Spatial-Temporal Data Analysis Across Multiple Scales

case study - Joint Modelling of Behavioural and Brain Imaging Data

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me in brief

Foundational research in AI, Mach Learning, Natural Comp:
- learning theory
- state space models and dynamical systems
- coevolutionary dynamics, population based approaches to optimisation

Methodology advancements:
- metric learning
- blending modelling with machine learning

Inter- and cross-disciplinary research – extract science from data:
- astronomy
- cognitive neuroscience
- biomedical sciences
- computational finance
Behavioral experiment

level-0: Zero-order model

Level-1: First-order model

Level-2: Second-order model

<table>
<thead>
<tr>
<th>Level-1</th>
<th>Target</th>
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<tbody>
<tr>
<td>A</td>
<td>B</td>
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<tr>
<td>0.18</td>
<td>0.72</td>
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<table>
<thead>
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<th>Level-2</th>
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<tbody>
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<tr>
<td>A</td>
<td>0.8</td>
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<tr>
<td>D</td>
<td>0.8</td>
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<tr>
<td>AB</td>
<td>0.2</td>
</tr>
<tr>
<td>XB</td>
<td>0.2</td>
</tr>
<tr>
<td>BC</td>
<td>0.2</td>
</tr>
<tr>
<td>YC</td>
<td>0.2</td>
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</table>
Model that tracks participants’ learning

- Mixture of Markov models of order $k = 0, 1, 2$
- Predictive distribution for the $t$-th gap item:
  $$p(s_t|s_{t-2}s_{t-1}) = w_0 \cdot p_0(s_t|∅) + w_1 \cdot p_1(s_t|s_{t-1}) + w_2 \cdot p_2(s_t|s_{t-2}s_{t-1})$$
- Probability vector $w$ is of central importance. Its time evolution $w_t$ shows how a participant learned the correct set of contexts
- Bayesian approach to update $w_t$.

Quantification measures on the models

- How well did a participant learn the underlying source?

\[
\text{KL}(\mathcal{M}_{\text{true},k} || \mathcal{M}_{t}^{\text{tracking},k}) = \sum_{c \in \text{Context}^k} p^k(c) \cdot \text{KL} \left( p^k(\cdot | c) \middle| p_t^k(\cdot | c) \right)
\]

- Probability maximization? To what degree?

\[
\text{KL}(\mathcal{M}_{\text{max},k} || \mathcal{M}_{t}^{\text{tracking},k}) = \sum_{c \in \text{Context}^k} p^k(c) \cdot \text{KL} \left( p_{\text{max},k}^k(\cdot | c) \middle| p_t^k(\cdot | c) \right)
\]

where

\[
p_{\text{max},k}^k(s|c) = \begin{cases} 
  \approx 1 & s = s_{\text{max}} \\
  \approx 0 & \text{otherwise} 
\end{cases} \quad \text{with} \quad s_{\text{max}} = \arg\max_s p^k(s|c).
\]

- Probability maximization or matching?

\[
\mathcal{D}_t^{\text{strategy}} = \text{KL}(\mathcal{M}_{\text{max},k} || \mathcal{M}_{t}^{\text{tracking},k}) - \text{KL}(\mathcal{M}_{\text{true},k} || \mathcal{M}_{t}^{\text{tracking},k})
\]
Learning the memory depth

Figure 4
Investigating behavioural experiments

Learning memory depth correlates with strategy choice

Figure 6
fMRI signals in ROIs - HPM modelling

Stimulus 1
3.0 sec

Cue
1.5 sec

Visual-perceptual Process’s Haemodynamic Response Function

Motor-functional Process’s Haemodynamic Response Function

Response Delay and Function

Prototypical Pattern $\chi(t)$

Response Magnitudes $\chi\alpha_v$ $\chi\alpha_v$ $\chi\alpha_v$

$\alpha_1$ $\alpha_2$ $\alpha_3$
Prototypes in space and time - ROI cortical activations

Prototype 1
Spatial Prior
\( \mathcal{N}(v; \mu_1, \Sigma_1) \)
Likelihood
\( p(\mathbf{y}(t) | \mathbf{x}(t)) \)
Prototypical Pattern
\( \mathbf{x}(t) \)

Prototype 2
Spatial Prior
\( \mathcal{N}(v; \mu_2, \Sigma_2) \)
Likelihood
\( p(\mathbf{y}(t) | \mathbf{x}(t)) \)
Prototypical Pattern
\( \mathbf{x}(t) \)

\[ p(\mathbf{y}(t)) = \mathcal{N}(v; \mu_1, \Sigma_1) p(\mathbf{y}(t) | \mathbf{x}(t)) + \mathcal{N}(v; \mu_2, \Sigma_2) p(\mathbf{y}(t) | \mathbf{x}(t)) \]

Simultaneous brain imaging and behavioral measurements

**group level fMRI modelling**

**fast vs. slow learners**

Bayesian formulation: **shared tight parameter priors in each group**

**hierarchy of common/individualized within-group modelling**

Regions of Interest

- **Frontal lobe**
  - **MFG** - middle frontal gyrus: attentional control.
  - **SFG** - superior frontal gyrus: coordination with sensory system.

Both involved in learning, in particular, in sequential organization and self-monitoring of actions.

- **Limbic system**
  - **CG** - cingulate gyrus: integral part of the limbic system involved with emotion formation and processing, implicit learning and memory. Influential in linking motivational outcomes to behavior.

- **Basal ganglia**
  - **Pu** - putamen (lat. nutshell): Sub-cortical (dorsal stratum) associated with motor control, cognition, emotions and learning.
HRF - time-to-peak

MFG
Prototype 1
Prototype 2

Pre Post Pre Post

SFG
Prototype 1
Prototype 2

Pre Post Pre Post

CG
Prototype 1
Prototype 2

Pre Post Pre Post

Pu
Prototype 1
Prototype 2

Pre Post Pre Post
Prototype volume

**MFG**

- Prototype 1
  - Pre: 0.75
  - Post: 1.5

- Prototype 2
  - Pre: 0.5
  - Post: 0.75

**SFG**

- Prototype 1
  - Pre: 0.5
  - Post: 1.5

- Prototype 2
  - Pre: 0.5
  - Post: 0.75

**CG**

- Prototype 1
  - Pre: 0.5
  - Post: 0.75

- Prototype 2
  - Pre: 0.5
  - Post: 0.75

**Pu**

- Prototype 1
  - Pre: 1.5
  - Post: 0.5

- Prototype 2
  - Pre: 0.5
  - Post: 0.75
ROI homogeneity

MFG

SFG

CG

Pu