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Multi-stability & fixational eye movements : an energy potential fields modeling approach

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I. Theory & Literature

Multi-stable perception occurs when an ambiguous stimulus drives perceptual alternations. Understanding its mechanisms has a direct impact on perceptual inference and decision making. A model proposed by Shpiro and colleagues explains the dynamics of **bi-stable** perception through neural **adaptation** and driving **noise** ξ . It uses a particle (x) in an **energy field** V .

$$\dot{x}(t) = -\nabla V(x) + A_0 \cos(\omega t + \phi) + \xi(t)$$
$$V(x) = -\frac{1}{2}x^2 + \frac{1}{4}x^4$$

Moreno-Bote, R., Knill, D. C., & Pouget, A. (2011). PNAS
Shpiro, A., Moreno-Bote, R., Rubin, N., & Rinzel, J. (2009). Journal of computational neuroscience

Fixational eye movements (**FEM**) have been studied and modeled by Engbert and colleagues using self-avoiding random walk of a particle in an **energy field** as a primary principle.

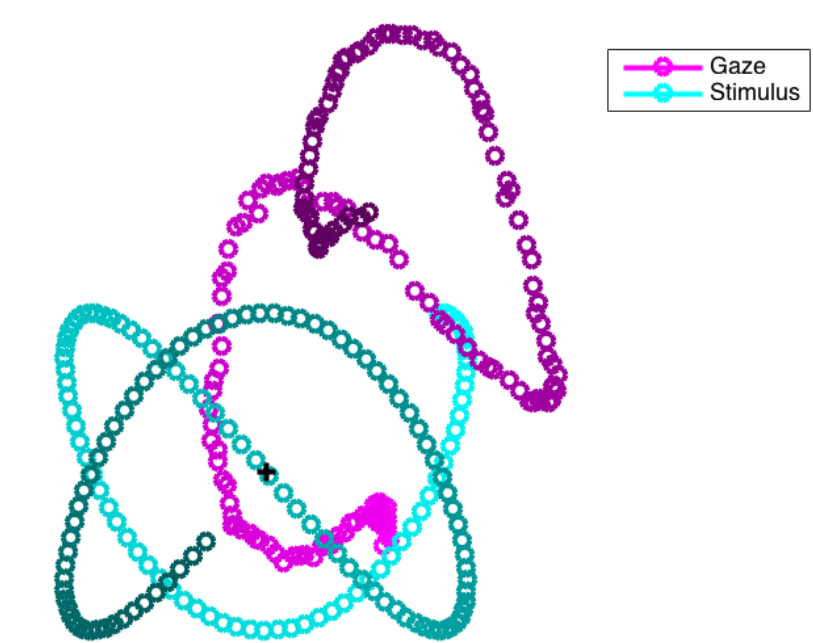
Engbert, R., Mergenthaler, K., Sinn, P., & Pikovsky, A. (2011). PNAS
Sinn, P., & Engbert, R. (2016). Vision research
Self-avoiding random walk from Engbert et al. 2011. →

What is the role of FEM in perceptual Multi-stability dynamics ?

II. Initial Observations

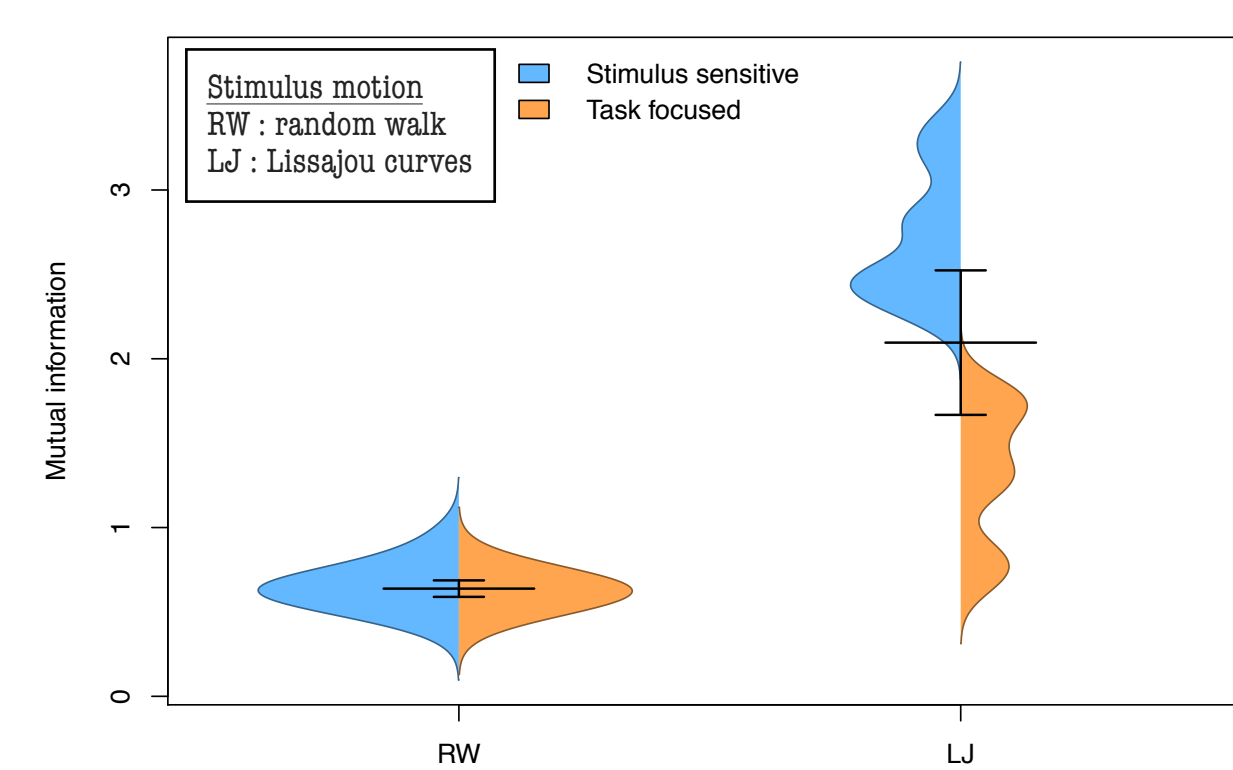
Eye movement data from an experiment, in which participants observed a moving Necker cube in a continuous viewing paradigm, revealed that **micro-pursuit within an ocular fixation** can occur; a type of movements not accounted for in current FEM models.

Qualitative observation :



Micro-pursuit observation in fixation 17, trial 31, subject 6.
MI = 1.7456

Quantitative observations : Mutual information analysis



Micro-pursuits observation and measurement using Mutual Information (MI)

Martins, A. J., Kowler, E., & Palmer, C. (1985). JOSA

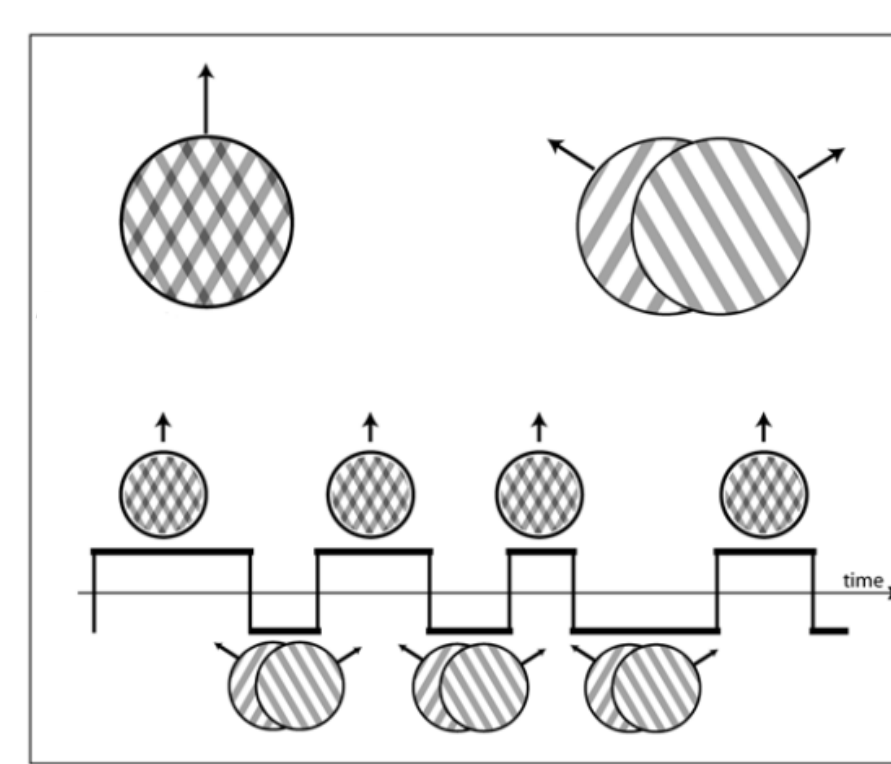
V. Experimental Design

We propose an experimental protocol that allows the gathering of initial data necessary for model inversion followed by prediction testing. The stimulus is the tri-stable **Moving Plaids**.

The 3 percepts are:
• coherence
• transparent left
• transparent right

Hypotheses (expected observations) :

- Oculomotor & perceptual spaces have inter-dependencies
- Events in perception lead to FEM events & vice-versa



Rubin, N., & Hupé, J. M. (2005). Binocular rivalry

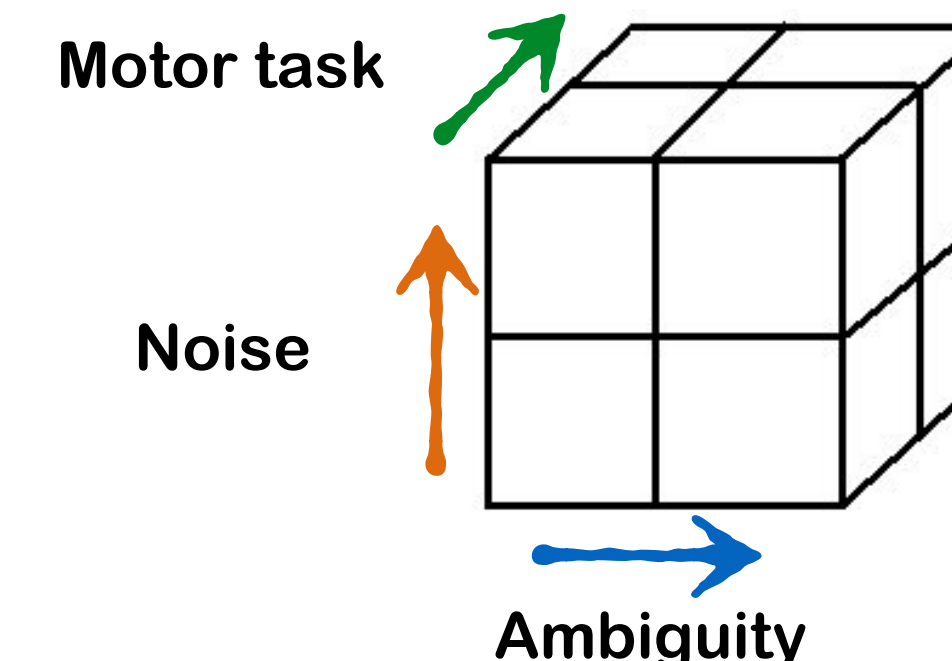
Experimental design :

Motor manipulation :

- Endogenous oculomotor events
- Exogenous oculomotor events
- Correlation between percept and eye movements

Noise manipulation :

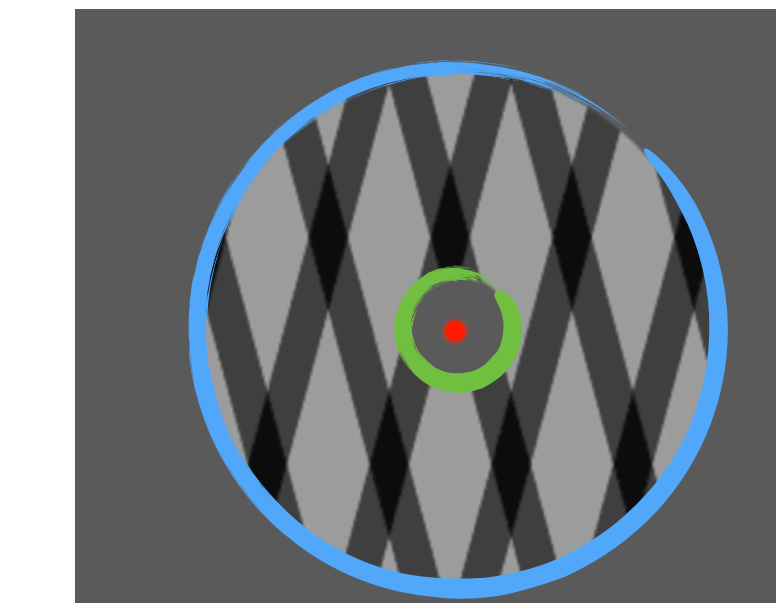
- Power of noise
- Low vs high levels of noise



Perception manipulation :

- Perceptual switch events
- Stimulus parameters

Experimental tasks :



Perceptual task : report depth perception using keyboard
Oculomotor task : fixate the fixation point

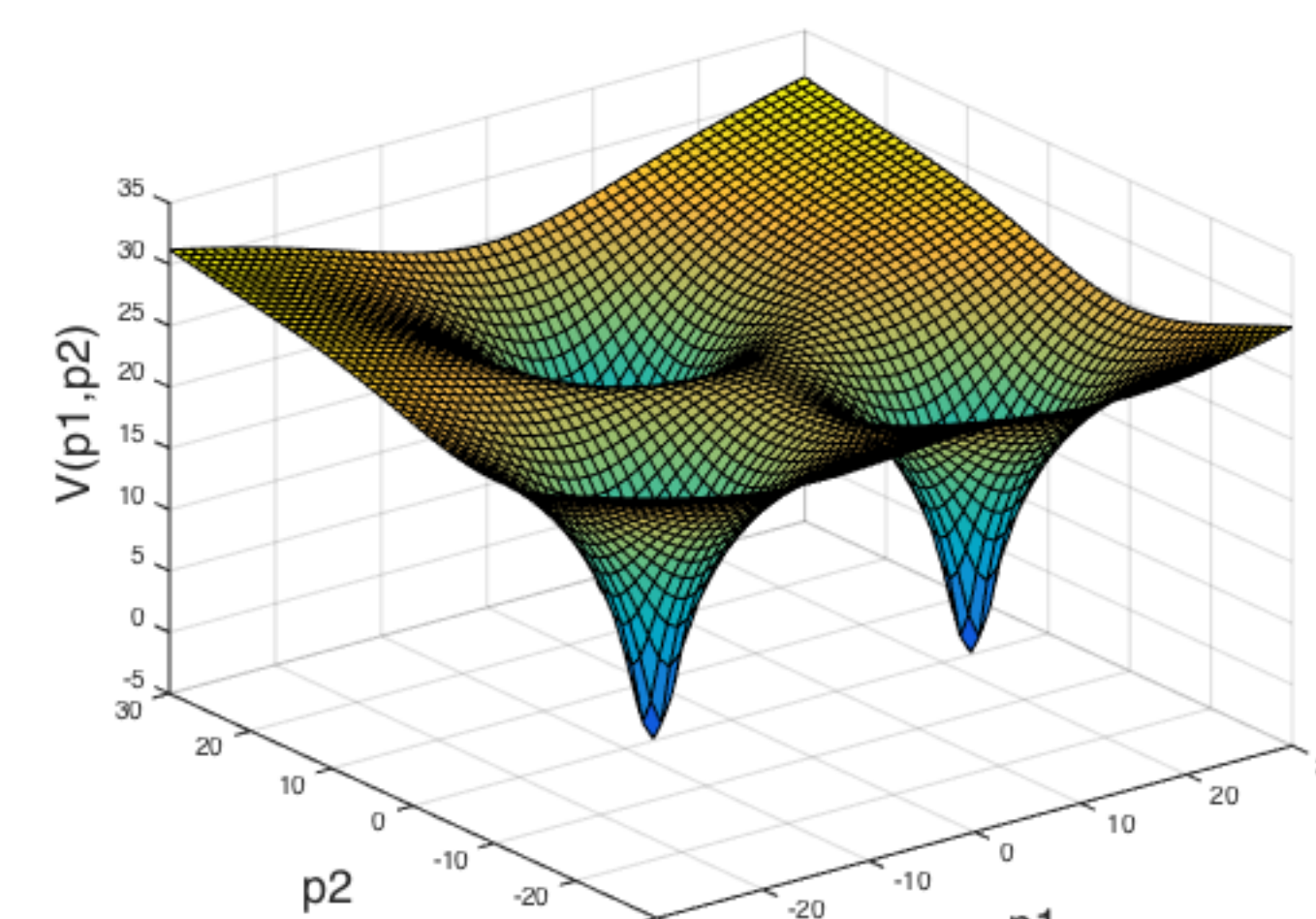
III. Method & Model

Therefore, we propose a modeling approach that could help predict and explain away **interactions between FEM and multi-stability dynamics**. It is based on **energy potential fields** where their distortions by **attractors** allow the emergence of multi-stability in the spatial domain for the gaze (w.r.t. the different visual attractors), as well as in the attentional and/or perceptual spaces. **Adaptation** δ and **noise** ξ can be used as causal forces that impact the observed dynamics of the system in a "top-down" and/or "bottom-up" manner.

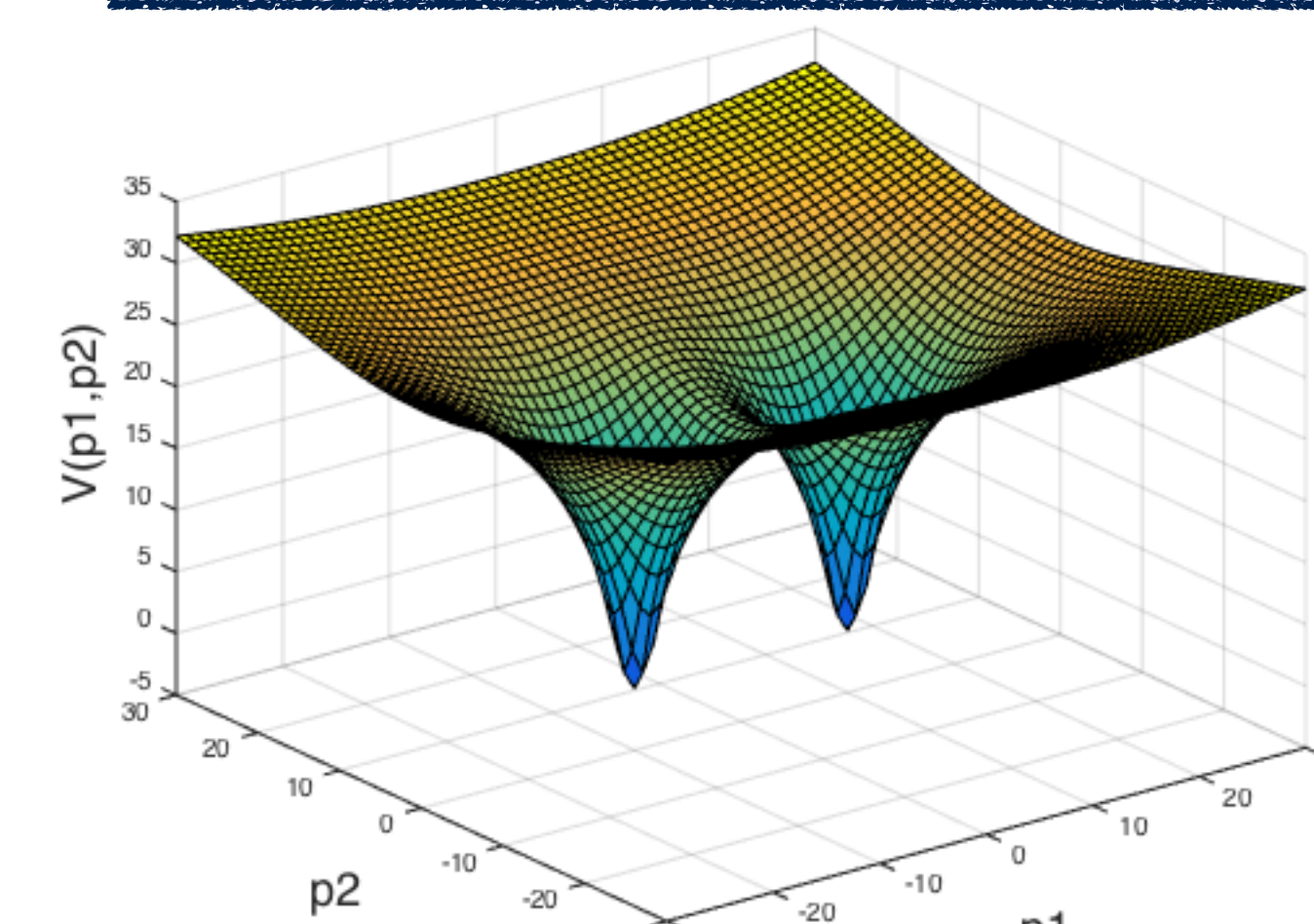
General multi-stable model :

$$\dot{p} = -\nabla V(p) + \xi(t)$$

$$V(p, t) = -\ln \sum_{i=1}^n \frac{1}{\|p - a_i(t)\|^{2\beta_i(t)} + \delta_i(t)}$$

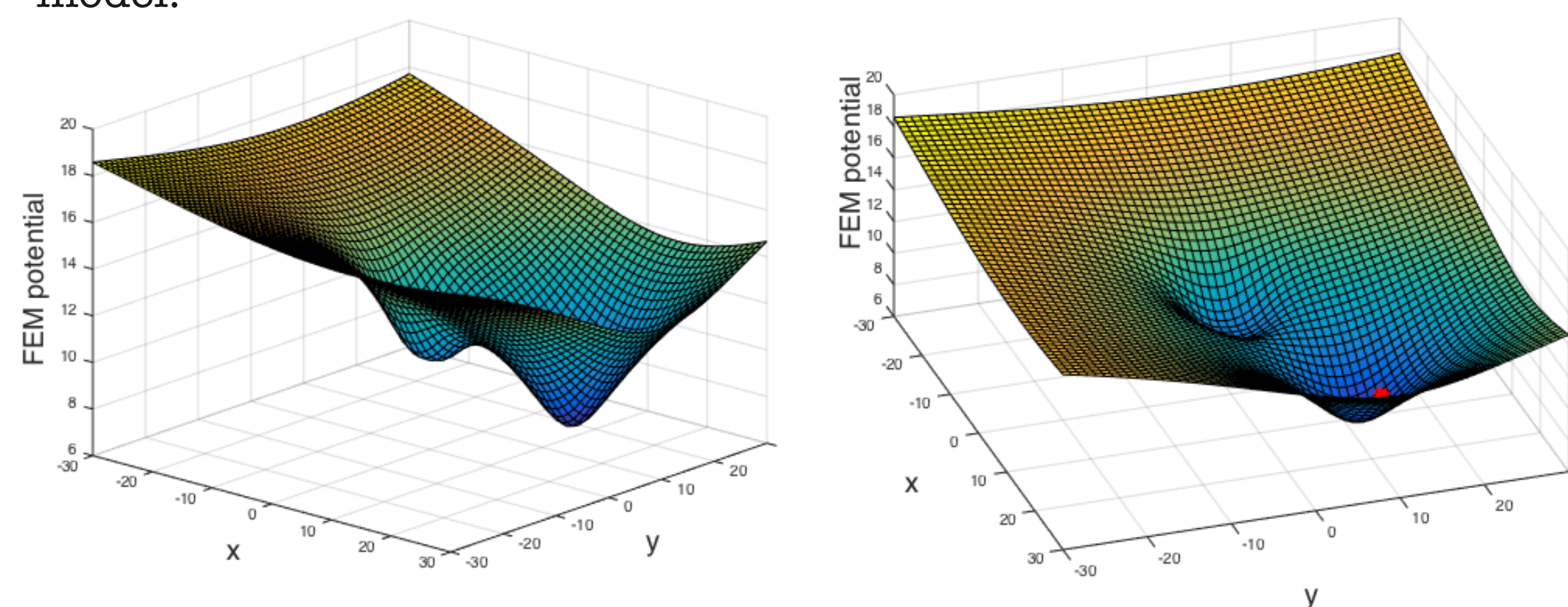


Examples of 2 (left) and 3 (right) attractors generated using the model.



Gravitational FEM (GraFEM) multi-stable model : Perceptual **memory** and/or **anticipation** of stimulus motion can be taken into account through potential field temporal distortion using an autoregressive model.

$$V_{FEM}(p, t) = \sum_{k=1}^d \epsilon_k V(p, t - \tau_k)$$



Examples of a 2-attractor GraFEM model with the red particle representing the gaze.

Parameters :

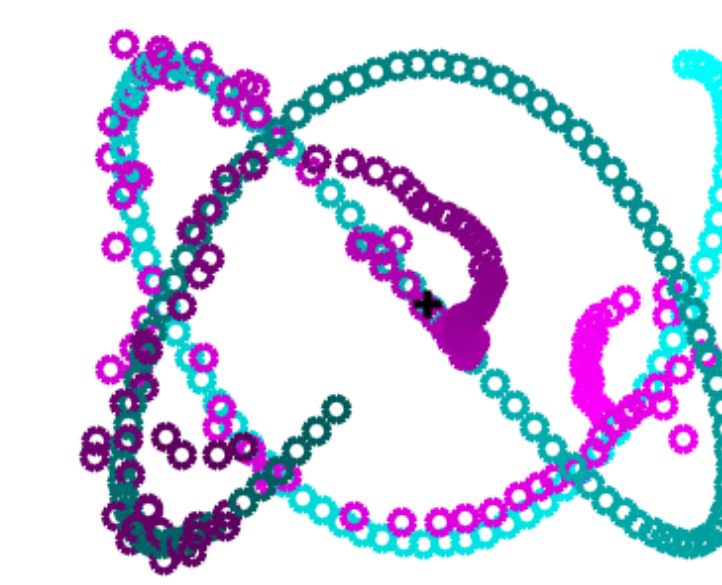
- ϵ_k : the rate of memory/anticipation loss for energy levels
- τ_k : the length of the time window for memory/anticipation
- d : order of the autoregressive model

IV. Simulations & Analysis

The model is able to generate all observed eye movement phenomena (drift, micro-saccades & tremor), and if reversed given data, could provide insight on the possible causal relationship between eye movements, perception and multi-stability.

The following simulated data was generated using conditions where 2 attractors were setup:

- a fixation cross attractor
 - a stimulus center of gravity attractor
- The parameters manipulated here are β_i , δ_i and the stimulus attractor position a_i for micro-pursuit.



Micro-pursuit
MI = 1.2781

Stable fixation with
drift & tremor

Micro-saccade detected using
Engbert & Kliegel algorithm.
Engbert, R., & Kliegel, R. (2005). Vision research

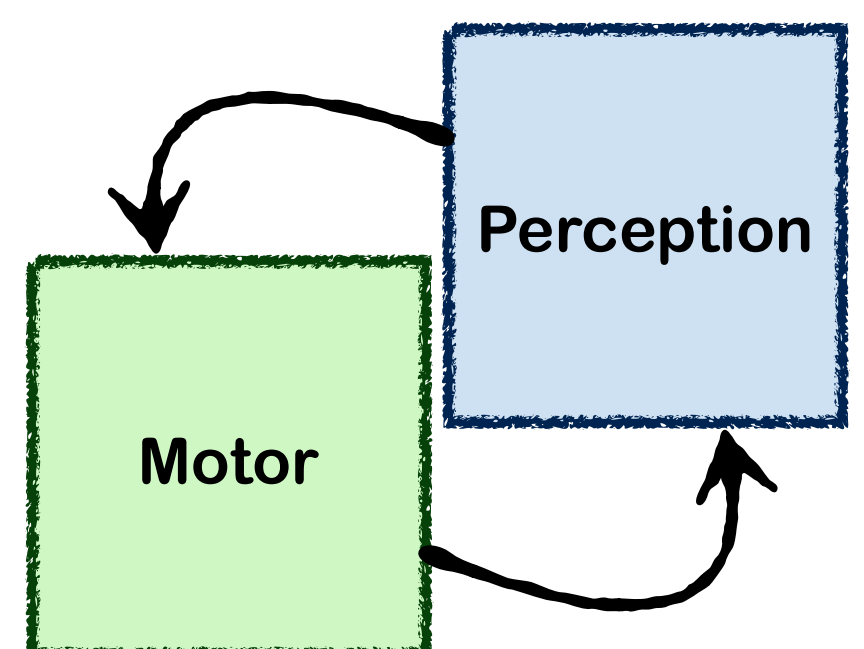
Parameters exploration over time and analysis :

p : (x,y) coordinates
 n : n = 2
 a_1 - (x,y) stimulus center of gravity
 a_2 - (x,y) fixation cross
 β : $1 < \beta_i < 4$
 δ : $1 < \delta_i < 1000$
 ϵ : $\epsilon_k = 1$
 T : $T_k = 5$

Can we link **spatial attractors** to **perceptual attractors** ?

By inferring the parameters of the functions that connect the oculomotor and perceptual model spaces, it is possible to test predictions and gain insights on the active internal forces that drive the observed dynamics of multi-stability.

Multi-stability as an underlying phenomenon emerging from all decision making: motor, attentional, perceptual



VI. Take Home Messages

- We propose a **generative** model for FEM that is based on the **energy potential** framework and that exhibits multi-stability w.r.t visual attractors.
- Multiple layers of information processing can be linked using this framework into a **meta-model of perception**.
- **Multi-stability can be considered an underlying phenomenon emerging in all decision making systems in this framework** (e.g. motor, attentional, perceptual).