Integrating Mind and Body in a Response-Selection Task: From Neural Decisions to Mouse Trajectories...and Back Again

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Embodied Neural Dynamics

- There has been a recent surge of research examining embodied cognition—using bodily states to track real-time cognitive dynamics [1].
- Here, we move beyond previous work by formalizing the relationship between the mind and body using the concepts of Dynamic Field Theory (DFT)
- We couple a dynamic neural decision-making system to a motor control dynamics. This approach is inspired by work on neural population dynamics in neurophysiology [2] and recent efforts to enable the coupling between cognition and perception/action in autonomous robots [3].
- As a behavioral target for this work, we model recent data using mouse trajectories to measure the continuous evolution of cognitive dynamics.

Response Selection

- We used a simple mouse movement task to develop our approach to integrating mind and body. Participants made mouse movements from bottom of screen to corresponding locations near the top of screen based on the color of a presented stimulus.
- We independently manipulated stimulus and response similarity in a 2 x 2 between-subjects design.
- The key question: Do stimulus and response similarity interact? If so, this would support the direct integration of perception and action during response selection.

Overview of DNF Model

- DFT simulates cognition using neural population dynamics within cortical fields tuned to continuous metric dimensions of perception and action. Neural interactions within a cortical field are locally-excitatory and laterally-inhibitory. With sufficient input, these interactions give rise to “peaks” of activation that reflect stable, localized decisions in the network.

The Current Architecture:

- Decision Field:** A 2-dimensional field with bi-modal neurons maps stimuli onto responses. These neurons are receptive to both the stimulus dimension (Color, see vertical axis) and response location (Space, see horizontal axis). “Pre-shaping” inputs reflect S-R mapping established via task instructions. Stimuli are input as ridges of activation across the response dimension reflecting the task goal: map this particular stimulus to a particular response based on a memory of the S-R mapping.
- Spatial Selection Field:** The 2-D decision field projects activation to a 1-D spatial field that selects a target direction in an allocentric frame of reference (i.e., direction along the virtual semi-circle). Activation in the 2-D field is passed through a non-linear thresholding function (sigmoidal function) with a soft threshold. Thus, sub-threshold (i.e., < 0) activation in the 2-D field can influence the growth of activation in the spatial field.
- Motor Control Dynamics:** The 1-D spatial field sets an attractor for the motor control dynamics with a fixed point at the center of mass of activation – the target direction – and the slope modulated by the excitatory strength of the peak. The velocity is also a dynamical variable with an attractor modulated by the distance between the current position and the target position and a slope modulated by the strength of activation in the spatial selection field.
- Movement Updating:** Once movement is initiated, the motor system does dead-reckoning, updating the heading direction based on the current heading direction and the attractor direction set by the spatial field. The velocity and heading direction are integrated over time to determine the x- and y-coordinates of the virtual mouse.

Movement Dynamics

- The behavioral RTs show an interaction between stimulus and response similarity: RTs are slower with far response metrics, slower with close stimuli, and particularly slow when these factors combined.
 - This significant interaction is not consistent with discrete stage theories of response selection [4, 5]
- Movement curvature tended to track the response metrics, with greater curvature with close response metrics. This is counterintuitive: one might expect greater curvature with far response metrics.
 - These data suggest that close responses are initiated early with less certainty about the target direction

Behavioral Data

Simulation Data

- The effects in the model arise from two factors:
 - First, there is stronger competition in the 2D decision field with close stimuli resulting in slower response times / slower decision stabilization.
 - Second, close response locations in the spatial selection field lead to faster movement initiation.
- These factors combine in SC-RC to yield greater curvature as the system stabilizes a decision.

Discussion

- In DFT, perceptual and motor information interact in a continuous fashion to produce responses. Peaks of activation form stable attractors that drive mouse movements toward the target.
- Our data and model are not consistent with proposals that model mouse trajectories using the minimum jerk model driven by discrete perceptual processing [5], or with theories that simulate curvature as a result of movement toward attractors in a dynamical potential field [6, 7]. In the latter case, this difference is due to stable, active control of the trajectory in DFT (vs. control via transient dynamics).

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At the start of the trial, the model only has inputs at the different S-R mappings

When the stimulus is presented, a ridge of neurons encoding the corresponding color is activated

Movement is initiated toward the center of mass of the choices as activation in the spatial field grows

The motor system veers toward the target direction as a peak stabilizes in the spatial field

The locations of the stimulus-responses mappings in the 2-D field were manipulated to reflect the different conditions