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Probabilistic inference under time pressure leads to a cortical-to-subcortical shift in decision evidence integration

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ABSTRACT

Real-life decision-making often involves combining multiple probabilistic sources of information under finite time and cognitive resources. To mitigate these pressures, people "satisfice", foregoing a full evaluation of all available evidence to focus on a subset of cues that allow for fast and "good-enough" decisions. Although this form of decision-making likely mediates many of our everyday choices, very little is known about the way in which the neural encoding of cue information changes when we satisfice under time pressure. Here, we combined human functional magnetic resonance imaging (fMRI) with a probabilistic classification task to characterize neural substrates of multi-cue decision-making under low (1500 ms) and high (500 ms) time pressure. Using variational Bayesian inference, we analyzed participants' choices to track and quantify cue usage under each experimental condition, which was then applied to model the fMRI data. Under low time pressure, participants performed near-optimally, appropriately integrating all available cues to guide choices. Both cortical (prefrontal and parietal cortex) and subcortical (hippocampal and striatal) regions encoded individual cue weights, and activity linearly tracked trial-by-trial variations in the amount of evidence and decision uncertainty. Under increased time pressure, participants adaptively shifted to using a satisficing strategy by discounting the least informative cue in their decision process. This strategic change in decision-making was associated with an increased involvement of the dopaminergic midbrain, striatum, thalamus, and cerebellum in representing and integrating cue values. We conclude that satisficing the probabilistic inference process under time pressure leads to a cortical-to-subcortical shift in the neural drivers of decisions.

1. Introduction

Decision-making often involves combining multiple pieces of information, each associated with some degree of uncertainty in predicting an outcome, within a tight deadline. For instance, to determine the best treatment for a patient, a physician would ideally perform an exhaustive set of diagnostic tests and integrate the test results, weighted by their respective reliability. However, this decision process, in addition to being computationally expensive, may take longer than is practical. If the case is urgent, a doctor might forego considering all available tests and base a quick but "good-enough" decision on a subset of information (Lamberts, 2000; Payne et al., 1988; Rieskamp and Hoffrage, 2008; Wright, 1974), a form of heuristic decision-making known as *satisficing* (Simon, 1956, 1955). While satisficing under uncertainty and high time pressure is ubiquitous in daily life, very little is known about its underlying computational principles and neural mechanisms.

In order to characterize such satisficing strategies, we recently developed a novel, multi-cue probabilistic classification task that allowed us to track the manner in which subjects weight and combine different cues to arrive at their decisions (Oh et al., 2016). Under low time pressure, information was integrated near-optimally across all available cues. By contrast, under high pressure, participants dropped the weaker, less predictive cues from the decision-making process, a satisficing strategy we called "drop-the-worst". To elucidate the neural dynamics underlying

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this shift in decision modes from optimal to satisficing, in the present study we combined this task, performed under low (1500 ms) and high (500 ms) time pressure, with functional magnetic resonance imaging (fMRI). Using variational Bayesian inference, we quantified participants' cue usage and related it to changes in regional blood-oxygen-level dependent (BOLD) signals.

While we are not aware of any previous study assessing the neural mediators of probabilistic inference under time pressure, prior reports on statistical learning under stress, and studies of the speed-accuracy tradeoff in perceptual decision-making, offer grounds for tentative hypotheses. Probabilistic inference has been studied extensively through variants of the weather prediction task (Gluck and Bower, 1988; Knowlton et al., 1994), where acquiring probabilistic cue-outcome relationship through feedback has been shown to be associated with activity in the striatum, hippocampus (Knowlton et al., 1996; Poldrack et al., 2001; Shohamy et al., 2004) and parietal cortex (Yang and Shadlen, 2007). In addition, other recent studies of probabilistic decision-making suggest an important role for the frontoparietal attentional control network in mediating learning in a multidimensional decision environment (Niv et al., 2015), and the orbital/ventromedial prefrontal cortex (vmPFC) in encoding expected reward, subjective value, outcome predictions, and credit assignment (Akaishi et al., 2016; Daw et al., 2006; Levy and Glimcher, 2012; O'Doherty et al., 2001).

Stress has been shown to bias decision-making strategies by reducing contributions of the prefrontal cortex (PFC) and encouraging habitual stimulus-response processes (Dias-Ferreira et al., 2009; Schwabe and Wolf, 2009). Specifically, learning the weather prediction task under stress induced by the cold pressor test has been associated with increased use of implicit, striatum-mediated strategies (Schwabe and Wolf, 2012). Similarly, time pressure on perceptual decision-making has been associated with a deterioration in information processing in early sensory areas (Ho et al., 2012) and increased activity in the striatum (Bogacz et al., 2010; Forstmann et al., 2008), indicating that the striatum may promote faster but possibly premature or sub-optimal decisions.

Here, we characterized how the brain encodes probabilistic cue information as participants shift from employing optimal to satisficing decision strategies with increasing time pressure. Based on the above studies, we predicted that probabilistic decisions will be mediated by both subcortical (striatum, hippocampus) as well as prefrontal (lateral and medial PFC) and parietal regions under low time pressure, with a preferential involvement of the striatum under high time pressure. The data supported this hypothesis and revealed details of the networks involved in this cortical-to-subcortical shift of activity.

2. Materials and methods

2.1. Participants

Thirty-two healthy volunteers participated in this experiment. Seven participants were excluded from further analysis: Five participants due to chance-level performance and two participants due to excessive head movement (> 20 *mm*). The final sample consisted of twenty-five subjects (13 females, mean age = 27 years, range = 18–40 years). All participants provided informed consent in line with Duke Medical Center institutional guidelines and were compensated with $40 for their time (2 h).

2.2. Stimuli

The task employed 16 unique compound stimuli (Fig. 1B), constructed by combining four different visual features, color (blue/red),

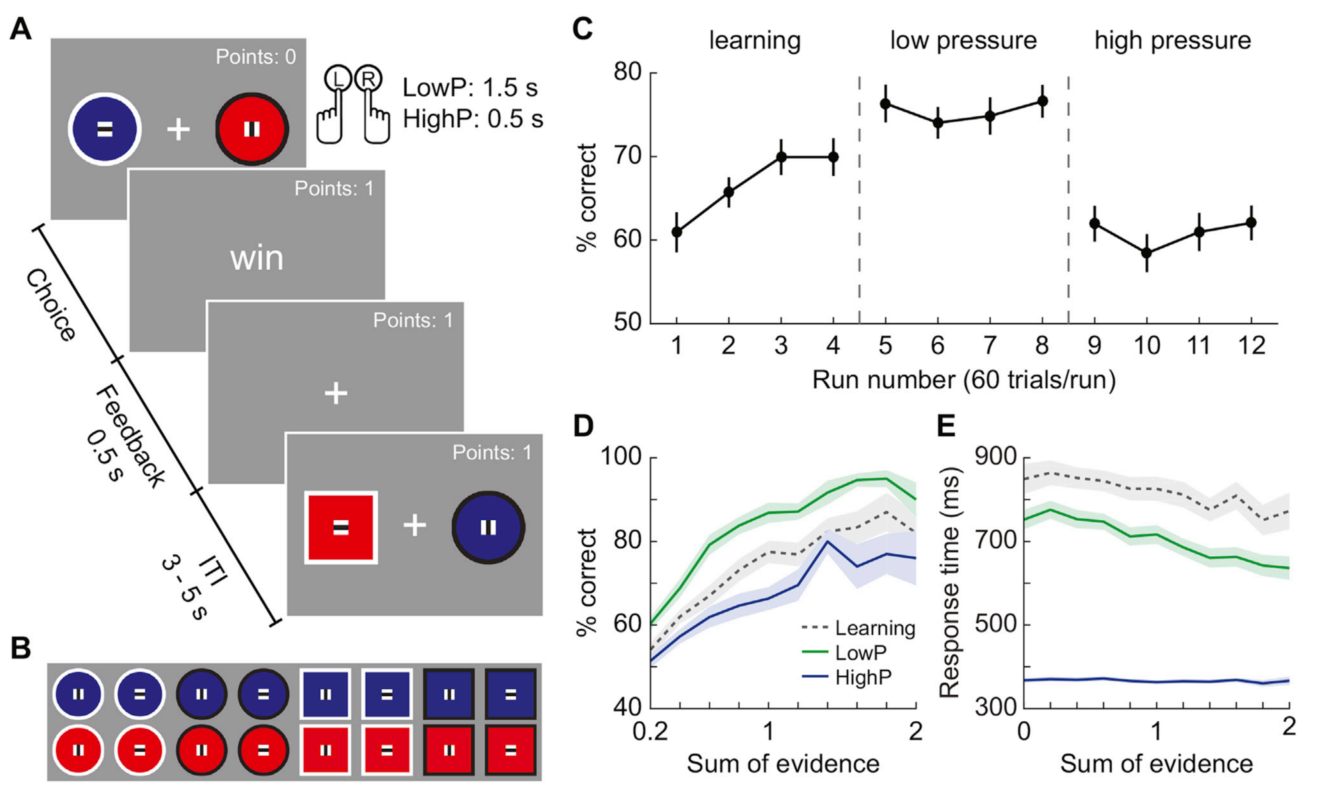

Fig. 1. Task design and behavioral results. **A**, Schematic of the multi-cue probabilistic task. Participants were presented with two different compound stimuli, each having four different features or cue dimensions (color, shape, contour, and line orientation). Participants then selected a stimulus that is more likely to win and received a probabilistic outcome ("win" or "lose"). **B**, Sixteen compound stimuli used in the experiment. Each stimulus was paired with all the other stimuli, yielding a set of 120 unique trials. **C**, Behavioral performance throughout the task runs. Plotted is the percentage of correct choices favored by the sum of cue weights, regardless of outcome feedback. Participants completed the low pressure (LowP) and high pressure (HighP) phases inside the fMRI scanner. Error bars indicate SEM. **D**, Percentage of correct choices as a function of objective sum of evidence (SoE). Decision performance significantly improved with increasing SoE in all three experimental phases. **E**, RT as a function of SoE. RT showed significant SoE modulation during the learning and low time pressure phases but this effect disappeared under high time pressure. Shaded area represents SEM.