Modeling the Neocortex with Meso-scale Models and Population Models

Sid Visser

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Motivation

Our brain is

- important
- complex
- prone to disorders
- hard to diagnose
Motivation

Our brain is

▶ important
▶ complex
▶ prone to disorders
▶ hard to diagnose
Outline

Introduction
  ▶ Background
  ▶ Definition of problem

Different models
  ▶ Meso-scale
  ▶ Population

Analysis
  ▶ Comparison
  ▶ Conclusions
About the neocortex

- Wrinkled surface on top
- 40cm x 40cm
- About 20\text{e9} brain cells
- Divided into layers
- Communicates on all spacial scales
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Figure 10. Nissl (left) and cytochrome oxidase (right) labeled cross sections of the visual cortex of a macaque monkey, showing the individual layers.
How to model?

Detailed

- Every neuron is modeled individually
- Lots of physiological parameters
- Hard to analyze

Population

- Populations of neurons are considered
- Few parameters that have little physiological relevance
- Allows some analysis
How to model?

**Detailed**
- Every neuron is modeled individually
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**Population**
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Goal of this research

- How well do population models match detailed models?
- Can parameters of both models be related?
- Can the behavior of either model be predicted by the other?
- Can a population model be expanded to a full-brain model?
- What physiological information can be obtained from EEG?
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Detailed model

Set-up

- Network of 656 cells (of 6 types)
- Realistic model for ion flows
- ±43000 connections
- Each connection has a unique delay
- Many realistic parameters
Which parameters?

- Global parameters
- Parameters that can be related to drugs, like
  - Anti-epileptic drugs
  - Novocaine
Which tools?

**Individual cells**
- Mean firing rate

**Populations**
- Population firing rate

**Network**
- Average of all activity
- Artificial EEG
Which tools?

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Which tools?

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Network
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Results

What does it look like? Click for animation
Increasing excitation

E-levels: **Low** - **Moderate** - **High**
Increasing excitation

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Increasing excitation

E-levels: Low - Moderate - High

![Graph showing local field potential over time with increasing excitation levels.](image-url)
Increasing excitation

E-levels: Low - Moderate - High
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Increasing excitation

E-levels: Low - Moderate - High

![Graph showing mean firing rate (Hz) for varying cell IDs and E-levels. The x-axis represents cell ID, and the y-axis represents mean firing rate (Hz). The graph displays data points for E-levels Low, Moderate, and High, with clear differentiation between them.]

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'Ping-pong' effect (oscillations)

- Delays play an important role!
Multistability and hysteresis

Multistability

- The system can have multiple equilibria/attractors
- These are hard to study in complex systems

Hysteresis

- Some attractors cease or lose stability for changes of parameters
- Multistability can be studied by slowly adjusting a parameter
Multistability and hysteresis

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Hysteresis

- Some attractors cease or lose stability for changes of parameters
- Multistability can be studied by *slowly* adjusting a parameter
Detailed model (overview)

Model
- 656 cells
- Realistic connections

Results
- Burst-suppression
- Oscillations
- Continuous activity
- Multistability and hysteresis
Population model (overview)

Set-up

- Firing rate population model
- Delay Differential Equations with 2 delays
Two populations:

\[ \dot{x}_1(t) = -\mu x_1(t) - F(x_1(t - \tau_i)) + G(x_2(t - \tau_e)) \]
\[ \dot{x}_2(t) = -\mu x_2(t) - F(x_2(t - \tau_i)) + G(x_1(t - \tau_e)) \]
Model

Two populations:

\[
\begin{align*}
\dot{x}_1(t) &= -\mu x_1(t) - \mathcal{F}(x_1(t - \tau_i)) + \mathcal{G}(x_2(t - \tau_e)) \\
\dot{x}_2(t) &= -\mu x_2(t) - \mathcal{F}(x_2(t - \tau_i)) + \mathcal{G}(x_1(t - \tau_e))
\end{align*}
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Two populations:

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Two populations:

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\end{align*}
\]
Choose $\mathcal{F}(x)$ and $\mathcal{G}(x)$ as sigmoidal functions:

$$(\tanh(x - a) - \tanh(-a)) \cosh^2(-a)$$
Remarks

Negative activity

- Negative values for $x_1$ and $x_2$ are allowed
- They represent a suppression of background activity

Parameter

- A similar parameter is chosen as in detailed model
Remarks

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**Parameter**

- A similar parameter is chosen as in the detailed model
E-levels: Low - Moderate - High
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Analysis
Analysis
Analysis

Range

$\mu$

$\mu$

Range
Population model (overview)

Model
- Firing rate population model
- Delay Differential Equations with 2 delays

Results
- Steady states at high or low activity
- Self-sustainable oscillations of 50Hz
- Bifurcation analysis reveals multistability
## Overview of types of behavior

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Detailed</th>
<th>Population</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>Burst-suppression</td>
<td>Background activity</td>
</tr>
<tr>
<td>Mod.</td>
<td>50Hz oscillations</td>
<td>50Hz oscillations</td>
</tr>
<tr>
<td>High</td>
<td>Saturated</td>
<td>Steady state at high activity</td>
</tr>
</tbody>
</table>
Summary and conclusions

Methodology

▶ Detailed model is developed of neocortex
▶ Populations are modeled with DDE system with 2 delays

Analysis and results

▶ Some parameters in both models can be related
▶ Both models are able to show similar behavior
▶ Bifurcation analysis provides new insights in multistability of both models