

# A neural mechanism for optimizing task performance

Eric Brown<sup>1</sup>, Jeff Moehlis<sup>1</sup>, Philip Holmes<sup>1,2</sup>, Ed Clayton<sup>3</sup>, Janusz Rajkowski<sup>3</sup>  
and Gary Aston-Jones<sup>3</sup>

<sup>1</sup> Prog. Appl., Comp. Mathematics, <sup>2</sup> Dept. Mech., Aero. Engineering  
Princeton University, Princeton, NJ 08544, U.S.A.

<sup>3</sup> Dept. Psychiatry and Laboratory of Neuromodulation and Behavior,  
University of Pennsylvania, Philadelphia, PA 19104, U.S.A.

January 21, 2004

## Abstract

Recent brain recordings suggest a link between different firing patterns in the brainstem nucleus locus coeruleus (LC) and different levels of performance in simple cognitive tasks. Starting from the dynamics of single spiking neurons, I will describe mathematical models for these firing patterns and possible mechanisms for the observed transitions between them. Then, in an extension of previous work, I will discuss a possible role for the LC in optimizing speed and accuracy in decision tasks, via release of neuromodulators which dynamically adjust the sensitivity (i.e. gain) of neural populations.

Fig. 1 illustrates Post-Stimulus Time Histograms (PSTHs) of neural activity in the brainstem nucleus *locus coeruleus* (LC), recorded from monkeys performing different tasks in the phasic and tonic LC modes. In the tonic LC mode, associated with labile behavior and poor performance on tasks requiring focussed attention, cells fire at relatively high baseline rates (2-5 Hz) but respond more weakly to task stimuli; in the phasic mode, associated with good performance on such attention tasks, baseline firing rates are lower (1-4 Hz) but evoked responses are stronger. The first task is target identification, in which subjects identify a target from two alternatives,

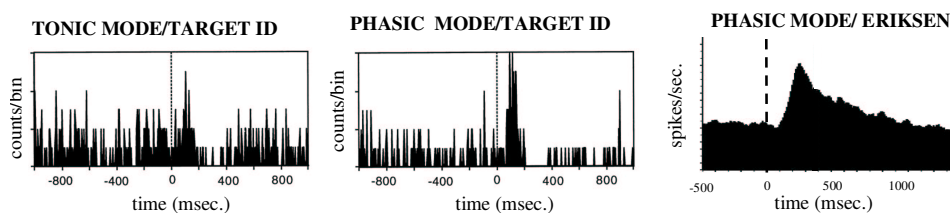


Figure 1: Post-stimulus time histograms (PSTHs) of LC activity in tonic (left) and phasic (center) modes during the target identification task, showing that LC response relative to baseline is greater in the phasic than the tonic mode, and that there is a refractory period in both [2]. (Right) Phasic mode PSTHs for the Eriksen task, showing no refractory period [1]. Vertical dashed lines indicate the onset of visual stimulus, which precedes the input  $I(t)$  to the LC (see Eqn. (1)) by approximately 100 msec.

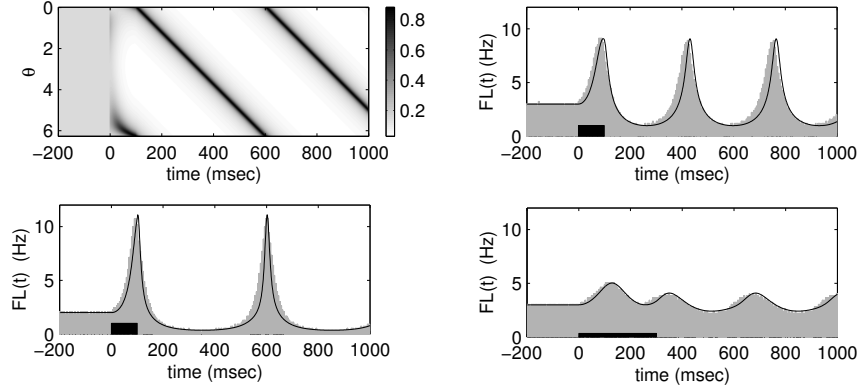


Figure 2: Phase density (top left) and firing rates  $FL(t)$  (other panels) for simulated population of *noise-free* LC neurons. Exogenous stimuli associated with behavioral tasks indicated by black bars: short stimulus (top and bottom left) and protracted stimuli (bottom right) are used, with total input current  $\bar{I}d = 10 \mu\text{A} \cdot \text{msec}/\text{cm}^2$  in both cases. Gray bars show spike rates computed directly from conductance-based equations, and black lines give (purely analytical) predictions of our phase reduced model.

e.g., horizontal or vertical bars. In the second, Eriksen task, the decision process is complicated by the presence of distracting symbols flanking the central target (or non-target) stimulus.

First, we develop a mathematical model which allows us to propose mechanisms for the different LC responses observed across behavioral and task conditions. Specifically, we reduce a model for a pool of LC neurons to differential equations for individual neuron phases, thereby retaining spike timing information, and analyze spiking probabilities in response to stimuli. This elucidates the dependence of spike histograms on model parameters and reveals how timescales in the neural substrate interact with those in the stimuli, leading to the following results: 1) Post-stimulus response is elevated in populations with lower spike rates; 2) Responses decay exponentially due to noise and variable pre-stimulus spike rates; and 3) Shorter stimuli preferentially cause depressed post-activation spiking.

The first of these findings explains the influence of baseline spike rate on response of LC neurons to exogenous stimuli, and suggests that any factor leading to decreased baseline rate contributes to stronger responses in the phasic vs. tonic mode; see Fig. 2 (top right panel vs. bottom left). We suggest that these lower rates may result from decreased excitatory or enhanced inhibitory input from brain areas afferent to the LC (including the anterior cingulate cortex (ACC), a region previously implicated in cognitive control) or from neuromodulators such as corticotropin releasing factor (CRF). The second finding tells us that, in order to produce the protracted LC responses seen in the Eriksen data, Eriksen task stimuli must elicit protracted inputs to the LC (since the impact of brief inputs decays quickly – not shown in Fig. 2). The third finding implies that, in contrast to the Eriksen task, inputs to the LC elicited by target detection task stimuli must be punctate, because the interval of depressed firing observed in the data (Fig. 1, top) can occur only following the offset of (pulsed) inputs to the LC (cf. Fig. 2, bottom left panel vs. bottom right). Indeed, these different LC inputs in the two tasks are a *prediction* of our model.

Recalling that LC neurons release the neurotransmitter norepinephrine, which has been

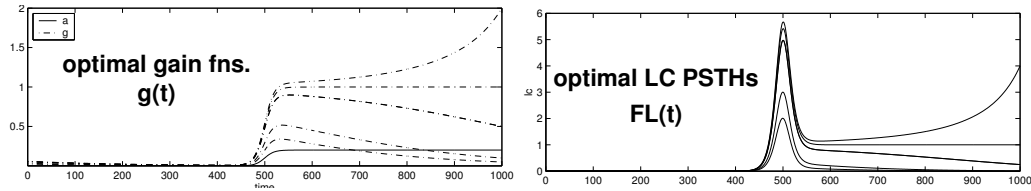


Figure 3: Optimal gain in a two-population firing rate model for sigmoidally increasing signal strength  $a(t) = a_0 + \frac{\bar{a}}{1 + \exp(-4r(\tau - t))}$  (solid line) and constant noise amplitude. Parameters:  $a_0 = 0.01$ ,  $\bar{a} = 0.1$ ,  $r = 30$ ,  $\tau = 1$ . Various optimal gain functions  $g(t)$  are shown as chain-dotted lines; all of these produced optimal performance in terms of percent correct responses, compared with the non-optimal constant  $g(t) \equiv 1$ .

shown to increase the gain of cortical neuron populations, we put our results on LC dynamics in a behavioral context by demonstrating that models of mutually inhibiting neural populations can make nearly optimal decisions about noisy, time dependent “sensory inputs” providing that their gain is allowed to vary in a fashion similar to that suggested by empirical LC firing rate dynamics. Fig. 3 shows an example in which there are a multiplicity of (identically) optimal gain solutions. From simple, empirically grounded assumptions about dynamics of the neurotransmitter norepinephrine uptake, the corresponding optimal transient LC firing rates (cf. PSTHs) that would be required to produce these gain values are also computed. Their similarity with empirical LC PSTHs supports a specific role for the LC in optimizing some cognitive tasks.

## References

- [1] E. Clayton, J. Rajkowski, J.D. Cohen, and G. Aston-Jones. Decision-related activation of monkey locus coeruleus neurons in a forced choice task. submitted, 2003.
- [2] M. Usher, J.D. Cohen, D. Servan-Schreiber, J. Rajkowski, and G. Aston-Jones. The role of locus coeruleus in the regulation of cognitive performance. *Science*, 283:549–554, 1999.