Decision-making reference point biases in the dorsal anterior cingulate cortex

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Abstract

Probabilistic decision-making is influenced by many subjective factors, including reward seeking, risk acceptance, and satisfaction. A significant aspect, often overlooked in trial-based reward paradigms, is reference-point bias, consisting in the assessment of potential gains and losses based on a relative reference point, based on current wealth status (Kahneman & Tversky, 1979). To address this gap, we set incremental reference points through the accumulation of virtual tokens leading to a fluid jackpot reward, and established their impact on behavioral performance and neural encoding in the dorsal anterior cingulate cortex (dACC) of macaque monkeys. As subjects accumulated more and more tokens, the trial execution approached the jackpot achievement. For higher accumulated tokens subjects exhibited faster and more accurate choices, indicating reference point-dependent behavior. Neuronal activity in the dACC corresponded with reward value during the visual presentation of offer cues, with enhanced encoding for higher ranges of accumulated tokens. Additionally, in easier trials where more valuable options were more salient, both decision-making speed and the neural representation of reward value were enhanced. These findings underscore the critical role of the dACC in integrating reward accumulation and decision-making processes, reflecting biases associated with reference point dependence.

Keywords: Decision-making, Reference point bias, dorsal anterior cingulate cortex, neural encoding of value

Introduction

Decision-making under risk involves evaluating potential gains and losses, thus predicting possible outcomes relative to time-dependent references (Kahneman & Tversky, 1979). Although the neural processes of risk and probability over decisions are better understood, the neural basis of reference dependence remains unexplored. A viable approach to studying such phenomena across trials is to consider the cumulation of virtual rewards as a time-varying reference for decision-making. While previous research has explored the influence of behavioral history on decisions (Braun, Urai, & Donner, 2018; Nogueira et al., 2017; Mochol, Kiani, & Moreno-Bote, 2021; Hermoso-Mendizabal et al., 2020), it has often relied on choice paradigms with immediate, trial-based rewards.

Token-based tasks enable the tracking of cumulative decisions, where choices lead to token accumulation, ultimately leading to the achievement of a jackpot reward (Maisson et al., 2021; Strait et al., 2016; Azab & Hayden, 2017, 2018; Farashahi, Azab, Hayden, & Soltani, 2018). These tasks offer insights into how reward probability, task difficulty, as well as token accumulation and jackpot proximity influence decisions and neural mechanisms at varying reference points. Here, we hypothesize that token count functions as a dynamic reference point and that its influence on value-based decisions is reflected in dACC neural activity.

Advances in neurophysiology have identified the dorsal Anterior Cingulate Cortex (dACC) as a key region involved in reward anticipation and cognitive effort estimation (Vassena, Holroyd, & Alexander, 2017; Aarts & Roelofs, 2011), as well as delayed reward processing (Strait et al., 2016; Azab & Hayden, 2017, 2018; Farashahi et al., 2018; Vassena, Deraeve, & Alexander, 2020; Blanchard & Hayden, 2014). Neural activity in this area has been associated with multi-trial (Shidara & Richmond, 2002) and virtual reward expectation (Hayden, Pearson, & Platt, 2009), impacting behavior (Kerns et al., 2004; Hayden, Heilbronner, Pearson, & Platt, 2011).

Methods

The token-based decision-making task. The task starts with the sequential presentation of two alternative offers on the opposite sides of the screen (Fig. 1A). Each presentation lasts 600 ms, followed by a 150 ms delay. Thereafter, the subjects are instructed to reacquire fixation, and to perform the choice via a choice-go cue consisting of both offers presentation. The choice is performed by directing the gaze to target option and holding fixation for at least 200 ms. Fixation breaks allow for changes of mind, by subsequent fixation of the alternative offer. The visual cues were split in two parts where the height bottom part indicated the success probability p^b of the offer and the height of the top part was comple-

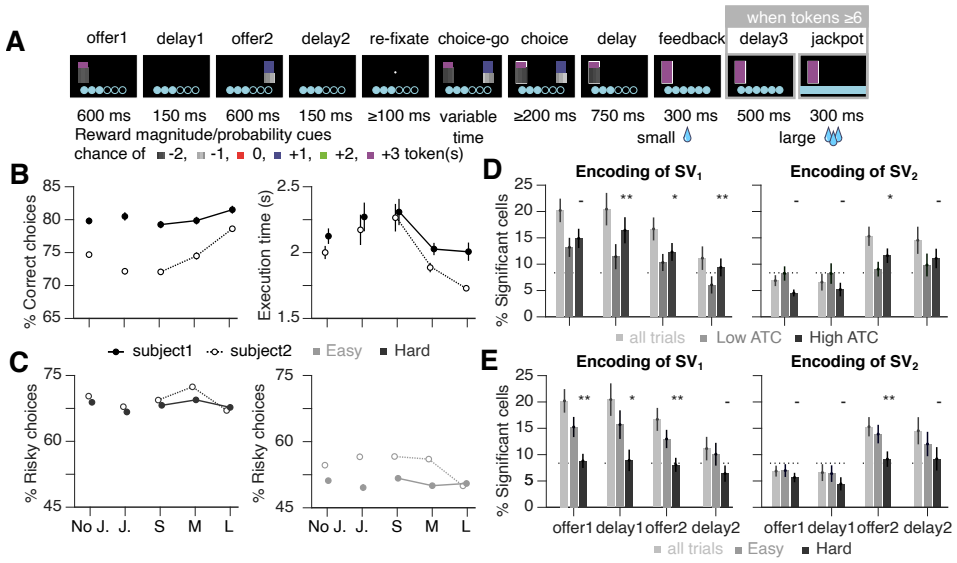

Figure 1: **Behavioral task, performances, and value encoding.** **A.** Behavioral task outline. **B.** Choice accuracy (left) and execution time (right, mean $\pm$ sem) for previous trial outcomes (No J.= no jackpot, J.=jackpot), and ATC at the start of the trial (S: ATC$=0,1$, M: ATC$=2,3$, L: ATC$=4,5$). **C.** Same as B, but for the fraction of risky choices in Hard (left, $\Delta_{EV}<1$) and Easy (right, $\Delta_{EV}\geq 1$) trials. **D.** Fractions of cells (mean $\pm$ sem) with significant encoding of SV_1 (left) and SV_2 (right) (Low: ATC$<$2, High: ATC$\geq$2). Data combined for the two subjects ($n=55$ cells in subject 1, $n=74$ cells in subject 2). Dotted lines: 95th percentile of same fractions for trial-order shuffles. One-tailed Wilcoxon signed rank tests are used to assess that fractions are higher in High ATC than in Low ATC ($^{*}p<0.05$, $^{**}p<0.01$, FDR corrected). **E** Same as D, but for Easy ($\Delta_{SV}\geq 1.9$) and Hard ($\Delta_{SV}<1.9$). One-tailed Wilcoxon signed-rank tests are used to assess that fractions were higher in Easy than in Hard trials.

mentary ($p^t=1-p^b$) to it. The color of the visual cues indicated the magnitude m of the probabilistic offers in (positive or negative) tokens $(m^b, m^t=[-2,-1,0,1,2,3])$. First offer presentation sides, as well as reward magnitude and probability were randomized across trials. The accumulated token count (ATC) was displayed at the bottom of the screen. Each trial ended with a small fluid reward (0.1 mL). When the counter hit ATC$=6$, a large jackpot reward (0.3 mL) was provided.

The data includes $n=227$ behavioral sessions in 2 subjects (subject 1: 109 sessions, 433.28 average trials/session; subject 2: 118 sessions, 500.68 trials/session), $n=108$ sessions (subject 1: 65 sessions, 479.16 trials/session; subject 2: 43 sessions, 519.35 trials/session) include extracellular activity of dACC (Area 24) recorded using single contact electrodes.

Analysis of behavior We computed the fraction of correct choices as the proportion of trials where subjects chose the offer with best expected value, defined as $EV=m^t p^t+m^b p^b$. The execution time is measured from the start of the trial, up to choice report. The fraction of risky choices is computed by defining risk $R=p^t(m^t-EV)^2+p^b(m^b-EV)^2$. The analysis is split for Easy and Hard trials by the median of the variable $\Delta_{EV}=|EV_1-EV_2|$, in our data settings $median(\Delta_{EV})=1$.

Neural encoding of value We computed the fraction of $n=129$ cells (subject 1: $n=55$, subject 2: $n=74$) encoding the subjective value of the offers by linear regression (Ferro, Cash-Padgett, Wang, Hayden, & Moreno-Bote, 2024). We defined the subjective value as $SV_i=\alpha_{1,i}EV_i+\alpha_{2,i}R_i, i=1,2$, whose weights are computed by fitting a logistic model of the choice: $logit(ch)=\alpha_0+\sum_{i=1,2}\alpha_{1,i}EV_i+\alpha_{2,i}R_i$. The spike count $\eta_{k,t}$ at time bin t in trial k is computed in 200 ms periods with 10 ms offset shifts. The fractions of cells showing significant encoding are computed via the linear regression $\eta_{k,t}=\beta_{0,t}+\beta_{1,t}SV_{1,k}+\beta_{2,t}SV_{2,k}$, thus via comparison of empirical $\beta_{1,t}$ or $\beta_{2,t}$ to null F-distributions. The fractions of significant cells at time bin t are averaged within trial epochs (offer1, delay1, offer2, delay2). The results are further assessed via permutation tests, building the null distribution via trial-order shuffled data. The analysis is applied to all trials, and by conditioning on ATC or difficulty. We set ATC ranges to Low (ATC$<$2) and High (ATC$\geq$2), and difficulty based on $median(\Delta_{SV})=1.9, \Delta_{SV}=|SV_1-SV_2|$, as Easy ($\Delta_{SV}\geq 1.9$) and Hard ($\Delta_{SV}<1.9$). While in the last case we achieved equally sized splits, in the first case the conditions are slightly unbalanced, with Low ATC in 45.18% of the total trials, and Hight ATC in 54.82%. We achieved even sizing by randomly resampling $n=10$ times trials in High ATC in equal size as for Low ATC, and averaged the resulting fractions of cells.

Results

Our findings indicate that subjects consider multiple factors, such as token count, risk and expected value, in their decision-making, extending beyond previous results. The subjects correctly reported the offer with best expected value, with more pronounced accuracy (Fig. 1B, left) and speed (Fig. 1B, right) when they accumulated a higher amount of tokens, i.e., as they got closer to the possibility of jackpot achievement. Subject 1 was generally more accurate, though slower than sub-

ject 2. The two subjects both showed a risk-seeking attitude, choosing the most risky option more often when the evidence for best EV contingency was Hard (Fig. 1C, left), compared to when it was Easy (Fig. 1C, right). In both cases, subject 2 showed a higher propensity for risk compared to subject 1, regardless of the previous trial outcome (be it jackpot or no jackpot), and most pronounced when ATC was lower (ATC≤ 3).

By investigating the role of dACC spiking activity, we found that the neural encoding of the subjective value of the respective offer is most pronounced during its presentation phase, i.e., we observed higher fractions encoding SV_1 during offer 1 presentation, and SV_2 during offer 2, reflecting temporal alignment of neural signals (Fig. 1D,E, all trials, left vs. right). More critically, encoding strength increased with higher token accumulation, suggesting that dACC activity reflects subjective value relative to a dynamic internal reference point (Fig. 1D,E). By stratifying the analysis by ATC levels (Fig. 1D) and difficulty (Fig. 1E), we found that neural encoding is significantly enhanced as more tokens are accumulated, and in trials where best offer contingency detection is easier.

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