The orbitofrontal cortex and the computation of subjective value: consolidated concepts and new perspectives

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Remarkable progress has been made in recent years toward understanding the functions of the orbitofrontal cortex (OFC). The finding that neurons in this area encode the subjective value monkeys assign to different goods while making choices has been confirmed and extended by numerous studies using both primate neurophysiology and human imaging. Moreover, new lesion studies demonstrated that subjective values computed in the OFC are causally and specifically related to choice behavior. Importantly, values in the OFC are attached to goods, not to actions or to spatial locations. Furthermore, subjective values appear to be computed in this area even if the situation does not require a choice. In the light of this growing body of work, we propose that the primary function of the OFC is the computation of good identities and subjective values in an abstract representation. In this view, OFC neurons compute the subjective value of a good whenever that good is behaviorally relevant.

Keywords: abstract representation; transitivity; context adaptation; decision making; economic choice; neuroeconomics

In the paper published in the proceedings of the first conference on orbitofrontal cortex (OFC) held at the New York Academy of Sciences, one of the authors reviewed evidence suggesting that one function of the OFC is to compute subjective values.[1] The main arguments presented then can be roughly summarized as follows. First, an economic choice study by Padoa-Schioppa and Assad, in which monkeys chose between different juices offered in variable amounts, had shown that neurons in the central OFC (in and around area 13 m) encode the subjective values animals assigned to the different goods.[2] In that study, subjective value was defined at the behavioral level from the trade-off between the two dimensions (or determinants) on which offers varied, namely juice type and juice amount. At the neuronal level, three types of neurons were found: *offer value* cells encoded the value of only one of the two juices; *chosen value* cells encoded the value of the chosen juice; *taste* cells encoded the identity of chosen juice in a binary way. These three variables were found to ex-

plain the activity of the neuronal population in OFC significantly better than numerous other variables tested in that study, including other value, value difference, total value, etc. Second, confirming previous observations,[3,4] that study had also shown that the neuronal representation of subjective value in OFC did not depend on the visuomotor contingencies of choice. For example, the activity of neurons encoding the *offer value* of apple juice did not depend on whether apple juice was presented on the left or on the right of the fixation point. Similarly, the activity of neurons encoding the *chosen value* did not depend on whether obtaining the chosen juice required a saccade to the left or to the right. Values were thus attached to particular goods (juices), not to particular spatial locations or to particular actions.[2] Third, work in multiple species has shown that OFC lesions induce specific deficits in choice behavior.[5–7] On the basis of the results from single cell recordings and lesion studies, our review paper thus proposed that economic choices might be

based on values computed in the OFC. The further hypothesis that choices actually take place within this neuronal representation has been recently formalized in a comprehensive model.[8]

Our current purpose is to describe how the understanding vis-à-vis the role of OFC in the computation of subjective value has evolved in the past four years. Indeed, remarkable progress has been made in this relatively short time thanks to work conducted in many laboratories using various experimental approaches. In essence, a wealth of new data support the proposal that OFC encodes subjective values and that these neuronal signals underlie economic choices. In particular, several studies have generalized the original findings[2] to choices between goods that vary on dimensions such as probability, time delay, and physical effort. Other studies characterized how the encoding of value in this brain region depends (or does not depend) on the behavioral context of choice. Finally, new lesion studies have provided more stringent evidence that OFC is specifically and causally linked to valuation and economic choice. The evidence accumulated in recent years thus motivates the proposal that the computation of subjective values in an abstract representation is not just one function of OFC, but rather the primary function of OFC.

Choices between goods that vary on multiple dimensions

The value an individual assigns to a good—for example a scoop of chocolate ice cream—is intrinsically subjective. Consequently, any operational measure of value requires a choice and thus a trade-off between different goods.[8] For example, if an individual in an ice cream shop is indifferent between one scoop of chocolate and two scoops of vanilla, one can say that these two goods have equal subjective value. Thus, assuming that value functions are linear, one can measure the subjective value of given quantities of either ice cream on the same scale (e.g., in units of vanilla scoops). Importantly, the concept of "good" is rather general and goods can vary on many dimensions. In the ice cream example discussed here and in our original study,[2] offered goods varied for the commodity (i.e., the flavor) and the quantity. However, goods can also vary on dimensions such as the probability of delivery, the time delay, the ambiguity associated with the offer, the physical effort necessary to obtain the good, and

other kinds of cost. By definition, subjective values integrate all these dimensions and thus provide the basis to make a decision.[8]

The proposal that neurons in the OFC encode subjective value was originally based on data from trade-offs between juice type and juice quantity.[2] In the past few years, important work has brought support to this proposal by examining choices that involve several other determinants. Roesch and Olson had previously found that neurons in the primate OFC are modulated both by the quantity of juice delivered to the animal and by the delay intervening before juice delivery. Consistent with a unitary representation of value, the two modulations had opposite signs.[4] Along similar lines, Wallis and colleagues found that the activity of neurons in the OFC (and other frontal areas) depends not only on the quantity of juice delivered to a monkey, but also on the probability and on the physical effort exerted by the animal to obtain the juice.[9,10] More recently, these same authors recorded from the central OFC during a choice task. They found that neurons in this area encode the subjective value defined by the trade-off between juice quantity and delay, and between juice quantity and physical effort.[11] Similarly, ongoing work in our laboratory examines choices between goods that vary on three dimensions: juice type, quantity, and probability. Preliminary results indicate that neurons in OFC encode subjective values as defined by the integration of all these determinants.[12] Another striking example of integration came from a study by Watson and Platt. In their experiment, monkeys chose between drinking a given amount of juice and drinking a different amount of juice while watching the image of a conspecific. Male macaques were willing to forgo some amount of juice for the opportunity to observe female perinea. Importantly, the activity of neurons in OFC encoded subjective value as defined by this behavioral trade-off.[13] Another interesting study demonstrated that neurons in the OFC encode both positive and negative values.[14]

Choices between goods that vary on multiple dimensions have also been examined in numerous imaging studies in humans. In particular, different experiments examined trade-offs between money amount and food type,[15,16] money amount and quantity of nonfood consumables,[17] money amount and probability,[18,19] money amount and ambiguity,[18,20] money amount and time delay,[21,22]

probability and time delay,[23] probability and number of electric shocks,[24] and (in hypothetical moral choices) number of lives at risk and likelihood of successful rescue.[25] In essence, all these studies found neural activity associated with subjective values in the medial or in the central OFC—an impressive consistency across laboratories, experimental procedures, and value determinants.

Although results from primate neurophysiology and human imaging are in many ways remarkably consistent, it is worth noting that some degree of discrepancy actually exists. In particular, imaging studies have often found value-related activity more medially compared to single cell studies. This discrepancy is particularly puzzling because, from an anatomical standpoint, orbital regions and medial regions are clearly distinct; they are interconnected with different sets of cortical and subcortical areas, and they are scarcely interconnected with each other.[26] The origins of this discrepancy remain unclear.[27] Elements that may possibly be relevant elements include the fact that anatomical regions in the two species might not correspond perfectly; the fact that single cell recordings in primates generally take place after a long training process; the fact that BOLD signals from central OFC often suffer from attenuation and/or distortion[28] (hence, negative results from the central OFC should sometimes be taken with a grain of salt); and the fact that in the medial OFC, neural activity related to value is potentially confounded with neural activity related to autonomic responses.[29–33] This said, several human imaging studies did actually find the most prominent choice- and value-related activity in the central OFC.[34–37] Therefore, although more work is necessary to understand possibly important differences across species and procedures, current evidence from human imaging overall supports the notion that subjective values are computed in the OFC.

With respect to rodents, new results have confirmed that if subjective values are indeed encoded in the rodent OFC, their representation does not integrate multiple determinants.[38–42] For example, food quantity and time delay are encoded by different groups of cells.[38] Moreover, neurons in the rodent OFC are spatially selective.[38,43] Physiological differences between rodents and primates might simply reflect a poor anatomical homology.[44] However, the diversity of results might, at least in part, reflect differences in behavioral paradigm—a gap that should stimulate further research in the coming years.

Effects of lesions

The disruptive effects of OFC lesions on choice behavior had long been documented.[45,46] In particular, using the reinforcer devaluation paradigm, it had been found that the effects of selective satiation on choices are greatly diminished following OFC ablation.[5–7] Nonetheless, critical new information has been gathered in the past few years thanks to a series of studies conducted in several laboratories. Specifically, deficits in value-based decision making (often tested using the reinforcer devaluation paradigm) were consistently found after lesions placed in central OFC (areas 11/13) but not after lesions placed in other brain regions including the medial OFC (area 14),[47] the dorsolateral PFC,[48,49] the ventrolateral PFC,[49,50] the anterior cingulate cortex,[49] and the hippocampus.[51,52] (Amygdala lesions, however, did affect value-based decisions.[52–54]) Conversely, lesions to the central OFC failed to induce any deficit in a variety of reward-related and cognitive tasks including basic food preference,[52] satiation,[54,55] rule- or strategy-based decision making,[49,50] serial object reversal learning,[47,56] response inhibition,[47] discrimination learning,[52] and working memory maintenance.[49] Taken collectively, these studies reveal a high degree of specificity. On the one hand, central OFC (with the amygdala) appears to be the only brain region indispensable for the computation of subjective values. On the other hand, computing and/or comparing subjective values appears to be the only mental function clearly disrupted by lesions of the central OFC.

Further support for a causal role of OFC in economic choice comes from a recent study in which Camille et al.[57] examined choices between different foods in humans. In economic theory, it is known that choices can be described by a value function if and only if preferences are transitive. In other words, if given any three goods A, B, and C, an individual chooses A over B, B over C, and C over A, her choices cannot be based on a functional representation of value. Extending earlier work,[57] Camille et al. found that patients with OFC lesions choosing between different combinations of foods violated preference transitivity significantly more often than matched controls.[58] (Since lesions were typically large, the

study did not disambiguate between subregions of OFC.) Compared with data from the reinforcer devaluation experiments, the importance of this result is twofold. First, it confirms a causal link between values computed in the OFC and choice behavior using an independent behavioral paradigm. Second, it makes a more categorical point: OFC lesions do not just alter preferences in favor or against one particular determinant of value, or make it more difficult to integrate internal and external determinants. Rather, OFC lesions disrupt the very ability to compute and/or to compare any subjective values.

In summary, lesion studies in recent years provided new and more stringent evidence suggesting that the relationship between (central) OFC and the computation of subjective value is specific—in both senses—and causally related to economic choice behavior.

Menu invariance and gain adaptation

The results discussed so far buttress the hypothesis that subjective values are computed in the OFC. Another recent set of studies examined in more detail the properties of this neuronal representation and, specifically, how the encoding of subjective value depends on the behavioral context of choice. Two main results have been reported.

First, a study by Padoa-Schioppa and Assad found that OFC neurons encoding the value of one particular good (e.g., apple juice) do so independently of the good offered as an alternative (e.g., grape juice or water)—a property called *menu invariance*.[59] The significance of this result follows from the close link between menu invariance and preference transitivity. To appreciate this link, consider three goods (A, B, and C) and one individual who chooses good A over B, B over C, and C over A and thus violates transitivity. If one describes them in terms of subjective value, these choices can be explained only if values depend on the menu (e.g., if the value assigned to good A is high when the alternative is good B and low when the alternative is good C). In other words, choices that violate transitivity can be explained only if values depend on the menu. Equivalently, if values do not depend on the menu, choices are necessarily transitive. Thus menu invariance observed in the OFC may explain the fact that human

and animal choices most typically satisfy preference transitivity.[60–62]

Second, values computed in different behavioral contexts can vary by orders of magnitude. For example, the same individual might choose some times between different ice cream flavors and other times between different cars for sale. In a computational sense, this large variability poses a serious challenge—an issue highlighted by the fact that OFC neurons encode values in a linear way.[2] In principle, the valuation system could meet this computational challenge through mechanisms of gain adaptation. Two recent studies, one in our laboratory and one by Kobayashi *et al.*, indeed demonstrated the existence of such mechanisms.[63,64] In essence, both studies found that the encoding of value undergoes range adaptation such that a given range of firing rates represents different ranges of values in different behavioral contexts. Range adaptation was observed both in *offer value* and *chosen value* cells, and both in positive and negative encoding cells (i.e., neurons for which the activity increased or decreased as a function of value).[63] Partial adaptation occurred on a trial-by-trial basis. However, full adaptation seemed to require at least 10–20 trials.[64] Finally, for *offer value* cells, the activity range did not depend on the preference status of the encoded juice.[63] Interestingly, these findings shed new light on earlier work by Tremblay and Schultz[3] and others.[65,66] Their observations appear best interpreted in terms of a range-adapting representation of subjective values (a cardinal measure) as opposed to a representation of relative preferences (an ordinal relationship).

These recent studies significantly deepened our understanding of how subjective values are represented in the OFC and provide key elements in the effort to explain choice behavior in terms of neurobiological mechanisms. In essence, the encoding of subjective value in the OFC is at the same time menu invariant (and thus instantiative of preference transitivity) and range adapting (and thus capable of supporting choices on different value scales). Interestingly, work in behavioral economics shows that under carefully designed conditions it is possible to elicit choices that systematically violate transitivity.[67,68] Thus it will be interesting to investigate in future work the limits under which menu invariance holds true in the OFC.

Generalizations and new perspectives

To summarize the results reviewed in the previous sections, a wealth of data indicates that neurons in the OFC encode the identity and the subjective value of different goods, that this neuronal representation is abstract (independent of the spatial contingencies of the task), and that during economic choice, subjective values computed in the OFC are causally related to the decision. As we have often emphasized,[8] proving that a neuron or a functional imaging signal actually encodes subjective value ultimately requires a choice task in which subjects trade-off between different determinants. However, this fact does not mean that individuals—and neurons in the OFC— compute subjective values only while engaging in economic choices. In fact, there is ample evidence to the contrary. Behaviorally, subjective values can guide a variety of cognitive processes in addition to choice, including perceptual attention, affective behavior, and associative learning.[8] Neuronally, numerous studies that did not include a choice in the sense defined here found in the primate OFC neuronal responses that are naturally interpreted in terms of subjective value.[3,4,9,14,69,70] Hence, it is reasonable to wonder whether any experimental result from the OFC eludes such an interpretation. As a generalization of our previous argument, we thus propose that the computation of good identities and subjective values in an abstract representation is not just a function of the OFC, but rather the primary function of the OFC. In this view, neurons in the OFC compute the subjective value of a good whenever that good is behaviorally relevant, whether or not the situation requires a choice.

The ramifications of this proposal remain to be examined and counter examples might be found in future work. As an initial test, we discuss in the remaining of this section the results of two recent studies that revisited previously addressed issues: spatial selectivity and hypothetical outcomes.

In the study by Tsujimoto *et al.*,[71] monkeys were presented in each trial with a visual instruction, after which they executed a saccade toward one of two targets. The two targets were always located on the left and on the right of the fixation point; in any given trial, a juice reward was associated with only one of the two targets (hence, the task did not involve a choice in the sense discussed above). In each trial, the correct target was identified by applying a rule—either "stay" or "shift," depending on the instruction—to the target selected in the previous trial. Thus to receive a juice reward, the animal had to remember the previous target and to apply the instructed rule. Among other results, the authors reported that the activity of neurons in the OFC recorded at the end of the trial varied depending on the target selected in that trial.[71] In principle, such differential activation could be due to spatial selectivity and, more specifically, to an underlying representation of motor responses or spatial locations in Euclidean space—an interpretation that would be at odds with other reports.[2,4,72,73] However, as emphasized by the authors, this signal is unlikely to represent a motor response per se. Likewise, this signal seems unlikely to represent a spatial location per se. Instead, this signal may have represented the identity of the chosen target in an abstract or symbolic representation. Indeed, it can be noted that in this study, targets were defined uniquely by their spatial location. Thus, a neuron encoding the identity of one of the two targets symbolically (as opposed to the spatial location of the target) would have presented the same differential activation found in the study. In this light, the (categorical) chosen target signal recorded by Tsujimoto can be viewed as akin to the taste (chosen juice) signal recorded in economic choice tasks.[2,59] Both signals encoded the identity of the chosen option (and both signals were most prominent at the end of the trial).[a] Notably, the identity of the chosen target was behaviorally

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[a]To elaborate on this point, consider an abstract representation of the two options such as that provided by symbols L and R. Now, consider a neuron encoding the identity of the chosen option in this abstract representation—for example, a neuron that responds only when the monkey chooses the L option. Because the L option is completely identified with one spatial location, such a neuron would respond when and only when the animal makes a saccade to that spatial location. In other words, the neuron would appear as spatially selective. Thus, Tsujimoto's results do not disambiguate between an abstract representation and a spatial representation of the chosen option. Experimentally, this issue could be addressed associating each option to multiple spatial locations treated as equivalent vis-à-vis the stay/shift instruction. In this design, we predict that OFC neurons would encode the identity of the chosen option, associated by multiple spatial locations, as opposed to the chosen spatial location per se.

relevant in the Tsujimoto study because it guided saccade selection in the following trials.

In the study by Abe and Lee,[74] monkeys executed saccades toward one of three possible targets. The task was designed as a rock–scissor–paper game in which the three targets represented the three options (R, S, and P), and a computer program played as the animal's opponent. On win trials, the three options delivered different amounts of juice; thus animals selected R, S, and P in different proportions. At the end of each trial, the animal was delivered the amount of juice won in that trial. In addition, the animal was visually shown the juice amounts it would have received for the two nonselected targets (hypothetical outcomes). The spatial locations of options R, S, and P remained fixed within a trial block and changed unpredictably at the end of a trial block. The task design induced two learning processes. First, at the beginning of each new trial block, the animal learned the new spatial configuration of options R, S, and P. Second, at steady state within a trial block, choices on any given trial were to some extent biased by the outcome of the previous trial. For example, following a loss trial, animals were more likely to select the target that would have lead to a win. In other words, both actual and hypothetical outcomes guided learning. The authors recorded from OFC (and lateral PFC). Their analyses highlighted three variables: the actual outcome, the chosen location, and the hypothetical outcome (in tie and loss trials). Prima facie, OFC neurons encoding the chosen location seems at odds with numerous studies that did not find any spatial selectivity in this region.[2,4,72,73] Furthermore, OFC neurons encoding the hypothetical outcome seems at odds with the fact that during simple economic choices vanishingly few neurons encoded the variable *other value* (analogous to the hypothetical outcome).[2,59] However, considerations similar to those discussed for the Tsujimoto study apply here. Indeed, within each trial block, options R, S, and P were only defined by their spatial location. Thus a neuron encoding not the spatial location of options R, S, and P per se, but rather their identity in any abstract or symbolic representation would have appeared as spatially selective. Moreover, both the spatial location and the value of the hypothetical outcome guided a learning process and thus were behaviorally relevant. Therefore the results of this study are in fact consistent with an abstract representation of option identities and their subjective values.

In conclusion, the results of both studies can be accounted for by an abstract representation of goods or options and subjective values in the OFC.

Conclusions

Remarkable progress in understanding the functions of the OFC has been made in the past few years thanks to an impressive convergence of results from animal neurophysiology, human imaging, and lesion studies. This large body of work suggests that the primary function of this brain region is the computation of good identities and subjective values in an abstract representation. Numerous important questions remain open, including addressing possible differences between species, understanding the neuronal mechanisms that result in choice fallacies, and many others. Yet the successes achieved in recent times promise new breakthroughs in the years to come.

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Conflicts of Interest

The authors declare no conflicts of interest.

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