Using Dynamic Field Theory to Bridge Brain and Behavior

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• How do neural processes give rise to cognition? What is the relationship between neural dynamics and behavioral dynamics?

• Dynamic Field Theory
  • Dynamical Systems theory
  • Embodied cognition
  • Neurocomputational framework

• First, basics of the modeling framework
• Then I’ll step through two different ways I have used this framework to integrate brain an behavior
Principles

• Simulate neural dynamics as activation variables over a field that is tuned to some stimulus or response dimension
  • Can think of activation as a temporally smoothed firing rate, intra-cellular potential, or as a local ensemble firing rate of a small population
  • Simulate population dynamics rather than individual neurons

• Activation is dominated by recurrent interactions (95-98% of cortical connections are not part of feedforward stream)

• Implemented as a dynamical system \( (u) \) which is a functional relationship between the rate of change \( (du/dt) \) and the current level of activation, \( u(t) \)
Equations

\[ \dot{u}(t) = -u(t) + h_u + \delta(t) + S(t) + \sigma(u(t))c_{uu} \]
Dynamics

\[ \dot{u}(t) = -u(t) + h_u + \delta(t) \]
Stability is important for...

- Decision making
  - Not just reading out which response is more probable or more strongly represented
  - Actively selects a response in real-time; decisions can fluctuate based on noise or other types of interactions within a more complex network

- Maintenance
  - Information representations can extend through time and in the absence of stimulation

- Driving a motor system (not addressed in the current talk)
Equations

\[ \dot{u}(x, t) = -u(x, t) + h_u + S(x, t) + \int c_{uu}(x - x')\sigma(u(x', t)) \, dx' - \int c_{uv}(x - x')\sigma(v(x', t)) \, dx' \]

\[ \dot{v}(x, t) = -v(x, t) + h_v + \int c_{vu}(x - x')\sigma(u(x', t)) \, dx' \]

Within a field representation Basic network is composed of an excitatory and inhibitory field

- Keep activation localized and is critical aspect of stability

- Induce competition between alternative representation (selectivity)
Representational Format

- Embodiment: representations are grounded in some aspect of perception/action

- More complex/”abstract” representations can be built by coupling fields along different dimensions (association areas)

- Architectures connecting excitatory and inhibitory populations in different ways can accomplish different functions
Mapping to Behavior

• RT and accuracy can be easily estimate based on the information activated for the response on each trial
Mapping to the Brain

• Blood-flow response is driven by population-level activity rather than the activity of individual neurons—Local Field Potential

• LFP: Low-frequency component of extra-cellular voltage; both excitatory and inhibition electrical current; measure of local input to, and local processing within a region of cortex

Logothetis et al. (2001)
Basic Method for Simulating Hemodynamics

• Estimate a LFP from the model, convolve with impulse response function, analyze like brain data

-LFP: summed absolute value of synaptic interaction
Target Problem

• Executive function: collection of processes that achieve goal-directed and flexible behavior
  • Functional outcomes such as inhibition, working-memory (maintenance, protection from distraction), task-switching (shifting/updating)
  • Selecting actions in arbitrary situations based on rules or learning
  • Autonomy; emergent control
Big Picture

Word-Object WM

Word-Object Attention

Allocentric Object WM

Allocentric Object Attention

CF and WM fields

Feature Attention

Retinal Perceptual System
Example 1: Development of Flexible Rule-Use

- Dimensional Change Card Sort (DCCS) Task

3-year-olds predominantly perseverate
4-year-olds predominantly switch

Development tied to changes in dimensional attention; stronger associations between labels and feature representations
Example 1: Development of Flexible Rule-Use

→ Simulation
Example 1: Development of Flexible Rule-Use

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Example 1: Development of Flexible Rule-Use

Hemodynamic Predictions

Frontal
Spatial
Featural

% Switch

Time from task onset (s)

Data Fits and Predictions

Hemodynamic Predictions

Frontal
Spatial
Featural

% Switch

Time from task onset (s)
Example 1: Development of Flexible Rule-Use

- Near-infrared spectroscopy
  - Measures blood-flow similar to fMRI
  - Uses 2 wavelengths of light differentially absorbed by oxy-Hb and deoxy-Hb
Example 1: Development of Flexible Rule-Use

Hemodynamic Predictions

- Frontal
- Spatial
- Featural
Example 2: Working Memory

- Change Detection

500 ms Sample Array
1200 ms Retention Interval
1800 ms Test Array
Example 2: Working Memory

→ Movie
Example 2: Working Memory
Example 2: fMRI Analysis Basics

• Typical analysis method is to use a GLM to model the amplitude of the BOLD response associated with different trial types by optimizing a beta parameter

\[ \hat{Y} = X\beta + e \]

• X is a matrix corresponding to the time course of different trial types (0 when trial is absent, 1 when trial is present)
• Substitute X with simulated amplitude of hemodynamics from the model
Example 2: Mapping components

Different system $\rightarrow$ Dorsal attentional network

Same system $\rightarrow$ fronto-parietal network

Also some unique mappings of components to cortical regions
Summary

• DFT provides a process based explanation of the relationship between behavioral and neural dynamics

• Same equations explained brain and behavioral dynamics

• Innovated new methods for analyzing hemodynamic data