A Retinotopic neural fields model of perceptual switching in 2D motion integration

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Abstract

The underlying cortical dynamics that select one percept out of multiple competing possibilities are not fully understood. Switching behaviour for a classical psychophysics stimulus, the multistable barberpole, was successfully captured in a feature-only, one-layer model of MT with adaptation and noise. However, without a representation of space, only some very specific stimulus could be considered. Here we propose a model that takes into account the spatial domain in a two-layer configuration modelled MT and VT cortical areas whilst incorporating adaptation to drive switches.

Keywords: Motion Perception, Multistability, Neural fields, Dynamical systems, Competition, Bifurcation

Context and motivation

Psychophysical observations on motion perception

• Motion perception results from a non-local integration process
• Motion integration is a dynamical process (Mason, Rybaczuk, et al., Visual Neuroscience 2000)

About underlying neural mechanisms and cortical area MT

• Several cortical areas are involved in motion estimation
• MT is highly specialized for visual motion (Born and Bradley, 2005)
• MT has a rich set of interconnections with other regions, including feedbacks to V1 (Angelucci and Buller, 2003)
• Cortical responses of MT have been linked specifically to the perception of motion (Britten, 2003)

Modeling neural mechanisms of motion perception

• Building on the first linear/non-linear models (Chey et al. 1997; Simoncelli and Heeger 1998), several approaches added extensions to modulate the motion integration stages: feedback between hierarchical layers (Groens et al. 2001; Bayer and Neumann 2004), inclusion of input form cues (Berthamyska et al. 2007; Bayer and Neumann 2007), luminance diffusion filtering (Tlapale et al. 2010), or depth cues (Black and Neumann 2010)
• Although these models reproduce the predominant percepts in a wide range of stimuli, in none of the articles describing them are multistable results depicted

About this work

• We work within the neural fields formalism: Neural fields are spatially structured neural networks which represent the spatial organization of cortical cortices; the neural field approximation represents the mean firing rate of a neural population at the continuum limit (Breussolff, 2012)
• Neural fields equations have been successfully applied to the study of motion in, e.g., Giese (1998), Daco and Roland (2010) and Tlapale et al. (2010a)
• We aim to develop tractable models of manageable complexity that allow for a detailed study of the temporal dynamics of multistable motion perception using powerful tools from dynamical systems theory

A neural field competition model to study multistability

J. Rankin, A. I. Mao, et al., Bifurcations study of a Neural fields Competition Model with an application to perceptual switching in Motion Perception, Journal of Computational Neuroscience, 2013

• One cortical area, feature only
• Continuous representation of MT activity across direction space \( p(t, \theta) \)
• An adaptation on the slow-time scale \( \alpha(t, \theta) \)
• Noise included in the model for comparison with psychophysics \( \Xi(t, \theta, \phi), \text{see paper} \)

A slow-fast system

\[
\frac{d\alpha}{dt} = -\alpha(t, \theta) + S(\xi(t, \phi) + \sigma(t, \theta) - \alpha(t, \theta) + X(t, \theta, \phi) + k_2(p)),
\]

\[
\frac{dX}{dt} = \sigma(t, \theta, \phi) + \alpha(t, \theta) + \sigma(t, \theta) \]

Description of the input

• Summary of results from Rankin, Mao et al. 2013
• We investigated multistability w.r.t contrast alongside concurrent psychophysics experiments
• Modeling results showed a shifting balance between adaptation and noise drives switching in different contrast regimes
• We provided predictions to test this hypothesis in psychophysics

Symmetric/Asymmetric aperture

• Examples of simulations (without noise)
• Qualitative study without noise
• A regime predicted in the simulations is not feasible for experimental study – How to select the aperture ratio to reflect the shape of the aperture?

Extension: Two cortical retinotopic areas

• Main features
  • Two cortical areas: V1 \( p_1(t, \theta, \phi) \) and MT \( p_2(t, \theta, \phi) \)
  • Feedforward integration \( G \)
  • Modulatory feedback \( \lambda \)
  • Lateral connectivity \( J_1 \) and \( J_2 \)
  • Adaptation at the level of MT \( \lambda \alpha(t, \phi, \theta) \)

• Mathematical description of the model

\[
\frac{d\alpha_1}{dt} = -\alpha_1(t, \theta, \phi) + S_1(\xi_1(t, \phi) + \sigma_1(t, \theta) - \alpha_1(t, \theta) + X_1(t, \theta, \phi, \phi) + k_2(p_1)),
\]

\[
\frac{d\alpha_2}{dt} = -\alpha_2(t, \theta, \phi) + S_2(\xi_2(t, \phi) + \sigma_2(t, \theta) - \alpha_2(t, \theta) + X_2(t, \theta, \phi, \phi) + k_2(p_2)),
\]

• Description of the input

• After discretization, the dimensionality of \( p_1(t, \theta, \phi) \) and \( p_2(t, \theta, \phi) \) at any time \( t \) is 256 x 256 x 64
• The simulations are performed with help of GPUs using CUDA.

Results

• Our feature only model has been previously used to study multistable switching for a symmetric aperture
• It can also capture asymmetry but it is ignoring the detail of the spatial interaction
• We proposed a retinotopic model that includes recurrent multi layer interactions that modulates motion integration and captures multistable behavior
• The retinotopic model allows us to investigate other stimuli
• We will use bifurcation analysis to investigate selectivity properties of different kernels (e.g., subtractive inhibition, DOG)

Conclusion

• Videos are available

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