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A general, flexible decision model, applied to visual search

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To survive, an organism must pursue multiple goals and switch between them at appropriate times. Generating such behavioral flexibility is an extremely important brain function, yet little is known about how a network of neurons can pursue different goals at different times. A network's behavior can only change with an organism's goals if it receives information about those goals as input. Thus, network responses must depend jointly on both current stimuli and current goals. How are these sources of information combined to generate behavior? And, given those combinations, how can different decision criteria be implemented depending on the task at hand?

Here we present a plausible network model for visual search that exhibits different decision criteria depending on the current goal. The network accurately performs several different search tasks based on the same stimulus set, and is capable of switching between tasks without retraining.

The model consists of three layers, each directly inspired by cortical neurobiology: (1) A layer of input or sensory neurons whose responses to stimuli are gain-modulated depending on current goals. Such gain modulation implies that sensory and goal-dependent information are combined nonlinearly, as documented in various experiments, but the exact form of this nonlinearity is not crucial. (2) A randomly connected layer of non-linear neurons that acts as a reservoir computer. As in a liquid-state machine, this layer is capable of generating widely different response patterns. (3) A standard race-to-threshold decision model containing two competing neural populations. These are used to indicate the system's decision, whether a target is present or absent in the display, depending on which population reaches a threshold first.

We illustrate the model's performance in a series of visual search tasks for which human behavioral data are available. We show that a single fixed network can perform all of these tasks correctly, qualitatively reproducing eight sets of experimental observations:

1. Variations in reaction times due to the number of displayed distractors (set size effects).

2. Differences in reaction times between conjunction and single-feature (or pop-out) searches.

3. Differences in reaction times between target-absent and target-present displays.

4. Reaction-time dependencies on the similarity between distractors and targets.

5. Search asymmetries; that is, differences in reaction-time curves when target and distractor objects are exchanged.

6. The redundant targets effect; that is, decreased reaction times as the number of targets present increases.

7. The ability to perform both singleton search (search for an object that stands out in some way) and directed-object search (search for a specific object).

8. Similar reaction-time curves for search in standard, static displays and in dynamic displays, in which the positions of all objects change randomly with a certain frequency.

The last point is particularly significant because other models predict large differences in reaction times between static and dynamic conditions, whereas ours does not. We also show that the model is robust to noise, and can perform either with perfect accuracy or exhibit behaviorally realistic error rates, depending on noise and training parameters.

Our model demonstrates that three key properties of cortical neurons – gain-modulation, recurrent connectivity, and race-to-threshold dynamics – can be combined to generate a powerful and flexible decision-making model. We suggest that these features, which are successful at replicating many aspects of visual search, may be combined in a similar manner to generate goal-dependent decisions in many other circumstances.

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