Activity in the Dorsolateral Prefrontal Cortex of Macaques during an Inter-temporal Choice Task

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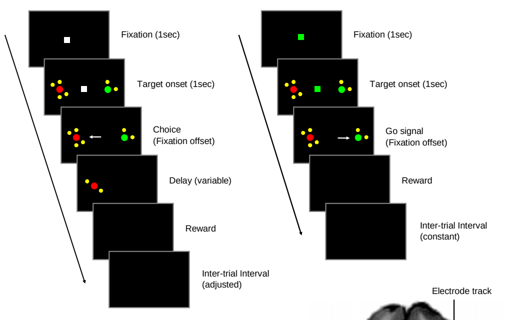
Introduction

Inter-temporal choice refers to a decision among potential outcomes that can be realized at different times. In such a situation, people and other animals often prefer a small but immediate reward over a large but delayed reward. This implies that an outcome expected in the future is discounted over time, which is referred to as temporal discounting. Our long-term goal is to understand the nature of neural mechanisms involved in temporal discounting and inter-temporal choice. As a first step, we investigated temporal discounting in monkeys during an inter-temporal choice task. Some preliminary neural data are also presented.

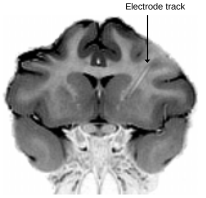
Methods

Choice Task : Two rhesus monkey were used. After the animal fixated a central target, two peripheral targets were presented along the horizontal meridian, and the animal indicated its choice with a saccade. One of the targets was green and delivered a small reward (TS, target for small reward), while the other was red and delivered a large reward (TL, target for large reward). The reward was delivered after a variable delay signaled to the animal by a clock consisting of small yellow dots (n=0 to 8) displayed around each peripheral target. After the animal made its choice, these dots were removed one by one at a constant rate (0.5 or 1 s/dot). The inter-trial interval was adjusted to prevent the animal's choice from influencing the onset of the next trial.

Control Task : This task was introduced to examine the visual effect of clocks on neural activity. In this task, the animal was required to make saccade to one of the peripheral targets according to the color of the central fixation target.



Neural Recording : Single-neuron activity was recorded from the dorsolateral prefrontal cortex (DLPFC; two monkeys) and caudate nucleus (CN; one monkey), using a multi-electrode recording system (Thomas Recording, Germany).



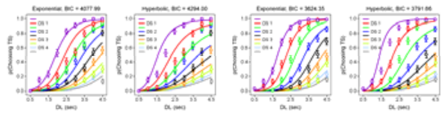
Results

Exponential vs. Hyperbolic Discounting

DS : delay for small reward   DL : delay for large reward

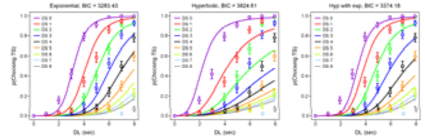
Exp 1 (0.5-4.5 sec delay, 2:3 reward ratio) — Exponential

Monkey D (March 2005)   Monkey J (March 2005)

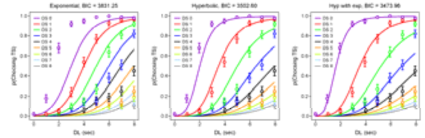


Exp 2 (0-8 sec delay)

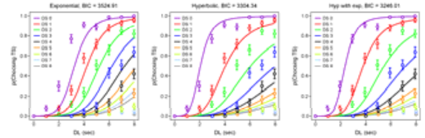
Monkey D (April 2005, 1:2 reward ratio) — Exponential



Monkey D (September 2005, 2:3 reward ratio) — Hyperb-E



Monkey J (April 2005, 1:2 reward ratio) — Hyperb-E



The animal's choices were analyzed with a logistic regression model combined with one of the following three discounting functions. The goodness of fit was measured with the Bayesian Information Criteria (BIC = –2 log L + k log N).

Exponential : $V = A \times e^{-KD}$

Hyperbolic : $V = \dfrac{A}{1+KD}$

Hyperbolic with exponent : $V = \dfrac{A}{1+KD^B}$

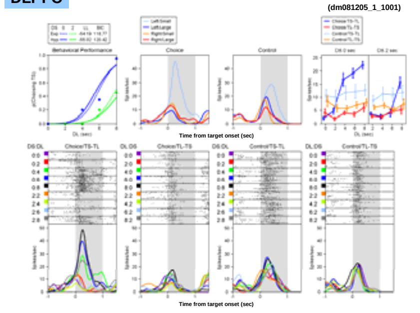
V : discounted value
A : amount of reward
D : delay
K : scaling constant
B : power

Summary of Behavioral Results

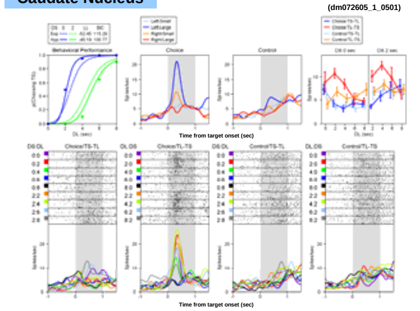
In Experiment 1, the exponential model performed better than the hyperbolic models, as indicated by smaller BIC. In contrast, hyperbolic models, especially the one with an exponent, outperformed the exponential model in Experiment 2. This may not be due to the difference in the range of temporal delays tested in these two experiments, since Monkey D initially showed exponential discounting in Experiment 2.

Activity of PFC and CN neurons during inter-temporal choice

DLPFC

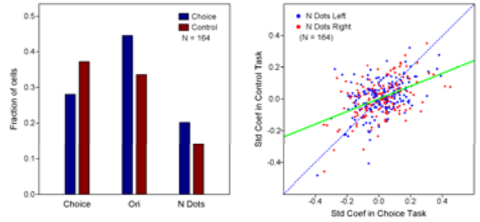


Caudate Nucleus



These examples show that some DLPFC and CN neurons modulate their activity according to the animal's choice, the reward magnitude, and the number of the dots. All three factors were significant in both neurons except the number of the dots in the CN neuron.

Population analysis in DLPFC



Model 1:

$$\text{Spike Count} = a_0 + a_1\,\text{Choice} + a_2\,\text{Orientation}$$

Model 2:

$$\text{Residual from Model 1} = b_0 + b_1\,\text{NDotsLeft} + b_2\,\text{NDotsRight}$$

Histogram: Fraction of DLPFC neurons modulated by different task parameters. To prevent potential confounding, effects of temporal delay (number of dots) were evaluated (model 2) after the effects of reward magnitude (orientation) and choice were factored out (model 1).

Scatter plot: Activity was more strongly modulated by the number of dots in the choice task, compared to the control task. However, the effect of the number of dots was not systematically related to the effect of reward magnitude (not shown), suggesting that the discount values may not be explicitly represented in DLPFC.

Conclusions

1. We developed a novel inter-temporal choice task for non-human primates.
2. During the initial stage of the behavioral training, the animals tended to make their choices based on exponential discounting. However, over time, both monkeys switched to a pattern consistent with hyperbolic discounting.
3. Neural activity in the DLPFC was often correlated with the reward magnitude and the amount of temporal delay. We tested the hypothesis that DLPFC neurons encode the discounted value of a particular target. The results from preliminary analyses have not supported this hypothesis. This suggests that signals related to the reward magnitude and temporal delay are not fully combined into discounted values in DLPFC.

References

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Acknowledgement

Supported by NIMH and NEI.