Dissociable Effects of Uncertainty in Perceptual and Cognitive Control

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Abstract

The ability to manage uncertainty is a hallmark of flexible control. But uncertainty is not a unitary construct: it arises from various sources that challenge diverse processing domains – from ambiguous perceptual inputs to conflicting cues about task-relevant features. To disentangle uncertainty sources in perceptual and cognitive control, we independently manipulated perceptual uncertainty (relative choice evidence) and task uncertainty (uncertainty about relevant feature sets) in a dynamic perceptual decision task. Across three experiments, we observed a double dissociation in behavioral effects: perceptual uncertainty reduced accuracy, while task uncertainty primarily slowed response times. Conceptually replicating and extending prior work, functional MRI revealed robust engagement of a fronto-thalamic network in response to task, but not perceptual, uncertainty. We propose that thalamocortical circuits track uncertainty in a differentiated fashion to exert domain-specific control. By establishing robust and dissociable effects, this work provides a foundation for understanding how the human brain manages diverse uncertainties.

Keywords: uncertainty; cognitive control; perceptual control

How limited or contrasting information (i.e., uncertainty) is managed by perceptual, choice, and executive neural systems is fundamental to understanding flexible control in the brain (Halassa & Kastner, 2017; Okazawa & Kiani, 2022). Here, we manipulate two uncertainty sources to establish their consequences on behavior, computations, and neural engagement.

Perceptual and task uncertainty

To induce distinct challenges to cognitive and perceptual processing, we adapted a task (Kosciessa et al., 2021; 2024) that requires participants to sample up to four visual features in a dynamic compound stimulus (Kéri et al., 2004; Mante et al., 2013) to indicate either the predominant color (red/green), movement direction (left, right), size (small, large), or saturation (low, high) (Fig. 1). Upon stimulus offset, a probe queried the prevalence of one target feature via 2-AFC. A cue informed participants about the feature set from which a probe would be selected. Task uncertainty was manipulated by cueing either one or four features. Perceptual uncertainty was manipulated via relative choice evidence, individually titrated for each feature to 65% and 90% accuracy.

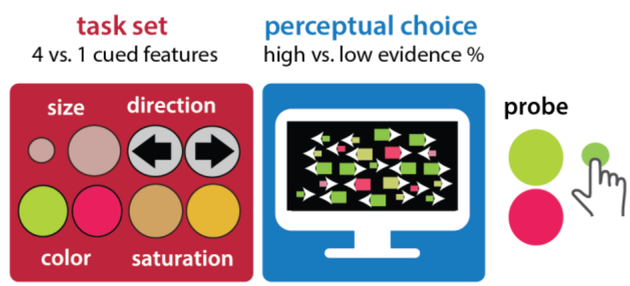

Figure 1: Schematic uncertainty manipulations.

Experiments & Methods

Three experiments investigated behavioral uncertainty effects. Experiments were approved by local ethics boards (ECSS or METC). Participants were healthy adults between 16 and 36 years of age.

EXP1: EEG (N=15). Two 144-trials task runs were acquired during 64-channel EEG acquisition.

EXP2: MRI & EEG (N=23). Three separate runs were acquired during one 3T fMRI and two 40-channel EEG sessions (N=20) prior to non-invasive brain stimulation.

EXP3: Behavioral Control (N=26). High task uncertainty prevents response preparation prior to probe onset while the target feature remains unknown. RT slowing could therefore reflect added response mapping demands. To test this possibility, we performed a control experiment in which left/right response mappings were either fixed or variable within blocks. Task uncertainty was varied at low perceptual uncertainty.

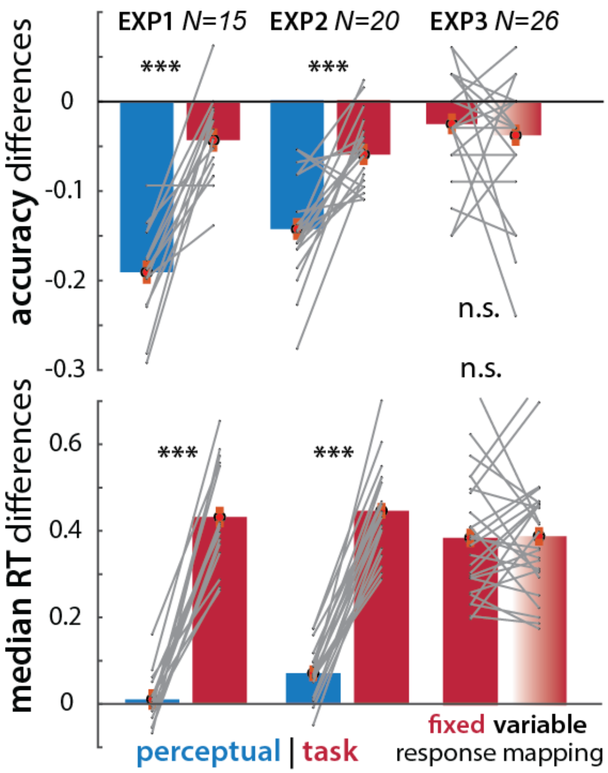

Figure 2: Behavioral uncertainty sensitivity.

Results: Behavior

We observed robust behavioral effects (Fig. 2) that were marked by a double dissociation: perceptual uncertainty predominantly decreased accuracy (expected based on evidence titration), whereas task uncertainty predominantly slowed responses. Response slowing due to task uncertainty did not differ between fixed and variable response mappings, suggesting that it does not primarily reflect increased motor preparation demands following unpredictable probes.

Results: fMRI

Replicating prior work using parametric manipulation (Kosciessa et al., 2021; 2024), task uncertainty increased activation of a multi-demand network during stimulus presentation (Fig. 3), including in the mediodorsal thalamus. Decreased activation was observed in medial prefrontal cortex (Muller et al., 2019) . Task uncertainty modulation was more pronounced when perceptual uncertainty was low. Notably, the network was not sensitive to perceptual uncertainty levels. Results indicate that fronto-thalamic network engagement modulation by task uncertainty is robust, replicable, and source-specific.

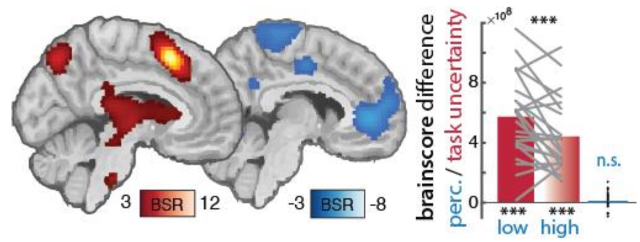

Figure 3: fMRI: First latent variable (*permuted* p < 0.001) from task PLS analysis of condition-specific stimulus regressors. BSR = bootstrap ratio. N = 23.

Conclusion

Decisions are subject to various uncertainties (Bach & Dolan, 2012). By disentangling uncertainty about relevant task sets from that regarding perceptual choice information, we show that decision behavior and neural engagement are differentially sensitive to either uncertainty source. This provides a starting point for clarifying specific computational and neural adjustment to either uncertainty type. We currently probe such via multimodal fMRI and EEG neuroimaging recorded during task performance, and test effects of deep brain ultrasound stimulation on behavior, computations, and neural dynamics.

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