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A multi-stable gravitational approach to fixational eye movements

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Agenda

- Context:
 - Experimental work on bi-stability
 - Observations of micro-pursuits
 - Current models of Fixational Eye Movements (FEM)
- Model description
- Perceptual multi-stability perspectives

Context

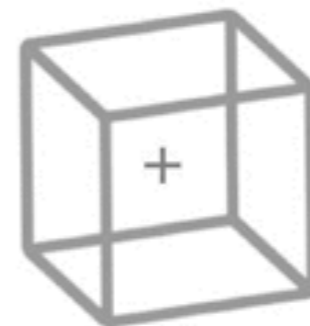
Motion on a Necker cube



FX



RW



LJ

Manipulate perceptual reversal dynamics of bi-stability (Necker cube) using retinal image motion:

FX: no stimulus motion (fixed)

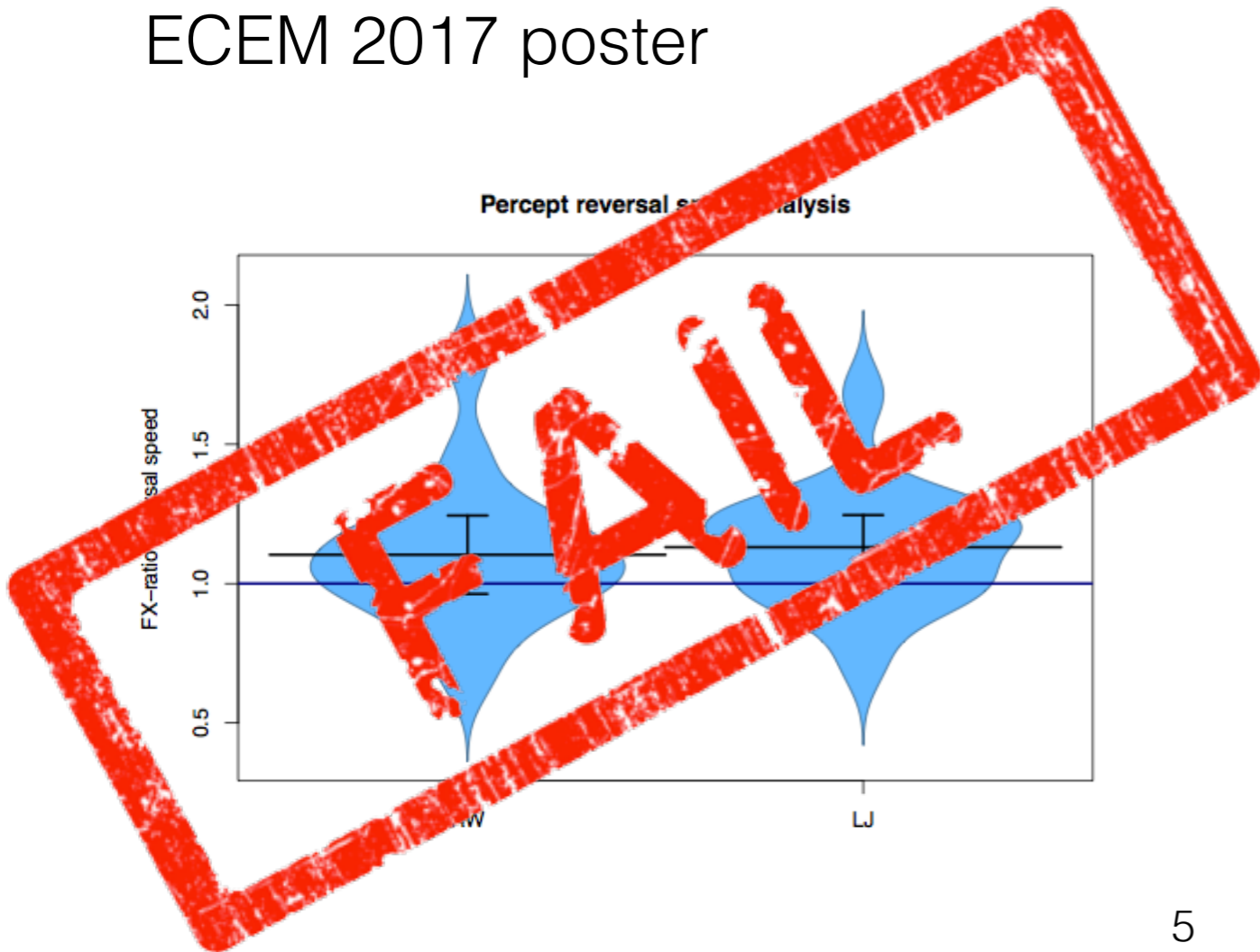
RW: unpredictable pseudo-random movement (random walk)

LJ: predictable smooth Lissajou trajectory

Experimental results

Perceptual dynamics results did not agree with hypotheses driven from bi-stability models

We investigated for a possible explanation in **ocular data**; ECEM 2017 poster



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Motion on a Necker cube leads to micro-pursuit-like eye movements and affects the dynamics of bistability

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Theory: models of perceptual bistability (Moreno-Bote et al., 2011 & Shpiro et al., 2009) are governed by two forces: *adaptation* & *noise*.

Experiment goal: manipulate perceptual dynamics using retinal image motion.

Method: Unpredictable motion → add noise & predictable motion → mitigate neural adaptation

Objectives

Study the effects of adaptation and noise on perceptual reversal speed:

Noise ↗

Probability of percept reversal ↗

Percept reversal speed ↗

RW

Retinal image motion ↗

Adaptation ↘

Percept reversal speed ↘

LJ

Theoretical models of bistable perception

Bistable perception: oscillation between different perceptual states under constant physical stimulus.

Models: Constant stimulation → neural adaptation → periodic suppression of alternative percept energy → adaptation drives the choice of percept.

Hypothesis: Predictable retinal image motion

- ↪ counteract adaptation effect
- ↪ observe lower reversal speed (cf. binocular rivalry results from Blake, Sobel & Gilroy, 2003).

Models: Visual processing noise → noise triggers percept reversal.

Hypothesis: Unpredictable retinal image motion

- ↪ variance of visual information input
- ↪ increase system noise
- ↪ observe higher reversal speed.

Figure 1: Schematic diagram of bistable energy potential.

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Eye-tracking analysis

Adaptation mitigation based on predictable motion of retinal image → excite new populations of neurons.

Δ Warning: depends on participants' gaze stability on fixation cross.

Measures:

M1. Inertia: $I_s = \frac{1}{N_s} \sum_{i=1}^N (x_i^2 + y_i^2)$ N_s : number of signal samples, (x_i, y_i) : spatial coordinates of signal s adjusted to different referential (e.g. center of screen, center of fixation, stimulus position, etc)

M2. Mutual information: $I(X;Y) = H(Y) - H(Y|X)$ with $H(Y)$ the marginal entropy and $H(Y|X)$ the conditional entropy under the assumptions of normal joint distribution and independence.

Fixational eye movements (FEM) displacement, mean sequence inertia (see M1) w.r.t. fixation event position (see Fig. 4a):

FX = RW
FX & RW < LJ

↪ LJ condition generates more FEM displacement than FX & RW.

Figure 4a: Statistics of inertia (log-scale) of gaze samples against fixation positions.

Experimental protocol

Task: stare at fixation cross (screen center) during a sequence of stimulus presentation (Necker cube - Fig. 2a) & report perceptual changes with keypad.

Participants: n = 26 (16 females and 10 males, M(age) = 28.35, SD(age) = 10.93, range = 20-71). 16 participants were analyzed after outliers & incoherent data removal.

Conditions:

FX: no stimulus motion (Fixed).

RW: pseudo-random movements (Random Walk)

LJ: smooth Lissajou trajectory

↪ Global sequence motion was matched between RW & LJ → 36 deg/sec

Experimental design: 3 blocks of 15 sequences (pseudo-random shuffle) of 5-9 reversals.

Figure 2a: Necker cube stimulus (Kormmeier & Bach, 2005)

Figure 2b: (left) Stimulus centre of gravity motion in RW, (right) Stimulus centre of gravity motion in LJ.

Figure 2c: Cube gravity centers for a RW sequence: S10, Seq 16

Figure 2d: Cube gravity centers for a LJ (LJ) sequence: S10, Seq 3

Figure 2e: Example of spatial trajectories over a fixation in ocular data.

Figure 2f: Statistics of mutual information. Black bars indicate mean and 95% confidence interval for the 16 participants. Color indicates the distribution of MI for each group - stimulus sensitive (n=9) & task focused (n=7) - based on their MI in LJ.

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Behavioral analysis

Percept reversal speeds (RS) calculated from measured phase times. As in Blake et al., (2003) RS [rev/min] was computed:

$$RS_{rev} = \frac{n_{rev} \times 60}{T_{seq}}$$

n_{rev} : number of reversals, T_{seq} : sequence total time.

Results:

RW will increase RS → **not strong enough**

LJ will decrease RS → **opposite**

LJ results differ from binocular rivalry (Blake, Sobel & Gilroy, 2003)

Figure 3: Violin plot of FX-ratio percept reversal speed with means and 95% confidence intervals.

Retinal image displacement analysis

Retinal image displacement, mean fixation inertia (see M1) w.r.t. gaze position (see Fig. 4d):

FX = RW = LJ

RW & LJ: variance of stimulus sensitive group smaller than task focused group.

↪ RW & LJ tend to affect control of retinal image motion in stimulus sensitive group.

Figure 4d: Statistics of inertia (log-scale) of retinal image shifts per condition and participant group.

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Conclusions

Stimulus motion leads to an increase in reversal speed as predicted by models but effect size is small.

Predictability of motion does not modulate noise and adaptation as expected. Retinal image shifts partially compensated by micro-smooth pursuits but does not suffice to explain behavioral results.

Experimental observations: Micro-movements of the eyes in the form of approximate smooth pursuits within fixation events detected → not studied in the context of multi-stability to our knowledge

↪ development of a multi-stable gravitational attractor-based model of fixational eye movements (Parisot et al., ECVF 2017).

References

Blake, R., Sobel, K. V., & Gilroy, L. A. (2003). Visual motion retards alternations between conflicting perceptual interpretations. *Neuron*, 39(5), 869-878.

Leopold, D. A., & Logothetis, N. K. (1999). Multistable phenomena: changing views in perception. *Trends in cognitive sciences*, 3(7), 254-264.

Kormmeier, J., & Bach, M. (2005). The Necker cube—an ambiguous figure disambiguated in early visual processing. *Vision research*, 45(8), 955-960.

Shpiro, A., Moreno-Bote, R., Rubin, N., & Rinzel, J. (2009). Balance between noise and adaptation in competition models of perceptual bistability. *Journal of computational neuroscience*, 27(1), 37-54.

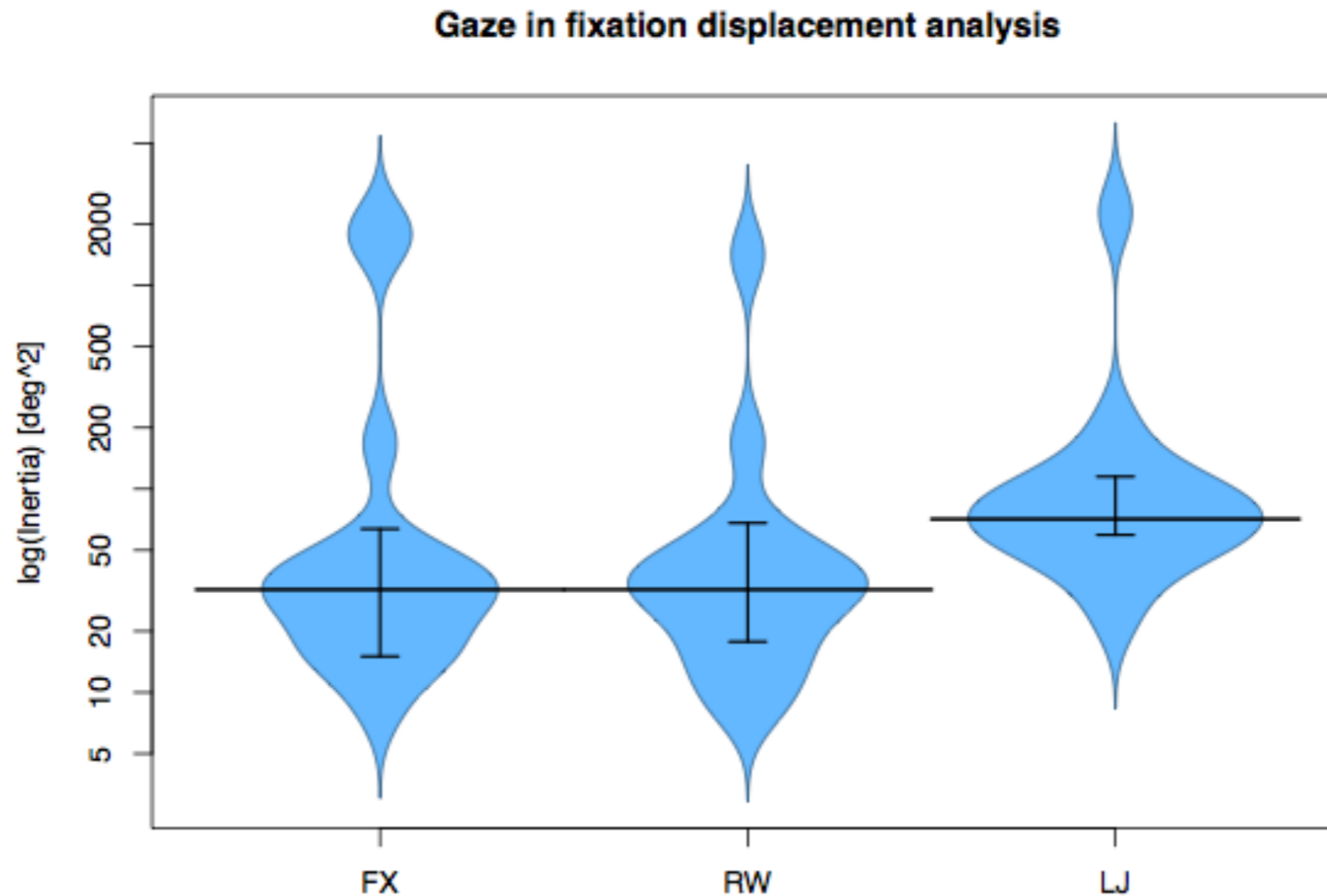
Moreno-Bote, R., Knill, D. C., & Pouget, A. (2011). Bayesian sampling in visual perception. *Proceedings of the National Academy of Sciences*, 108(30), 12491-12496.

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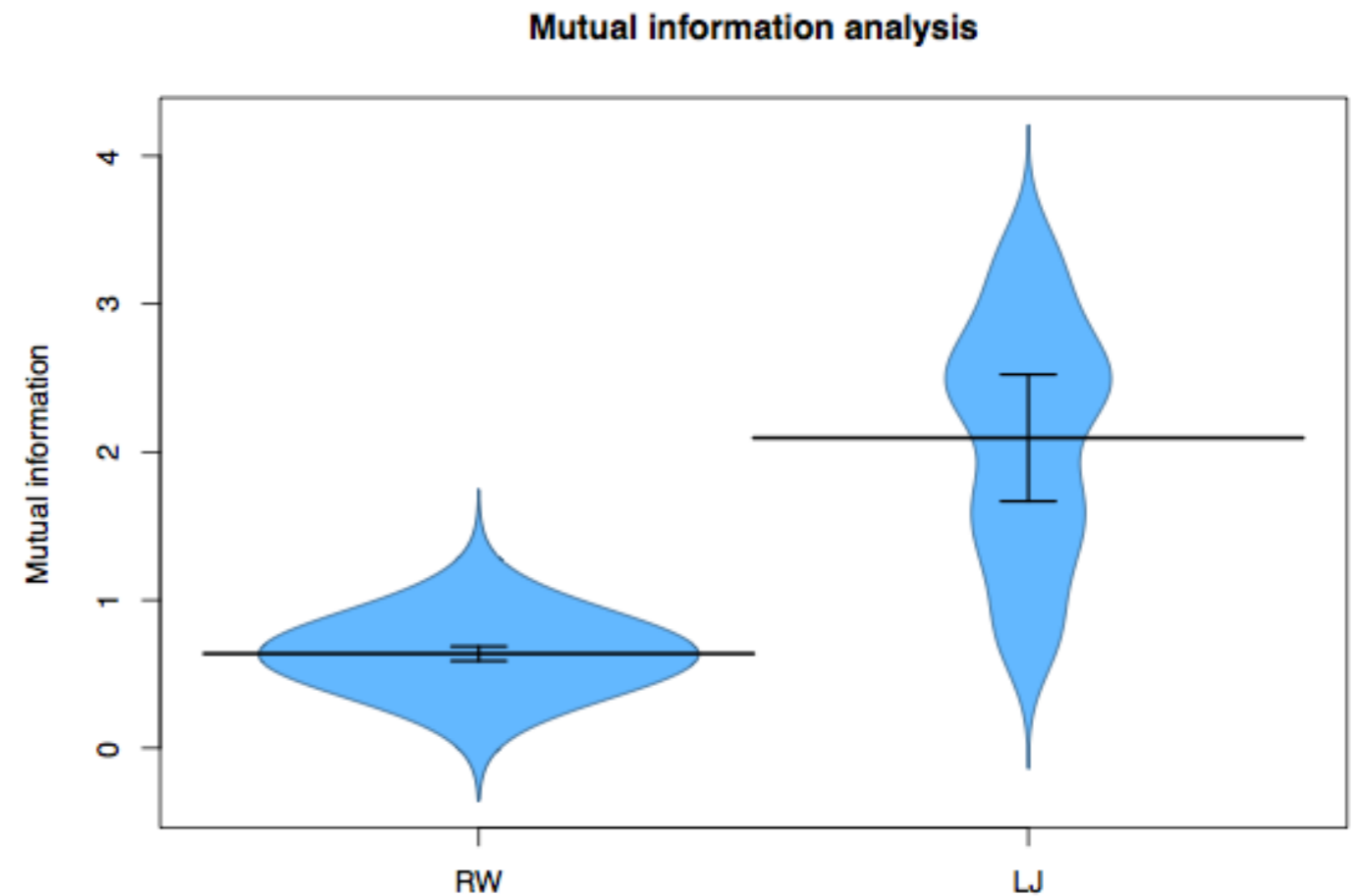
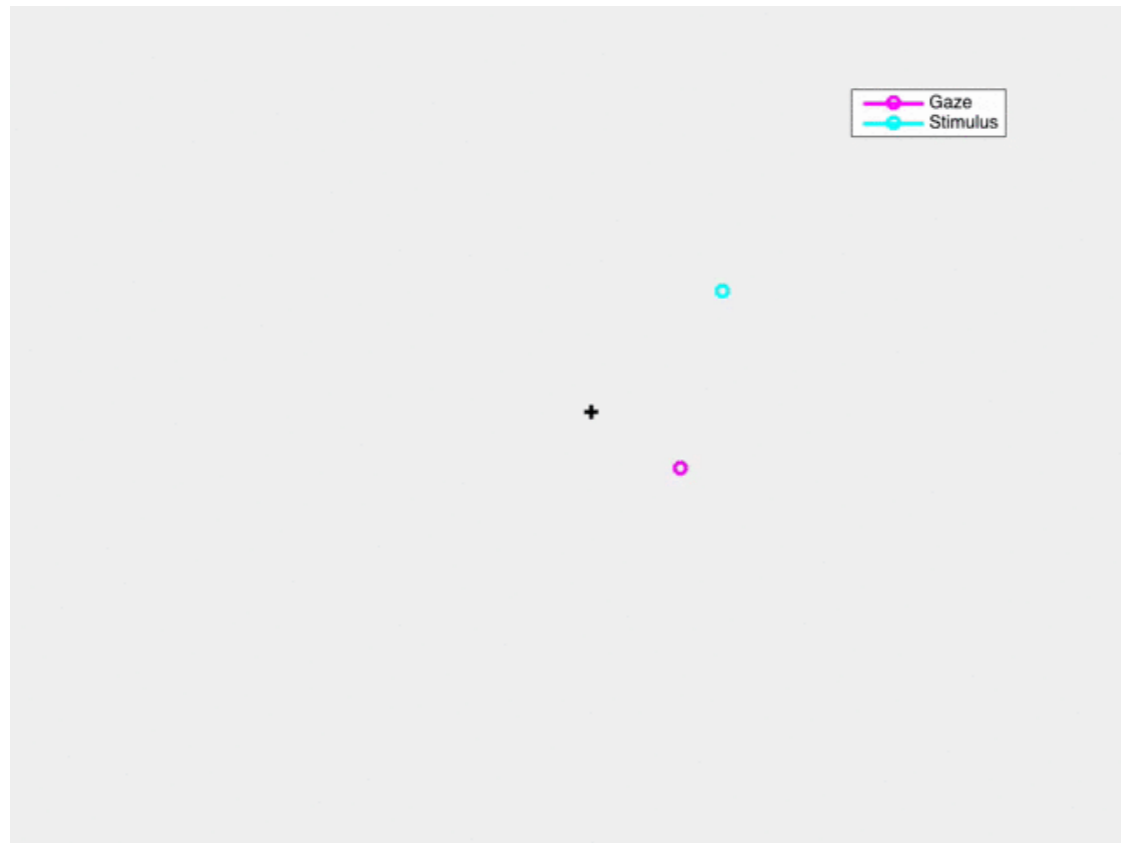
Fixational Eye Movements

Investigation of Fixational Eye Movements (FEM) displacement

Predictable condition (LJ) had higher gaze motion w.r.t. center of fixation than other conditions



Micro-pursuit eye movements



Observation of **small amplitude smooth pursuit-like fixational eye movements** ($FEM < 1^\circ$):

Mutual information used as a measure of similarity between Gaze and Stimulus

Only observed once before: Martins, A. J., Kowler, E., & Palmer, C. (1985).

JOSA

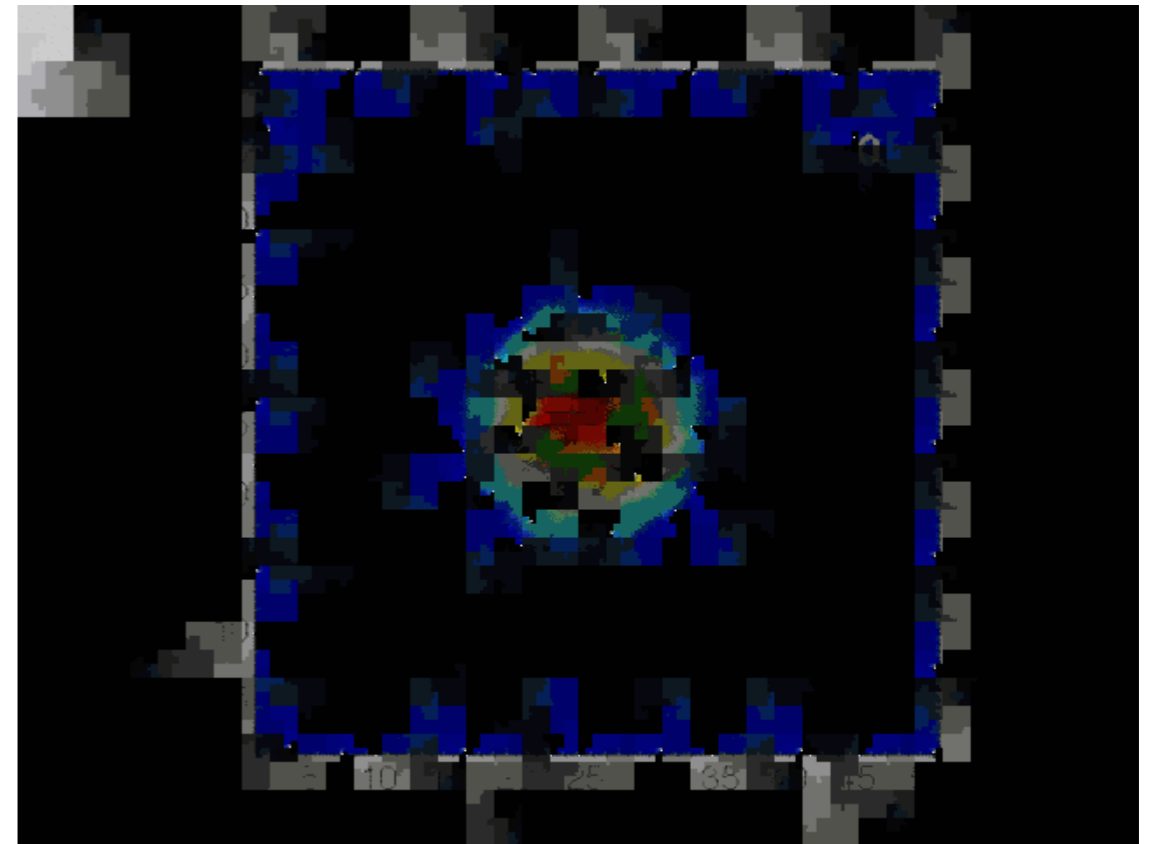
Fixational Eye Movements models

Compatibility with micro-pursuit eye movements?

Current generative model:

- Integration of micro-saccades, small amplitude saccades, and other FEM
- Use of **potential fields**

To our knowledge, no model can account for micro-pursuit eye movements!



Engbert, R., Mergenthaler, K., Sinn, P., & Pikovsky, A. (2011). *PNAS*

Sinn, P., & Engbert, R. (2016). *Vision research*

Model Description

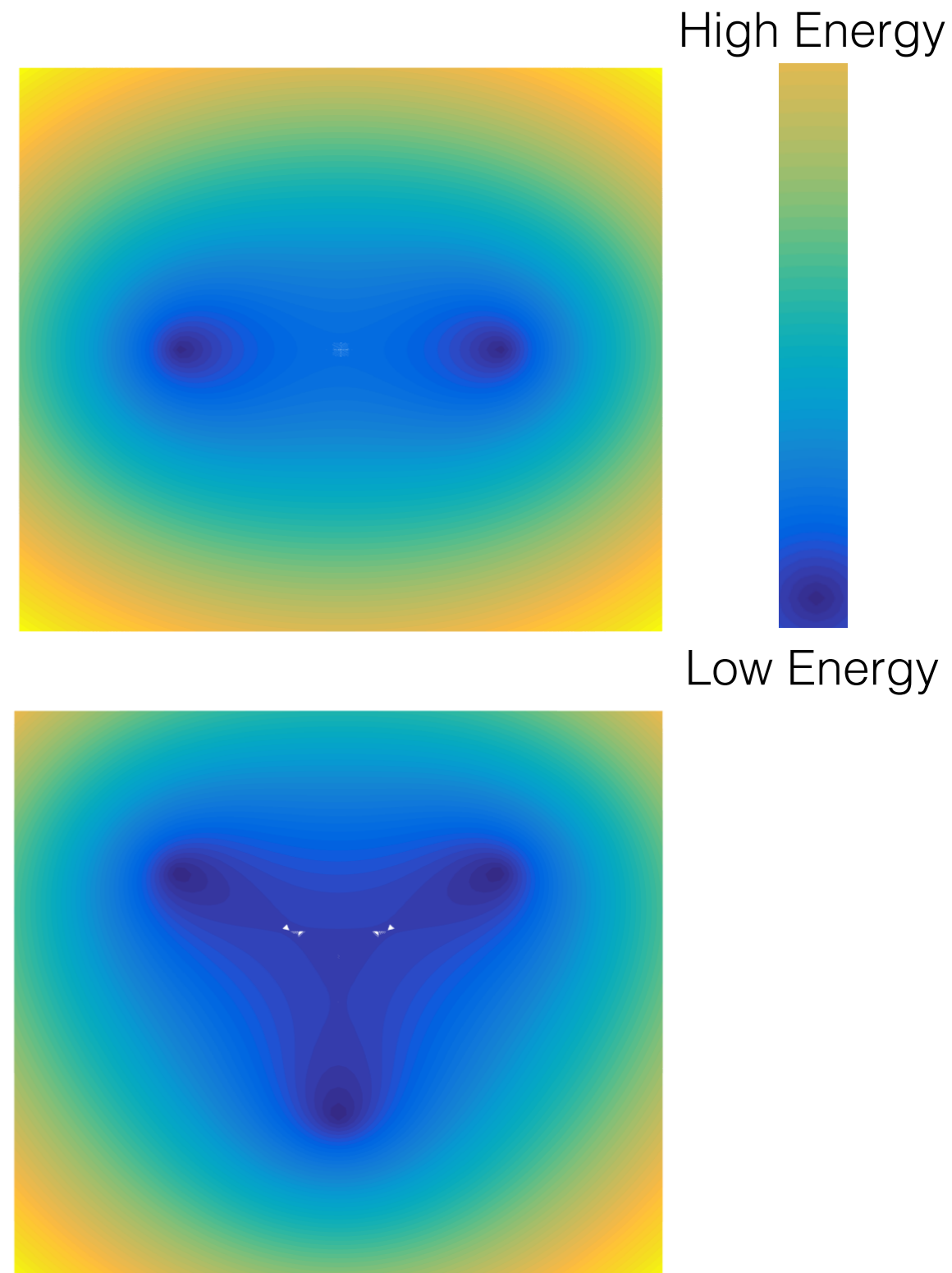
GraFEM: Gravitational potential Fixational Eye Movements model

Map of visual field

Gravitational energy **potential field (V)** can generate multiple **attractors**

Attractor **parameters:**

- position (x,y coordinates)
- depth (energy)
- slope

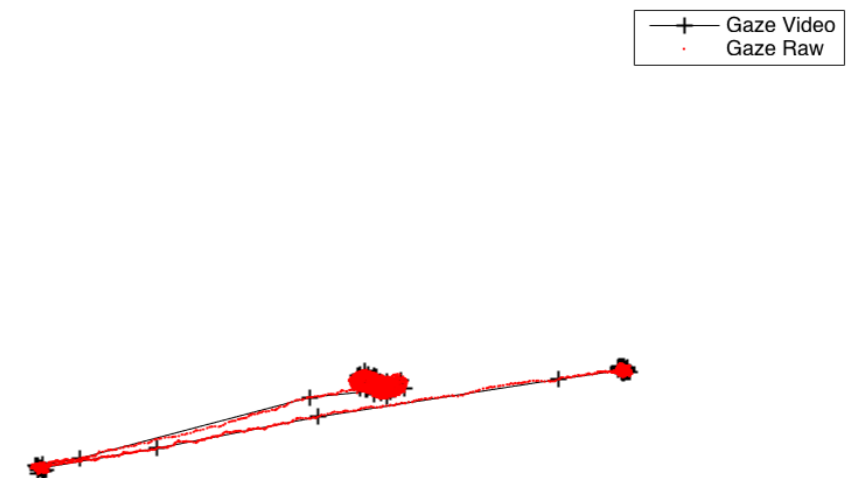
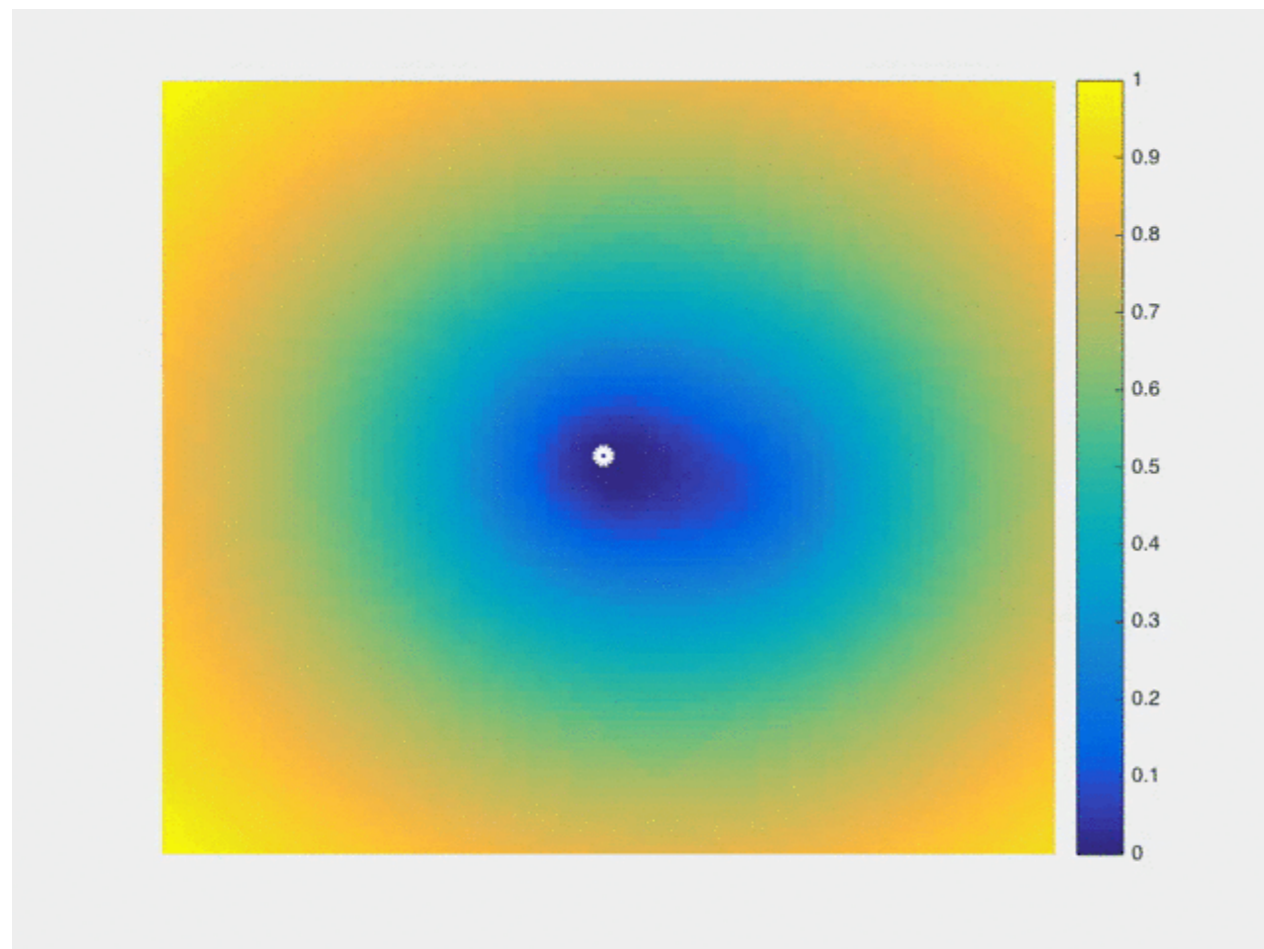


Gaze: a particle in the energy potential

Gaze-dynamic: **particule (p)** in the **potential field** and with added **noise**

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

Result:

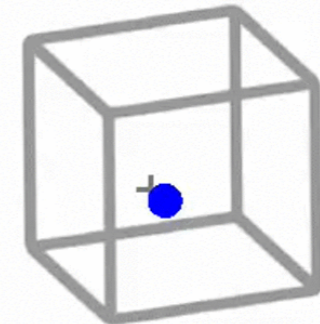
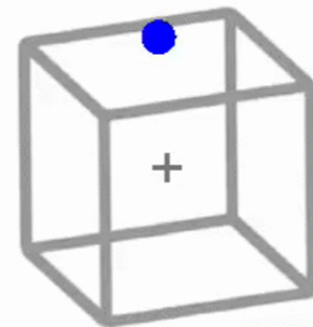
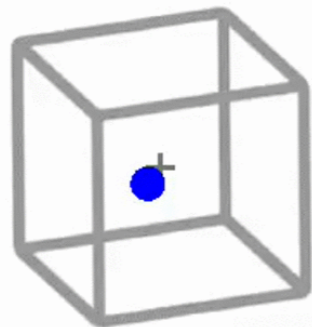
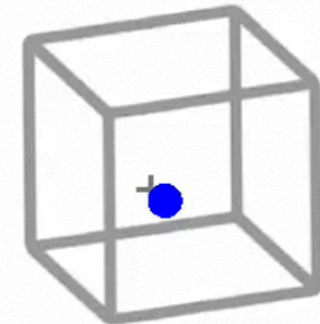
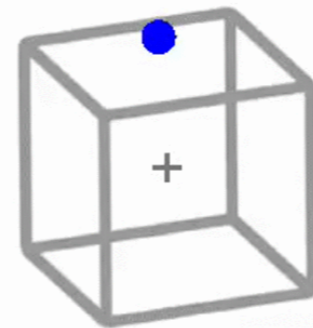
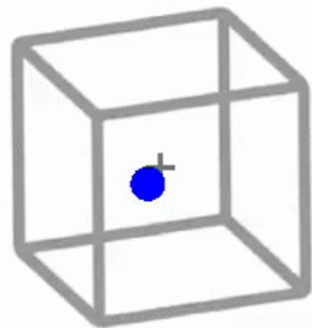


FEM simulations

Fixation

Micro-saccade

Micro-pursuit



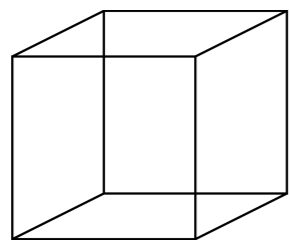
Can you differentiate the lines with simulation or data?

Perceptual multi- stability perspectives

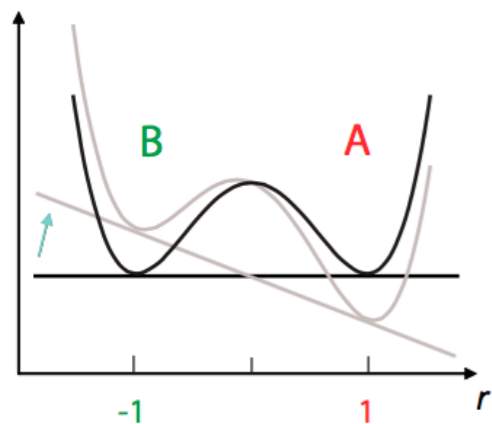
GraFEM: a multi-stable model?

GraFEM → **multi-stable** model with **spatial attractors**

Multi-stable models → predict perceptual dynamics and behavior for ambiguous figures (e.g. bi-stability) where **attractors are perceptual states**

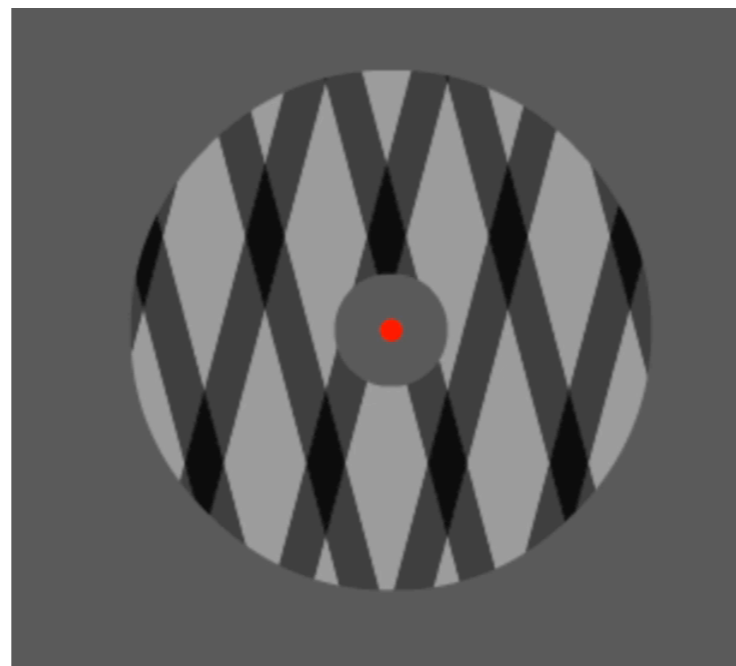


Necker cube

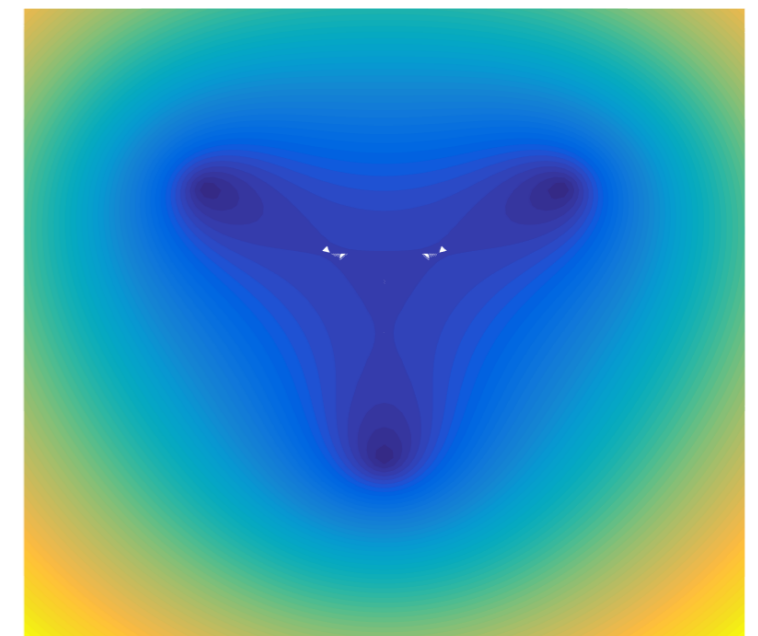


Bi-stability

⋮



Tri-stability



Moreno-Bote, R., Rinzel, J., & Rubin, N. (2007). *Journal of neurophysiology*

Moreno-Bote, R., Knill, D. C., & Pouget, A. (2011). *PNAS*

Huguet, G., Rinzel, J., & Hupé, J. M. (2014). *Journal of vision*

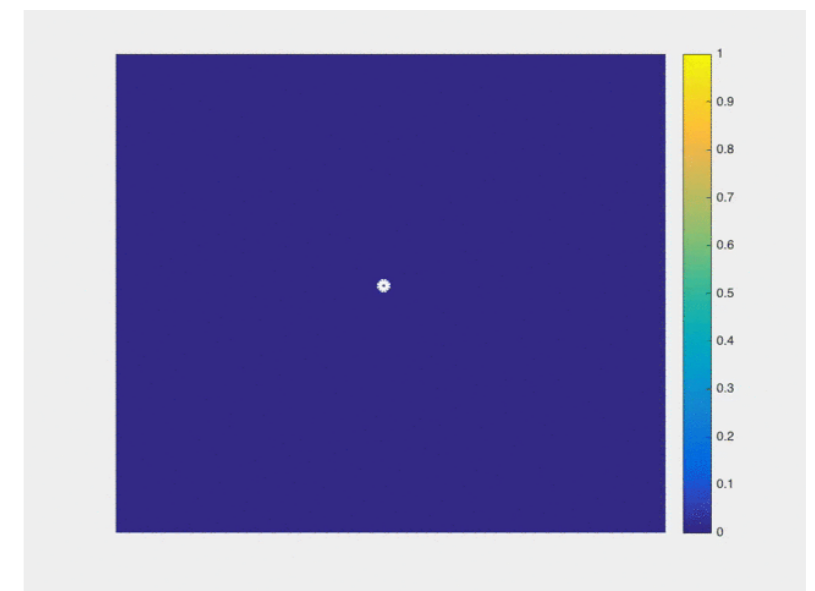
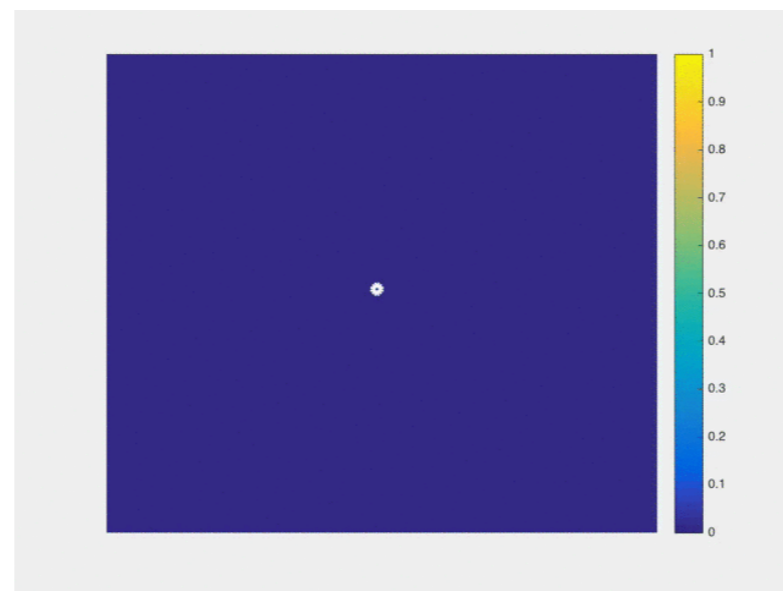
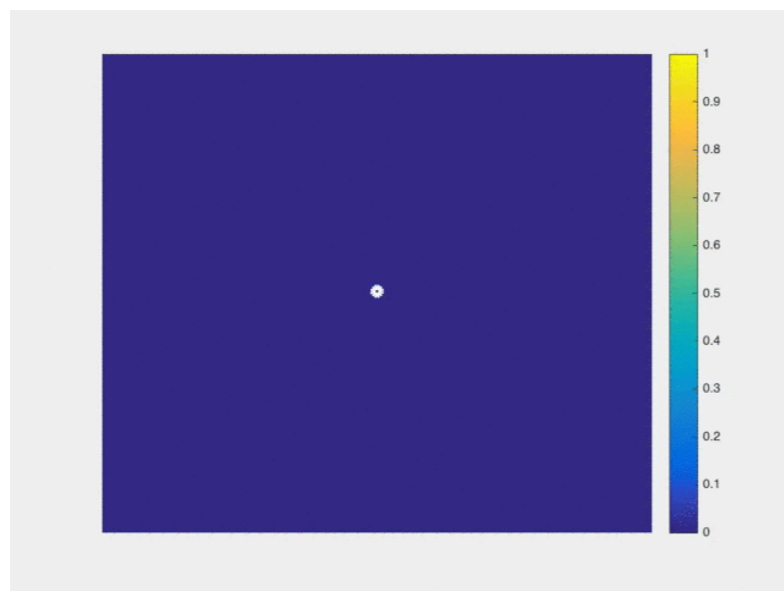
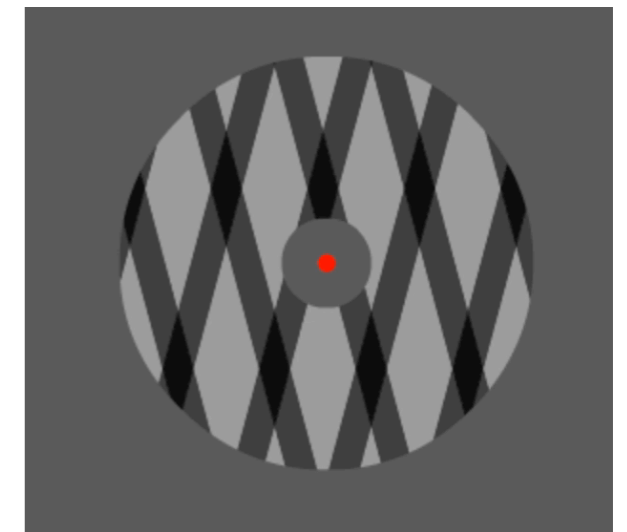
http://www.cerco.ups-tlse.fr/~hupe/plaid_demo/demo_plaids.html

Perspectives

Integration of both spaces to investigate interactions between eye movements & visual perception

Moving plaids: first naïve approach

Eye movement **predictions** on perception?



Take home message

- Observations of **micro-pursuits** FEM: only observation since Martins, Kowler, & Palmer, (1985). *JOSA*
- Description of **GraFEM**: an FEM generative model that can be extended to **all eye movements**
- GraFEM is multi-stable w.r.t. spatial attractors
- Development of links between eye-movement and perceptual models



GraFEM