NEUROECONOMICS INSIGHTS FOR DECISION ANALYSIS

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In recent years, neuroeconomics has emerged as an exciting interdisciplinary field with the stated aim of combining knowledge from economics, psychology, and neuroscience in order to increase the understanding of decision-making behavior. The combination of these different disciplines has provided an opportunity to begin specifying the brain basis of decision-making, as well as informing theoretical models of decision-making. In addition, there is now the growing awareness that many of the findings from the field can potentially have implications for more practical decision analysis situations.

According to the classical economic perspective [1], decision makers approach choice situations by analyzing the attainable outcomes and their associated probabilities. The well-known expected utility model of decision making under risk is a good formulation of this behavior, with this model based on an axiomatic foundation that reflects a rationality assumption on the part of the decision maker [2]. Despite the model’s theoretical elegance, it has been often demonstrated that it does not provide an adequate description of typical decision making, and neuroeconomic studies are beginning to demonstrate how a better understanding of the neural processes involved can help explain these discrepancies.

In this article, we will first provide some brief details about typical methods used in neuroeconomic studies, before examining how knowledge about the valuation system in the human brain can yield insight into how decisions are made, and how this knowledge can in turn help build better models of decision and choice. We will then discuss a particularly well-known behavioral anomaly, the framing effect, and how understanding of the brain’s emotional mechanisms can lead to better models of this behavior, before we conclude with some general observations about the relevance of this new discipline for decision analysis.

METHODS

One important approach to neuroeconomics has been to utilize the varied set of methods developed by neuroscientists to examine higher-level cognitive processes. These methods vary widely both in their use and in terms of what questions they can answer, but together they provide a highly flexible set of tools for examining the neural substrates of decision making. Broadly speaking, they can be divided into two types, those that observe the normal functioning brain and those that examine perturbations in these normal functions.

The most frequently used methods measure the degree of “activation” of various brain regions while people are making choices and decisions. For instance, the commonly used method of functional magnetic resonance imaging (fMRI), (see Ref. 3 for information on the method) leverages the physiological fact that changes in neural blood flow leads to corresponding changes in local magnetic properties of the brain, which in turn can be detected by an MRI machine. These blood flow changes are thought to be directly related to regional neural activity, thus providing a measure which correlates...
with neural firing. The majority of the results we discuss in this article are based on fMRI studies; however, other noninvasive measuring techniques are used by neuroeconomists, such as those that measure electrical (EEG) and magnetic field (MEG) changes related to brain activity.

A different approach has been to examine the functioning of the disrupted brain to make inferences about normal behavior. Indeed, the study of decision making processes in the human brain was largely motivated by behavioral deficits that were apparent in patients with brain damage. For example, brain lesions in the frontal lobes of the brain appear to be associated with uncontrolled behavior: patients take excessive risks regardless of their intellectual capabilities or other demographic or psychological factors. The lack of an appropriate skin conductance response to emotional stimuli in this patient group set forth the idea that brain damage to the frontal lobe interfered with behavior through inappropriate integration of emotional knowledge in the decision-making process [4,5], thus providing an important initial clue as to how the brain’s organization related to decision-making processes. In addition to examining the behavioral deficits of patients with lesions, there are also methods to temporarily disrupt neural processing using electrical and magnetic signals in healthy participants, such as Transcranial Magnetic Stimulation (TMS).

PREFERENCES AND VALUATION

Reward Processing in the Brain

The functioning of the human brain and the nervous system is based on millions of brain cells called neurons. In practical terms the brain is a vast network of neurons that communicate with each other. While structurally, the human brain can be divided into separate regions, some of which appear to be functionally specific, there is also much overlap between these regions.

Reward processing in the human brain is closely related to the neurotransmitter dopamine. Dopamine is produced in the brainstem and then projected to multiple areas in the brain. Areas of the brain such as the striatum and orbitofrontal cortex (OFC) receive input from these dopaminergic neurons and are thought to process the rewarding value of stimuli (Fig. 1). Additionally, ventromedial prefrontal cortex (VMPFC) is often mentioned in this context as well. Since the anatomical definitions of medial OFC and VMPFC are somewhat overlapping, and indeed often used in parallel to refer to the same location, we adopt here for simplicity the notation of using OFC when we refer to a prefrontal region that reacts to rewards (medial OFC and VMPFC) and punishments (lateral OFC) [6].

Figure 1. The striatum is located in the basal ganglia at the center of the brain. The orbitofrontal cortex (OFC) is a subsection of the frontal cortex that is specialized in valuation. The figure indicates the approximate anatomical locations of the regions of interest.

The target regions of dopamine neurons have been shown to react to both primary and secondary rewards. Striatum activity increases with the receipt of primary rewards such as water and juice [7], and OFC activity reflects the rewarding value of stimulus in multiple different modalities like taste and olfaction [8]. In addition to primary rewards, both the striatum and OFC react to the receipt of secondary rewards such as financial incentives [9–12]. OFC is also sensitive to more subjective features of the stimuli, and is involved in the calculation of the hedonic value of rewards [6,13]. OFC even tracks modulations in the hedonic value that are driven by contextual information. In one study where participants evaluated...
wine, the perceived pleasantness of the wine and the OFC activity varied as a function of retail price, though the actual wine consumed remained the same: high price increased the pleasantness estimation both in the brain and in the behavioral measures [14]. Of course, in terms of rational models, the consumption experience of identical wines should not depend on the surrounding context (price), but this research demonstrates that the brain’s computations are not fully in accordance with a classical utility calculation process.

Anticipation and Evaluation of Future Rewards

In order to choose the option that provides the highest level of satisfaction, decision makers need to anticipate the rewarding value of each outcome in the relevant choice set. As this is clearly an important issue to economic decision making, anticipatory reward mechanisms were among the first topics that were widely researched in neuroeconomics. The research to date indicates that the reward circuitry in the brain demonstrates increased activation not only when rewards are obtained but also during the anticipation of rewarding outcomes [8,15,16]. Importantly, these anticipatory patterns of activation are not just correlates of the subjective value of the reward, but also have an influence on future economic choices themselves. Negative anticipatory affect during decision making is related to an increase in risk aversion, and positive anticipatory affect in contrast is associated with an increasing risk seeking attitude [17].

In addition to anticipatory reward processing, decision makers in risky choice scenarios must also take into account the probability of each outcome option in order to reach an overall estimate of the attractiveness of the prospects. In a typical experiment, participants encounter a series of uncertain prospects in turn, after which the prospects are resolved, revealing the gain or loss to the participant. As an example, in one task participants view eight cards face-down in random order, one of which is the target card. The task of the participants is to place a bet on the cards. If participants place the bet on the target card they win the bet, otherwise they lose an equal amount of money from their total earnings. The magnitude of the outcome is manipulated by providing the participants with either 1 or 5 Euros to bet with. The probability of receiving the reward is manipulated by allowing the participants to place the bet on either just one card (low probability) or on the corners of four adjacent cards (high probability). By using this paradigm, Yacubian and colleagues showed that both the striatum and OFC encode anticipation of probabilistic rewards [18]. The findings of this experiment indicate that both the reward magnitude and also the associated probabilities are directly encoded in the valuation network itself: the striatum and OFC had higher activation levels in the high bet and high probability conditions than in the low bet and low probability conditions, respectively. Further, the results of this experiment show that the reward circuit also provides a measure for the overall desirability of a risky prospect as it encodes the expected value of a prospect, integrating the value and probability information for rewarding stimuli.

Other fMRI experiments that have studied the valuation of risky prospects have reported similar findings in reward circuitry for manipulations of outcome magnitudes and probabilities as well as for the overall expected value of the prospect [19–23]. Thus, the findings suggest that the evaluation of risky prospects is not solely performed by higher-level “rational” calculations in the brain but instead both the magnitude of the outcomes and probability of receiving them can be processed via the basic reward mechanisms of the brain.

As prior research indicates, people do not react linearly to anticipated outcomes and their probabilities. The very early work of Bernoulli showed that outcomes are processed in a subjective manner rather than relying on the objective numerical value [1]. Typically the utility associated with one additional unit decreases as the outcome level becomes higher. Intriguingly, the activation in the striatum to anticipated monetary gains appears to have the same property: the incremental additions to the strength of the striatum activity
become smaller as the magnitude of reward increases linearly [24]. This property of the striatal response is in line with the decreasing marginal utility effect which is well-characterized at the behavioral level. This finding implies that the striatum might be involved in the calculation of subjective utility of the reward rather than simply reflecting the absolute reward value. Similarly, to reward magnitude, the striatum does not react linearly to probabilities but instead it overweights small probabilities and underweights large probabilities [25]. Similar nonlinear weighting pattern of probabilities is also apparent in the behavior of decision makers [26]. These results imply that the behavioral deviations from linearity may have their roots in the properties of the reward system, both in terms of the sensitivities of the valuation and probabilistic nature of rewards and punishments.

Thus far, we have discussed the anticipatory reactions related to the expectation of financial incentives. However, it is also the case that this mechanism may underlie decisions of a nonfinancial nature, suggesting that the basic reward system may be a mechanism for most, if not all, of the typical day-to-day decisions we take. For instance, the striatum has been shown to reflect the preference for a variety of consumer products [27,28], as well as encoding the anticipatory value of hedonic outcomes [29]. The striatum activity also reflects modulations in the expected hedonic value in a similar fashion to the way the OFC encodes the influence of price on the experienced pleasantness of wines. In an fMRI study, participants evaluated the expected hedonic value of several potential vacations, after which participants were forced to make a choice between two options of similar desirability to them [29]. Behaviorally, a commitment to one of these previously equally valued options increased the estimated hedonic value of the chosen option, and decreased the valuation of the unselected one. The change in the expected pleasure of the two vacation destinations was also reflected in the striatum, with higher activity here for the chosen option than for the rejected one. Another study indicated that the subjective hedonic expectations are indeed influenced by the basic reward processing mechanisms, with a pharmacological manipulation which increases dopamine levels, also increasing hedonic expectations for future life events [30].

Reference Dependence of Valuation

Normative decision-making models, such as the expected utility model, assume that valuation is done in respect to the total amount of wealth. One of the main insights of prospect theory [26], a descriptive theory of decision-making under risk, is that decision makers tend to value outcomes in a reference dependent manner. In accordance with this theoretical model, the brain seems to process gains and losses in a similar way. The most dramatic example of reference dependence is that the anticipated and experienced gains and losses activate different brain networks. For instance, the calculation of the expected value of a prospect has been suggested to be performed by the striatum when calculating the expectation of gains [18,22] and by more affective brain structures (amygdala) when calculating the expectation of losses [18]. In addition, the anticipation of a negative outcome has been linked to a brain structure (insula) that is often associated with processing of negative experiences such as pain [17], whereas anticipation of rewards is reflected in the striatum and OFC activity.

The reference dependence of striatum activity has been implied by multiple studies. In one early neuroeconomics study, participants played lotteries while undergoing fMRI. Two types of lotteries were used, one consisting of positive and zero outcome options, and one with negative and zero outcome options. When people received the zero outcome from the negative lottery (a relative gain), striatum activity was higher than when the zero outcome was received from the positive lottery (a relative loss) [31]. Generally, the striatum seems to process the outcomes with respect to subjective expectation [18,32], though some parts of the striatum have recently been shown to reflect reference independent calculation together with some subregions of OFC [33].

In addition to performing calculations with respect to other possible rewards, Tom
and colleagues have shown that the striatum induces nonlinear reactions to gains and losses in a task where participants made choices accepting or rejecting mixed gambles [34]. The researchers found a common network, including the striatum and OFC, that was activated for gains and deactivated for losses. These areas also showed a pattern of loss aversion, namely, that the slope of the deactivation for losses was greater than the slope of activation for gains in a majority of participants. Therefore, the striatum again demonstrates some of the properties of descriptive models of risky choice, showing loss aversion rather than the patterns predicted by classical expected utility maximization. Also of interest was that during decision making, no brain areas where found that were specifically activated by evaluation of increasing losses, in contrast to other studies that have reported increased activity in emotional regions, such as amygdala and insula, for losses [17,18]. One possible explanation for this difference is that the Tom et al. study restricted analysis purely to the decision-making phase (decision utility), and excluded anticipatory effects (anticipated utility) by only resolving the lotteries after the fMRI scanning.

Besides the set of possible outcomes, other contexts also influence the valuation process, such as social aspects [35] and numerical representations of financial gains [36]. Fliessbach et al. [35] scanned two participants simultaneously with fMRI while they performed a simple visual counting task. Participants received monetary rewards of varying magnitudes for correct performance, whereas incorrect answers had no financial consequences, and participants were informed of the performance and rewards of both players. Of interest were trials where both were correct but one of the participants received a higher reward than the other. Across reward levels, participants’ striatum activity was higher when they received more than their partner relative to when they received less than the other player, demonstrating that participants evaluated their outcome relative to that of their partner, as opposed to purely evaluating the payoff.

**Summary and Implications**

Studies in neuroeconomics have indicated multiple properties in the valuation network of the brain that either support or contradict the assumption of rational evaluation of risky prospects. One important property of the reward circuitry is that it appears to anticipate the utility of future outcomes, providing the decision maker with necessary information for comparing the possible outcome options and selecting the most attractive course of action. Further, this circuit also informs the decision-maker of the desirability of risky prospects by integrating the subjective value and probability of expected outcomes, thus reflecting the overall attractiveness of risky alternatives. These results suggest that the valuation of risky prospects is done in the basic reward circuitry of the brain in accordance with the principles of expected utility maximization. However, when the outcome values and probabilities are manipulated, the reward circuitry does not always behave as predicted by expected utility maximization. For instance, the probabilities are represented in a nonlinear fashion in the valuation process; reward circuitry processes outcomes as gains and losses relative to a reference point; and even arbitrary contexts such as the rewards of others and the numerical presentation of the financial rewards, influence the valuation of outcomes. None of these properties meet the requirements of expected utility maximization but they are reflected in the behavior of decision makers and accounted for in descriptive models of decision making under risk [26].

In sum, the brain evidence indicates that both the evaluation of the attractiveness of risky prospects and the behavioral biases observed in these estimations, are reflected in the reward circuitry of the brain. One implication of these findings is that the evaluation of risky prospects is not controlled by higher-level deliberation, but that instead prospects are valued via more fundamental mechanisms, which also potentially explains the well-observed behavioral deviations from utility maximization.

When interpreting neuroscience findings it is important to take into account the so-called “reverse inference” fallacy, which
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refers to the difficulty of inferring mental states of the decision-maker based on the activated brain regions, as one specific brain region can be involved in multiple processes. While there is a growing amount of evidence implicating striatum and OFC in the processing of rewards, it should not be concluded that these areas are reward-meters, where activity can be read off and taken as a metric of positive or negative valence. Despite this caveat, however, the investigation of how the brain computes and processes rewards and punishments offers a very useful window into basic decision making.

FRAMING EFFECT AND THE BRAIN

We have discussed above how behavioral findings such as loss aversion and reference dependent valuation can be observed at the neural level, and here we extend that by discussing another well-characterized behavioral anomaly, the framing effect [37]. The framing effect is a phenomenon where decision makers display different preferences in choice situations which are identical other than for largely irrelevant contextual effects. The effect is often described as resulting from the general tendency of decision makers to be risk averse in the gain domain and risk seeking in the loss domain. For example, imagine the following two scenarios in Fig. 2. In the first scenario you are given $50 and then asked to make a choice between two options: keep $20 of the initial endowment or play a lottery where you have 40% chance of keeping the whole endowment and 60% chance of losing everything. In the second scenario, after you first received the initial endowment of $50, you are asked to choose: either lose $30 or participate in a lottery identical to that of the first scenario. Importantly, both of these scenarios are equivalent—they provide a choice between gaining $20 for sure and having a 40% chance of receiving $50. However, when people answer these questions separately, they tend to prefer the sure option in the gain domain (scenario 1: risk averse) and the lottery in the loss domain (scenario 2: risk seeking). Thus, the framing of the choice options influences the risk attitude of the decision maker and causes preference reversals. This violates the invariance principle of normative decision-making models which holds that the preference structure is independent of the phrasing of the choice options. The framing effect can be observed in multiple types of decisions and even in participant groups, such as financial planners, who are dealing with risk on a daily basis [38]. As a practical example, when people consider selling their stock investments during an economic slump, it makes a difference whether they think about the money they can save or the money they will lose in case of selling. When people think about the money they could save by selling the stocks, they often prefer the safe option of selling the

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<td>$50</td>
<td>Option A: keep $20</td>
<td>Option A: $20</td>
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<td>40% keep all 60% lose all</td>
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<td>$50</td>
<td>Option A: lose $30</td>
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<td>40% keep all 60% lose all</td>
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Figure 2. Example scenarios for the framing effect. The dashed lines indicate typical choices that people make in line with the framing effect.
stocks and keeping the money (risk averse in gain domain), but when they think about the realized losses related to the sale, they prefer more risky courses of action (risk seeking in loss domain).

One possible explanation for this phenomenon is that the presence of risk in the choice situations elicits emotional reactions which intrude in the decision-making process [39]. Behavioral research suggests that, increasing the emotional salience of the choice situation strengthens nonlinearities in the valuation process [40] which leads to further deviations from risk neutrality [41], thereby strengthening the framing effects. This hypothesis of emotional involvement in framing effects was tested by De Martino et al. in a fMRI study, where participants made choices similar to those described above [42]. Choices where participants adhered to the standard bias (safe choice in the gain domain and lottery choice in the loss domain) were compared to those situations where participants chose in the opposite direction (lottery choice in the gain domain, and safe choice in the loss domain). This comparison showed activity in an area related to valuation and processing of emotional stimuli (amygdala; Fig. 3), supporting the hypothesis that emotional processes contribute to the framing effects. The researchers also examined which brain mechanisms were related to resisting the framing effect, and found activity in a region that is commonly involved in conflict detection and cognitive control (anterior cingulate cortex; Fig. 3). This implies that resistance to the framing bias requires detection of conflict between the rational course of action and an emotional tendency, and regulatory control of the emotional mechanisms to override the bias.

Framing effects are not equally strong in all individuals. In a follow-up study, the researchers were interested in these differences between individuals [43]. They hypothesized that genetic variation might be able to explain these differences, and examined variation in a gene 5-HTTLPR, which has previously been shown to modulate amygdala and anterior cingulate function. The results showed that people with the short allele form of the gene demonstrated strong behavioral framing effects, which were also reflected in the activation in amygdala. In contrast, the people with the long allele variant showed a weaker behavioral effect, which was not reflected in the pattern of amygdala activity. By performing a connectivity analysis between brain regions, the researchers were able to show that the coupling between anterior cingulate and the amygdala increased when participants with long alleles were countering the framing effect. This increase in the connectivity did

![Figure 3. Framing effect is related to activity in amygdala and resisting the frame involves anterior cingulate cortex (ACC) activity. The picture on the right is a slice of the brain that is cut along the midline of the head. The picture on the left is a parallel slice taken from the brain at the level of eyes. These pictures indicate the anatomical locations of the regions of interest, and do not represent data from the actual measurement.](image-url)
not occur in the subjects with short alleles. On the basis of the results, the researchers claim that the participant group with the long alleles has more efficient dynamic regulatory control over the emotional amygdala reactions than the group with short alleles, which further leads to reduced behavioral framing effects. Thus, the results indicate both the role of emotional reactions and the regulation of those reactions in enhancing and controlling of behavioral framing effects, respectively, and how individual variability in the control mechanisms influences the sensitivity to the framing effects.

Summary and Implications
The fMRI experiments outlined here indicate the role of affective neural processes in driving the behavioral framing effects, and the importance of cognitive control in decreasing them. These findings imply that even when the decision situation does not have any clear emotional context, the presence of risky prospects can activate emotional brain regions. The effect of this emotional activation differs in positive and negative domains: in a positive frame involvement of emotional brain regions increases risk aversion, and in a negative frame the emotional activation leads to risk seeking attitude. Additionally, the susceptibility of individuals to framing effects differs, and these differences can at least partly be explained by genetic variation. These findings suggest that it might be possible to decrease framing effects either by decreasing the emotional reaction induced by risky prospects or by increasing the cognitive control of the decision scenario.

CONCLUSIONS
In this article, we have outlined the importance of both reward circuitry and the balance of emotional and cognitive control in the evaluation of risky prospects, and we have described how these mechanisms can be related to decision biases that have previously been observed in the behavior of decision makers. As this existing research suggests, neuroscience studies can provide insights in the decision-making processes, and give potentially valuable information for further development of economical models. Further, a better understanding of the neural architecture underlying behavioral biases may provide opportunities to minimize the errors associated with these processes.

This work also suggests that different biases may have different fundamental causes and so might differ in how easy they are to overcome. For example, biases associated with reward mechanisms might be more persistent than the biases that arise from the imbalance of emotional and control signals. Another important role for the striatum is as part of the learning mechanism in the brain [44], which may imply that the biases that are reflected in the striatum activity are more difficult to overcome. One conception of the role of the striatum is that it is not engaged in the processing of rewards and punishments per se, but rather that it tracks so-called reward prediction error, that is, the difference between what we expect and what we receive [32], thus computing gains and losses in respect to the reference point of expected outcome. If there is a bias in the calculation of the prediction error signals, these biases are continuously reinforced in the behavior, complicating efforts to overcome the resulting behavioral biases. For example, in a loss-aversion account, if outcomes that are worse than expected are followed by an exaggerated reward prediction error signal, this will lead to the learning of loss-averse behavioral patterns for choice situations involving losses.

Despite this however, research indicates that either neural or intentional control mechanisms have the ability to reduce the behavioral biases in certain conditions [45,46]. This may be because cognitive mechanisms can overcome more affective reactions that also enhance the biases. For instance, in the case of loss aversion, there is evidence that points toward the role of emotions in enhancing the bias [28,47], and that the decision maker can reduce the influence of this emotional reaction in their decision making process by intentionally choosing to use an emotion regulation strategy [46]. As discussed earlier in this article, framing effects are also driven by emotional mechanisms. The tendency of decision makers to be
risk averse in gain domains and risk seeking in loss domains appears to be related to increased emotional brain reactions, whereas resisting the biases involves use of cognitive control mechanisms. Those individuals who have better control over their affective responses show smaller framing effects than other people. Thus, these results also indicate the importance of regulation of emotional signals in reducing biases in the decision-making process, and suggest that it is possible that the framing effects in risky decision making could also be reduced by exerting intentional control over the emotional reactions with existing emotion regulation strategies. Overall, the role of emotional reactions in inducing decision biases, and the possibilities to reduce these influences with simple instructions to the decision maker, are important aspects to take into account when designing decision support tools.

An important future step for neuroeconomics is to increase the understanding of individual variability in the sensitivity to decision biases. For developing the most efficient methods to reduce and control the decision biases on an individual level, it is important to learn more about individual differences in choice situations, which will lead to better understanding of the brain mechanisms central to decision making biases. In order to achieve a more complete picture of the neural calculations on an individual level, more attention should be paid to the functioning of larger brain networks involved in the decision making, and in particular, how the different parts of the network communicate with each other. Some initial steps toward this goal have already been taken, for instance, by categorizing people in different groups based on their genotype. Though neuroeconomics is a young field, it offers enormous potential for the better specification of decision-making behavior, and as such promises to open up interesting new avenues for decision analysis in the near future.

REFERENCES

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FURTHER READING