Title: Value-based decision making: Control, value, and context in action

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Prediction and control are the keys to adapting to a changing environment. When exposed to such environments the exquisite sensitivity of humans and other animals to regularities in predictive relations between events and their consequences allows us mentally to represent key structural features. Nevertheless, this information is not sufficient for our behavior to remain adaptive; it is not enough to know that 'A leads to O' in order to decide whether to pursue A or choose some other course of action. Rather, this information needs to be integrated with the current value of events. Understanding how, when, and where such integration occurs is the crux of contemporary research in decision-making.

Within this field, the processes that mediate the cognitive and emotional evaluation of events are of central interest, but the unique focus of this research is how such processes are integrated to decide what to do. The psychological and neural bases of this integrative process are the necessary determinants of value-based decision-making and constitute the focus of the papers presented in this issue. There is a long history to this research, beginning in the debates surrounding the relative importance of cognitive and behavioral control during the last century. Over the last ten years or so there have been considerable advances in our understanding of the determinants of environmental control, the values that determine decision-making and their integration within a specified context to support and constrain value-based decisions. These developments have come with advances in behavioral, statistical, and computational methods, but perhaps most prominently in techniques that improve our ability to access the neural processes involved. Such developments are clearly on display in the articles collected in this issue which, when taken together, reveal currently important trends and themes in this research area. Generally, these themes coalesce around three core processes: the nature of the control, value, and contextual components central to any decision.

A number of the current papers focus on the nature of the behavioral and cognitive control processes necessary for decisions to remain adaptive. For example, papers by both **Schultz** et al., [1] and **Bhui et al.,** [2] assess factors contributing to rational and irrational choice in monkeys and humans. Both recognise that rational choice is, in some sense, a luxury of static or relatively simple environments, and that irrational choices, biases, or errors are a natural consequence of greater complexity and limitations in cognitive resources. Other papers examine the neural bases of control processes. **Eldridge et al.,** [3] examine the function of what they argue constitutes a primate visual prefrontal cortex that, in conjunction with inferior temporal and perirhinal cortices, generate the control structures for stimulus-based decisions. **Wang et al.,** [4] focus on the perception of behavioral control in humans and the role of corticostriatal networks in biasing choices towards increasing perceived control, whereas **Balleine** et al., [5] examine the role of the cortico-striatal pathway and particularly intrinsic structure of striatal circuitry in goal-directed control in rodents.

Several other papers challenge assumptions in the field for determining and studying behavioral and cognitive control processes. **Schreiner et al.,** [6] importantly point out that, whereas many methods to studying decision-making use discrete testing or trial-based designs, most problems are actually continuous; one decision begets another and they

suggest that developing more continuous foraging and decision problems may be more ecologically valid. **Liljeholm** [7] and **Bennett et al.,** [8] focus on alternative views of decision-making exploring how models of agency and of policy may be developed to explain choice. Both consider how objective structural knowledge of the environment can be translated into subjective beliefs to guide choice, the former through a model of instrumental divergence and the latter using a reinforcement model of policy gradients. In contrast, **Doya** [9] explores whether the sensory and motor cortices serve as the substrates for dynamic Bayesian inference and optimal control, respectively, and how these map on to perceptual and value-based decision-making.

Papers on the nature of value processes address a number of subthemes. The orbitofrontal cortex (OFC) has become key neural area in understanding the nature of value processes, however several papers here question the exact nature of that role. For example, both **Zhou et al.,** [10] and **Perkins and Rich** [11] argue that values are secondary to the role of OFC in representing the structure of the task or environment. Zhou et al., point to data from rodents and from computational models suggesting the OFC does not assign the subjective values of outcomes and that any role in inferring value is derived from its function in inferring task environments. Perkins and Rich point to data largely from unit recording in primates suggesting OFC represents outcome identity and other information necessary for inferring both value and non-value information. **Wang and Kahnt** [12] broaden this view to a circuit involving hippocampus and amygdala, reviewing evidence OFC is necessary for the inference of associative structure and so for changing values only when this information is partially observable. **O'Doherty et al.,** [13] dive deeply into the question of how subjective values are constructed, suggesting that the value assigned to outcomes often fluctuates and that the brain – here largely the ventromedial prefrontal cortex - computes value at the time of decision by determining the weights attributed to individual features of the outcome. They suggest that these weights are represented hierarchically according to levels of abstraction and propose several cognitive architectures that could underlie this process.

It is well known that predicted values can shape choice, and here papers by **Ostlund and Marshall** [14], **Winstanley and Hynes** [15] and **Hoang and Sharpe** [16] explore this process in rodents. Both Ostlund and Marshall, and Winstanley and Hynes, examine evidence that probabilistically unreliable predictors of reward provoke more general motivational influence over actions and consider the relevance of these processes to compulsive disorders. Winstanley and Hynes in particular examine evidence that cues for unreliable predictors used in electronic games such as gambling machines, increases their addictive qualities. Hoang and Sharpe extend this analysis to motivational processes involving interactions between hypothalamus and the amygdala, the former for more distal reward orientation and the latter inferring specific and proximal predictors of reward.

The role of midbrain dopamine neurons in reward and reward prediction errors has been one of the more influential findings in decision-making. Papers by **Tanaka et al.,** [17] in primates and **Hamid** [18] in rodents review recent studies examining these processes. Tanaka et al., describe evidence that these neurons incorporate non-reward information into prediction error calculations, specifically the effort to achieve the reward. In contrast,

Hamid describes research into the projections of dopamine neurons into the cortex and striatum during decision-making and makes the case for regional specialization in dopamine-related computations based on specific task demands rather than global error signals.

Finally, a number of papers are concerned with the role of spatial, temporal, and more abstract contexts in value-based decision-making. **Abiero and Bradfield** [19] focus on the contextual control of goal-directed actions. Although not usually context dependent, they point out that such actions are context-specific when first acquired, when multiple contingencies are disambiguated, and under stress, and they consider the unique psychological factors that may contribute to this dependency. Likewise, **Roughley and Killcross** [20] examine the neural bases subserving the disambiguation of conflicting actions associated with single-cues and point to a potentially general role for infralimbic cortex in this process, analogous to the function of contexts. **Palminteri and Lebreton** [21] review the role of context in the development of subjective value, particularly how the value of one option is dependent on other options within a specific context. Although this likely improves decision-making, the authors note that such context dependency necessarily limits the generalisation of value information to other situations in which a choice may not be optimal. Similar ideas are explored by **Hunter and Daw** [22] who suggest that comparisons made within contexts may produce rationality in noisy, dynamic situations, but that the context-dependency of value may result in irrational choices when values are applied across contexts.

Camerer [23] considers the implications of some ideas from neuroeconomic theories for habits and their influences on choice, developing a model that uses context to cue habits when reward is reliable and suggesting a machine learning approach to establish the context cues necessary for these effects. **Soltani et al.,** [24] in contrast, focuses on temporal context reviewing how the brain processes and integrates sensory and behavioural information on different timescales, and suggest that a finer-grained understanding of these computations is needed. Finally, **Eckstein et al.,** [25] review reinforcement learning models of decision-making revealing that the results of these models are often overgeneralized across tasks, models, and populations, and that parameters from such models often measure different things across tasks. They suggest that a greater understanding of the influence of contextual factors will be required to generalize such models sufficiently to provide useful explanations.

As a whole, the articles in this special issue provide a detailed snapshot of the current state of the field. From this overview, it is clear that researchers are delving more deeply into the critical determinants of value-based decision-making: control, value, and contextual dependencies, and their neural correlates to achieve a more finely detailed understanding of how such decisions are achieved across multiple individuals, species, tasks, and situations. These papers were originally developed to serve as targets for discussion during a general meeting of scientific groups on this subject, something unfortunately put aside due to the COVID pandemic. We hope that this meeting will go ahead in the future but,

whatever comes, we believe these papers reveal the essential state of the field and will be of use to specialists and others interested in decision-making processes across species.

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