A Theoretical Formalization of Consequence-Based Decision-Making

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Decision-making often entails anticipating the consequences of one's choices over time. However, real-world choice outcomes are not always immediate, adding significant challenges to determining their long-term implications for behavior. Most previous studies on reward-driven decision-making focus on task paradigms in which the decision outcomes are immediate and explicitly cued. However, the cognitive and neurobiological mechanisms by which the brain learns about and incorporates delayed and uncertain consequences remain unclear. Moreover, learning to make adaptive decisions depends on exploring options, experiencing their consequence, and reassessing one's strategy for the future. However, how the brain gauges delayed consequence for decision-making remains poorly understood.

To investigate this, we designed a novel decision-making task in which each decision altered future options to decide upon. The task was organized in groups of inter-dependent trials, and the participants were instructed to maximize cumulative reward value within each group. In the absence of any explicit performance feedback, the participants had to test and internally assess specific criteria to make decisions. Crucially, participants had to learn the decision-making strategy by making exploratory decisions in the absence of any explicit feedback. The absence of explicit feedback was key to specifically study how the assessment of consequence forms and influences decisions as learning progresses.

We formalized this operation mathematically by means of a multi-layered decision-making model. It uses a mean-field approximation to describe the dynamics of two populations of neurons which characterize the binary decision-making process. The resulting decision-making policy is dynamically modulated by an internal oversight mechanism based on the prediction of consequence. This policy is reinforced by rewarding outcomes. The model was validated by fitting each individual participants' behavior. It faithfully predicted non-trivial patterns of decision-making, regardless of performance level.

These findings provide an explanation to how delayed consequence may be computed and incorporated into the neural dynamics of decision-making, and to how adaptation occurs in the absence of explicit feedback.

Preprint:
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bioRxiv 2023.02.14.528595; doi: https://doi.org/10.1101/2023.02.14.528595