Information coding in frontoparietal regions reflects individual differences in uncertainty-driven choices

Alexander Paunov, Maëva L'Hôtellier, and Florent Meyniel*
(alexander.paunov@cea.fr, maeva.l.hotellier@ens.psl.eu, florent.meyniel@cea.fr)
INSERM-CEA Cognitive Neuroimaging Unit (UNICOG), NeuroSpin Center, CEA Paris-Saclay, Gif-sur-Yvette, France Université de Paris, Paris, France

Dalin Guo, Zoe He, and Angela Yu*
(dag082@ucsd.edu, wah016@ucsd.edu, ajyu@ucsd.edu)
Department of Cognitive Science, University of California San Diego, San Diego, CA, USA

Abstract:

Adaptive decision-making in noisy and changing environments must be jointly constrained by reward and uncertainty. Whereas rewards have robust behavioral effects in sequential decision-making, effects of uncertainty tend to be smaller and heterogeneous across subjects. Here we use a novel two-armed bandit task, which dissociates unexpected uncertainty from reward and expected uncertainty, and fMRI, to study the neural bases of individual differences in the neural representations of unexpected uncertainty. We find that (i) contributions of unexpected uncertainty to choice are heterogeneous across individuals but stable within individuals and (ii) variability in the neural representation of unexpected uncertainty corresponds to variability in its use during choices, in frontoparietal cortical regions previously implicated in uncertainty-related computations, but not in reward regions.

Keywords: sequential decision-making, unexpected uncertainty, individual differences, frontoparietal network

Introduction

Expected reward robustly predicts choices across individuals, whereas there are strong individual differences in information-seeking and attitudes toward uncertainty, which have been linked to pathological behavior (compulsive gambling; Dezza et al., 2021) and clinically relevant measures (trait anxiety; Fan, Gershman, & Phelps, 2022). Here, we study the neural underpinnings of individual variability in the approach/avoidance of uncertainty with fMRI, using a novel bandit task, which dissociates reward and distinct forms of uncertainty.

Previous work has shown that reward and uncertainty are represented in distinct cortical networks, with key regions, respectively, in ventral medial prefrontal cortex (VMPFC; e.g., Rushworth et al., 2011) and frontal and parietal regions in lateral PFC and inferior parietal lobe (IPL; e.g., Badre et al., 2012; Meyniel & Dehaene, 2017). In addition, different forms of uncertainty have been distinguished: expected uncertainty (EU), related to estimation and outcome noise, and unexpected uncertainty (UU), related to changes in the environment (Yu & Dayan, 2005; Soltani & Izquierdo, 2019), which are also neurally dissociable (e.g., Payzan-LeNestour et al., 2012).

Here, we ask whether fMRI response profiles in regions representing unexpected uncertainty reflect stable individual differences in uncertainty approach and avoidance during free choices. We focus on unexpected uncertainty for two reasons: first, recent work has found a relationship between UU and trait anxiety ('volatility-induced uncertainty', Fan et al., 2022); second, we find evidence for stronger individual heterogeneity on this form of uncertainty in our data.

Methods

Experimental Design

Fifty-two healthy adults completed a behavioral and an fMRI session of a two-armed bandit task, with 8 and 4 runs of 96 trials each, respectively (Fig. 1A).

Runs were composed of interleaved segments of free- and forced-choice trials, in which subjects selected one of two arms and received a reward between 1 and 100 points. Forced trials were included (i) to decorrelate reward and uncertainty behaviorally, as they are generally inversely related (more rewarding options are sampled more frequently) and (ii) to identify brain regions selectively recruited in choice (Wilson et al., 2014).

Rewards for each arm were drawn from 3 discrete mean reward levels: 30, 50, or 70 points, and shifted independently for each arm in the course of a run (generative volatility=1/24). Rewards were drawn from Gaussians, with each run consisting of two periods with a cued change in reward variability (generative standard deviation=10, 20 pts), whose goal was to decorrelate expected and unexpected uncertainty.

Model

Learning. Learning was modeled with a Bayesian ideal observer with full knowledge of the task except for volatility, which was fit to each subject's choices.

Decision-making. The following trial-wise estimates were derived from the ideal observer: *expected reward (ER)*: the posterior expectation of reward mean; *expected uncertainty (EU):* the probability that the most likely reward level is not the true reward level; and *unexpected uncertainty (UU):* posterior probability of having one (or more) shift in reward level (change point) in the recent past (last three trials).

Decisions were modeled with a logistic regression (with predictors z-scored for comparability):

$$\Delta Q = w_{0beh} + w_{ERbeh}{*}\Delta ER + w_{EUbeh}{*}\Delta EU + w_{UUbeh}{*}\Delta UU.$$

fMRI. The key predictor of interest is total UU (mean across arms) at the time of decision—which is independent of current choice—controlling for (i) relative ER across arms (chosen-unchosen) and (ii) EU of the chosen option:

$$\text{fMRI signal} = w_{0fmri} + w_{ERfmri}{*}ER_{CHOSEN\text{-}UNCHOSEN} + w_{EUfmri}{*}EU_{CHOSEN} + w_{UUfmri}{*}UU_{TOTAL}$$

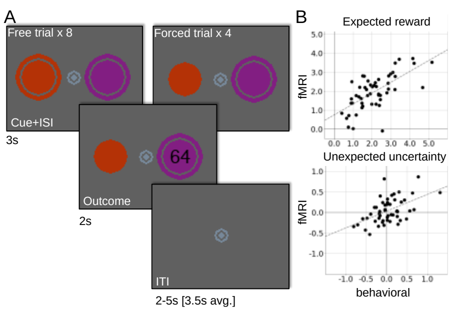

Figure 1: (A) Task. (B) Stable, hetero-geneous policy.

Main results

Behavioral results

Choices are strongly driven by expected reward (Fig. 1B top, w_{ER}=1.92, SE_{ER}=0.12, $t_{(51)}$=16.05, $p=10^{-22}$, fit across both sessions), with stable coefficients across sessions (r=0.66, $p=10^{-9}$). By contrast, the effect of unexpected uncertainty is smaller and highly heterogeneous across subjects (Fig. 1B bottom, w_{UU}=0.04, SE_{UU}=0.04, $t_{(51)}$=0.97, *n.s.*), but still reliable across sessions (r=0.52, $p=10^{-6}$), suggesting stable individual variability in uncertainty approach and avoidance tendencies.

fMRI results and discussion

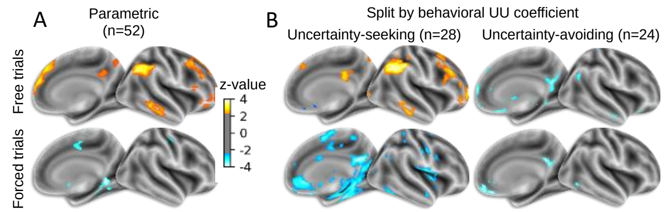

Figure 2: Random effects z-maps of UU_{TOTAL} (p<0.01 unc.; right hemisphere shown) (A) as a function of behavioral UU coefficient, and (B) split into groups by the sign of the behavioral UU coefficient.

Across all subjects (Fig. 2A), the signed magnitude of behavioral sensitivity to UU (w_{UUbeh}) correlates with fMRI responses to UU_{TOTAL} (w_{UUfmri}) in uncertainty-responsive regions, but not in reward regions, despite robust activations in reward regions to ER (not shown). This pattern interacts with free-forced periods: it is only present in free trials, suggesting that the encoded UU representations are specifically related to decision-making.

Splitting subjects into uncertainty-seeking and uncertainty-avoiding groups by the sign of their behavioral UU coefficient (Fig. 2B) shows enhanced encoding of UU (mean w_{UUfmri}) during free trials in the IPL/LPFC of the uncertainty-seeking but not of the uncertainty-avoiding group. Given the broad similarity of the frontoparietal regions to the dorsal attention network, uncertainty-seeking is plausibly associated with an attentional bias toward uncertainty.

In sum, we find that the tendency to approach or avoid uncertain options corresponds to neural responses to UU in uncertainty-sensitive but not reward-sensitive regions, suggesting candidate neural substrates of individual differences in uncertainty seeking. These results raise the question of whether exploring uncertain options leads to stronger uncertainty representations or if the prior saliency of the representations drives uncertainty-seeking. Next steps include testing whether individual differences can be linked to (i) biases in neuromodulatory activity (notably, noradrenaline, dopamine), and (ii) psychometric measures of impulsivity and anxiety.

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