Excessive neural replay of aversive and uncertain options predicts human irrational decision-making

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Abstract:

Choice deliberation is guided by the uncertainties of available options and their associated outcomes. However, it is unclear how these choice components are involved in the brain's decision process. Neural replay, a neuromechanism involving the rapid sequential reactivation of states, has recently been proposed to underlie human cognition including value-based decision-making, but yet is unclear how outcome value and uncertainty are involved. With magnetoencephalography (MEG) recordings during a gambling-style task (N=30), we probed the role of replay in evaluating outcome value and uncertainty for choice. We found that forward replay increased for option paths with more aversive outcomes and greater uncertainty during deliberation, which then predicted irrational choices. Moreover, we observed that individual differences in obsessive-compulsive tendencies exacerbated the modulation of value and irrational choice related replay. These findings highlight the significance of replay dynamics in prospective deliberation involving value and uncertainty, and suggest a mechanistic explanation for how these processes may go awry in psychopathology.

Keywords: Neural Replay; Decision Making; Value-based Decision Making; Obsessive-Compulsive Disorder

Introduction

Decision-making involves considering both potential outcomes and the associated uncertainties of choice options (Kahneman & Tversky, 2013). For instance, one might weigh whether to place funds in a low-interest stable savings account or to invest in riskier stocks. However, how these components impact brain decision processes remains unclear. To gain insight, we examined neural replay, the rapid sequential reactivation of states (Skaggs & McNaughton, 1996; Liu et al., 2019), which has been theorized to support memory, learning, and decision-making in human cognition (Momennejad, 2000; Mattar & Lengyel, 2022). Initial studies have shown neural replay deployed during online value-based decision-making (McFadyen et al. 2023; Wimmer et al., 2023), but it is still unclear how outcome value and uncertainty influence this process. Here, we employed magnetoencephalography (MEG) while participants played a two-choice gambling-style task (N=30) to investigate how replay is modulated by value and uncertainty during decision deliberation and how biases in replay, including biases linked to individual differences in mental health levels, influence choice.

Methods & Results

Decision task and behaviour

Participants first learnt that there would be three (option) paths, each that led to one of three outcome types (reward, neutral or shock) (Fig. 1A). Each of these paths consisted of three images (9 total "states", S1-S9), and each outcome type was also represented by an image (S10-S12). In the decision task, participants had a choice between a probabilistic (probabilistically transitions to one of two paths; "gamble") or a deterministic (transitions to one path; "certain") option (Fig. 1B). On every trial, they were shown a cue screen consisting of one path state linked to a probability and another (from same path) linked to an outcome state. Capitalising on the learned knowledge of the path sequences and outcome states, participants were able to connect the transition probability to the outcome value for each path (Fig.1C). Hence participants were able to calculate the expected value (EV = transition probability * outcome value) of each path and thus of the choices. A choice was considered rational if participants chose the option with the higher EV. The gamble transition probabilities (50/50%, 70/30%, 90/10%), the outcome type, and the outcome magnitude (1-5) varied for each path across trials. We found that participants made significantly more rational (than irrational) choices (M=76.79%, SD=5.29%; $t(29)=27.76$, $p<0.001$, 95% CI=[46.63 57.53]) demonstrating that they were able to perform the decision task reasonably well.

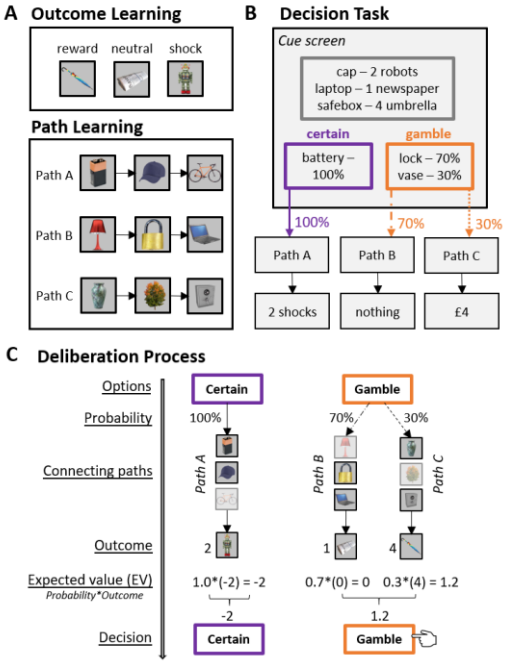

Figure 1. Decision paradigm.

Forward replay occurs during deliberation

While participants deliberated their decision, we wondered if neural replay of the paths occurred during time (cue screen onset until choice). To do this, we first classified each path state by a pattern of evoked multivariate neural activity from a pre-task functional

localizer. With these state classifiers, we quantified the states' reactivation during deliberation time. To detect sequential reactivation of the path states ("sequenceness"), we adopted the temporally delayed linear modelling (TDLM) framework (Liu et al., 2021). This included quantifying the evidence for all state pair transitions in different transition intervals between states (10-600ms, 10ms steps), and then assessing how much these state pair reactivations corresponded to the paths' sequential structure (e.g., S1→S2, S2→S3, S1→S3 for path A consisting of S1→S2→S3). During deliberation time, we observed significant (threshold determined by non-parametric permutations) forward sequenceness (average of all valid state pair transitions) occurring with 20-60ms intervals, with most sequential replay at 40ms interval (Fig. 2A).

Replay is modulated by value and uncertainty

Next, we examined if path sequenceness was linked to key components for choice evaluation: outcome value (range—reward: +1 to +5, neutral: 0, shock: -1 to -5) and transition probability (recoded to uncertainty: 50% (very uncertain) 70%/30% (uncertain), 90%/10% (somewhat uncertain), 100% (certain)). We used a linear mixed effects approach to predict trial-by-trial sequenceness strength of each path with its outcome value or transition uncertainty accounting for decision time, plus per participant and replay interval effects. We found that forward sequenceness was weaker for beneficial outcome paths (β=-0.0007, SE=0.0003, p=0.006) (Fig. 2B) while stronger forward sequenceness was linked to higher path transition uncertainty (β=0.0009, SE=0.0003, p<0.001) (Fig. 2B). Thus, increased forward replay was associated with components of prospective choice evaluation consisting of more aversive potential outcome values and higher option transition uncertainty.

Biased value and uncertainty replay predict irrational choice

We asked if these replay patterns influenced the rationality of choice. We thus added the rationality (yes/no determined by EV) of the trial's choice as a regressor interacting with path outcome value and transition uncertainty predicting forward sequenceness strength. We observed choice rationality having a positive interaction effect with outcome value (β=0.002, SE=0.0008, p=0.02) and a negative interaction effect with transition uncertainty (β=-0.002, SE=0.0008, p=0.007) on sequenceness strength (Fig. 2C). In other words, stronger modulation of forward sequenceness with aversive outcome value and increasing uncertainty was associated with irrational choice.

Obsessive-compulsion exaggerates value and irrational choice replay

Lastly, we explored individual differences in mental health symptoms in relation to replay and its link to decision components and irrational choice. We characterised participants by their levels of anxious-worry, obsessive-compulsion and depressive-affect using factor analysis (Fig. 2D). We then constructed mixed-effects models where these scores interacted with outcome, uncertainty, and choice rationality to predict forward replay strength. We found negative significant outcome value and obsessive-compulsion interaction (β=-0.003, SE=0.0007, p=0.002, corr.) (Fig. 2E), plus three-way outcome value, choice rationality and obsessive-compulsion (β=0.002, SE=0.0008, p=0.009, Bonf. corr.) interaction, on forward sequenceness strength (Fig. 2F). These results indicate that individuals with high obsessive-compulsion have even stronger forward sequenceness with aversive path outcome value, in addition to stronger modulation of sequenceness with outcome value dissociating irrational versus rational choices. This suggested that obsessive-compulsion influenced replay underlying prospective evaluation with an increased sensitivity of replay to outcome values and its prediction of irrational choice.

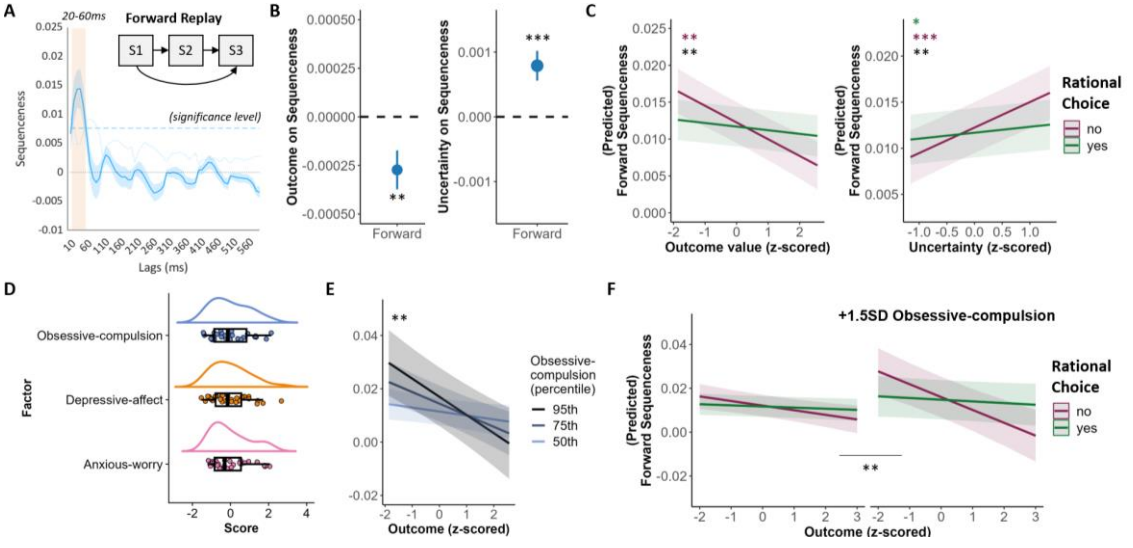

Figure 2. Deliberative forward replay linked to value and uncertainty.

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