A Dynamic Neural Field Model of the Hemodynamics Associated with Response Selection and Dual-Task Performance

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Response Selection & Dual-Task

- Response selection (RS): process of binding stimulus and response information allowing for meaningful, goal-directed behavior; thus, RS is a fundamental and pervasive aspect of everyday functioning
- Traditional view: amodal central processor, operating over abstract symbols binds stimuli and responses

Why the dual-task paradigm? It reveals fundamental aspects of RS such as resource limitations by pushing RS to the limit
- Subjects are presented with two stimuli simultaneously

Thus, RS has distinct behavioral and neural signatures that are revealed by the dual-task paradigm. A deeper understanding of RS, then, can be achieved by a theory that is able to bridge between brain and behavior, accounting for both types of evidence

Dynamic Field Theory

- DFT moves beyond traditional accounts by grounding RS behaviors in the integration of perception and action using neural population dynamics in a real-time, process-based model.
- What is RS in DFT? It is a dynamic, real-time binding of stimulus and response information achieved by activating neural populations tuned to each dimension and associating them in bi-modal (2D) fields.
- Because DFT simulates behavior through neural population dynamics, we can simultaneously capture behavioral and neural dynamics. Here, we present the first model that is able to quantitatively simulate behavioral and fMRI data in a dual-task paradigm.

The Dual-Task Model

- The model is composed of modality-specific networks of fields (Vis-Man, Aud-Voc, Vis-Voc, Aud-Man). Sensory input fields receive stimuli on a given trial. Once activation peaks build, these fields project activation to modality-specific 2-Dimensional SR fields. The SR fields form associations between stimuli and responses. SR peaks build in these fields and then project activation to motor output fields which drive behavior.
- As peaks of activation are built (reflecting the selection of responses), Hebbian traces accumulate for particular SR associations. This makes peaks build more quickly on subsequent trials; this is the source of flexible associations between stimuli and responses that can be rapidly established through task instruction.
- Bi-stable frontal neurons modulate, prioritize, or coordinate activity between ‘tasks’; these neurons are ‘dumb’ in that they do not care about the particular task, only the modalities of the stimulus and response. The neurons are activated when a peak is built in an associated sensory input field and are turned off when a peak is built in an associated motor output field.
- Critically, frontal networks for different modalities are mutually competitive, which leads to slower activation of these networks with simultaneous task presentation; this is the sources of dual-task costs.

Different parameters for the different modalities of input and output fields produce differences in the rate of learning for different task pairings: visual and manual fields have higher resting level and a slower timescale of activation than the auditory and vocal fields. Thus, Hebbian traces have a smaller effect within the visual and manual fields. These parameter differences reflect differences in speed of processing and peak stability within these different modalities which could be probed in other tasks such as WM tasks.
- The parameters for the SR fields were all at the same values

Mapping to Neural Function and Generating Hemodynamics

- The inferior frontal junction (IFJ) is sensitive to dual-task conditions in a way that varies with practice: there is larger IFJ activation early in learning; this activity decreases to single-task levels by the end of learning.
- Frontal neurons in the DNF model are potential candidates to correspond to IFJ activity: they are sensitive to the number of tasks being executed at any given time while also mediating the coordination and execution of these tasks by modulating the activity of SR fields.

The BOLD signal is most strongly correlated with the Local Field Potential (LFP) which reflects the synaptic activity over a large population of neurons.

LFPs can be estimated from DNF models by computing the sum of the absolute value of excitatory and inhibitory interactions at each timestep.

To generate a BOLD signal, we convolve this timescourse of synaptic activity with a general impulse response function.

We ran the model in the same paradigm as Dux et al. (2009): 8 sessions composed of dual-task and single task trials for each task.

Discussion

- The DNF model successfully captured changes in the neural dynamics of RS while also capturing decreases in RT and dual-task costs over learning
- This is the first model of RS to quantitatively simulate both behavior and hemodynamic responses simultaneously. The same dynamics underlying behavior were used to directly compute the hemodynamics associated with behavior on a trial-by-trial basis.
- ACT-R: Generated both behavior and hemodynamics; however, this is not a real-time neural model. Rather, the mapping from model behavior to mean hemodynamics was indirect and computed over separate steps. Our model, on the other hand, behaved in real-time, selecting responses on every trial via emergent neural population dynamics.
- Leabra: Simulated both behavioral and neural dynamics; however, fits to both data sets were qualitative in nature.
- DFT provides a rich theoretical framework that we are currently extending to the full set of modality pairings as well as other response selection paradigms (e.g., PRP).
- Further, the model is generative by making both behavioral and neural predictions (e.g., the metric details of stimuli and responses should interact with the dynamics of RS; the hemodynamic response associated with dual-task conditions with Vis-Voc/Aud-Man pairing should be more persistent over learning).
- These behavioral and neural effects emerged from cascading neural dynamics and not from a discrete processing stage or from an a-modal RS stage.

Research supported by NSF BCS-0548629 and NIH R01 MH080421

References