71.7 Neuronal signals related to delayed reward and its discounted value in the macaque dorsolateral prefrontal cortex

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Introduction

During an inter-temporal choice task, a decision maker has to choose between a small but immediate reward and a large but delayed reward. It has been shown that humans and animals discount the value of rewards over time via hyperbolic discount functions, but the neural bases of temporal discounting are poorly understood. To examine the shape of temporal discount function in non-human primates and to investigate the neural basis of inter-temporal choice, we developed a novel oculomotor free-choice task and examined the neural activity in the prefrontal cortex of rhesus monkeys while they performed the task.

Methods

Behavioral Task : A trial began when the monkey fixated a small white square presented at the center of a computer screen. After a 1-s fore-period, two peripheral targets were presented along the horizontal meridian for 1 s (cue period). One of the targets was green and delivered a small reward (**TS**) after a relatively shorter delay (**DS**), while the other was red and delivered a large reward (**TL**) after a relatively longer delay (**DL**). The reward was delivered after a variable delay (0, 2, 5, or 8-s) signaled to the monkey by a clock consisting of small dots (yellow or cyan) displayed around each target. Once the monkey chose a target, the dots in the chosen target were removed one by one at the rate of 1/s and 4/s for the yellow and cyan dots, respectively, and the reward was delivered when all the dots were removed. The intertrial interval was adjusted to prevent the monkey's choice from influencing the onset of the next trial.

Neural Recording : Single-neuron activity was recorded from the dorsolateral prefrontal cortex (DLPFC) of the right hemispheres of two monkeys, using a multi-electrode recording system (Thomas Recording, Germany).

Intertemporal Choice Task

Recording Site


Number vs Delay
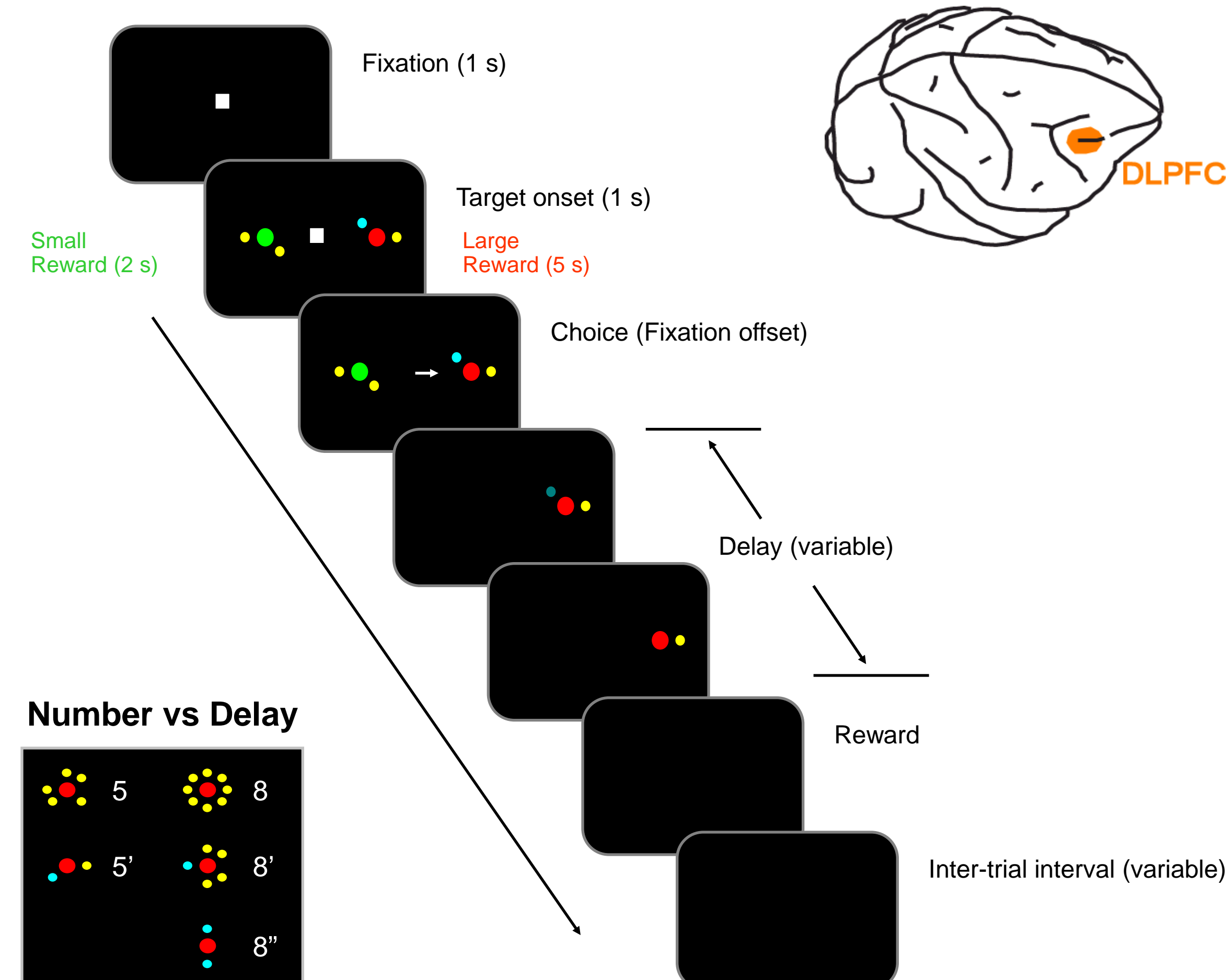
Results

Prefrontal neurons displayed diverse effects of task-related variables during an inter-temporal choice task

BEHAVIORAL RESULTS. The monkey's behavior was analyzed with a logistic regression model combined with exponential or hyperbolic discount functions. The discount rate and other free parameters of regression model were estimated with a maximum likelihood procedure. The goodness of exponential and hyperbolic discount function was compared using the likelihood ratio or Bayesian Information Criteria (BIC). Among 145 recording sessions, hyperbolic discount function fit the monkey's choice behavior better in 121 sessions (83%).

ANALYSIS OF NEURAL DATA. Effects of the number of dots (N), the delay for reward (D), and the discounted value (DV) for a given target were evaluated with a regression model (Model 1) that also included the monkey's choice (CHO) and the position of the large reward target (ORT). The relative contribution of each variable is visualized by plotting the sum of the following two quantities: (i) the variable in question multiplied by its regression coefficient, and (ii) the residual (error) from the regression model.

Model 1: Spike Count = a0 + a1 * CHO + a2 * ORT + a3 * NL + a4 * NR + a5 * DL + a6 * DR + a7 * DVL + a8 * DVR

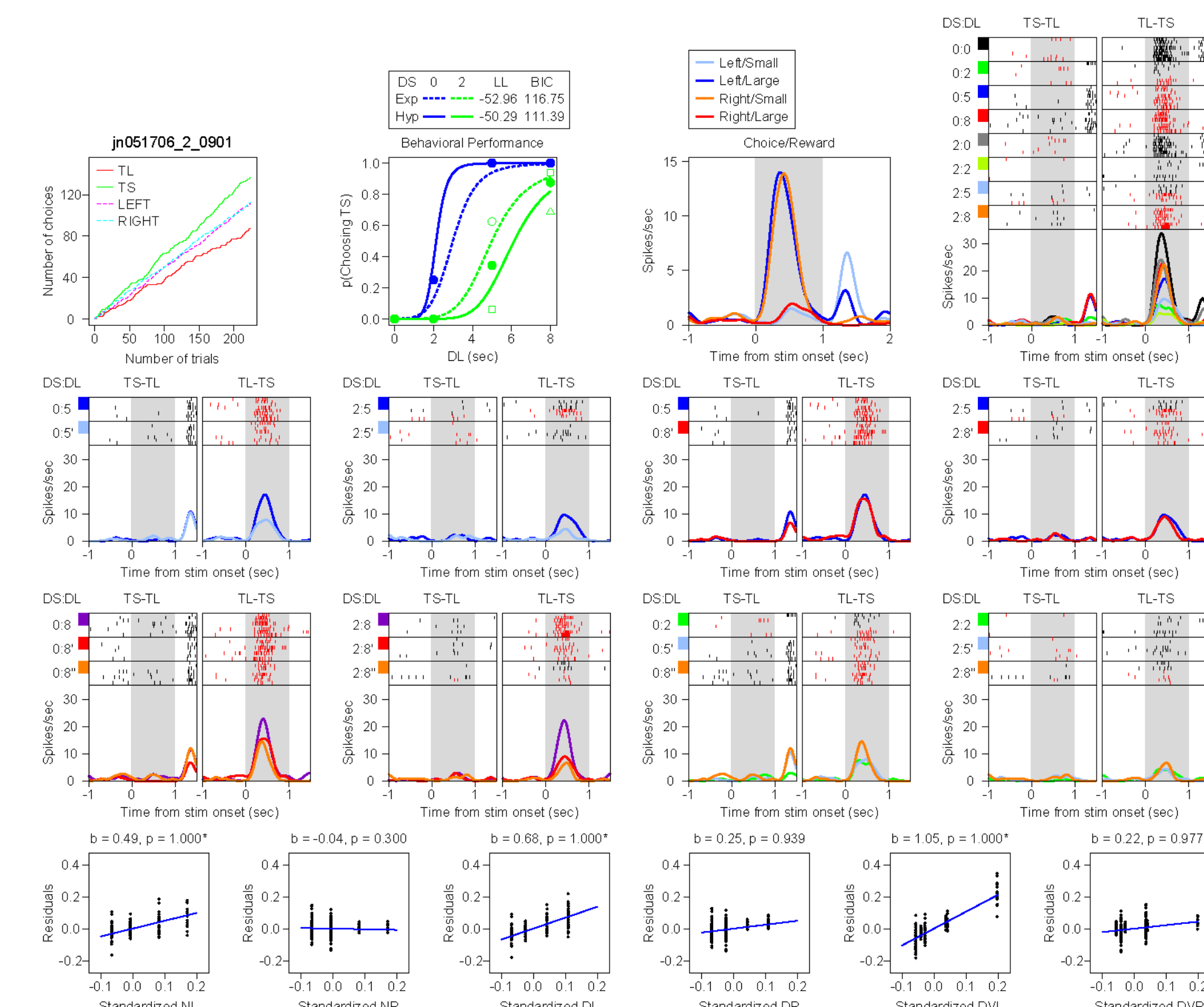**Neuron with N effect**
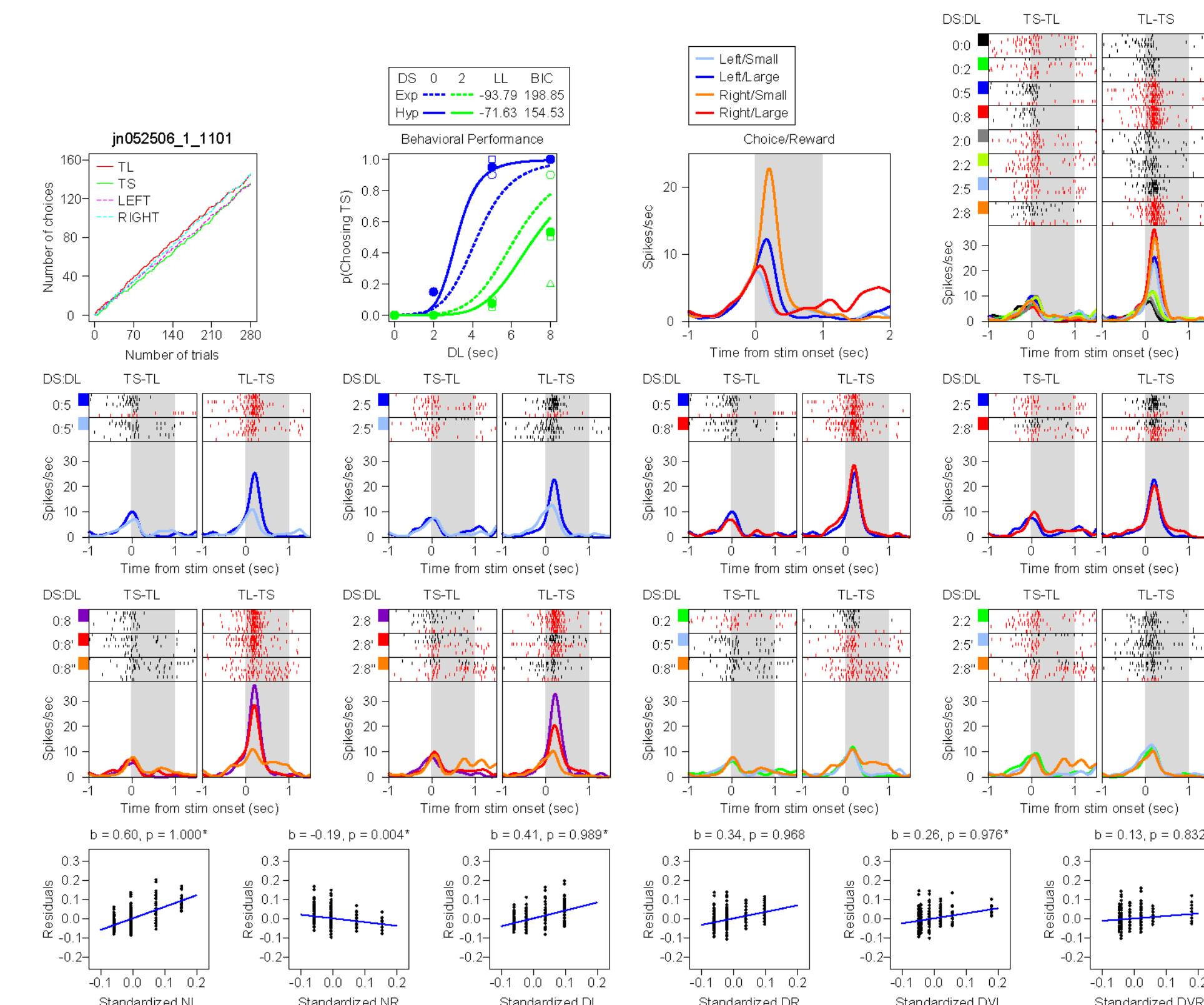
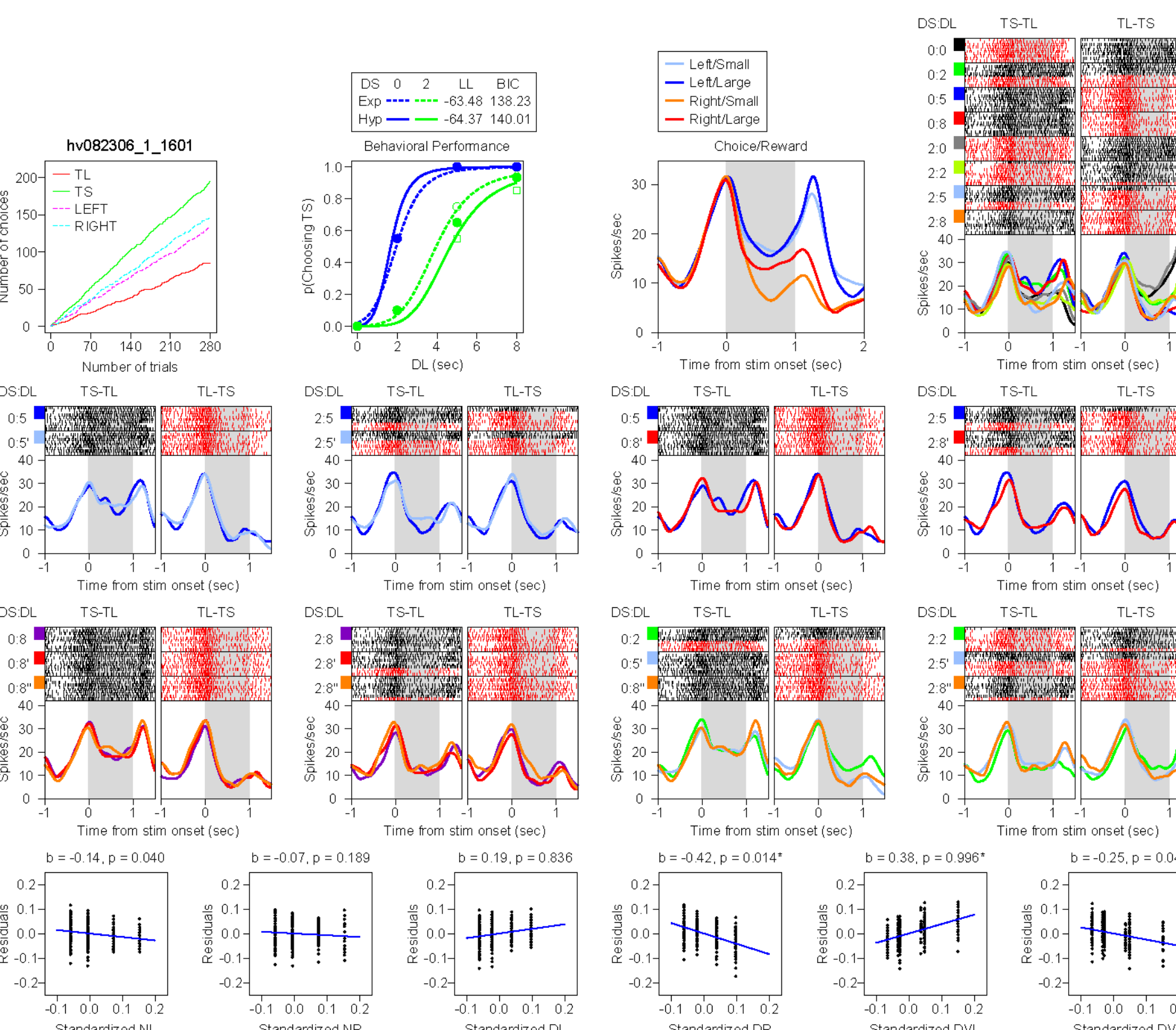**Neuron with D effect**
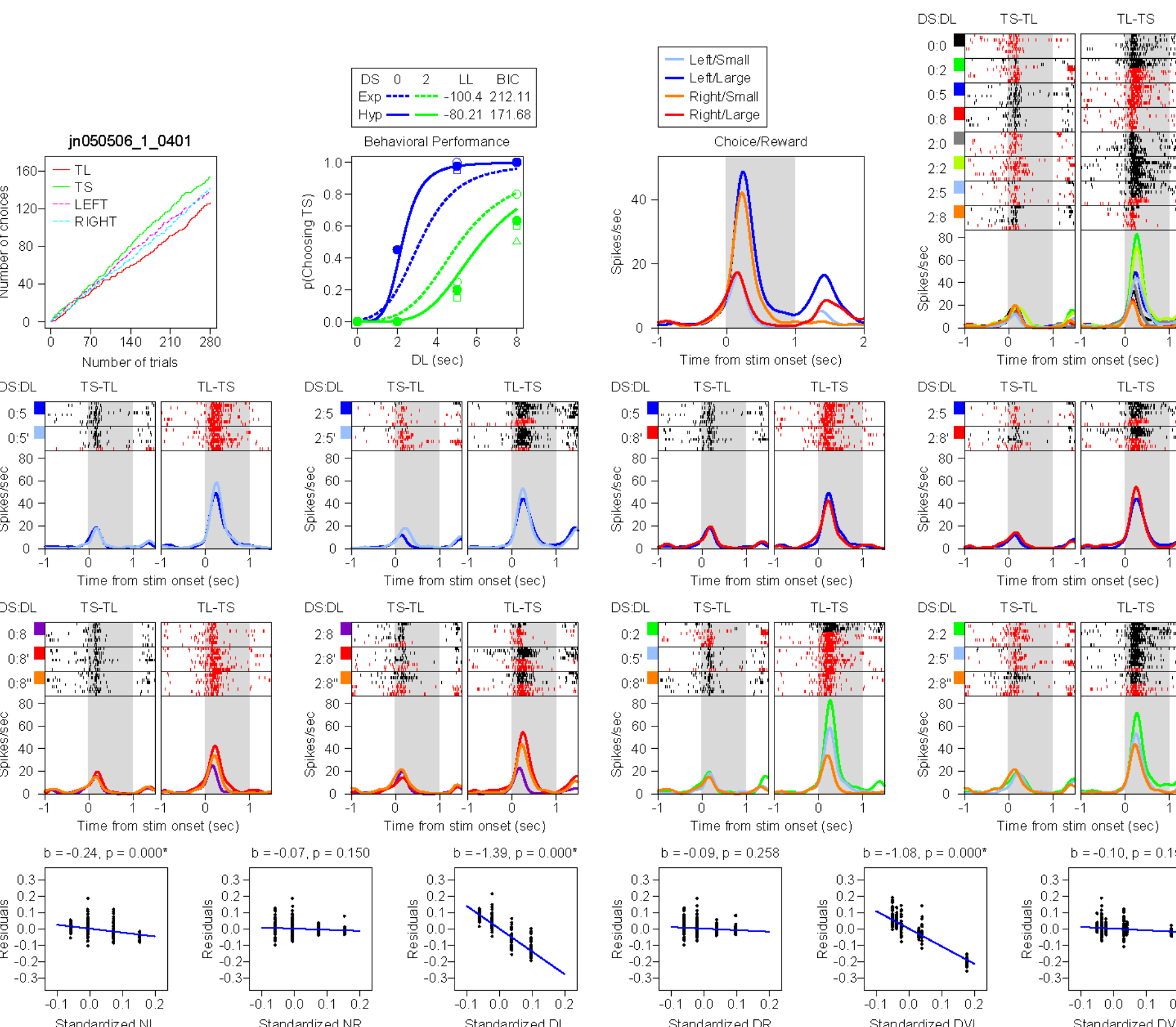
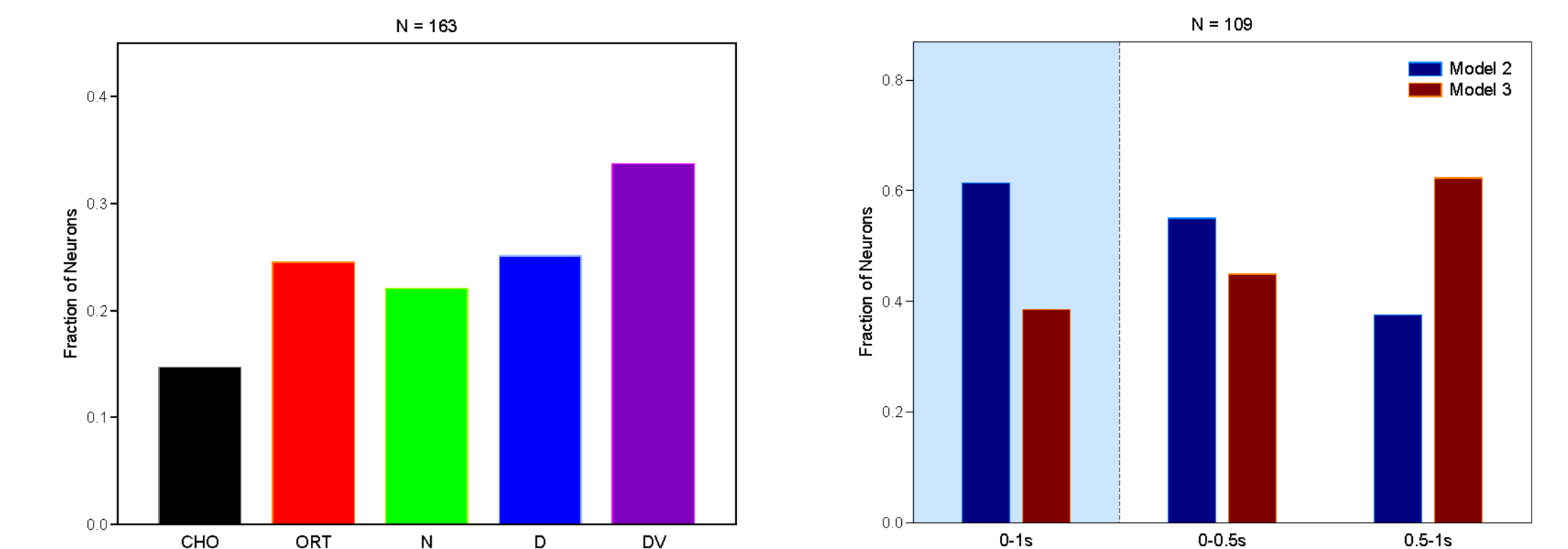**Neuron with DV effect**

Neuron with DV effect

Population result

LEFT: During an inter-temporal choice task, DLPFC neurons modulated their activity according to multiple variables. Fraction of neurons that displayed significant modulations in their activity during the cue period according to various variables included in the regression model (Model 1).

RIGHT: Signals related to discounted values in the prefrontal cortex emerged gradually. Prefrontal activity was affected more often by physical parameters such as N and D during the first half of the cue period, and by discounted values during the second half of the cue period. This was tested by comparing a regression model that includes the position of the large reward target (ORT) and the delay of each target (DL and DR; Model 2), and a regression model that includes the discounted value of each target (DVL and DVR; Model 3) using BIC. This analysis was applied to the neurons in which Model 1 was significant (N=109).

Model 2: Spike Count = a0 + a1 * CHO + a2 * ORT + a3 * DL + a4 * DR

Model 3: Spike Count = a0 + a1 * CHO + a2 * DVL + a3 * DVR

Conclusions

1. Individual neurons in the primate prefrontal cortex displayed diverse patterns of activity related to key variables in the inter-temporal choice task, such as the delay for reward and the discounted value for each target.

2. The results from the regression analyses suggest that the signals related to discounted values or discounted utilities might emerge gradually during the cue period, and may be computed from the amount of expected reward and its temporal delay.

References

1. Frederick S, Loewenstein G, O'Donoghue T. (2002) *Time discounting and time preference: a critical review.* **Journal of Economic Literature** 40(2):351-401.
2. Mazur JE. (2001) *Hyperbolic value addition and general models of animal choice.* **Psychological Review** 108(1):96-112.

Acknowledgement