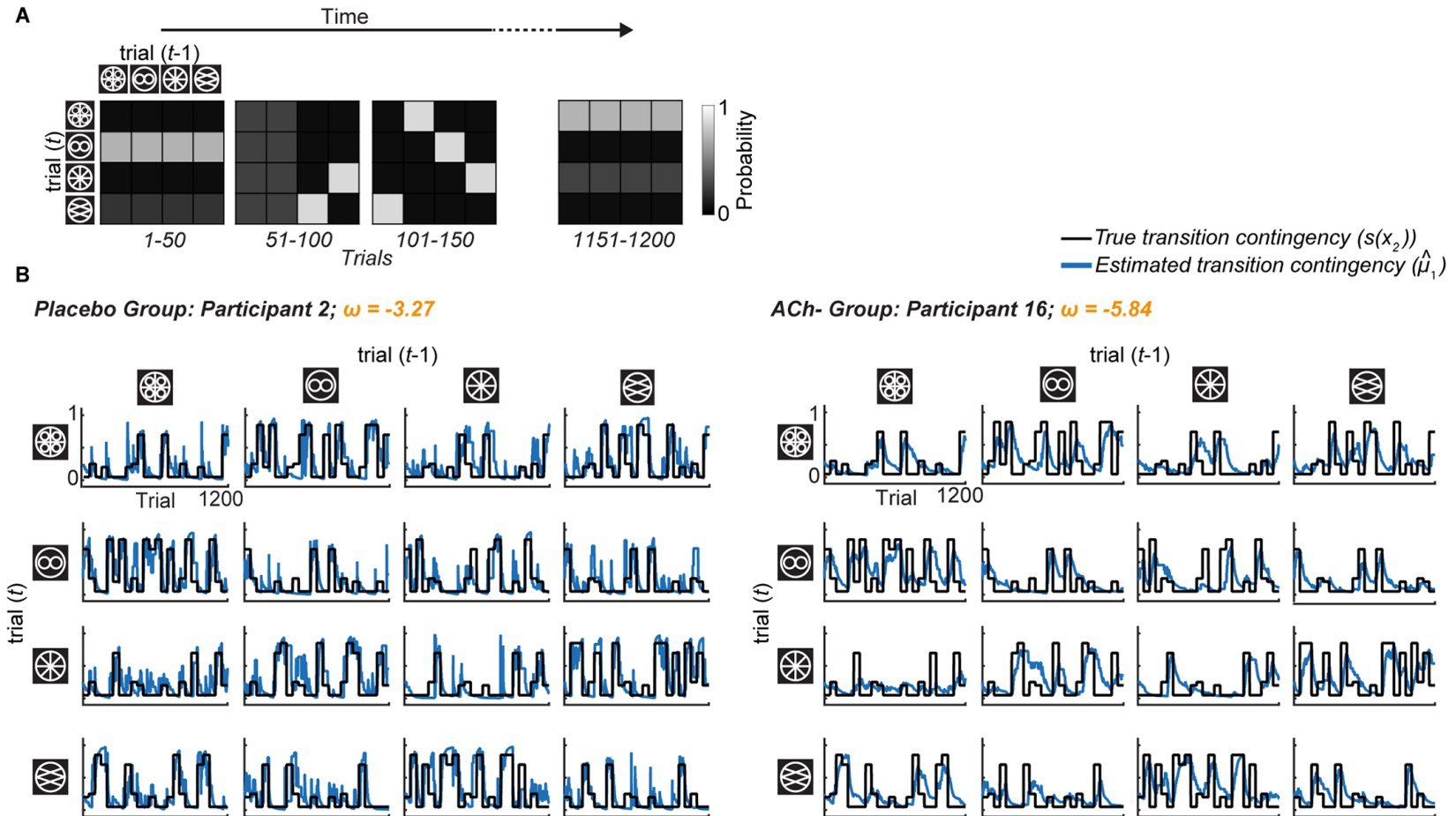
HGF: empirical evidence (Marshall & Mathys et al., PLOS Biol., 2016)



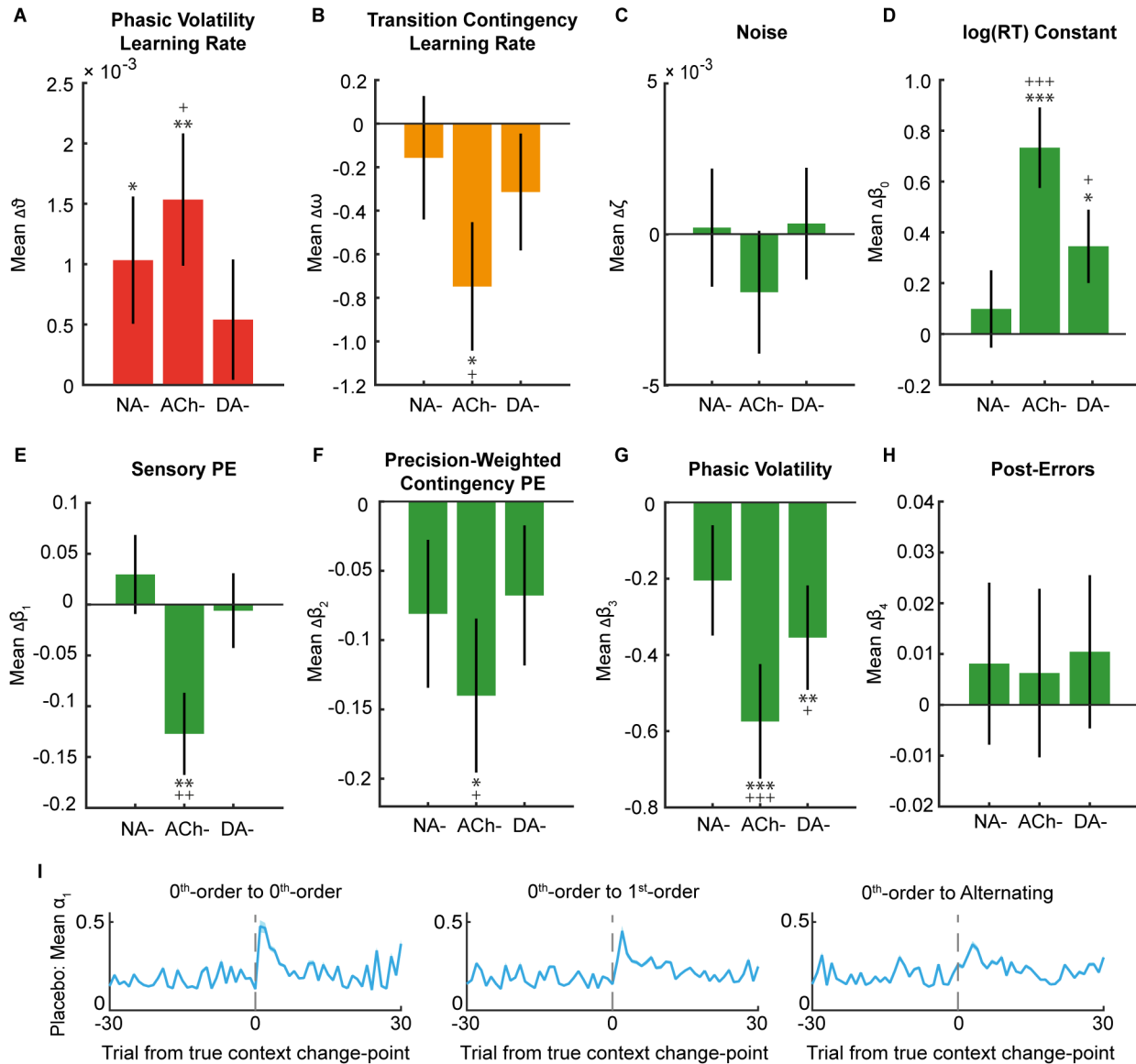
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HGF: empirical evidence (Diaconescu et al., arXiv preprint)

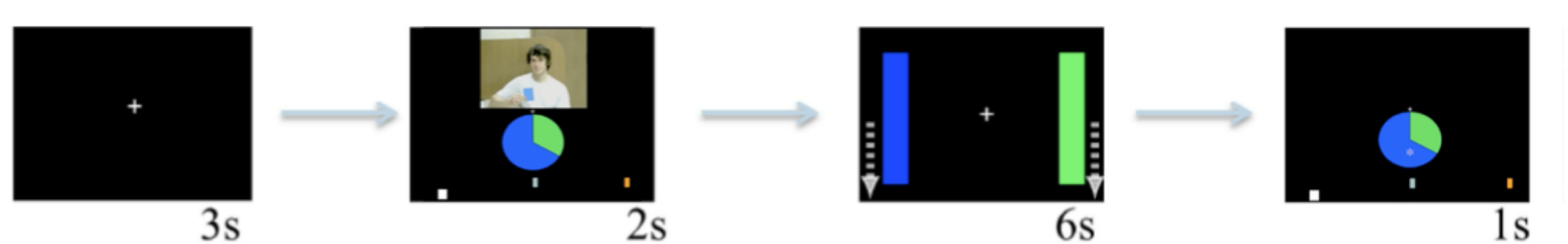
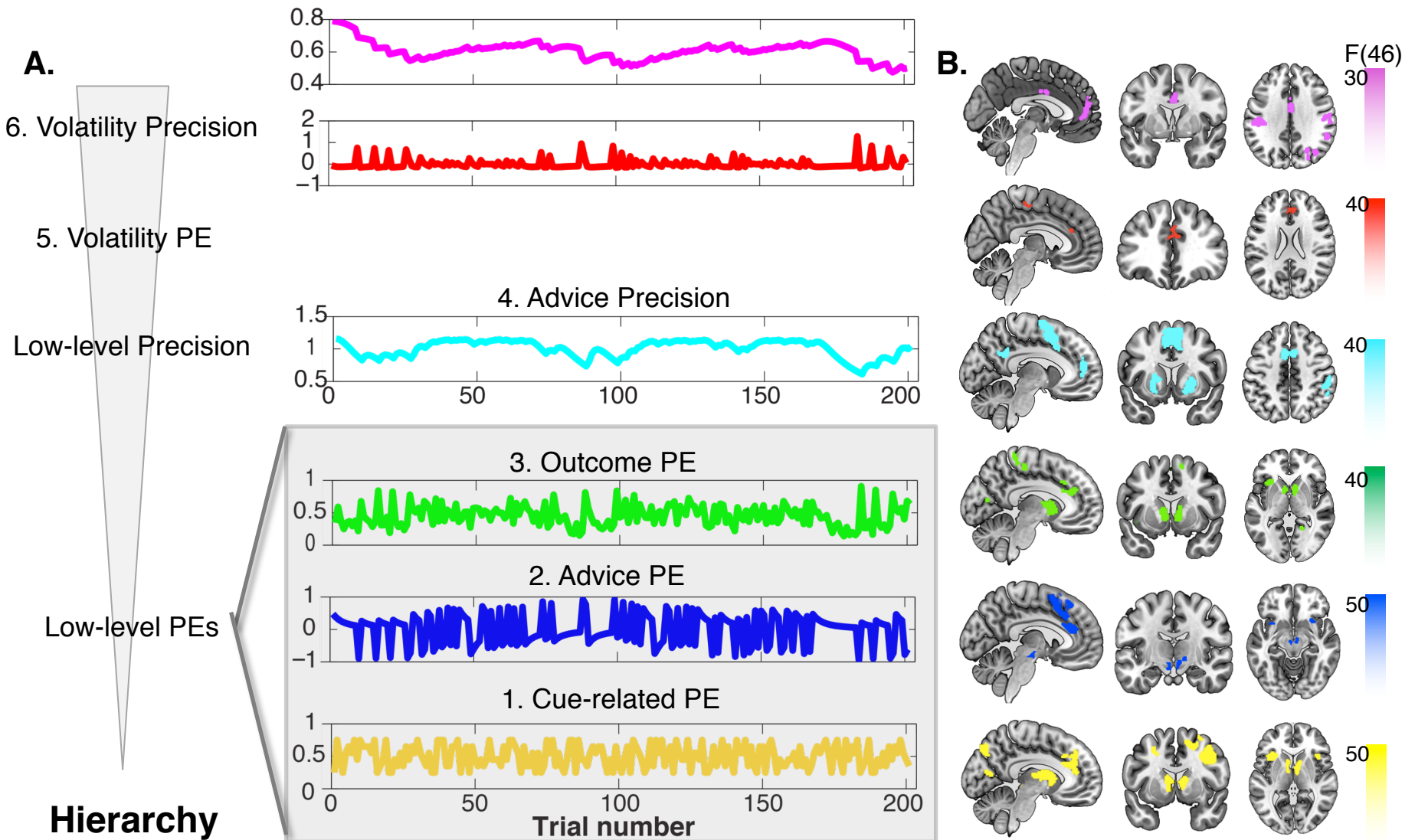
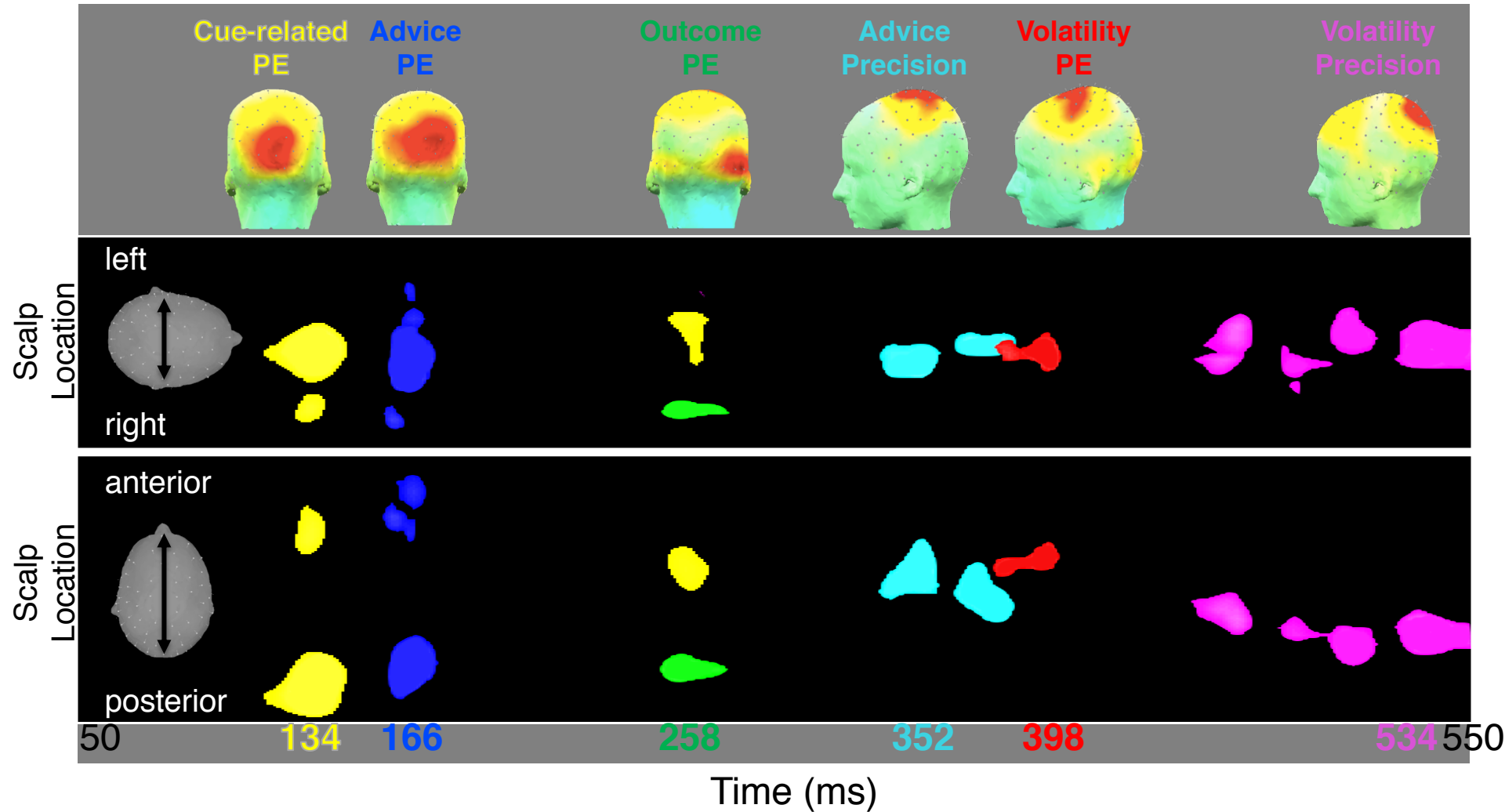


Fig. 1. Experimental Paradigm: 100 male volunteers played a binary lottery task and received advice about which option to choose from a more informed agent who was also incentivized to influence the participants' choices. To decide whether to take his advice into account, participants also inferred on the other's intentions and how they changed in time.

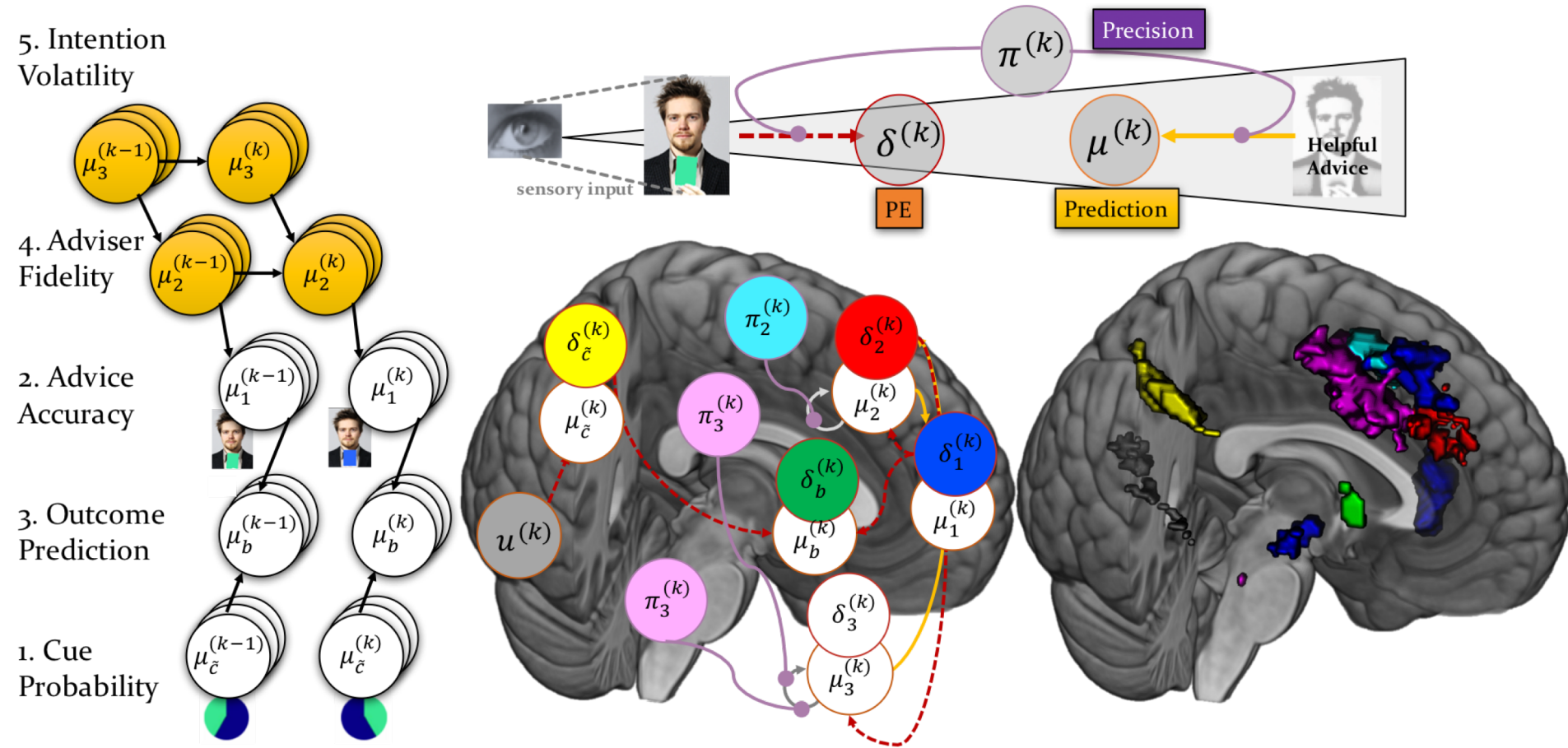
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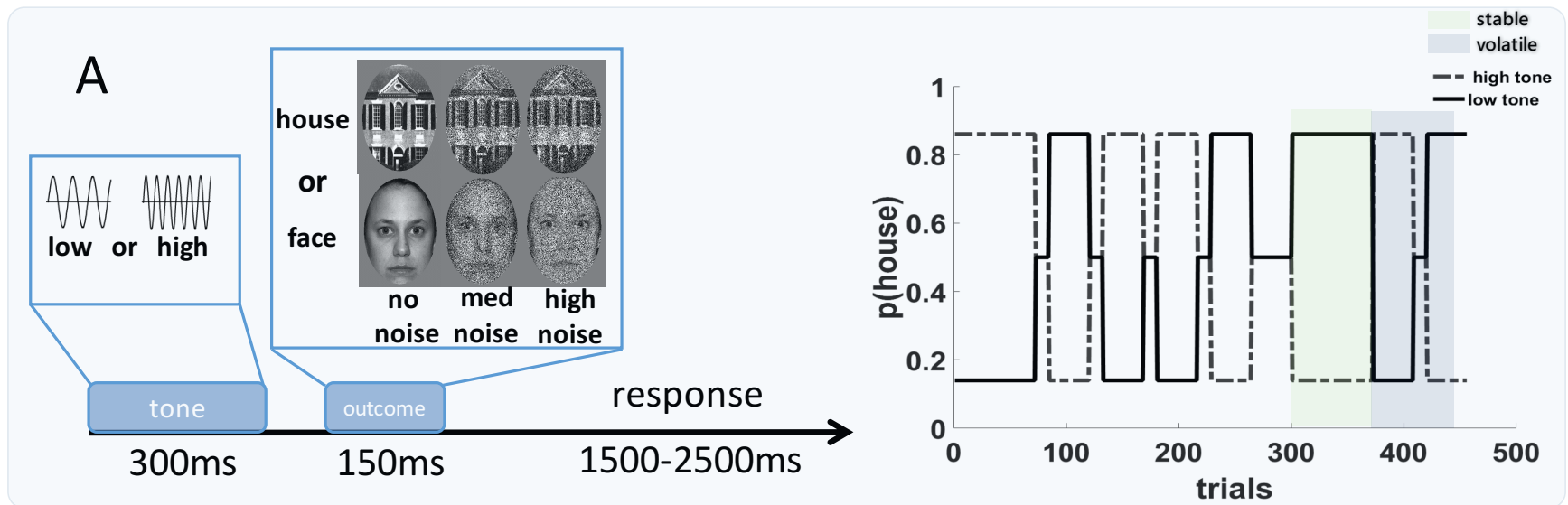


HGF: empirical evidence (Diaconescu et al., arXiv preprint)

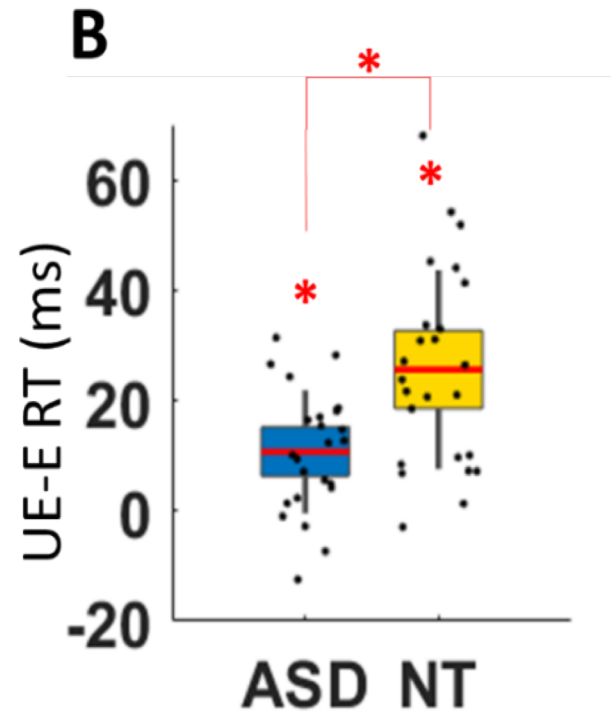
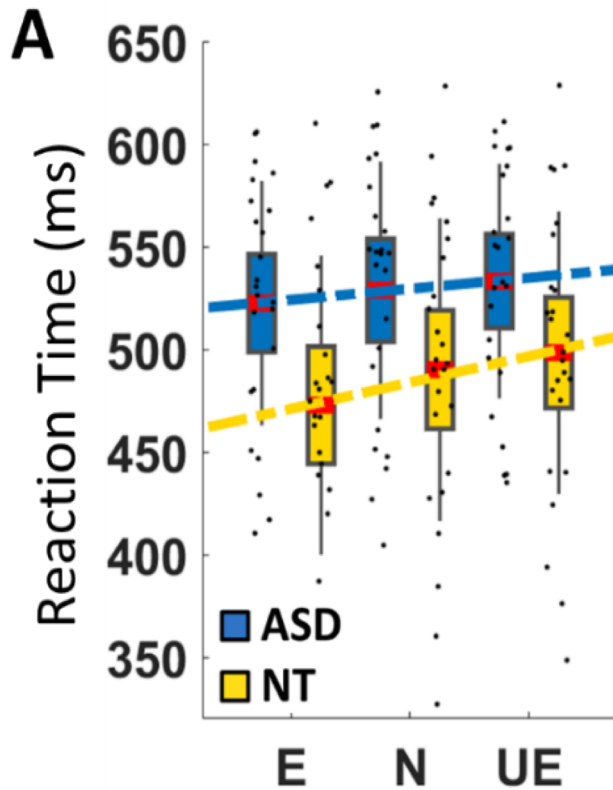


Association learning and autism

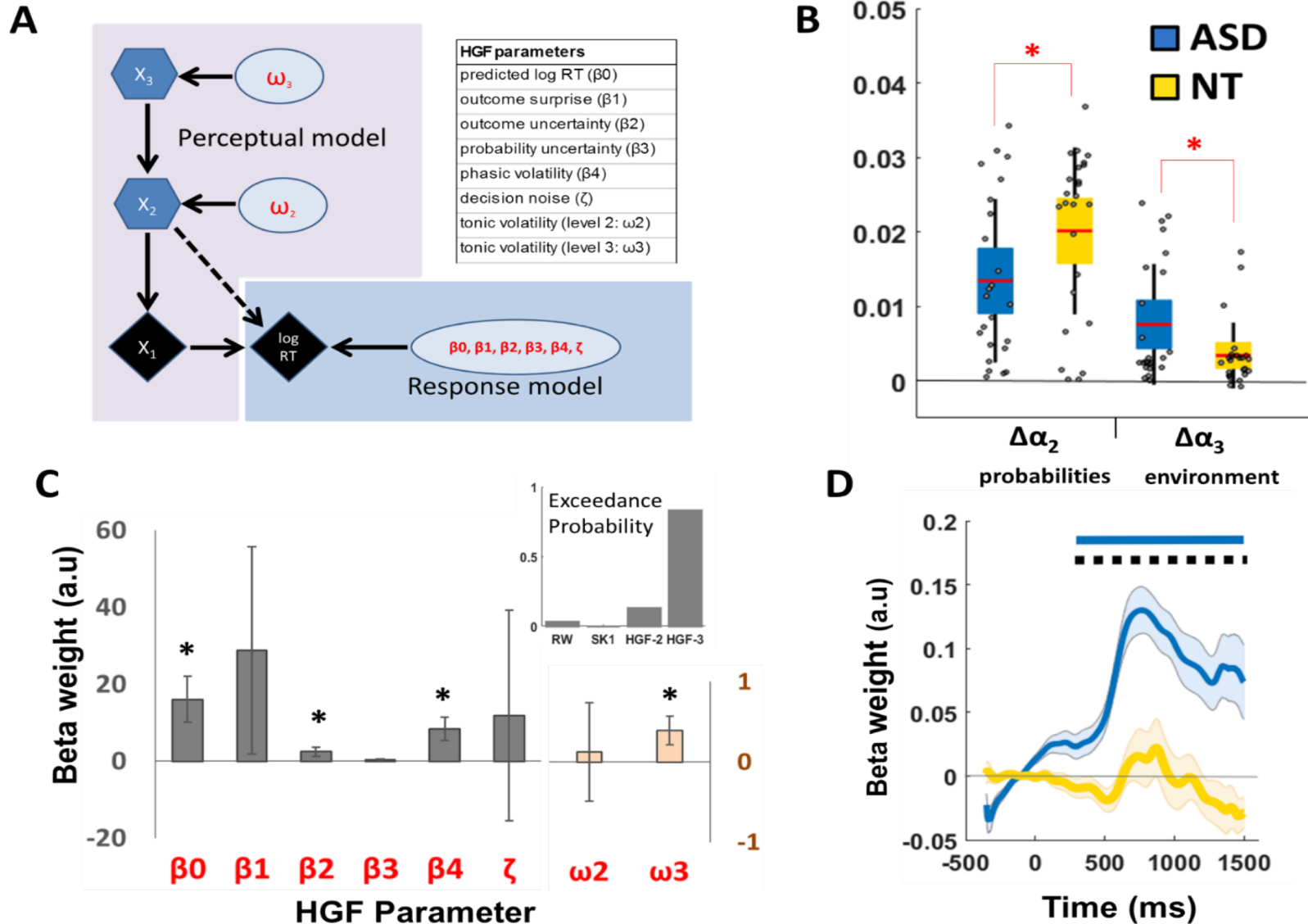
(Lawson, Mathys, & Rees, Nature Neuroscience, 2017)



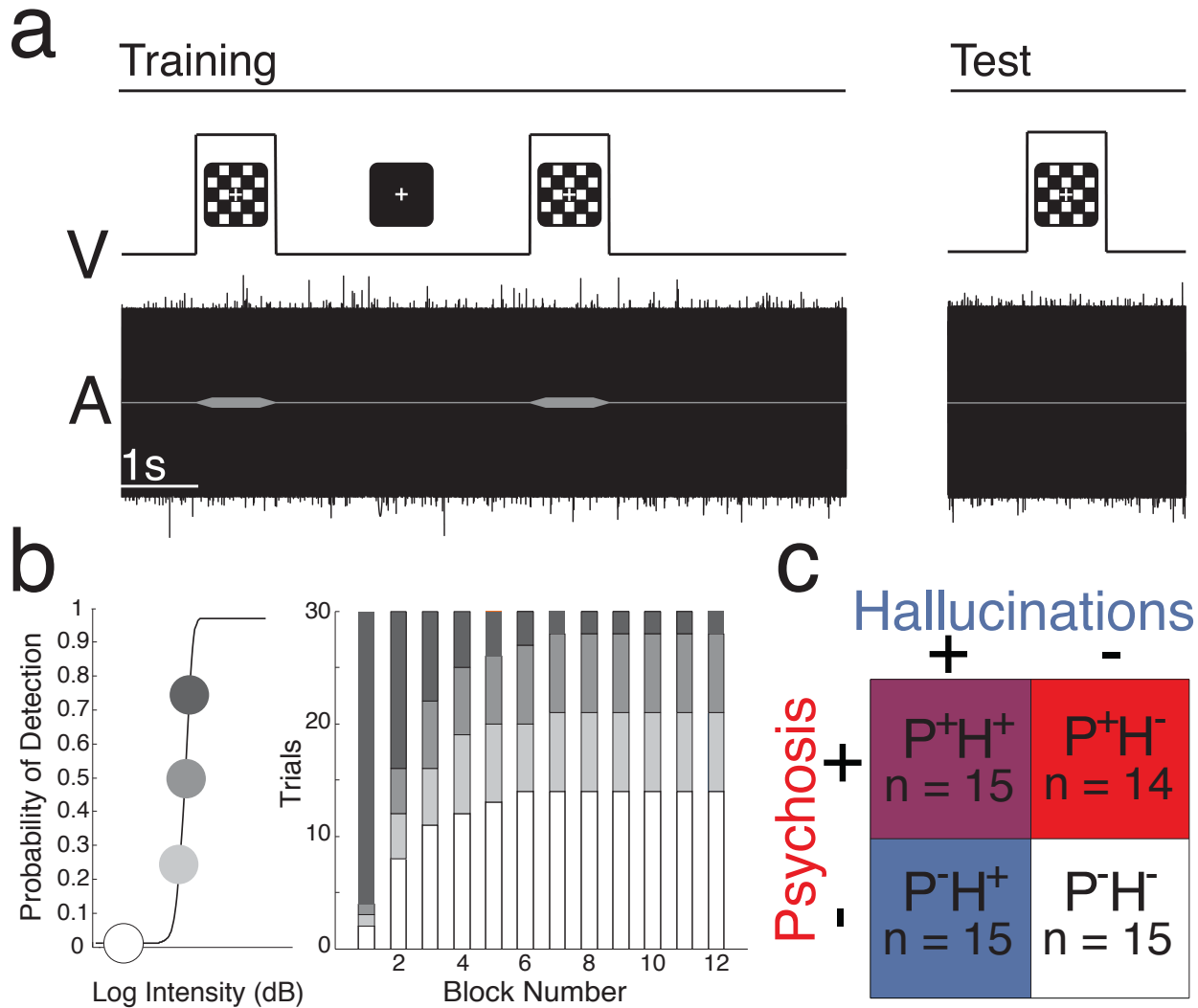
Association learning and autism



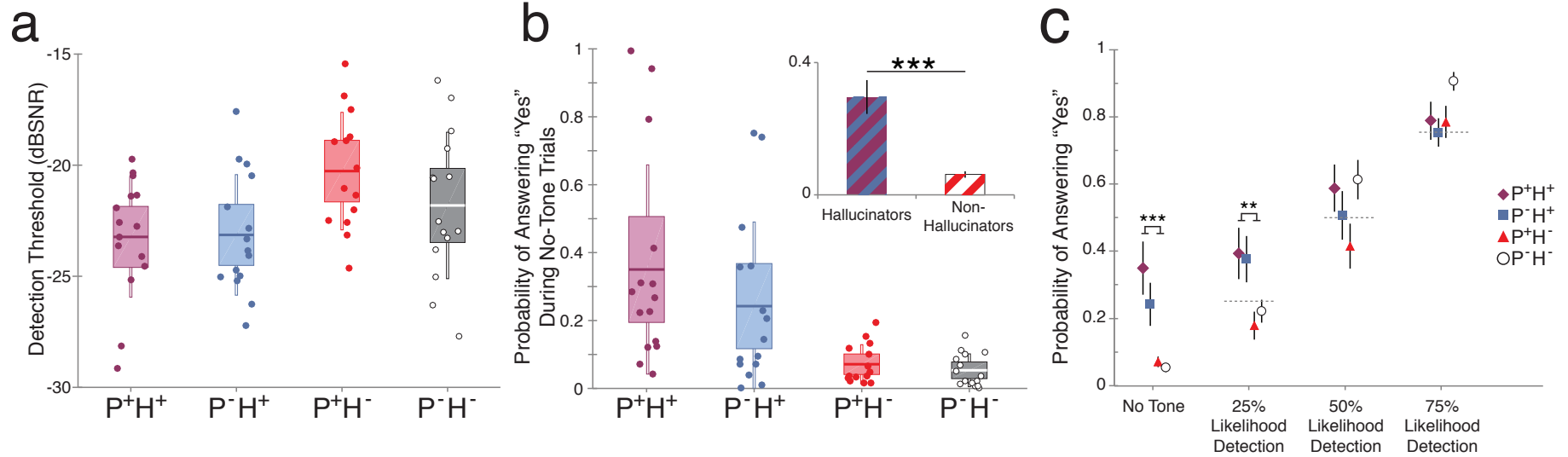
Association learning and autism



Conditioned hallucinations (Powers, Mathys, & Corlett, Science, 2017)



Conditioned hallucinations



Conditioned hallucinations

- Belief/percept formation model specifically created for this task
- Probability that the subject will respond “yes” to detection on a given trial:

$$P(\text{"yes"}|\textit{belief}) = \textit{sigmoid}(\textit{belief})$$

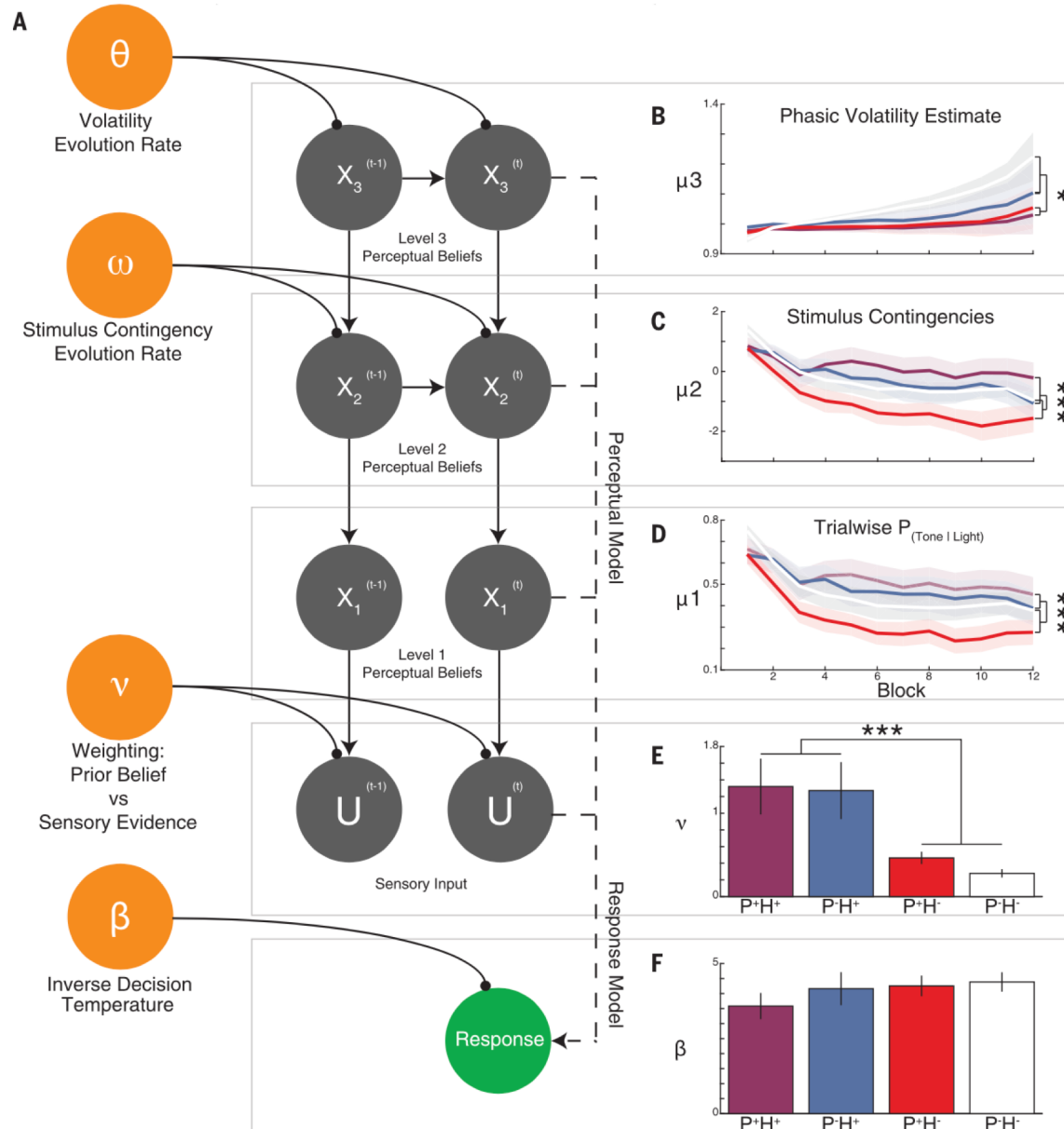
- *belief* is formalized as the Bayesian posterior mean of a beta distribution

$$\textit{belief} = \textit{prior} + \frac{1}{1 + \nu} (\textit{input} - \textit{prior})$$

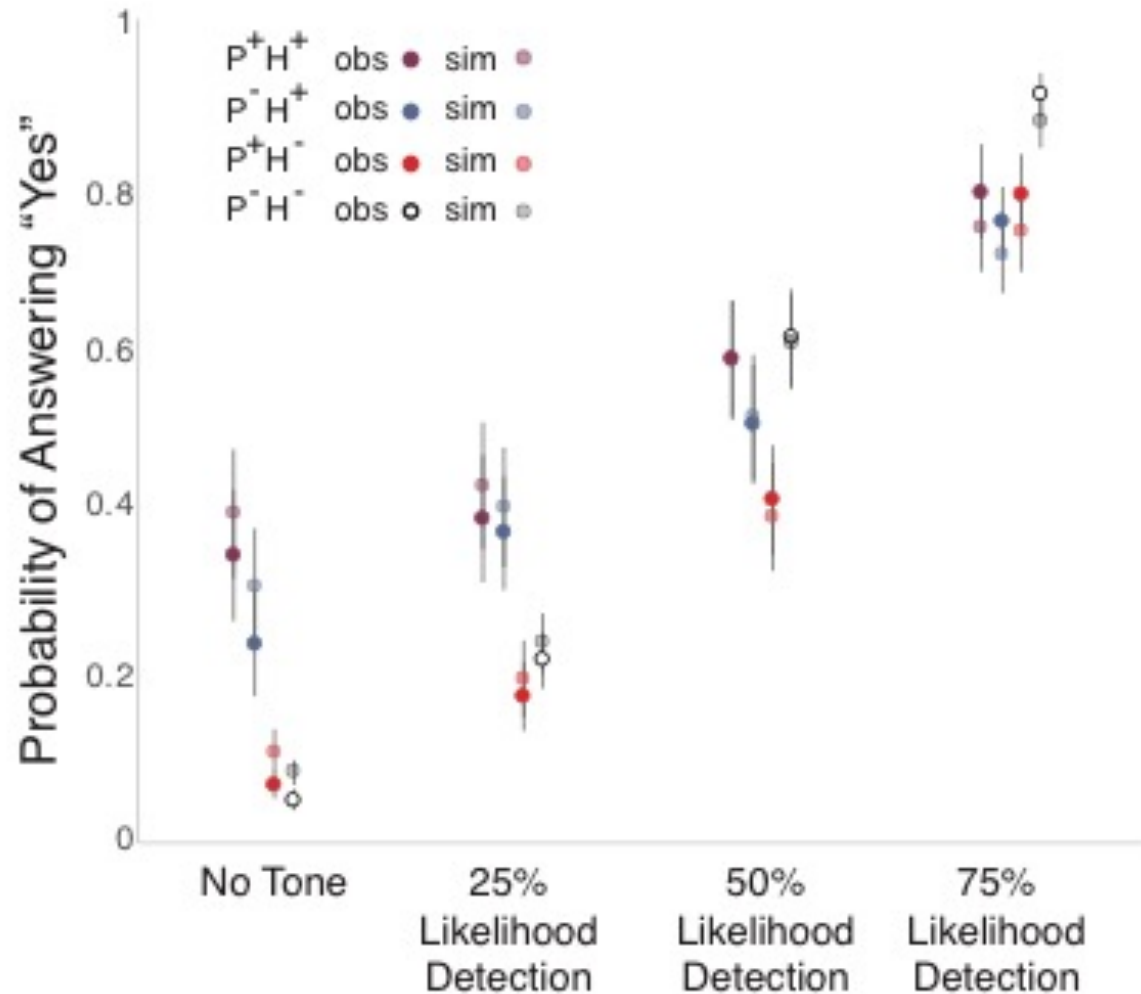
where

- *input* is given by experimental design: the true positive rate of the tone presented without light at each trial: 25%, 50%, or 75%
- *prior* is the prior from learning using the HGF: $\hat{\mu}_1$
- ν is a subject-specific parameter indicating the relative weight of the prior compared to the input.
- For $\nu = 1$, prior and input have equal weight; for $\nu > 1$ the prior has more weight than the input; and for $\nu < 1$ the input has more weight than the prior.

Conditioned hallucinations



Conditioned hallucinations



Conditioned hallucinations

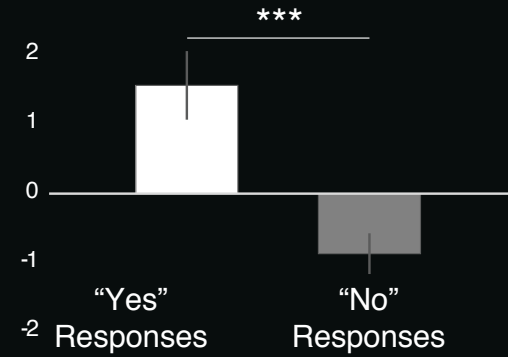
a

Thresholding, Tone-Responsive Regions



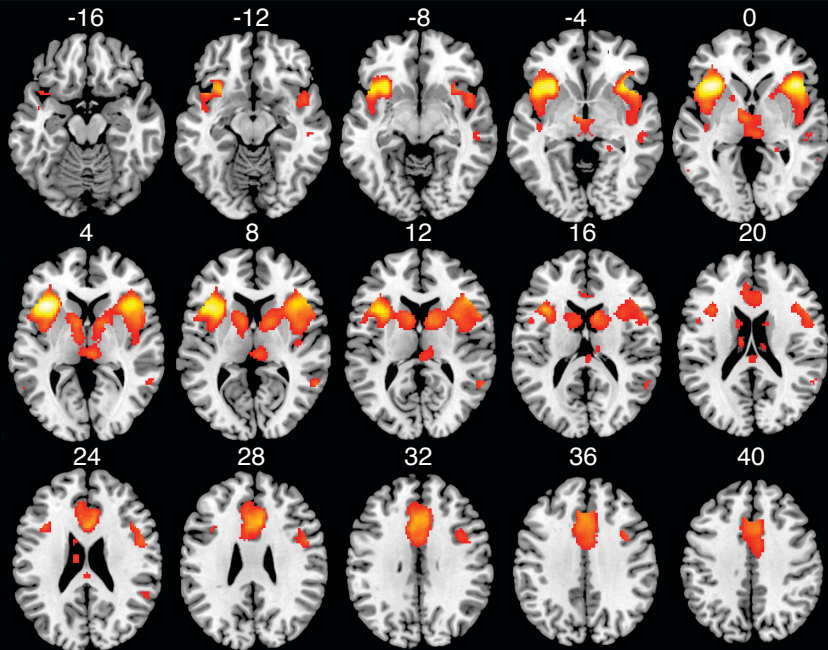
b

First Eigenvariate,
No-Tone Test Trials



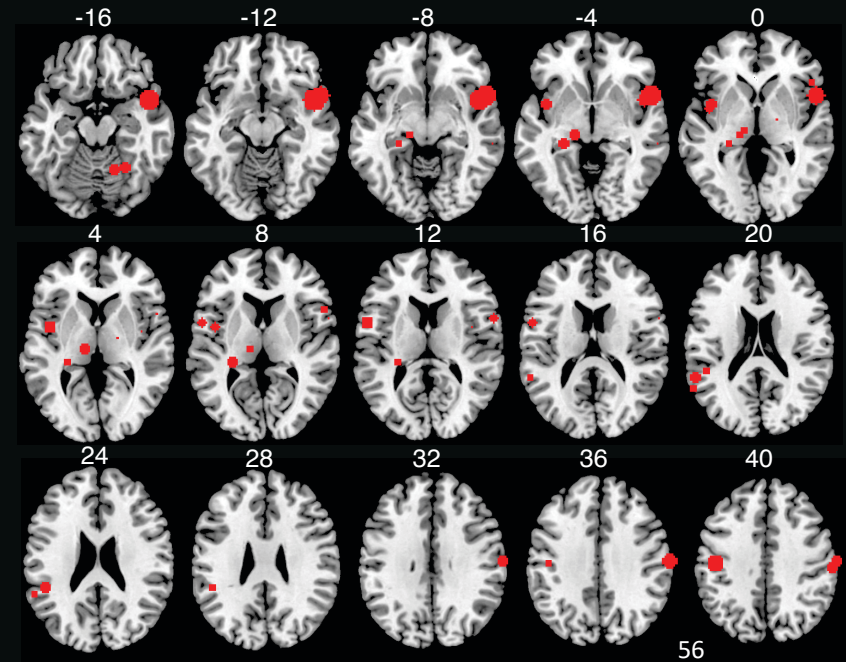
c

Test, "Yes" > "No" Responses, No-Tone Trials



d

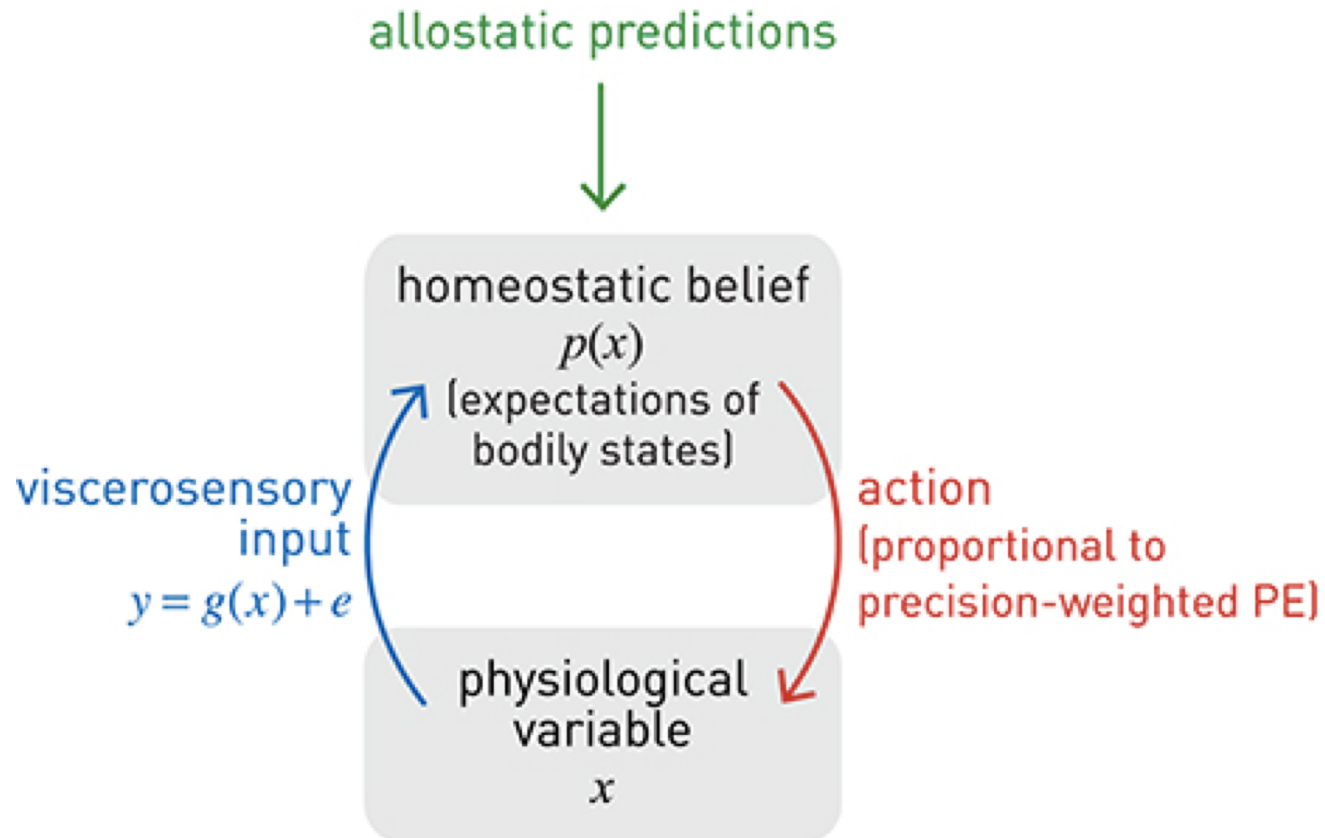
Areas Active During AVH Symptom Capture



How to estimate and compare models: the HGF Toolbox

- Available at **<https://www.tnu.ethz.ch/tapas>**
- Start with README, manual, and interactive demo
- Modular, extensible
- Matlab-based

Action as active inference



Action as active inference

Model:

$$p(x) = N(x; \mu_t, \pi_t^{-1})$$

$$p(y|x) = N(y; g(x), \pi_{data}^{-1})$$

Inference (i.e., belief update):

$$\mu_{t+1} = \mu_t + \frac{\pi_{data}}{\pi_t + \pi_{data}} (y_t - g(\mu_t))$$

$$\pi_{t+1} = \pi_t + \pi_{data}$$

Action as active inference

Delta priors on mean and precision of state:

$$\begin{aligned} p(y|m_H) &= \int p(y|\mu_t, \pi_t) p(\mu_t) p(\pi_t) d\mu_t d\pi_t \\ &= \int N(y; g(\mu_t), \pi_t^{-1}) \delta(\mu_t - \mu_{prior}) \\ &\quad \delta(\pi_t - \pi_{prior}) d\mu_t d\pi_t \\ &= N(y; g(\mu_{prior}), \pi_{prior}^{-1}) \end{aligned}$$

Negative of log-evidence L is Shannon surprise S :

$$\begin{aligned} L &= \ln p(y|m_H) & S(y|m_H) &= -L \\ &= \frac{1}{2} \left(\ln \pi_{prior} - \pi_{prior} (y - g(\mu_{prior}))^2 \right) + c \\ &= \frac{1}{2} \left(\ln \pi_{prior} - \pi_{prior} (PE(y))^2 \right) + c \end{aligned}$$

Action as active inference

Definition of action:

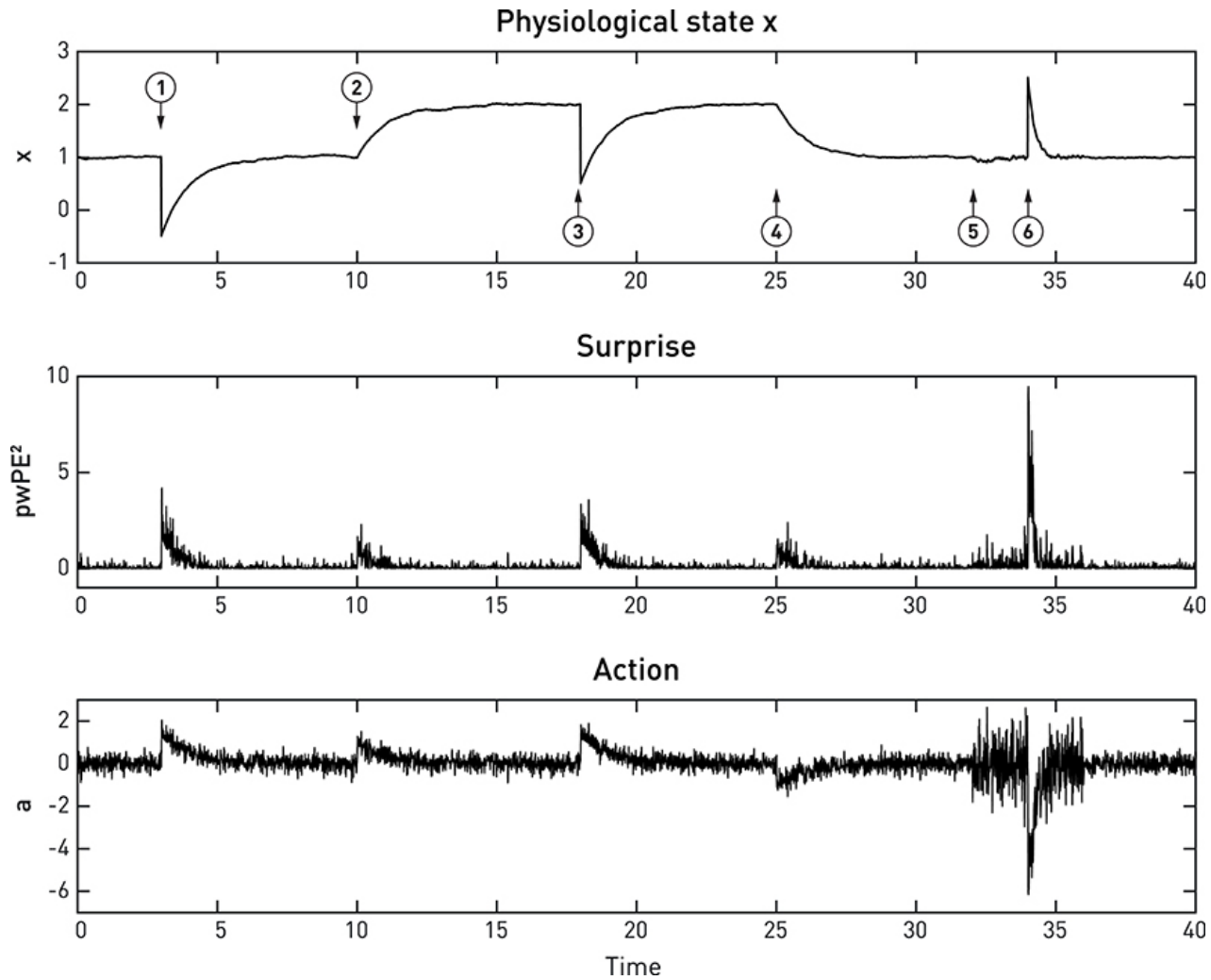
$$\begin{aligned} a(t) &= \frac{\partial L}{\partial x} \\ &= \frac{\partial \left[-\frac{1}{2} \pi_{\text{prior}} (y(x, t) - g(\mu_{\text{prior}}))^2 \right]}{\partial x} \\ &= \frac{\partial \left[-\frac{1}{2} \pi_{\text{prior}} PE(y)^2 \right]}{\partial x} \\ &= -\frac{\pi_{\text{prior}}}{2} \frac{\partial [PE(y)^2]}{\partial y} \frac{\partial y}{\partial x} \\ &= -\pi_{\text{prior}} PE(y) \frac{\partial g}{\partial x} \end{aligned}$$

precision-weighted prediction error

Action induces gradient descent on surprise S :

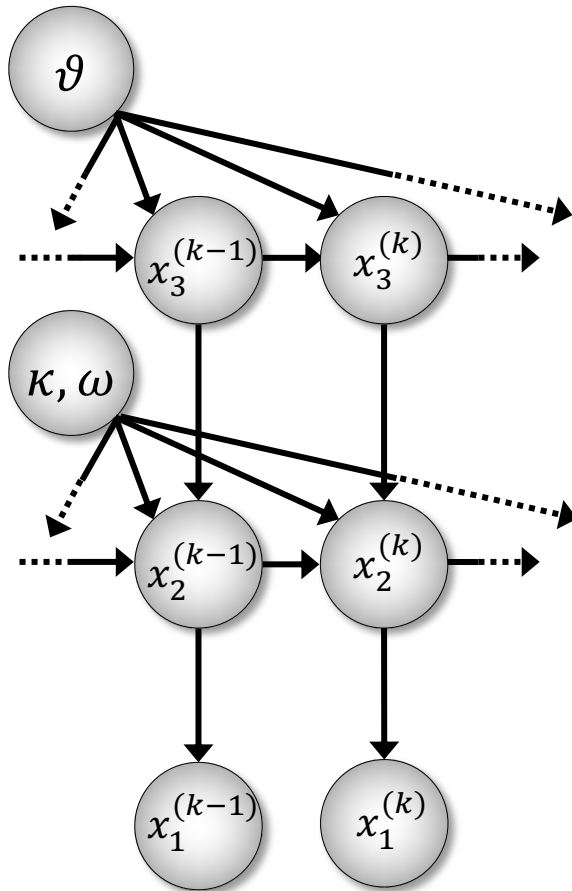
$$\frac{dx}{dt} = \lambda^{-1} f(a(t)) \quad \frac{dx}{dt} = -\lambda^{-1} f\left(\frac{\partial S}{\partial x}\right)$$

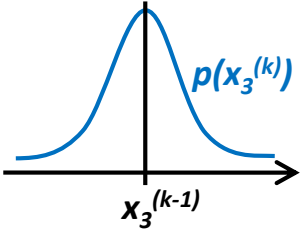
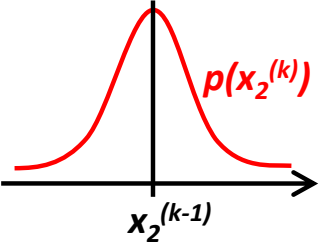
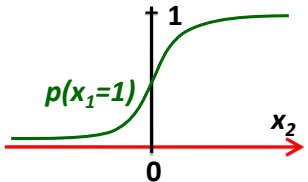
Action as active inference



Bonus material

Application to binary data



State of the world	Model
Log-volatility $\mathbf{x}_3$ of tendency	$p(x_3^{(k)}) \sim N(x_3^{(k-1)}, \vartheta)$ Gaussian random walk with constant step size ϑ 
Tendency $\mathbf{x}_2$ towards category "1"	$p(x_2^{(k)}) \sim N(x_2^{(k-1)}, \exp(\kappa x_3 + \omega))$ Gaussian random walk with step size $\exp(\kappa x_3 + \omega)$ 
Stimulus category $\mathbf{x}_1$ ("0" or "1")	$p(x_1=1) = s(x_2)$ $p(x_1=0) = 1-s(x_2)$ Sigmoid transformation of x_2 

Update equation for binary observations

- $x_1 \in \{0,1\}$ is observed by the agent. Each observation leads to an update in the belief on $x_2, x_3, \dots$, and so on up the hierarchy.
- The updates for x_2 can be derived in the same manner as above.

$$I(x_2^{(k)}) = \ln s(x_2^{(k)}) + x_2^{(k)}(x_1^{(k)} - 1) - \frac{1}{2} \hat{\pi}_2^{(k)} (x_2^{(k)} - \mu_2^{(k-1)})^2$$

$$\mu_2^{(k)} = \mu_2^{(k-1)} + \sigma_2^{(k)} \delta_1^{(k)}$$

- At first, this simply looks like an uncertainty-weighted update. However, when we unpack σ_2 and do a Taylor expansion in powers of $\hat{\pi}_1$, we see that it is again proportional to the precision of the prediction on the level below:

$$\sigma_2^{(k)} = \frac{\hat{\pi}_1^{(k)}}{\hat{\pi}_2^{(k)} \hat{\pi}_1^{(k)} + 1} = \hat{\pi}_1^{(k)} - \hat{\pi}_2^{(k)} (\hat{\pi}_1^{(k)})^2 + (\hat{\pi}_2^{(k)})^2 (\hat{\pi}_1^{(k)})^3 + O(4)$$

- At all higher levels, the updates are as previously derived.

VAPes and VOPEs

The updates of the belief on x_1 are driven by value prediction errors (VAPes)

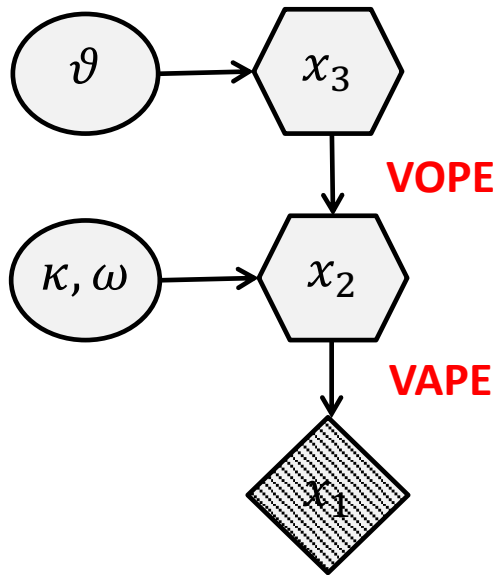
$$\mu_1^{(k)} = \mu_1^{(k-1)} + \frac{\hat{\pi}_u}{\pi_1^{(k)}} \left(u^{(k)} - \mu_1^{(k-1)} \right), \text{ VAPE}$$

while the x_2 -updates are driven by volatility prediction errors (VOPEs)

$$\mu_2^{(k)} = \mu_2^{(k-1)} + \frac{1}{2} \kappa_1 v_1^{(k)} \frac{\hat{\pi}_1^{(k)}}{\pi_2^{(k)}} \delta_1^{(k)} \text{ VOPE}$$

$$\delta_1^{(k)} \stackrel{\text{def}}{=} \frac{\sigma_1^{(k)} + \left(\mu_1^{(k)} - \mu_1^{(k-1)} \right)^2}{\sigma_1^{(k-1)} + \exp \left(\kappa_1 \mu_2^{(k-1)} + \omega_1 \right)} - 1$$

3-level HGF for binary observations



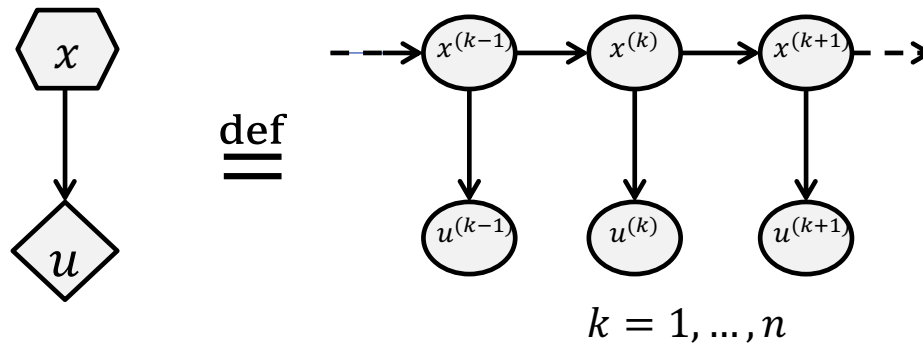
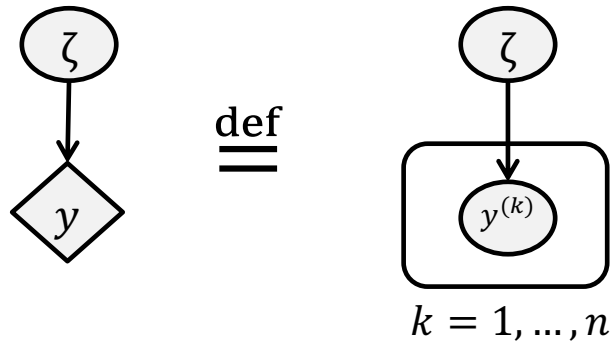
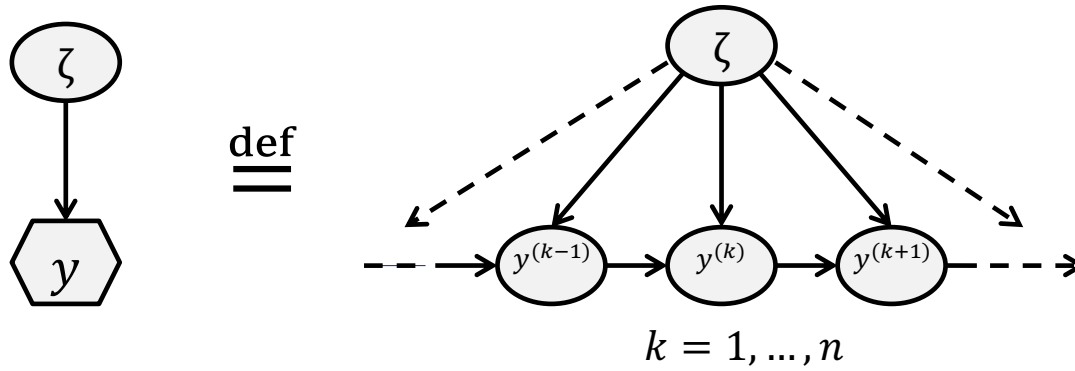
$$x_3^{(k)} \sim \mathcal{N} \left(x_3^{(k-1)}, \vartheta \right)$$

$$x_2^{(k)} \sim \mathcal{N} \left(x_2^{(k-1)}, \exp \left(\kappa x_3^{(k)} + \omega \right) \right)$$

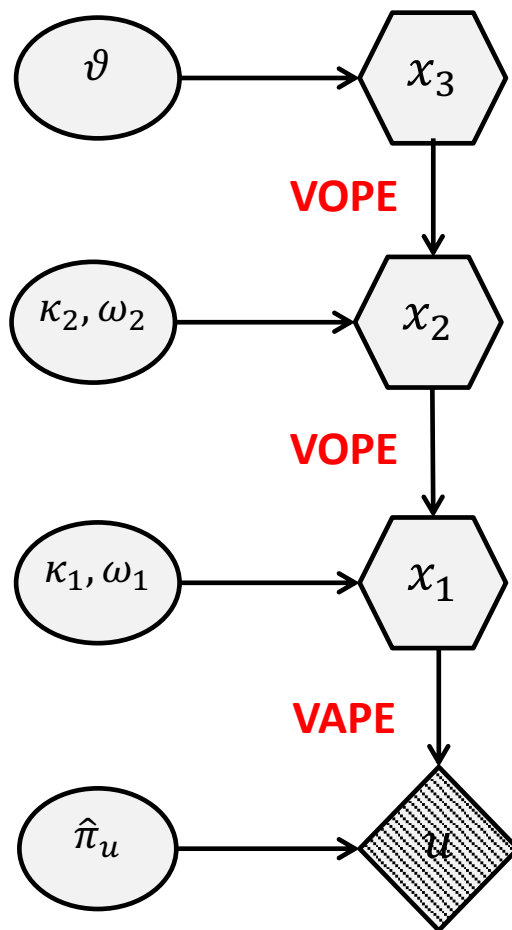
$$x_1^{(k)} \sim \text{Bern} \left(s \left(x_2^{(k)} \right) \right)$$

Mathys et al., 2011; Iglesias et al., 2013; Vossel et al., 2014a; Hauser et al., 2014; Diaconescu et al., 2014; Vossel et al., 2014b; ...

Notation



3-level HGF for continuous observations



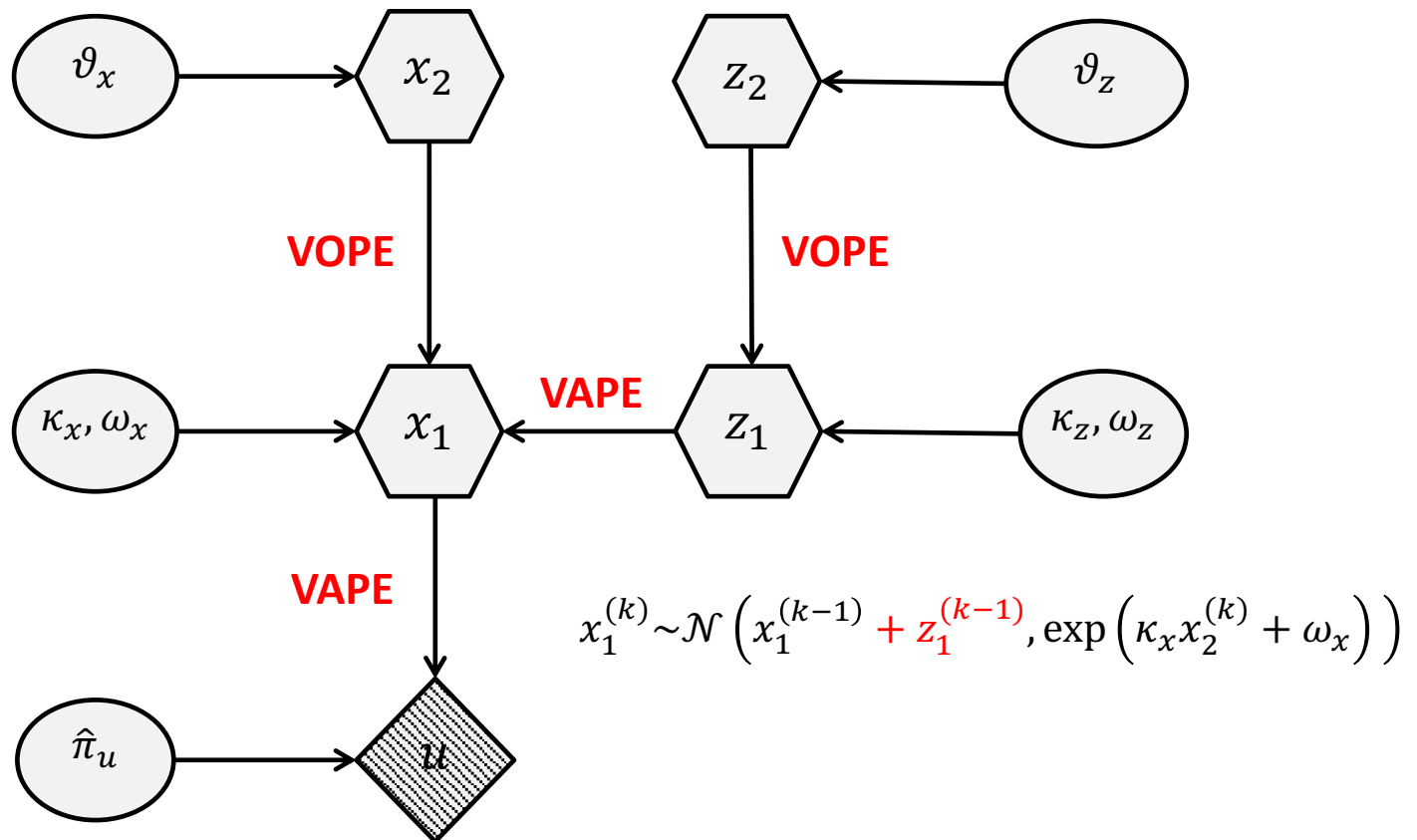
$$x_3^{(k)} \sim \mathcal{N} \left(x_3^{(k-1)}, \vartheta \right)$$

$$x_2^{(k)} \sim \mathcal{N} \left(x_2^{(k-1)}, \exp \left(\kappa_2 x_3^{(k)} + \omega_2 \right) \right)$$

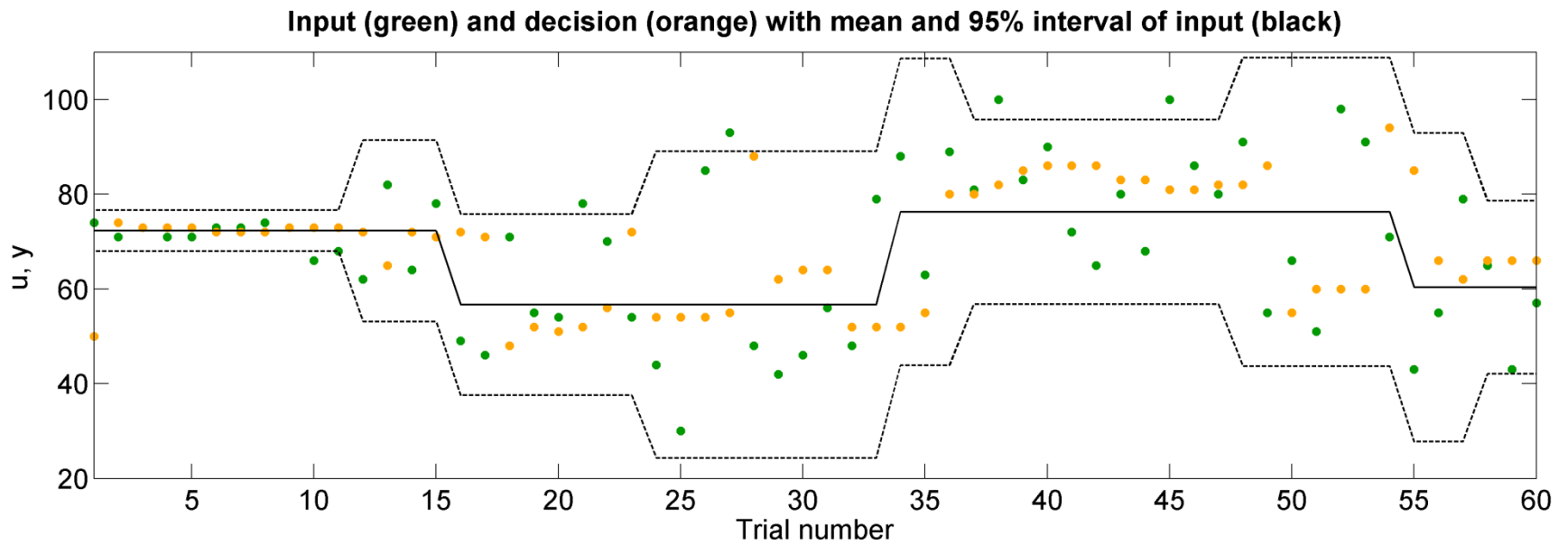
$$x_1^{(k)} \sim \mathcal{N} \left(x_1^{(k-1)}, \exp \left(\kappa_1 x_2^{(k)} + \omega_1 \right) \right)$$

$$u^{(k)} \sim \mathcal{N} \left(x_1^{(k)}, \hat{\pi}_u^{-1} \right)$$

Variable drift

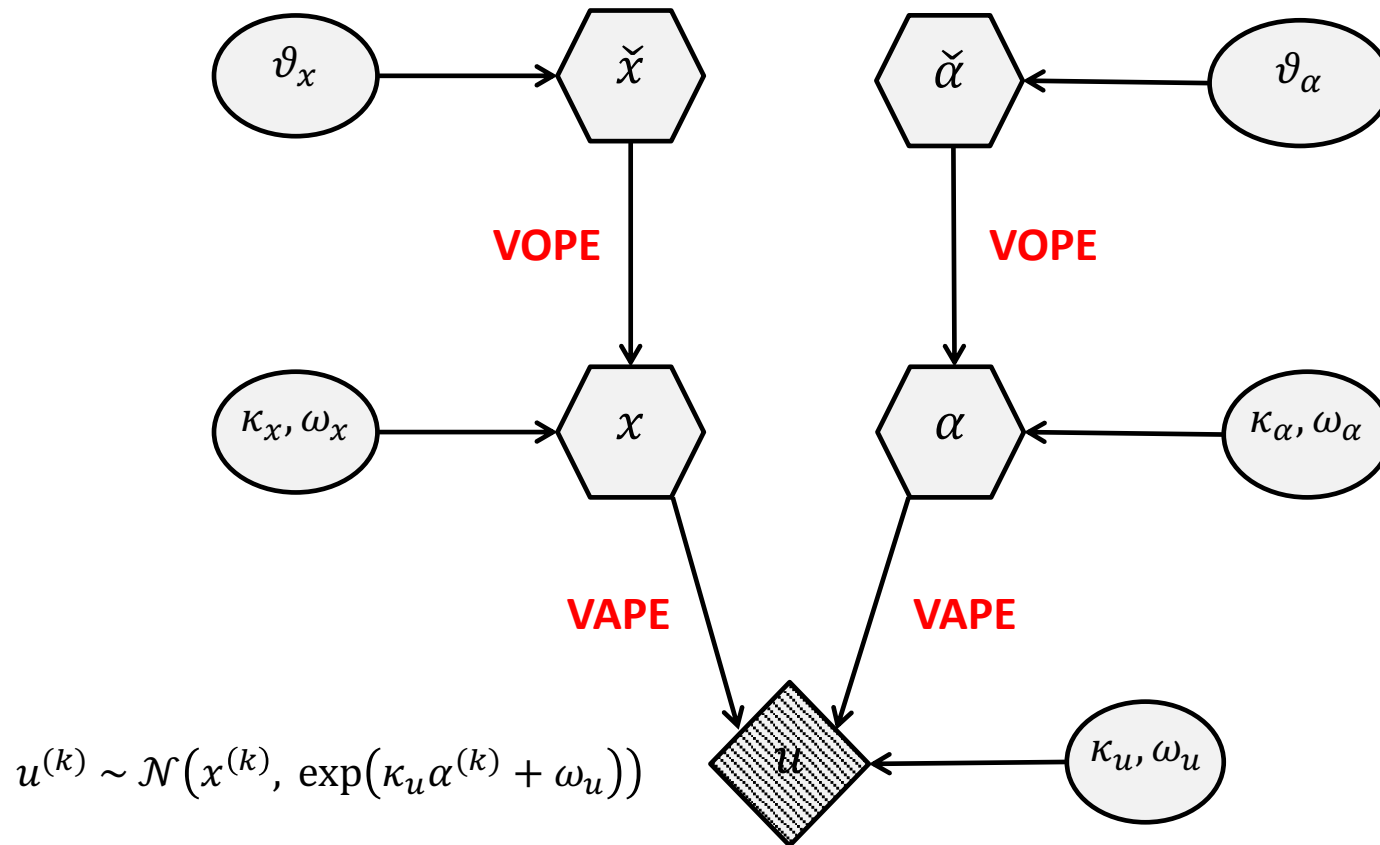


Jumping Gaussian estimation task



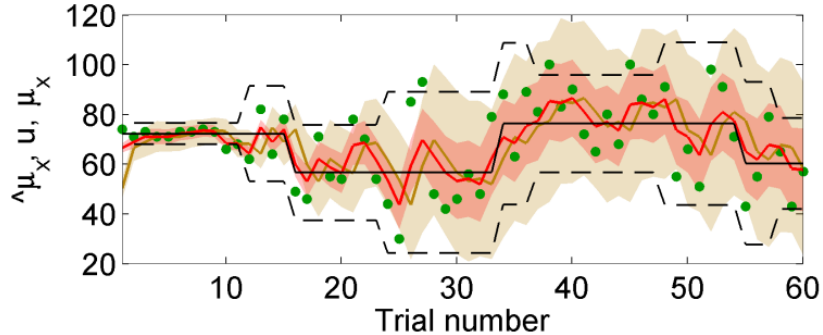
Data from Chaohui Guo

Independent mean and variance model

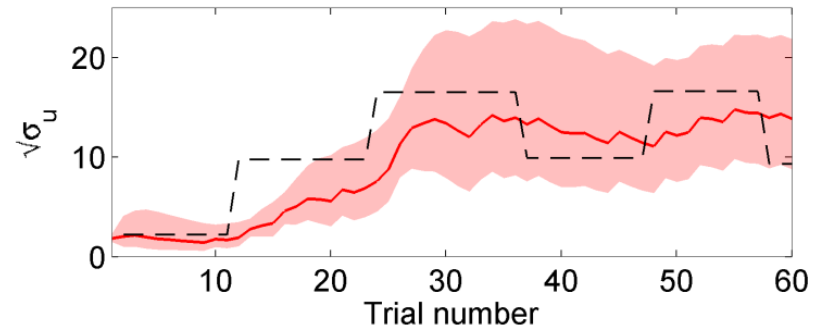


Jumping Gaussian estimation task

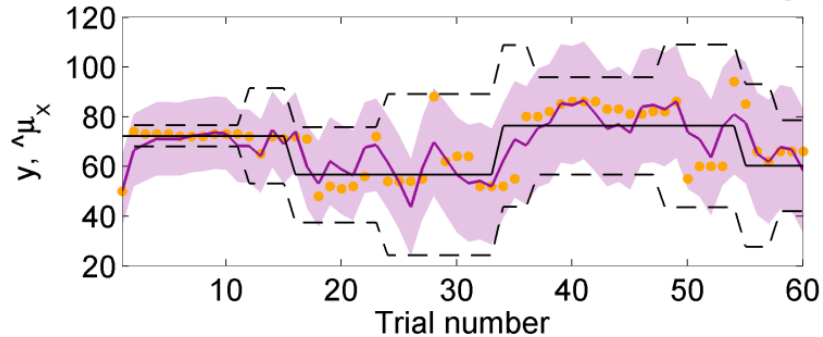
Prediction of input (brown), input (green), posterior belief (red)



Belief on noise (red), true noise (dashed black)



Prediction of decision (purple), decision (orange)



Learning rate (blue; right scale), input (black; left scale)

