Does the brain calculate value?

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Abstract

How do people choose between options? At one extreme, the “value-first” view is that the brain computes the value of different options, and simply favours options with higher values. An intermediate position, taken by many psychological models of judgment and decision-making, is that values are computed but that the resulting choices depend heavily on the context of available options. At the other extreme, the “comparison-only” view argues that choice depends directly on comparisons, with or even without any intermediate computation of value. In this paper, we place past and current psychological and neuroscientific theories on this spectrum, and review empirical data that have led to an increasing focus on comparison, rather than value, as the driver of choice.

Value-based vs. comparison-based theories of choice

How does our brain help us to decide between going to a movie or the theatre; renting or buying a house; or undergoing risky, but potentially life-transforming surgery? One type of theory holds that the brain computes the value of each available option [1-5]. Most theories of this type represent values by real numbers [6-9]; and such numbers might be represented in, for example, the activity of a population of neurons [10]. The values are then fed into a decision process where options with higher values are generally preferred. We call these 'value-based' theories of decision making. Although value-based theories may be (and frequently are [11]) augmented to account for the ubiquitous effects of context on decision and choice, they retain the assumption that objects or their attributes are associated with values on something like an internal scale.

A second very different, type of theory is founded, instead, on the primitive notion of 'comparison', rather than value. According to some comparison-based viewpoints [12], the brain computes how much it values each option but only in terms of how much the option is better or worse than other options. According to other comparative views [13,14], the brain never computes how much it values any option in isolation at all; it chooses only by directly comparing options.

In this paper, we distinguish these three broad categories of models, and illustrate how a variety of theories of decision making in the cognitive and brain sciences lie on the spectrum between value- and comparison-based accounts (Table 1). This distinction is important because current approaches to decision making and choice can be seen as varying along two dimensions: first dimension is the existence or nature of the (value) scales on which items are assessed (e.g., some models assume ratio, interval, or ordinal scales, while others assume no scale at all); and second dimension is the granularity of representation of those items (e.g., whether the basic units are features, items, or states). We also review empirical evidence that discriminates between theories, arguing that many of these data are consistent with purely comparison-based or scale-free approaches.

TYPE I: Value-first decision making

Theories of how brains 'do' make decisions frequently derive from economic theories of how decisions 'should' be made. In the classical version of this theory, 'expected utility theory' (EUT) [1], each option can be associated with a numerical value indicating its 'utility'. The optimal decision maker then chooses the option with the maximum utility; or, if the outcome is probabilistic, the option with the maximum 'expected' utility; or, if the outcome is delayed, the outcome with the maximum 'discounted' utility. It is natural, therefore, to suggest that the brain may approximate such optimal decision making by assigning, and making calculations over, numerical utility values for available options. (Economists frequently note that they assume only that people reason 'as if' they possessed such utilities [11]. But theories of the neural and cognitive basis of decision making cannot be agnostic in this way, because their primary concern is to specify the representations and mechanisms underlying choice.)

Stable scale-based theories of decision-making are embodied in utilitarian ethics and early economic theory. Utility, or happiness, was taken to be an internal psychological quantity, which can be numerically measured and, potentially, optimized. Much of modern economics, after the 'ordinalist revolution' [2,3] has been more circumspect, claiming only that people make choices 'as if' consulting a stable internal utility scale. But recent theories in behavioural economics have returned to a psychological concept of utility to explain people's choices [4,5].

What such approaches have in common is their assumption that the utility of an option is 'stable' in that is its utility is independent of other available options. This implies, for example, that if a banana is preferred to a sandwich, this preference will be stable whatever additional options (e.g., apples, cakes, or crisps) are added. This stability follows because the utility of a banana or a sandwich are computed independently of other options and a banana is preferred to a sandwich if it has the higher utility. The 'independence from irrelevant alternatives' has significant intuitive appeal and has been used as a foundational axiom in models of choice. In reality, it may be difficult to calculate the value of a complex choice. But if such values can be determined, the process of choice itself is easy: choose the highest. Notice that stable utility models are able to capture the fact that people's choices may change systematically when their state changes. For example, I may prefer a cheese sandwich to a chocolate cake. But just having eaten a cheese sandwich, I may then prefer to follow up with the cake. This is because the 'marginal utility' of a second sandwich may be substantially less than the first. But stability does imply that if I prefer the sandwich to the cake, this will still be true if a third option (e.g., an apple) is available.

Note that this assumption about stable utility scales is aside some random fluctuations in utility functions due to noise in the choice process [6,7] (e.g., there are at least three ways to think about noise: the Fechner type model where noise is added to the utility of each option, the random preference model, where noise is added to model parameters, or the tremble approach, where there is some probability of a random choice [6]). Practical examples and implications that stem from this noise/tremble-based view include attempts to dispel errors and cognitive illusions, which distort access to assumed stable underlying preferences [8].

Large parts of economic theory depend only on the assumption that options can be ordered from least preferred to most preferred (possibly with ties) [2]. For example, if I must choose between three sandwiches, and houmous < cheese < ham (where '<' represents a preference relation), then I will presumably choose ham. This is 'ordinal' utility. A great deal of work in judgment and decision making and economics, however, focuses on choices between gambles, such as a 50% chance of £80 (such gambles, which are not limited to monetary outcomes, are known as *prospects*). Crucially, ordinal utility is insufficient to explain choice over gambles. Suppose we have three outcomes, *bad*, *medium* and *good* (knowing only that *bad* < *medium* < *good*). We cannot say whether we prefer *medium* for sure, or, say, a 50/50 chance of *bad* or *good unless we* know how much better *good* is than *medium*; and how much worse bad is from *medium*: and this requires a cardinal (interval) scale, in which is possible to say, for example, that the difference between bad and medium is twice as large as the difference between medium and large.

The application of utility theory to risky decision making is made possible by the realization that an interval scale can be constructed from binary choices between lotteries [1]. Interval scales can be represented by real numbers, but where there is no fixed zero point, and no fixed units of measurement: Fahrenheit and Celsius are, for example, cardinal measures of temperature. According to EUT, a person's stock of, say, money, m, will have a utility $U(m)$. If a gambler is uncertain whether her wealth is m_1 or m_2, the utility of this state is $p.U(m_1) + (1-p)U(m_2)$, where p is the probability of m_1. EUT, like other theories of choice we shall discuss below, treats money and probability as having a completely different status; and the way they combine is not part of a general theory of multi-attribute choice. A crucial property of EUT is that the value of a prospect is independent of other prospects. In riskless choice, a popular extension of EUT theory, 'multi-attribute utility theory' [9], postulates that the overall evaluation $v(x)$ of an object x is defined as a weighted addition of its evaluation with respect to its relevant value attributes (the common currency of all these attributes being the utility for the evaluator). What is important to this theory is that each person can assign different weights to different attributes. However, for a particular individual, the utility of each option is independent of the other options.

Observed choices both in the lab and the real world depart from the predictions of EUT in a number of ways, leading to variants of the account aimed at capturing observed patterns of choice behavior. 'Prospect theory' [15] differs from EUT in assuming that values are assigned to changes (gaining or losing an object, experience, or sum of money). Changes are determined relative to a reference point, which is often the status quo. The value function is concave for gains and convex for losses. Prospect theory also assumes that agents overweight changes in probability moving from certainty to uncertainty more than intermediate changes. These properties allow an account with key departures from EUT. But prospect theory retains the property that the value of each prospect is independent of other prospects.

'Cumulative prospect theory' [16] and the closely related 'rank-dependent utility theory' [17] share the assumption that whole prospects are valued independently of one another, but allow the values of sub-components of a prospect (e.g., probabilities; amount to be won) to be interdependent. Because such models are defined over 'cumulative' probabilities (i.e., probabilities of doing at least as well as x—note, the probabilities of individual outcomes are not directly represented), and because it is cumulative probabilities that are transformed, the weighting attached to a particular outcome depends on how the outcome compares to other outcomes within the prospect. More extreme outcomes end up being weighted more heavily. But, at the level of whole individual prospects, the value assigned to a prospect is independent of other prospects because the calculation of cumulative probabilities and their weighting is independent of other prospects.

‘Disappointment theory’ [18,19] and the ‘transfer of attention and exchange’ (TAX) model [20] are two other significant modifications of expected utility in which independence from irrelevant alternatives holds at the level of whole prospects. In fact, within psychology, many models also preserve the assumption that values of whole options are computed, though they allow for effects of reference points.

So far we have considered cases in which choices are based on stable values, and in which choices are not influenced by the context of other options available at the time of choice. Note that there is a difference between the value of an option being affected by a kink in a utility function and the value of an option being affected by other options in the choice set. The former is an intra-option effect, and relates to Type I models, while the latter is an inter-option effect, and is characteristic of comparison-based models – described as Types II and III below.

Apparently consistent with Type I models, some recent work in neuroscience, especially in neuroeconomics, has been interpreted as promising a direct neural measure of value, in terms of levels of activity in key brain regions [21–25]. Such assumptions underpin much current economic practice, such as the use of contingent valuation methods to compare otherwise incommensurable goods (lower pollution; more car ownership) by relating them into a common ‘currency’ (i.e., money). However a huge range of challenges such models is given by empirically observed context effects (e.g., ‘preference reversals’ [26,27]; ‘prospect relativity’ [28]; memory effects [29]). Box 1 presents recent evidence for a specific type of context effect that implies lack of context independent value-based judgments. These results resonate with the idea that preferences are constructed afresh, rather than revealed, in the light of the salient options in each new situation [30]. Box 2 presents recent evidence in neuroscience, which suggests that comparative (relative or contextual) valuation is fundamental at a neural level too.

We now therefore turn to a second class of model, in which choice may be influenced – in systematic and predictable ways – by the context of other options available but in which the assumption that value is computed is nonetheless retained.

Type II: Comparison-based decision making with value computation

Decision theories here classified as Type II still assume scales for utility – i.e. attributes have scale-based values that can be compared on an interval scale (i.e., the comparisons are better than ordinal). Those models are based on comparisons to allow for context effects, again at the level of whole prospects, but also now at the level of attributes. Thus such models have accommodated effects of context in a variety of ways. In economics, models of utility gained from income have for example increasingly acknowledged a role for social comparison, such that the value associated with a given income or reward is not independent of the context of other rewards or incomes. Thus, Fehr and Schmidt's model of 'inequity aversion' [31] assumes that value associated with a given reward is reduced to the extent that rewards are distributed unequally; while models of income satisfaction assume that value comes not just from an income but from how that income either relates to a mean, reference-level income [32] or relates to relative ranked position within a whole distribution of incomes [33,34]. Note that such accounts simply assume additional terms in the equation that calculates utility.

Within psychology, the majority of models also preserve the assumption that values of whole options are computed, though they allow for effects of context in a variety of ways. In some models, values are assigned to each option but the computation of this utility from the attributes may be influenced by attributes of other objects in the choice set. ‘Regret theory’ [35] assumes that people first represent the utility of an outcome of a prospect, and that this utility is then modified by anticipated feelings of regret they may have on experiencing the outcome (with respect to foregone outcomes of, crucially, other prospects). Similarly, according to Tversky and Simonson’s well-known ‘componential-context model’ [36] of context dependent preference, each attribute of an object has a value that depends only on its magnitude. The value of an option is a weighted sum of its attribute values and the weighting of each attribute is modified according to the trade-off between attributes in the previous choice sets. Each option is also evaluated in terms of its advantages and disadvantages relative to other options and the asymmetric value function (from prospect theory) is applied to these differences so that the disadvantages loom larger than the advantages. Thus, to account for context effects, objects need not have stable values even though their attributes do.

In another sub-class of models, the values of whole objects are not computed, and choice relies instead on integrating just the relative values of different attributes. In these ‘comparison-only’ models, like attributes are compared across options. Thus, the choice between options is made in relative rather than absolute terms, allowing explanation of many context effects. But these models still postulate an underlying utility scale for each attribute. Here we briefly discuss several popular recent models to illustrate our point. The ‘stochastic difference model’ [37] assumes a value function that transforms the objective attribute values into subjective ones and then a separate function that compares attribute values within a dimension (and if the difference between two options exceeds a given threshold then a decision is made – choose the highest). Accumulation of relative evidence is also used by ‘decision field theory’ [38] – a dynamic and stochastic random walk choice model of decision making under uncertainty; and its multi-alternative neural network implementation [39]. In decision field theory, differences in attribute values are integrated in a random walk in which attention fluctuates across attributes. The 'leaky competing accumulator model' [40] takes the same approach—value is represented by activation in neural units and value differences are accumulated, though loss aversion is key to predicting context effects in the leaky competing accumulator model, whereas lateral inhibition is central to decision field theory.

The most recent examples of this approach are the 'perceived relative argument model' of decision making under risk [41], which introduces relative between-lottery comparisons of probabilities and/or payoffs; and the 'tradeoff model' of intertemporal choice which replaces alternative-based discounting with attribute-based tradeoffs between relative interval differences and payoff differences [42].

Finally, Parducci's seminal 'range-frequency theory' [43] of contextual judgment assumes that a subjective value given to an attribute is a function of its position within the overall range of attributes (measured on an interval scale), and its rank within the immediate context. This model preserves the assumption that values of attributes are computed, though it allows for effects of context in those two specific ways.

The approach outlined here – comparison with value scales – is also followed in neuroeconomics where some researchers share the view that comparison occurs when objects are assigned value (i.e., the first stage is comparative). For example, one recent 'Bayesian inference model' [44] based on neural data suggests that the brain may not lack absolute value scales, but rather that estimates of value are noisy and often inherently uncertain (as often are sensory percepts), which compels people to make statistical inferences (e.g. Bayesian) from all the information available. Accordingly, relative comparisons are used to infer distributions of values. Note that other neuroscientists still maintain the view that evidence suggests a two-stage model in which values are first assigned to goods and actions and then a choice is made from a set (i.e., the first stage is pre-comparative) [45].

Type III: Comparison-based decision making without value computation

The ‘comparison with scales’ models reviewed above retained the assumption that value – of either attributes or objects – is calculated, and that the results inform choice. A third more extreme possibility is that the notion of stable internal scale values can be dispensed with and that comparison is the only operation involved. Thus, Type III theories are here defined to include models without scales that involve ordinal comparison only. [That is, the perceptual system might be like a pan balance, which responds by tipping to the left, or right, depending on which of two items is heavier, but provides no read-out of the absolute weight of either item.] This comparative approach does not assume that observable binary choices result from consulting stable (context-independent) internal values. However, to the extent people compare to the same context (e.g., recurrent environments in the real world) stability will result: Apparent stability is not evidence against Type III accounts.

We have already noted a variety of context effects. Value-based theories can explain such phenomena only by assuming that utilities are relative to all the other options in the choices set (i.e., each alternative is evaluated with reference to all other alternatives).

Some researchers argue instead that these effects are due to a human inability to represent absolute magnitudes, whether perceptual variables, utilities, payoffs, or probabilities [28,46]. The most recent type of comparative theories assumes that people make judgments and decisions without consulting a utility scale based on the absolute magnitudes of stimuli (even for key 'economic' variables such as time and probability) [13]. According to these models, 'direct' comparison, rather than value, is fundamental to judgment and choice, which implies that absolute differences between attribute levels often do not matter and different processing rules may apply to compare objective values (e.g., numbers) directly. Note also that in explaining some of the evidence in Box 1 (e.g., the work on relative pain valuation) and Box 2, Type III models can be considered as the 'most natural' and the ones that should be assumed in the interests of parsimony unless there is positive evidence for value as well as comparison.

This viewpoint is embodied in the 'decision by sampling' theory [13,47,48] (Figure 1). In decision by sampling, attribute values are compared in a series of binary, ordinal comparisons. The number of favorable comparisons is tracked in a set of counters, one for each option. The option whose counter first gets to threshold is chosen. Value is never calculated—the counters only track ordinal comparisons. Despite this, because attributes are compared against a sample of attribute values from memory, which reflects distribution of these attributes in the environment, decision by sampling is able to account for classic patterns of economic behavior (e.g., diminishing marginal utility of wealth, losses looming larger than gains, hyperbolic temporal discounting, and overestimation of small probabilities and underestimation of large probabilities) as properties of the distribution of attribute values.

Another class of models in which choices are made without valuing options is given by the lexicographic semi-order models [49,50] (but see [51,52]). For example, in the 'priority heuristic' [14,50] one prospect is preferred over the other if they differ sufficiently in the minimum gain. If tied on minimum gain, the probability of the minimum gain is considered. Finally, if tied again, the maximum gain is considered. This approach is part of a family of models known as ‘fast-and-frugal heuristics’ [53], which involve sequential (in order of importance) application of reasons to eliminate/select choice alternatives. The approach can be traced back to earlier heuristic models such as the ‘elimination by aspects theory’ [54] in which choice alternatives are compared sequentially one attribute at a time to eliminate unsatisfactory choice alternatives until only one remains. Note that although there is a representation of value for attributes and thresholds, the problem can be viewed as a set of binary comparisons (e.g., “if value < threshold then eliminate”). There is no direct value computation. Future research should study how people select the dimension for comparison (see Box 3), which is a key issues for this class of theories.

Comparative theories such as decision-by-sampling and the priority heuristic are similar in spirit to what we denote here as ‘reason-based’ models, which provide memory-based accounts of decision phenomena by modeling how the number and order of retrieved reasons (pros and cons for each option) produce direct comparisons between options. For example, ‘query theory’ [55] offers a memory-based account of endowment effects, which suggests that people construct values for options by posing a series of queries whose order differs for sellers and choosers (or for immediate vs. delayed consumption respectively when explaining the discounting asymmetry of intertemporal choice [56]). Because of output interference, these queries retrieve different reasons (arguments, attributes) of the object and the exchange medium, producing different valuations (e.g., reasons to receive an immediate profit vs. reasons to wait for a bigger payment in the future). Query theory is closely related to earlier ‘reason-based choice’ [57] accounts of inconsistencies in preference, according to which such inconsistencies are the result of subtle task differences that may affect the generation or consideration of reasons. ‘Fuzzy trace theory’ [58] also postulates that memory retrieval of reasons (e.g., health-related values, knowledge, experiences) underpins the subjective interpretation and representation of choice information. In summary, reason-based models do not assume any value function, and instead rely only on counting-up bits of evidence for and against and on explicit thought processes such as 'arguments'.

Concluding remarks

Value-based theories of choice in neuroscience, psychology and economics require that people and animals can map options, or at least attributes of options, into an internal value scale representing their value. We referred to these as Type I approaches. What makes a value scale appealing is its ability to bridge across domains. However, mounting evidence suggests that any independent value scale is unstable even within the same domain [59], which implies that it will be even more malleable across domains. Some comparative theories accommodate context sensitivity by postulating that option values are derived in relation to all available options. Relative evaluation models (here dubbed Type II) assume a value function that transforms an option's relative advantage on each attribute (thus, such models deal with contextual distortions by assuming that the reference point is all other options in the choice set); while other purely comparative models (Type III) even suggest that there is no reason to suppose the existence of value scales (functions), because many decision phenomena can be explained by heuristics employing direct (scale-less) comparisons between options. According to such accounts the very concept of an underlying utility scale needs revisiting in view of the mounting theoretical and empirical support for the view that preferences can be derived from the fundamental process of comparison [60]. Accepting this position would require rethinking of some fundamental assumptions across the human sciences (see Box 4).

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Box 1. Psychological evidence in support of comparison-based approaches

Even subjective sensory experiences, which can be measured in physical units (frequency, sound pressure, luminance, force), are a function of the comparison of each stimulus, rather than involving a separate evaluation of each element of the sensory input. For example, the subjective judgment of the grayness of a patch is determined by the ratio of its luminance to the luminance of the brightest patch in the scene (known as 'Wallach's ratio rule'), not by any function of its absolute degree of luminance. This observation implies that if the visual field is made up entirely of dull grey patches (as when viewed in the context of natural scenes), then the brightest patch will be perceived as a pure white, as is empirically observed [61]. In another modality, the judged sweetness of a given sucrose concentration is highly context-dependent, being higher when the concentration appears in a positively-skewed distribution than when the same absolute concentration appears in a negatively-skewed distribution (moreover, the absolute sucrose concentration judged to be most pleasant is lower in a positively-skewed distribution) [62]. More generally, subjective magnitude judgments for a wide variety of sensory stimuli are context dependent in predictable ways [43,63]. The neurophysiology of the sensory pathway confirms this picture—from the earliest stages of sensory processing, the system 'normalizes' absolute sensory values, possibly to increase information coding efficiency [64].

A range of decision phenomena are consistent with the view that decision makers have a set of comparative preferences concerning options. For example, the perceived value of a risky prospect (e.g., "*p* chance of *x*") is relative to other prospects with which it is presented, which is known as 'prospect relativity' [28]. In particular, when judging the value of '50% chance of winning £200' and respondents have options of £40, £50, £60, and £70, the most popular choice is £60. When people have options of £90, £100, £110, £120, the most popular choice is £100.

Similar context effects were observed when skewing the distribution of options offered as monetary equivalents for gambles, whilst holding the maximum and minimum constant—when most values were small, gambles are under-valued compared to when most values were large [65].

Prospect relativity is also observed in risky financial decisions when choices of saving rates and investment risk are affected by the position of each option in the rank of presented options [66]. Relativity effects are also seen in judgments of income. For example, wage satisfaction is predicted not by an individual's absolute earnings but instead by the ranked position of their wage within their workplace [34], and general life satisfaction is predicted not by absolute income but by ranked position of income within a social reference group [33]. Similar context effects are also found in interactive decision-making when people play many one-shot Prisoner's Dilemma games against anonymous opponents [67]. Players' cooperation and their predicted cooperation of the co-player in each game depend on the "cooperativeness" of the preceding games.

People seem to have comparative representations of utility even for subjective experiences, such as pains [68] (see Figure I). In an auction-based experiment, participants received a single electrical shock and were then asked to decide how much they were willing to pay, from a given monetary endowment for that trial, to avoid fifteen further shocks. Individuals offered to pay more to avoid a particular pain when it was relatively more painful compared to recent trials. Furthermore, the price offers were strongly determined by the cash-in-hand for each trial, rather than overall wealth. The estimated consumer demand curves for pain relief also exhibited these highly unstable patterns. This evidence suggests that the subjective value people assign to non-market goods, here pain relief, is extremely comparative. Prices (willingness-to-pay) offered to avoid pain are also shown to be biased towards random hypothetical price anchors provided by the respondent’s social security number [69].

Box 2. Neurobiological evidence in support of comparison-based approaches

Although the neurophysiological basis of valuation is complex [70], recent evidence in neuroscience suggests that comparative valuation is fundamental at a neural level. Neurophysiological recordings in monkeys and humans have shown evidence that comparative reward coding in neural substrates (e.g., via dopamine projections to the striatum and the orbitofrontal cortex) is strongly implicated in simple choice behaviour [71–73] (see Figure II). For example, comparative coding is observed in the orbitofrontal neurons of monkeys when offered varying juice rewards presented in pairs within each block of trials [73]. The recorded neuronal activity depended only on whether a particular juice was preferred in each block of trials, not on its absolute value. An fMRI study with humans found similar results in the medial orbitofrontal cortex—a brain region involved in value coding [74]. Such neural patterns—outcomes activating orbitofrontal neurons only when they are comparatively better—are also exhibited with unpleasant stimuli [75].

Comparative valuation also implies that neural signals rescale according to the range of values in the decision context. Such patterns of activity are observed in dopamine neurons in monkeys [72]. When the animals were presented with stimuli that predicted two volumes of fruit juice, the dopamine neurons fired when larger volumes were expected and become deactivated when smaller juices amounts were expected. Also, even though the ranges of juice volume differed throughout the experiment, the range of neural activity was fixed. This result suggests that the neuronal activity is independent of the expected range of stimuli, which is compatible with the view that neural activity represents only the comparison to other recent items. In summary, there is no convincing evidence for a common neural currency that is used to independently value stimuli across contexts.

Platt and Padoa-Schioppa [76] review recent imaging evidence for both absolute and relative/comparative value in different neural circuits. The key finding is that the brain has several representations of value, which depends on the purpose and domain of the function (perception, action control, economic choice), and indeed, such representational redundancy is evident in the representation of other functions (e.g., in motor control). This evidence can explain why participants in decision experiments sometimes behave as if they are guided by relative judgments and sometimes behave in more absolute manner.

Box 3. Outstanding questions for comparative theories of choice

- What empirical evidence can strictly distinguish between comparison-based decision making with and without value computation?
- If people lack 'common currency' of utility and hence cannot make stable comparisons between options that vary on several dimensions, then conducting "contingent valuation" of non-market goods, e.g., concerning health or the environment, is not possible. What method should replace it for policy analysis?
- If consumers and voters choose in a purely comparative way, what economic and political systems might be expected to arise to both exploit comparative effects and to alleviate them?
- To what extent to different theoretical accounts map on to Marr's different levels of analysis of cognition: (1) functional/normative, (2) algorithmic/computational, and (3) implementational/mechanistic? How far can different approaches be viewed as complementary perspectives on choice behavior?

Box 4. Implications of comparative theories across other fields

Philosophy: Bentham's [77] utilitarianism—the notion that utility is calibrated on a stable psychological scale, may need a revision in view of the evidence that people possess only relative utilities.

Politics: If a 'neural signal' for value were stable within and across individuals, then it would be possible to imagine directly measuring the neural correlates of human well-being, or perhaps their valuation of particular types of experience, event, or outcome. A natural aim of public policy would then be to maximize the expected level of such well-being. The utilitarian approach to politics could finally be put on a scientific basis. Comparative models imply that this can be accomplished only if the decision context is relatively stable and consistent.

Economics: Comparative theories may appear to have disturbing implications for normative decision theories, whether in the valuation of non-market goods (such as environment and health), or, in the foundations of micro-economics. Stable utility functions, for example, may just be an illusion [29]. However, even elementary binary or comparative judgments might be used to 'construct' a utility scale, which is more stable and precise than any direct judgments. Using binary choices, people can reliably discriminate about 100 loudness levels for a single type of stimulus (e.g., tones). Thus, following Fechner [78] and Thurstone [79] we can construct a loudness scale from a selection of binary options. This 'Fechnerian' scale will reliably predict which of pairs of tones will be judged to be louder, which means that the scale and the predictions are not context dependent.

Marketing: When products are complex, people probably choose using simple heuristics or focusing on a subset of features. So, firms might create products which are appealing to the comparative mind, but which include hidden attributes that are highly profitable (e.g., high-profit printer ink, or hidden fees in credit cards and banking).

Healthcare: Explicit judgments concerning health-state experiences (e.g., pain) are typically expressed in complex social and economic contexts. This is the case when patients are forced to make abstract comparisons between experienced or imagined health states and other non-health-related goods, such as money. Lack of stable value scales would require increasing experience in order to mitigate this trade-off problem, but experience cannot easily do so for never-experienced symptoms. Therefore, new methods of health state valuations are required (e.g., a combination of choice-based and happiness-based measures [80], or 'building' a scale by using the binary comparison method outlined above).

Table 1. Choice theories discussed in the article according to their type with key references for each theory (presented in the order of appearance in the text)

Theory type	Theory	Key References
Type I: Value-first decision making	Expected utility theory	[1]
	Revealed preferences theory	[2]
	Reference-dependent preferences model	[4]
	Stochastic expected utility theory	[6,7]
	Multi-attribute utility theory	[9]
	Prospect theory	[15]
	Cumulative prospect theory	[16]
	Rank-dependent utility theory	[17]
	Disappointment theory	[18, 19]
	Transfer of attention and exchange (TAX) model	[20]
	Neural value models	[21, 22, 45]
	Bentham's utilitarianism	[77]
Type II: Comparison-based decision making with value computation	Inequity aversion theory	[31]
	Comparison income model	[32]
	Generalised exemplar model of sampling	[34]
	Regret theory	[35]
	Componential-context model	[36]
	Stochastic difference model	[37]
	Decision field theory	[38]
	Multialternative decision field theory	[39]
	Leaky competing accumulator model	[40]
	Perceived relative argument model	[41]
	Tradeoff model of intertemporal choice	[42]
	Range-frequency theory	[43]
	Bayesian inference model	[44]
Type III: Comparison-based decision making without value computation	Decision by sampling theory	[13,47,48]
	Priority heuristic	[49]
	Fast-and-frugal heuristics	[53]
	Elimination by aspects theory	[54]

	Query theory	[55,56]
	Reason-based choice	[57]
	Fuzzy trace theory	[58]

Figure 1. Illustration of a comparative theory without value functions: 'decision by sampling' [13]. Only binary ordinal judgments (>, <) are possible, which implies that only rank matters. Attribute values are compared with a small sample of other attribute values from memory and from the immediate context, and the distribution of these influences preferences. For example, as small amounts of money are encountered more often than large amounts in bank account credits (left). Against this context, a £100 increase in a prize from £100 and £200 improves the rank position substantially more than a £100 increase from £900 to £1,000 (right). Thus decision by sampling predicts people will behave as if they have diminishing marginal utility in any environment where the distribution of money is positively skewed.

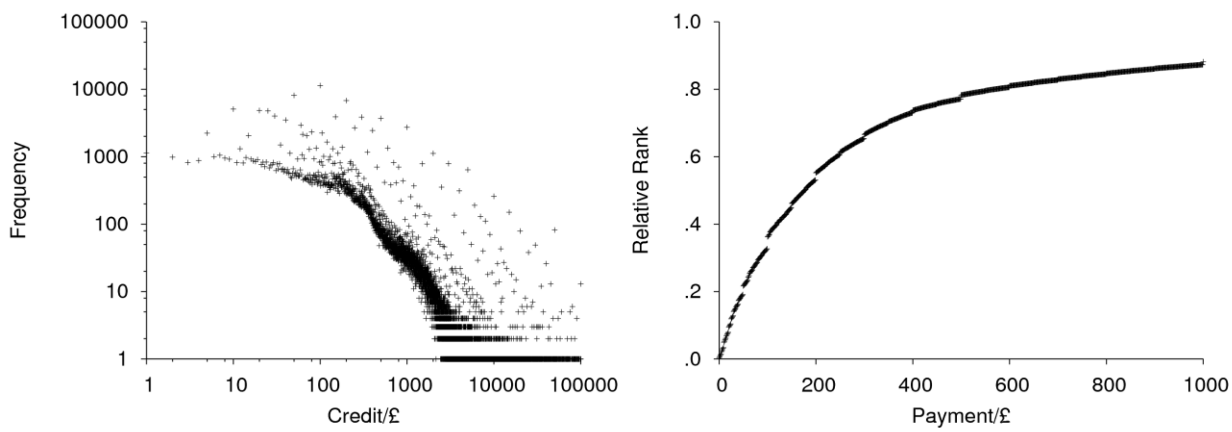
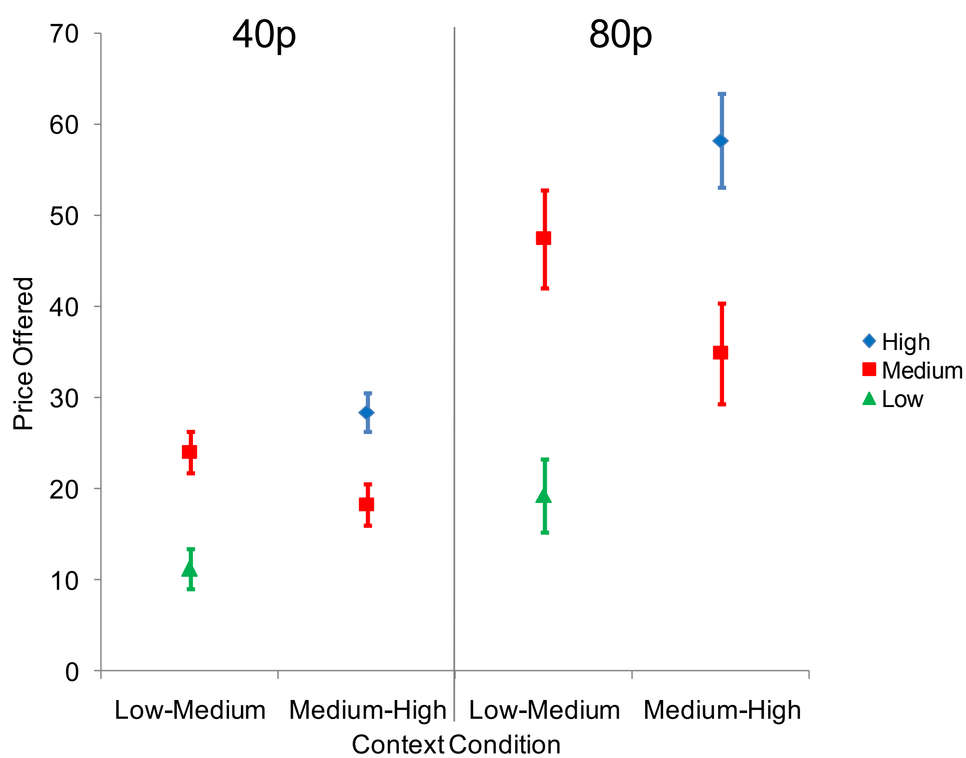


Figure I. Comparative representations of utility for immediate subjective experiences such as pains [68]. (a) Mean price offers to avoid pain from electric shocks depending on endowment (40p vs. 80p per trial) and context pairing. The medium pain level (red squares) provokes markedly different mean price offers according to whether it occurs in a block with low, or high level pain. Furthermore, the price people are willing to pay for relief from the same pain is strongly determined by money-in-the-pocket (80p endowment brings about twice bigger offers than 40p endowment). (b) Demand curves for medium pain relief (depending on context and endowment)—these reflect the quantity of pain relief that can be expected to be sold at different prices. The curves exhibit the relativistic patterns observed for the price offers.

(a)



(b)

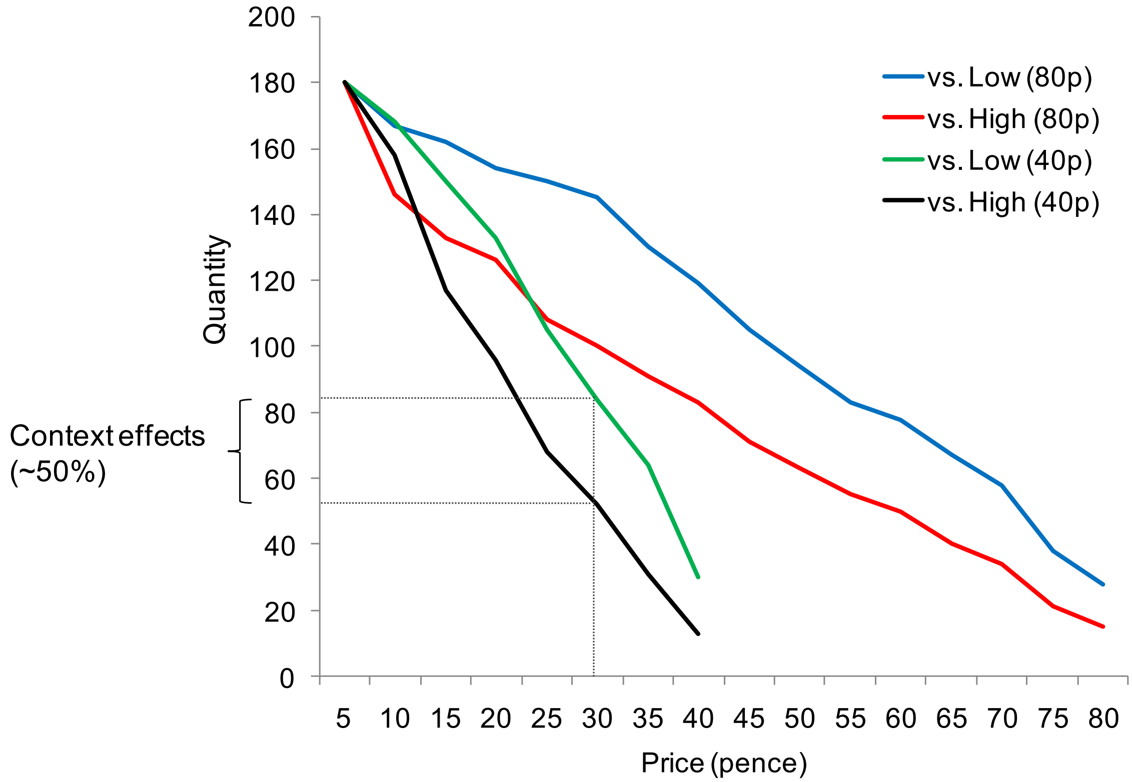
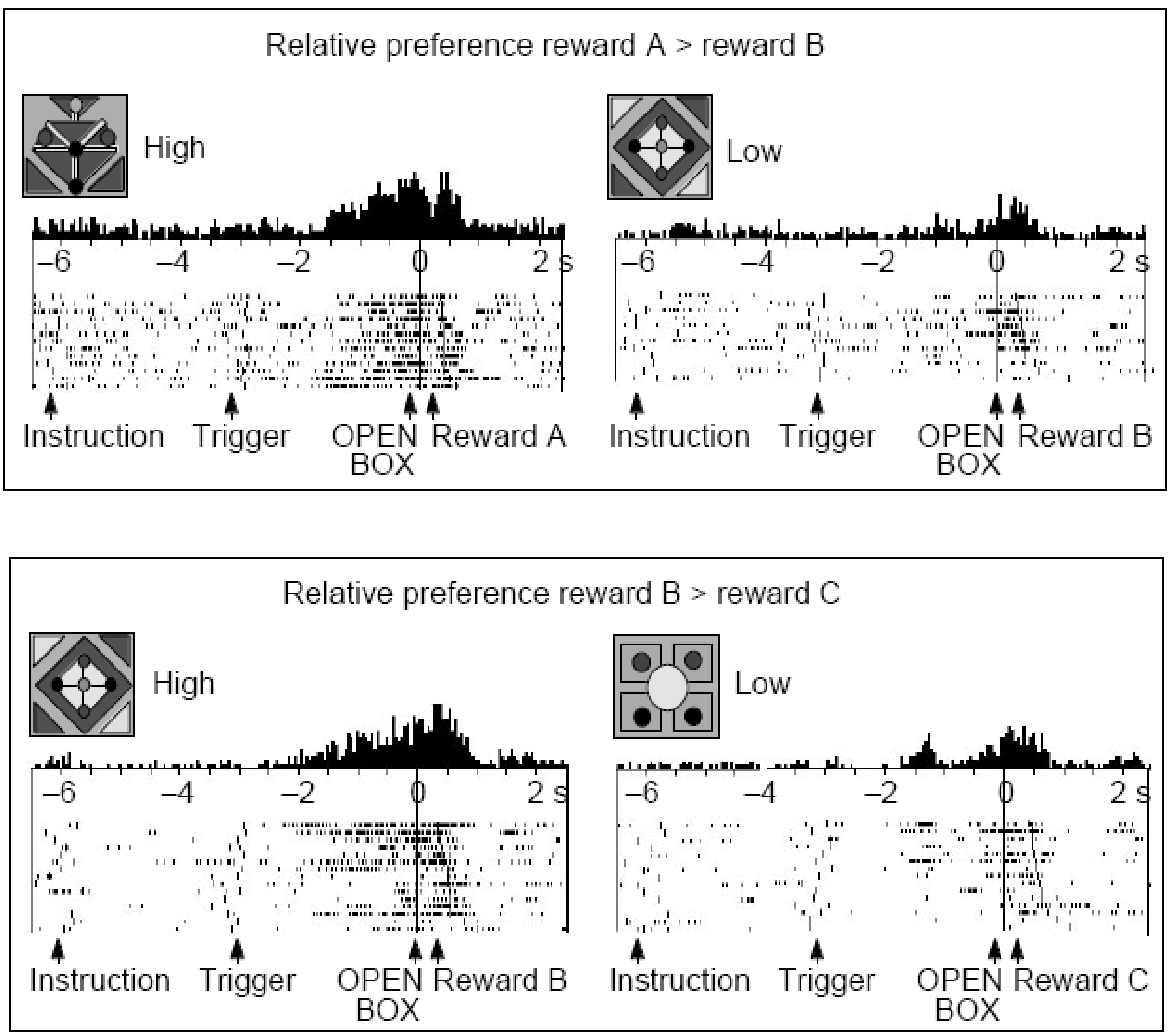
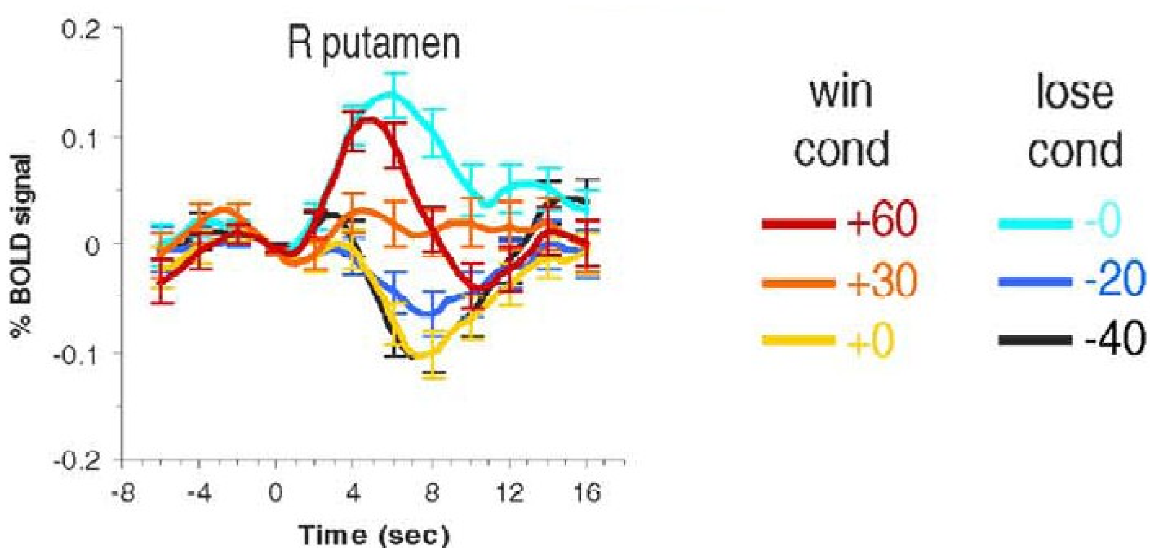

200
180
160
140
120
100
80
60
40
20
0
Quantity
Context effects
(~50%)
vs. Low (80p)
vs. High (80p)
vs. Low (40p)
vs. High (40p)
5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80
Price (pence)

Figure II. Comparative evaluation in the brain. (a) The macaque orbitofrontal cortex responds to a reward only when it is the preferred outcome in a pair [73]. (b) fMRI BOLD signals from the human ventral striatum exhibit similar response patterns, i.e., the activity is based only on the ordinal ranking of a monetary outcome in the present context (highest activity when the best option and lowest activity for the worst option), irrespectively of whether outcomes are losses or gains [71].

(a)



(b)


R putamen
% BOLD signal
0.2
0.1
0
-0.1
-0.2
-8
-4
0
4
8
12
16
Time (sec)
win cond
lose cond
+60
+30
+0
-0
-20
-40