

Neural Activity Related to Temporally Discounted Values in the Prefrontal Cortex of Macaques

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Decision making often involves a tradeoff between magnitude of a reward and its delay. For example, people and other animals sometimes prefer a small but more immediate reward to a large but more delayed reward. This indicates that the subjective value of a reward is depreciated as a function of its delay, a process known as temporal discounting. To understand the neural basis of temporal discounting, we trained two rhesus monkeys in an oculomotor inter-temporal choice task. Each trial began when the animal fixated a small white square presented at the center of a computer screen. After a 1-s fore-period, two peripheral targets were present along the horizontal meridian. The animal was required to shift its gaze towards one of these two targets when the central square was extinguished after a 1-s delay period. One of the targets was a green disk and delivered a small reward, whereas the other target was a red disk and delivered a large reward. The time between target fixation and reward delivery was indicated by a clock consisting of yellow and cyan dots that disappeared at the rate of 1s/dot and 4s/dot, respectively. The delay for each target varied pseudo-randomly across trials.

The animal's behavioral data were analyzed using a logistic regression model that included the difference between the temporally discounted values for the two targets. Discounted values were calculated using an exponential or hyperbolic discount function, and the model parameters were estimated using a maximum likelihood procedure. In 85% of the sessions, a hyperbolic discount function provided a better fit to the data. We also recorded the activity of 160 neurons in the dorsal lateral prefrontal cortex (DLPFC) of the same animals. The activity during the 1-s delay period was analyzed using a linear regression model that included a set of variables related to the stimulus display, such as the position of the large-reward target and the number of dots for each target, as well as the animal's choice and the discounted value for each target. When corrected for multiple comparisons, 32.5% of DLPFC neurons showed significant modulations in their activity related to the discounted utility of a particular target. To examine the time course of neural signals related to the discounted values and other stimulus parameters, we also carried out the same regression analysis using a sliding window. During the first 300 ms after target onset, the percentages of neurons that significantly modulated their activity according to the number of dots, discounted values and choice were 19.9%, 14.7% and 7.1%. During the 300-ms interval in the middle of the delay period, the corresponding percentages were 18.6%, 34.6%, and 12.2%, and they became 10.9%, 28.8% and 19.9% during the last 300-ms interval in the delay period. Therefore, the fraction of neurons signaling the number of dots decreased during the delay period, whereas the fraction of neurons encoding discounted values and the animal's choice increased. Similarly, during the first half of the delay period, the regression model that included variables related to reward magnitude and delay tended to perform better than the model that included discounted values, whereas the reverse was true during the second half of the delay period. Thus, signals directly extracted from the stimulus display might be gradually converted to discounted values and choices in the DLPFC.