Multisensory Predictive Learning

CSE Course on Artificial Neural Networks &
CogSci Course on Modeling of Cognitive Processes
BraSci Course on Computational Neuroscience

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Lecture 1: Dynamic Coordination and Sequence Learning

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Motivating (Big) Questions

• How can brain computation be so flexible and reliable?
• How does brain combine multisensory signals, such as vision, audition, and touch?
• How can the brain compute so fast in language and visual information processing?
• What are the organizational and processing principles used by the brain?
• How does the brain learn continuously from the multisensory data and adapt to a changing environment?
• How can we build brain-like flexible computational systems that learn and adapt continuously and life-long?
How can brain computation be so flexible and reliable?
How can the brain produce mental imagery?

[Image of a person in an MRI machine with notes and brain scans]

PET = Positron Emission Tomography

[Ima: Imagery, Per: Perception, B: Baseline, STG: Superior Temporal Gyrus, Mid F: Middle Frontal, Ant Inf F: Inferior Frontal]

[Kosslyn et al., Nat. Rev. Neuroscience, 2001]
How can brain computation be so fast?
What is the organizational principle of the brain?

Sporns et al., Trends in Cognitive Sciences, 2004
How does the brain integrate the multisensory signals? How does it combine perception, action, and memory?
Course Outline

• Part I: Multisensory Integration
  – Integration of vision and touch
  – Sensorimotor control and learning
  – Bayesian decision theory

• Part II: Sequential Bayesian Filtering
  – Kalman filters
  – Particle filtering
  – Dynamic population coding

• Part III: Prediction in the Brain
  – Predictive brain
  – Simulation and prediction
  – Mental imagery and emulation
Dynamic Coordination
Why are dynamic coordination and sequence learning so fundamental?

• Temporal structure in the world
  – Life is a sequence of interactions with the world
  – Brains are evolved to detect and take advantage of the correlation in interactions

• Action as ordered sequences of muscle recruitment
  – Brains generate motor actions through recruitment of muscles
  – This is constrained by the physics of the world

• Brains as dynamic systems
  – Brains are groups of neurons and ordered couplings between them
  – Because neurons and synapses are endowed with dynamic properties (e.g. receptor kinetics), neural circuits are complex dynamic systems

[Laurent, 2011]
Dynamic Coordination

[Sirota and Buzsaki, 2005]
Dynamic Coordination: Mechanisms

• **Temporal binding**
  – Binding-by-synchrony hypothesis (Singer, Engel, Koenig, et al.)

• **Reversibly switching synapses**
  – Momentarily activate a network of mutual connections (von der Marlsburg)
  – Dedicated control units (Luecke et al.)

• **Several alternate neurons with their own connection patterns**
  – Selecting among these neurons

• **Contextual gain modulation**
  – Amplify relevant activities and suppress irrelevant ones.

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Dynamic Coordination in Visual Perception

[Fregnac et al., 2005]
Sentence Comprehension

Coherence differences between SO- minus SS-sentences (BL-WL)

[Weiss et al., Int. J. Psychophysiol., 2005]
[Weiss et al., Int. J. Psychophysiol., 2005]
Coordination: What It Is and Why We Need It
[von der Malsburg, 2011]

• What is coordination in the brain?
• How is coordination evaluated?
• How is purpose defined, enforced, and achieved?
• How are the environment’s statistics to be captured?
• What is the nature of our environment’s statistics?
• What is the nature of structured relationships?
• How are natural patterns put together?
What Is Coordination?
[von der Malsburg, 2011]

• What are the things that must be put together?
• What does it mean to belong together?
• How does the system learn what belongs together?
• The detection of significant patterns by focal attention
Dynamic Coordination in Brain and Mind
Dynamic Coordination in Brain and Mind  

• How is flexibility combined with reliability?
• How is holism combined with localism?
• What is dynamic coordination?
• What neural mechanisms express dynamic coordination?
• To what extent does dynamic coordination depend on distributed self-organization and to what extent on executive control?
Dynamic Coordination

- Novel context-sensitive patterns of macroscopic activity can be created by modulating the strength and precise timing of local neural signals without corrupting the information that these local signals transmit.
- Distinction between coding and coordinating interactions
- Temporal binding hypothesis
- Holistic organization and locality
Computational Goals of Dynamic Coordination

• Contextual disambiguation
  – Scene perception
• Dynamic grouping
  – Binding problem
• Dynamic routing
  – Communication between brain regions
• Dynamic embedding
  – Linguistic syntax
Dynamic Coordination at Four Levels of Organization

• Evolution level
• Local cortical microcircuits
• Brain systems
• Cognition and behavior
Evolution Level

- Microcircuits
  - Commonalities across species
- System architecture
  - Long-range lateral connections
- Cognitive capabilities
  - Language and consciousness
- Subcortical structures
  - Role of basal ganglia
Microcircuit Level

- Canonical cortical microcircuits
- Elementary computational operations and mechanisms
- Is feedforward transmission driving?
- Glutamate receptor subtypes
- Inhibitory interneurons
- Apical and distal dendritic components
- Windows of opportunity created by rhythmically synchronized disinhibition
- Synaptic assemblies
Brain System Level

• Lateral and descending connections
• Contextual modulation
• Neural basis of gestalt grouping
• Temporal structure and synchrony
• Dynamic linking
• Neuronal basis of attention
• Dynamic routing
• The role of prefrontal cortex
Cognition and Behavior Level

• Gestalt perception
• Contextual disambiguation
• Attention and working memory
• Reasoning
• Central executive functions
• The distinction between multimodal coordination and multimodal sensor fusion
• Bayesian analysis
• The relation between cognition and the precise temporal structure of neural activity
• Disorders of dynamic coordination
Homework

1. One-page summary of the paper by Phillips, von der Malsburg, and Singer, Chapter 1, DCB
2. One-page summary of the paper by von der Malsburg, Chapter 10, DCB