The representation of economic value in the orbitofrontal cortex is invariant for changes of menu

Camillo Padoa-Schioppa & John A Assad

Economic choice entails assigning values to the available options and is impaired by lesions to the orbitofrontal cortex (OFC). Recent results show that some neurons in the OFC encode the values that monkeys (*Macaca mulatta*) assign to different goods when they choose between them. A broad and fundamental question is how this neuronal representation of value depends on the behavioral context. Here we show that neuronal responses in the OFC are typically invariant for changes of menu. In other words, the activity of a neuron in response to one particular good usually does not depend on what other goods are available at the same time. Neurons in the OFC encode economic value, not relative preference. The fact that their responses are menu invariant suggests that transitivity, a fundamental trait of economic choice, may be rooted in the activity of individual neurons.

Economic choice is the behavior observed when individuals make choices solely on the basis of subjective preferences (for example, out of a restaurant menu). Behavioral evidence suggests that economic choice entails a two-stage mental process: values are initially assigned to the available options and a decision is then made between these values[1–3]. With respect to brain structures, lesion and imaging studies indicate that neural processes underlying economic choice partly take place in the OFC[4]. Indeed, lesions to the OFC impair choice behavior in various domains, leading to such deficits as eating disorders[5–7], erratic choices[8,9] and abnormal gambling[10–12]. Imaging experiments in healthy subjects show that the OFC activates when individuals make choices[13,14] and when they earn money[15,16]. Single-cell recordings in nonhuman primates link the OFC more specifically to the process of value assignment. Neurons in the OFC often respond to the delivery of one particular food or juice[17]. However, their responses are also modulated by the amount of juice[18,19], the satiation state of the animal[20] and the time until juice delivery[21], all of which are consistent with OFC neurons encoding the juice value.

In a recent study, we recorded the activity of individual neurons from the OFC while monkeys engaged in economic choices[22]. In the experiments, monkeys chose between two beverages offered in variable amounts. Their choices provided an operational measure of the values that the monkeys assigned to the two juices[22]. We found three types of neuronal responses: *offer value* responses, which encoded the quantity or value of one of the two offered juices, *chosen value* responses, which encoded the value of the chosen juice independently of the juice type, and *taste* responses, which were binary responses reflecting which one of the two juices was chosen independently of the amount[22] (see Discussion). From a conceptual point of view, responses encoding the *chosen value* are particularly interesting because they capture two defining traits of value: that value is subjective and that value represents a common

unit for qualitatively different goods[22] (a common currency[23]). Neurons in the OFC thus provide a neuronal representation of economic value.

A broad and fundamental question is whether and how this representation of value varies depending on the behavioral context. From a computational perspective, two seemingly opposite traits would seem desirable. On the one hand, an effective representation of value should be stable. For example, a person choosing between different brands of pasta in a grocery store might first compare brands X and Y and choose Y, and later compare brands Y and Z and choose Z; behaviorally, it is desirable for that person to be consistent and also choose Z over X. Such consistency is guaranteed if the neuronal activity representing the value of one particular good (for example, X) does not depend on what other goods are available at the same time (for example, Y or Z). On the other hand, values can vary by many orders of magnitude. For example, the same person can choose sometimes between different brands of pasta (worth about $3), other times between different laptops (worth about $3,000), and yet other times between different houses (worth $300,000 or more). To represent value efficiently in these very different situations, a neuronal representation of value should somehow adapt to the general choice context, in a way conceptually analogous to how the visual system adapts to ambient light.

Different ways in which the behavioral context can vary may thus be conceptualized as follows. On the one hand, the specific context can change rapidly from one moment to the next, as when a person compares different brands of pasta in a grocery store. We refer to these changes as changes of 'menu'. On the other hand, the general context can change on a longer time scale, as when a person goes from a grocery store to a meeting with the realtor. We refer to these changes as changes of 'condition'.

A previous study showed that some neurons in the OFC respond differently to the delivery of a given juice depending on the behavioral

Department of Neurobiology, Harvard Medical School, 220 Longwood Avenue, Boston, Massachusetts 02115, USA. Correspondence should be addressed to C.P.-S. (camillo@alum.mit.edu).
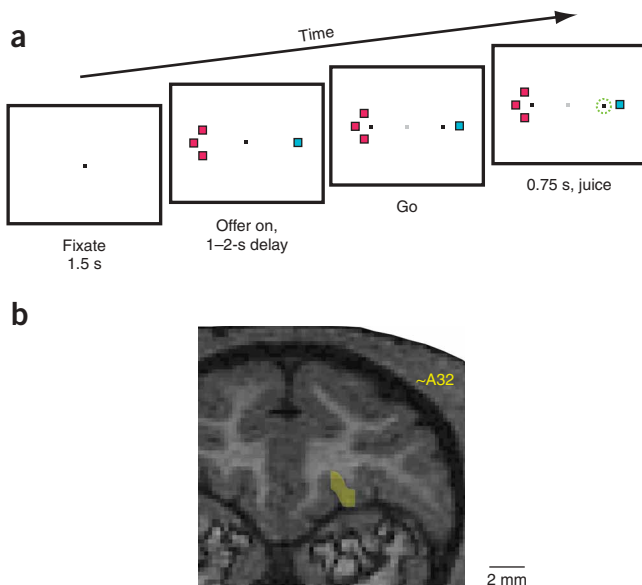
Figure 1 Experimental design. (**a**) Trial structure. The offers were represented by sets of colored squares on a computer monitor and monkeys indicated their choice by making an eye movement. At the beginning of each trial, the monkey fixated a spot (0.2° of visual angle) in the center of the monitor. Two sets of squares appeared on opposite sides of the fixation point (7° to the left and to the right of the fixation point; 'offer'). Different colors indicated different juice types and the number of squares indicated the juice amount. For example, a monkey presented with three red squares and one blue square chose between three drops of agua frescas Kool-Aid and one drop of peppermint tea. After a randomly variable delay (1–2 s), two saccade targets (0.2° of visual angle) appeared near the offers ('go' signal). The monkey indicated its choice on the saccade target and maintained fixation for 0.75 s before juice delivery (juice). The trial was aborted if the monkey broke fixation before the 'go'. Trials were separated by a 1.5-s intertrial interval, and center fixation was imposed within 1°. (**b**) Recording region. We tentatively identified the recording region as area 13m (see Methods).

context[24]. In this study, monkeys were given one of three types of juice (labeled A, B and C, in decreasing order of preference) in fixed amount. Trials were blocked, with only one pair of juices being employed in each block. The study found OFC neurons that responded to juice A, but not to juice B, in A:B blocks, and to juice B, but not to juice C, in B:C blocks. It was proposed that these neurons might encode the relative preference of the juices. Notably, the experimental design did not distinguish between OFC responses adapting to the menu or to the condition.
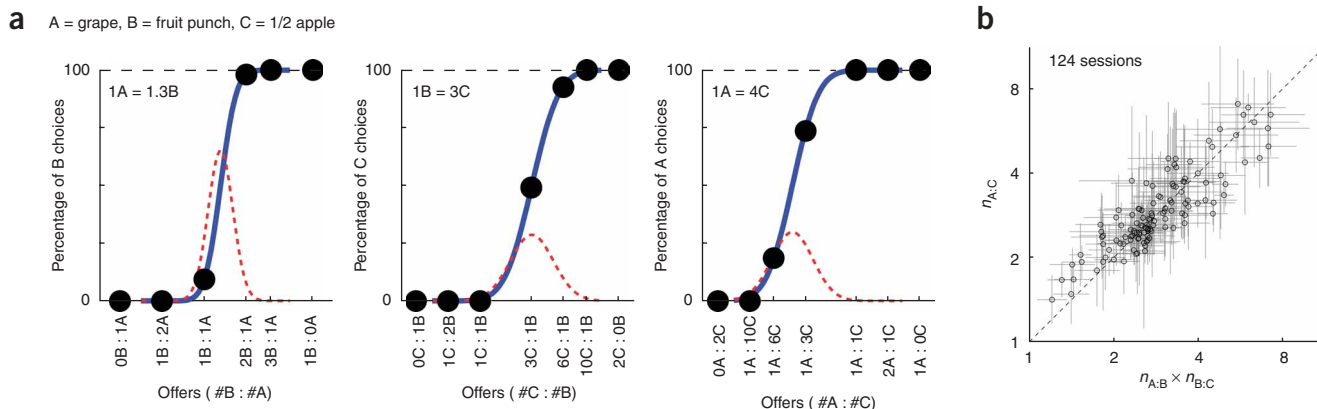
In the present study, we re-examined the issue of context dependence in the light of the distinction between menu and condition. In particular, we examined whether the neuronal representation of value in the OFC depends on the menu. To address this question, we recorded the activity of individual OFC neurons while monkeys chose between three different juices (labeled A, B and C, in decreasing order of preference). In each trial, monkeys chose between two juices that were offered in variable amounts. Notably, trials with the three juice pairs (A:B, B:C and C:A) were randomly interleaved. Replicating our previous results[22], we found that single-juice-pair responses encode three variables: *offer value*, *chosen value* and *taste*. We also found that neuronal responses in the OFC are typically invariant for changes of menu. For example, if a monkey chooses between juices A, B and C offered pairwise, the activity of neurons encoding the value of juice B does not depend on whether juice B is offered against juice A or against juice C.

RESULTS

In each trial, monkeys chose between two competing offers (**Fig. 1**). For any juice pair, the quantities of the two juices varied randomly. Trials with the three juice pairs were randomly interleaved, and left/right positions were counterbalanced for any given offer type.

Choice patterns and value transitivity

The experimental design and data analysis were based on the following assumption. If a monkey is offered the choice between a quantity q_X of juice X and a quantity q_Y of juice Y, its choice only depends on the ratio q_Y/q_X. In the language of economic theory, this corresponds to the assumption of 'linear indifference curves'. In essence, this amounts to assuming that the relationship between the juice quantity and the assigned value (the 'value function') is the same for different juices (up to a scaling factor). Several elements suggest that the assumption

was warranted in our experiments (see **Supplementary Results** and **Supplementary Fig. 1** online).

In one representative session (**Fig. 2a**), the monkey was offered grape juice (A), fruit punch (B) and diluted apple juice (C). For any given juice pair (A:B, B:C and C:A), the quantities of the two juices offered to the monkey varied from trial to trial. We thus obtained three choice patterns corresponding to the three juice pairs. We fit each choice pattern with a sigmoid, from which we obtained an estimate for the relative value of the two juices (see Methods). The relative value corresponds to the indifference point (the ratio of quantities for which the monkey would choose either juice with equal frequency). $V(x)$ indicates the value of x, and $n_{X:Y}$ indicates the relative value of juices X and Y, such that $V(X) = n_{X:Y}V(Y)$. For the session illustrated (**Fig. 2a**), the sigmoid fits provided the relative values $V(A) = 1.3V(B)$, $V(B) = 3.0V(C)$ and $V(A) = 4.0V(C)$. Notably, these values satisfy the relationship $1.3 \times 3 \approx 4$. In other words, the monkey's choices in this session satisfied the condition of 'value transitivity'.

Transitivity is a fundamental trait of economic choice behavior[25,26]. Given three options, X, Y and Z, if an individual prefers X to Y and Y to Z, she ought to prefer X to Z (preference transitivity). Analogously, if an individual is indifferent between X and Y and between Y and Z, she ought to be indifferent between X and Z (indifference transitivity). The importance of transitivity for economic theory cannot be overstated. For example, economic value cannot be defined unless choices satisfy transitivity[25,26]. Monkeys' choices in our experiments generally satisfied two conditions (**Fig. 2**). First, monkeys generally had strict economic preferences (that is, for offer types away from the indifference point, data points were close to 0% or 100%). Second, monkeys' preferences generally satisfied transitivity. Indeed, in 121 out of 124 (98%) sessions, monkeys preferred 1A to 1B, 1B to 1C and 1A to 1C. Furthermore, choice patterns usually were strictly increasing. In other words, for any n and m such that $n > m$, if the monkey preferred 1A to nB, it also preferred 1A to mB. This implies preference transitivity, because for $n > m$, monkeys generally prefer mB to nB.

Under the assumption of linear indifference curves, indifference transitivity is satisfied if the following relationship holds statistically true: $n_{A:B} \times n_{B:C} = n_{A:C}$. We refer to this condition as 'value transitivity'. As noted above, in the session illustrated (**Fig. 2a**), monkeys' choices satisfied value transitivity (because $1.3 \times 3 \approx 4$). Monkeys' choices in our experiments satisfied value transitivity in general. We plotted the product $n_{A:B} \times n_{B:C}$ versus $n_{A:C}$ for each of the 124 sessions in our dataset (**Fig. 2b**). Consistent with value transitivity, data in the scatter plot lie close to the identity diagonal. Even using a liberal criterion to identify transitivity violations (z test, $P < 0.1$; see Methods), measured relative values satisfied value transitivity in 122 out of 124 sessions (98%). Using a slightly less

Figure 2 Analysis of choice patterns. (**a**) One session. The three panels refer to the three juice pairs (A:B, B:C and C:A). In the first panel, the x axis represents the offer type, and different offer types are ordered by the ratio q_B/q_A (log scale), where q_A and q_B are the quantities of juices A and B offered to the monkey. The y axis represents the percentage of trials in which the monkey chose juice B. Analogously, in the second and third panel, the y axis represents the percentage of trials the monkey chose, respectively, juice C and juice A. In the three panels, black dots are data points, blue continuous lines are fitted sigmoids and red dashed lines are the underlying normal distributions. For each fitted sigmoid, the mean and s.d. of the normal distribution provided an estimate and error of measure for the log relative value (see Methods). The three relative values (top left in each panel) were each computed from the corresponding sigmoid. (**b**) All sessions. In the scatter plot, the x axis represents the product $n_{A:B} \times n_{B:C}$, the y axis represents $n_{A:C}$, and each data point represents one session. All 124 sessions in our data set are shown. For each session, gray error bars represent the errors of measure (s.d.). The diagonal dashed line corresponds to $n_{A:C} = n_{A:B} \times n_{B:C}$. Relative values measured in any given session satisfy transitivity unless they are significantly removed from this line (see text).

liberal criterion (z test, $P < 0.05$), measured relative values satisfied value transitivity in all 124 sessions.

In summary, monkeys in our experiments assigned to different juices values that satisfied transitivity. One important implication of value transitivity is that we could measure quantities of the three juices on a common value scale (for example, in units of $V(C)$, see Methods).

Neuronal database and single-juice-pair responses

We analyzed the activity of 557 OFC neurons recorded while two monkeys engaged in this task. Cell activity generally did not depend on either the spatial configuration of visual stimuli or the direction of the eye movement (replicating our previous results[22]); we thus collapsed data across these dimensions. We analyzed neuronal responses in seven time windows: 0.5 s pre-offer (a control time window), 0.5 s post-offer, late delay (0.5–1.0 s after the offer), 0.5 s pre-go, reaction time (from 'go' to saccade), 0.5 s pre-juice, and 0.5 s post-juice. Neuronal responses recorded in different time windows likely differ for their functional importance. However, the results of this study (in particular, menu invariance) held similarly true in all time windows. In the following, we describe the results pooling together neuronal responses from different time windows. However, we also report the results broken down by time window (see below).

In the analysis of neuronal activity, we first considered, for each cell, the activity recorded with each juice pair separately. We defined a response as the activity of one neuron in one time window. Pooling time windows, we identified 1,660 responses that were significantly modulated by the offer type (ANOVA, $P < 0.001$). We analyzed this dataset using the same procedures employed in our previous study[22], and we defined 19 variables that OFC responses might potentially encode (**Supplementary Results**). Each response was linearly regressed separately on each variable, and we identified the variables that best explained this population. The results obtained with this new dataset closely replicated our previous findings[22]. Single-juice-pair OFC responses encoded one of three variables: *offer value*, *chosen value* and *taste* (**Supplementary Results**).

Classification is consistent across juice pairs

We next examined whether the neuronal representation of value in OFC depends on the menu. We considered two possible types of menu dependence: classification conflict and menu-dependent encoding. A case of classification conflict would be that of a neuron encoding different variables depending on the juice pair. For example, one cell could encode *offer value A* when the monkey chooses between A and B, and *offer value B* when the monkey chooses between B and C (this putative cell would always encode the value of the preferred juice). A case of menu-dependent encoding would be that of a neuron that always encodes the same variable, but such that the linear relationship between the cell activity and the variable depends on the particular juice pair. As described below, our analyses argue against both of these hypotheses.

Table 1 Population summary

		Offer value	Chosen value	Taste
1	Pre-offer	0	0	1
208	Post-offer	75	80	51
163	Late delay	43	47	60
103	Pre-go	35	32	29
71	Reaction time	18	27	17
239	Pre-juice	46	58	127
234	Post-juice	51	61	113
1,019	Total			
351	At least one			

Results obtained pooling trials with the three juice pairs. The first column indicates the number of cells modulated by the offer type in each time window (ANOVA, $P < 0.001$). Of the 557 cells in our data set, 351 (63%) passed the ANOVA criterion in at least one time window. The three columns on the right indicate the number of responses classified as encoding each of the three variables. Because OFC responses are typically menu invariant, this classification is based on simple regressions of neuronal responses onto different variables. A variable 'explains' a response if the slope of the regression differs significantly from zero ($P < 0.05$); responses explained by more than one variable are assigned to the variable with the highest R^2. Responses that pass the ANOVA criterion, but are not explained by any variable (48/1,019 = 5%, unclassified), do not appear in the three columns on the right.

We illustrate three cases of classification consistency (**Fig. 3**). The first neuron (**Fig. 3a**) encodes *offer value C*, independently of whether the monkey chooses between C and B or between C and A; the activity of the neuron is low and not modulated when the monkey chooses between A and B. A second neuron (**Fig. 3b**) encodes the *chosen value* for each of the three juice pairs. Finally, a third neuron (**Fig. 3c**) encodes *taste B*, independently of whether the monkey chooses juice B over juice A or over juice C; the activity of the neuron is low and not modulated when the monkey chooses between A and C. These examples suggest that the variable encoded by individual OFC neurons does not depend on the juice pair. Indeed, across a population of 760 relevant instances (cases in which at least one of the three single-juice-pair responses passed the ANOVA criterion), classification conflicts were significantly less frequent than would be expected by chance ($P < 10^{-6}$, bootstrap analysis; **Supplementary Results**). A specific analysis also showed that instances in which *offer value* or *taste*

responses reflected the preference ranking as opposed to the identity of the encoded juice were very rare (4 out of 760; **Supplementary Results**).

Neuronal encoding is invariant for changes of menu

According to our definition, a neuronal response encodes one variable if there is a linear relationship between the cell activity and that variable[22]. If the coefficients of the linear relationship depend on the juice pair, the encoding is menu dependent. Conversely, if the coefficients do not depend on the juice pair, the encoding is menu invariant. This latter situation was typically observed in the OFC (**Fig. 4**). The same three neuronal responses described above (**Fig. 3**) were plotted against variables *offer value C*, *chosen value* and *taste B*, respectively (**Fig. 4**). For each neuron, the encoding would be menu dependent if the regression lines differed significantly from one another, either for their intercepts or for their slopes. To the contrary, in each case the regression lines are very similar to one another, indicating that the encoding is menu invariant. A formal statistical test required an analysis of co-variance (ANCOVA). Pooling trials with the three juice pairs, we restricted the analysis to responses significantly modulated by the trial type ($P < 0.001$, ANOVA). In total, 1,019 responses from different time windows satisfied this criterion (**Table 1**); the subsequent analysis was restricted to this population.

We defined seven variables: *offer value A*, *offer value B*, *offer value C*, *chosen value*, *taste A*, *taste B* and *taste C* (see Methods). We then analyzed each neuronal response with an ANCOVA, using one of the seven variables as the predictor and grouping data by the juice pair. We computed the full linear model, including the three factors [variable], [juice pair] and [variable × juice pair] interaction, and we obtained the R^2. For each response, we repeated this analysis separately with each of the seven variables, and we identified the variable encoded by the response as the one that provided the highest R^2. Focusing now on that particular variable, we established whether each of the three factors [variable], [juice pair] and [variable × juice pair] provided a significant contribution to the explained variance ($P < 0.01$). For example, referring to the three regression lines in **Figure 4b**, the factor [variable] would be significant if a single regression line (not shown) of all the data points had a nonzero slope; the factor [juice pair] would be significant if the three intercepts differed significantly from one another; the interaction [variable × juice pair] would be significant if the three slopes differed significantly from one another. In this case (**Fig. 4b**), the factor [variable] was significant ($P < 10^{-12}$), but the two other factors were not ($P > 0.25$).

Results were consistent across the neuronal population. Analyzing each of the 1,019 responses with the ANCOVA, we obtained a total of 868 significant effects across the three
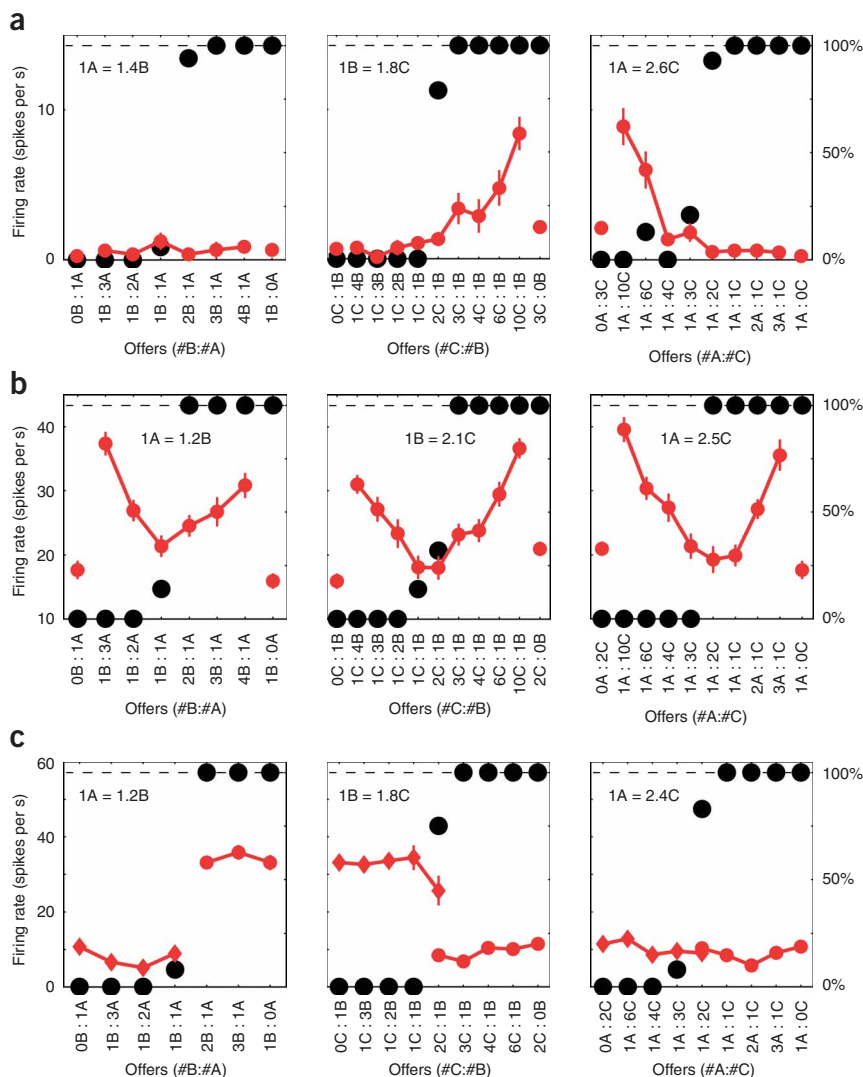
Figure 3 Responses of three OFC neurons. (**a**) Response encoding *offer value C* independently of the juice pair. The three panels refer to trials A:B, B:C and C:A. In each panel, black symbols represent the behavioral choice pattern (right *y* axes) and red symbols represent the neuronal activity ± s.e.m. (left *y* axes). Relative values (top left) are computed assuming transitivity (see Methods). (**b**) Response encoding *chosen value* independently of the juice pair. Data are presented as in **a**. (**c**) Response encoding *taste B* independently of the juice pair. Data are presented as in **a**. Here we separated trials depending on the chosen juice.
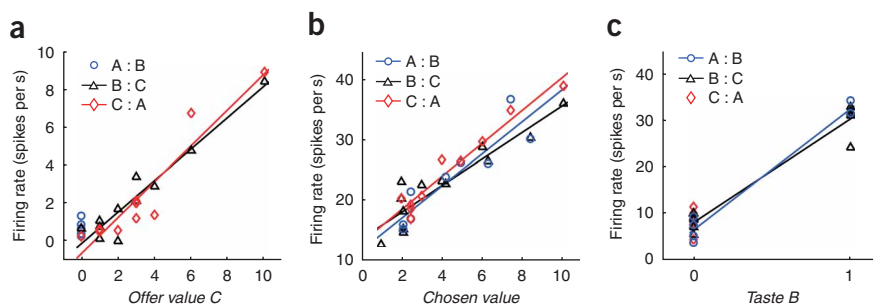
Figure 4 Menu invariance. Each panel represents one response (one neuron) and different symbols and colors refer to the three juice pairs (blue circles for A:B, black triangles for B:C and red diamonds for C:A). (**a**) Same neuronal response as in **Fig. 3a**, combining data from the three juice pairs. The firing rate is plotted against variable *offer value C*. Each symbol represents one trial type. The regression lines were obtained from a full-model ANCOVA; no regression line is plotted for A:B trials because the data points are collapsed on the x axis (*offer value C* = 0). (**b**) Same neuronal response as in **Fig. 3b** plotted against variable *chosen value* (expressed in units of *V*(C)). (**c**) Same neuronal response as in **Fig. 3c** plotted against variable *taste B*. All regression lines (**a**–**c**) were obtained from an ANCOVA.

factors. Of these, 767 (88%) were provided by the factor [variable]. In contrast, factors [juice pair] and [variable × juice pair] rarely yielded significant effects (respectively, 9% and 3%; **Table 2**). The measure of explained variance corroborated this result, as the factor [variable] typically accounted for most of the explained variance (**Fig. 5**).

Notably, menu invariance held true for all response types and in all time windows (**Table 3**). For example, restricting the analysis to responses encoding the *offer value* in the post-offer time window, 62 out of 71 (87%) significant effects were provided by the factor [variable]. Similarly, restricting the analysis to responses encoding *offer value B* or *taste B*, 86 out of 105 (82%) significant effects were provided by the factor [variable]. In conclusion, neuronal responses in the OFC were typically invariant for changes of menu.

DISCUSSION

In summary, by interleaving trials with different juice pairs, we observed that monkeys assign to three beverages values that respect transitivity. Replicating our previous results[22], we found that single-juice-pair responses in the OFC encode three variables: *offer value*, *chosen value* and *taste*. The main result of this study is that neuronal responses in the OFC are invariant for changes of menu. In other words, the activity of neurons encoding the value or taste of one particular juice typically does not depend on what other juices are available at the same time.

Neurons examined here do not encode or reflect the relative preference (that is, the ordinal ranking) of the offered juices. So how can our results be reconciled with observations from a previous study[24] (see Introduction)? One possibility is that recordings in the previous study[24] were from a different brain region. Consistent with this hypothesis, the percentage of task-related neurons in the population (<10% in any time window) was small compared to our estimate (>35% in post-offer, pre-juice and post-juice time windows; 63% pooling time windows; **Table 1**). Another possibility is that observations in the previous study[24] critically depended on the fact that trials were presented in blocks. In principle, a block design could affect neuronal responses in multiple ways. For example, in the previous study[24], A:B blocks could be considered high-value blocks, whereas B:C blocks could be considered low-value blocks. Observations of the previous study[24] thus suggest that the activity of OFC neurons might adapt to the behavioral condition (that is, to the general behavioral context defined across many trials, see Introduction). In this view, the

changes in neuronal activity observed in the previous study[24] were not due to menu dependence, but rather to a slowly adapting neuronal representation. Similar adaptation phenomena might also take place in other brain regions[27–29].

If the population of OFC neurons examined here were found to undergo analogous adaptation, we would suggest the following hypothesis. In any given behavioral condition, OFC neurons encode value in a menu invariant way; however, OFC neurons adapt flexibly to different behavioral conditions and thus maintain high value sensitivity. Further work is necessary to test this hypothesis.

Response types, menu invariance and transitivity

So far we have described transitivity as a trait of choice behavior and menu invariance as a trait of neuronal responses in the OFC. In fact, transitivity and menu invariance are intimately related concepts, both at the behavioral and neuronal levels. At the behavioral level, human and animal economic choices typically satisfy transitivity[3,8,30–33]. However, transitivity violations can sometimes be observed[34–37]. When they occur, transitivity violations are due to preferences that depend on the menu[36,38,39]. In other words, at the behavioral level, menu invariance implies transitivity. An analogous implication holds true at the neuronal level; a neuronal representation of value reflects transitivity if it is stable and invariant for changes of menu (**Supplementary Results** and **Supplementary Fig. 2** online). In this light, we shall now discuss the implications of menu invariance for different neuronal response types in the OFC.

Taste responses are binary responses reflecting the chosen juice independently of its amount. Because they do not encode value, transitivity does not apply. Menu invariance indicates that *taste* responses reflect the identity of the chosen juice as opposed to its preference ranking. Notably, we label these as *taste* responses because gustatory activity was previously reported in this area[17]. However, we use this label somewhat loosely. Indeed, as they appear before juice delivery (ref. 22 and **Table 1**), *taste* responses are not purely sensory, at least not in a traditional sense (they may also represent the expectation of one particular juice). Furthermore, *taste* responses could in fact encode a more complex impression such as flavor.

Chosen value responses were previously shown to encode the subjective value that monkeys assign to the juice that they choose to consume[22]. These responses encode value *per se*, as opposed to any physical property of the juice. *Chosen value* responses thus embody two defining properties of economic value: that value is subjective and that value is a common unit for qualitatively different goods[3,23]. Menu

Table 2 Analysis of menu-dependent encoding (ANCOVA), pooling time windows

	Offer value	Chosen value	Taste	Total	Percent
Variable	206	291	270	767	88
Juice pair	28	20	27	75	9
Interaction	6	13	7	26	3

Number and percentage of significant effects attributable, for each variable (columns), to the three factors (rows).
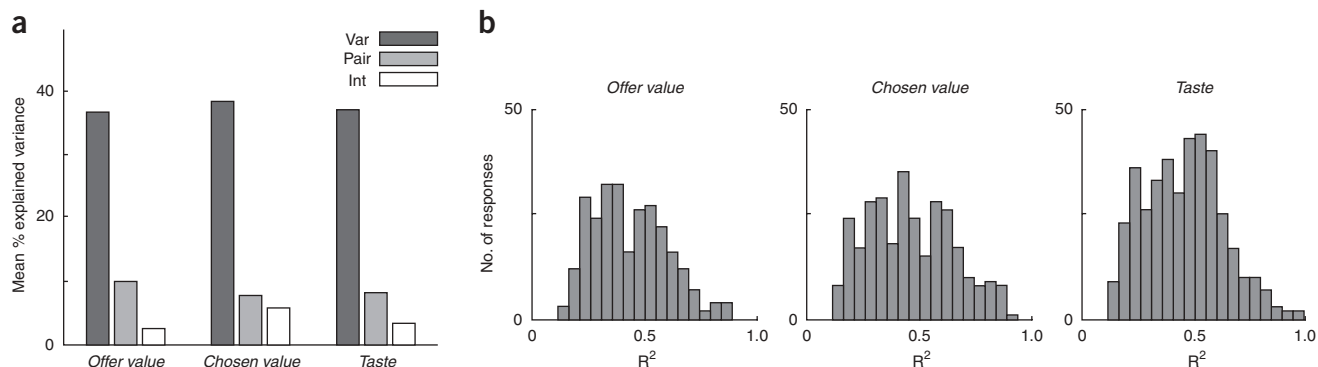
Figure 5 Explained variance. (**a**) ANCOVA. The plot shows the percentage of variance explained by the three factors [variable] (var), [juice pair] (pair) and [variable × juice pair] (int), separately for the three response types. The percentage of explained variance is averaged across responses, pooling time windows. (**b**) Linear fit. Because OFC responses were typically menu invariant, we estimated the variance explained by the encoded variable with a simple linear regression. The histogram shows the number of corresponding responses for different R^2, separately for the three response types. The medians of the three distributions were 0.42, 0.44 and 0.46, respectively.

invariance implies that *chosen value* responses also embody the other defining trait of economic value: transitivity. One open question is whether and how *chosen value* responses contribute to the choice process.

Offer value responses are interpreted more tentatively, since in this case we cannot distinguish juice value from juice quantity (or from other variables proportional to the juice quantity). We label them *offer value* responses because lesions to the OFC lead specifically to choice deficits[5–12] and because other responses in this area (namely, *chosen value* responses) encode value as opposed to quantity. However, more work is necessary to establish whether *offer value* responses encode value or quantity. If *offer value* responses encode the juice quantity, menu invariance implies that these responses reflect the identity as opposed to the preference ranking of the encoded juice. Conversely, if *offer value* responses encode the juice value, menu invariance implies that these responses reflect transitivity. In this respect, it is worth noting that neurons encoding the *offer value* (in particular, shortly after the offer) could naturally contribute to the choice process, and that menu invariance holds true in all time windows, including the post-offer time window. One intriguing possibility is that preference transitivity may be rooted in neuronal menu invariance.

The proposal that OFC value-encoding responses (that is, definitely *chosen value* responses and possibly *offer value* responses) reflect transitivity is limited in at least three important ways. First, in some circumstances, behavioral preferences depend on the menu and thus violate transitivity[34–39]. In such cases, OFC responses might also depend on the menu. Second, while invariant for changes of menu, OFC responses might vary depending on the behavioral condition, as defined above. Although this hypothetical adaptability does not imply transitivity violations *per se*, whether and how value-encoding responses in OFC reflect transitivity across behavioral conditions remains to be established. Third, further work should verify whether menu invariance holds true when choices involve different types of goods and different sensory or motor modalities.

Menu invariance could suggest that neurons encoding *offer value* or *taste* do not receive information about any juice other than the encoded one. However, it is also possible that a given neuron may adaptively respond to different juices in different behavioral conditions.

Relation with other brain systems

How is economic value computed, and how do value signals in the OFC affect various aspects of behavior? These fundamental questions remain largely open. Current anatomical maps[4] divide the medial and orbital prefrontal cortices in 22 distinct brain areas, organized in two mostly segregated networks. In the orbital network (including 13m and the surrounding areas), anatomical input from all sensory modalities converges with anatomical input from limbic areas including the amygdala[4,40]. The orbital network thus seems well placed to compute a quantity such as subjective value. However, this computation may involve multiple brain areas. Future work should thus examine other regions that are anatomically connected to the area examined here.

Table 3 Analysis of menu-dependent encoding (ANCOVA), by time window

	Number of significant effects								
	Offer value			Chosen value			Taste		
	var	pair	int	var	pair	int	var	pair	int
Post-offer	62	8	1	80	5	3	31	2	0
Late delay	38	6	2	37	4	0	32	8	0
Pre-go	15	4	0	33	2	2	12	5	0
Reaction time	8	4	2	25	2	1	8	2	1
Pre-juice	38	4	1	53	3	4	99	6	4
Post-juice	45	2	0	63	4	3	88	4	2
	Percentage of significant effects								
	Offer value			Chosen value			Taste		
	var	pair	int	var	pair	int	var	pair	int
Post-offer	87	11	1	91	6	3	94	6	0
Late delay	83	13	4	90	10	0	80	20	0
Pre-go	79	21	0	89	5	5	71	29	0
Reaction time	57	29	14	88	7	4	73	18	9
Pre-juice	88	9	2	88	5	7	91	6	4
Post-juice	96	4	0	90	6	4	94	4	2

Same results summarized in **Table 2**, broken down by time window. Top, numbers correspond to the number of significant effects attributable to the three factors [variable] (var), [juice pair] (pair) and [variable × juice pair] (int). Bottom, same data reported as percentages (normalized by time window). Menu invariance is particularly clear in the most salient time windows (post-offer, pre-juice and post-juice), where responses are more frequent and modulation is higher.

Apart from a possible role in economic choice behavior, value-encoding responses in the OFC might inform various other brain systems, including sensory, motor and viscero-motor systems. Through sensory and motor systems, these value signals may contribute to attention and action selection[2,41,42]. Through the viscero-motor system, these value signals may contribute to the generation and control of emotional and autonomic responses[43,44]. However, the lack of direct anatomic connections indicates that, at least for motor and viscero-motor systems, these putative modulations are indirect[4,40,45].

Notably, the representation of value in the OFC differs from that found in the lateral intraparietal area (LIP)[41,46]. In general, neurons in the LIP activate when a visual stimulus is placed in their response field and when the monkey plans the corresponding eye movement. LIP responses are enhanced if the value associated with the stimulus or the saccade is increased. Thus for neurons in the LIP, value modulates responses that are sensory or motor in nature[2]. In contrast, neurons in the OFC encode economic value *per se*, independently of visuomotor contingencies[22,42]. Another critical difference is that the value modulation in the LIP depends on the menu; for any given LIP neuron, the modulation is proportional to the value of the corresponding stimulus/saccade divided by the value sum of all possible stimuli/saccades[46], as if reflecting a value weight. In contrast, the representation of value in the OFC is invariant for changes of menu.

Conclusions

The behavioral context in which economic choices are made can change from moment to moment (changes of menu) or on a longer time scale (changes of condition). By interleaving trials with different juice pairs, we found that the representation of economic value in the OFC is invariant for changes of menu; neuronal responses encoding the value of one particular juice do not depend on what other juice is available at the same time. Neurons in the OFC thus encode the economic value in a cardinal (number-like) sense, and not the relative preference (the ordinal ranking). Moreover, OFC value-encoding neurons reflect transitivity. Whether and how the representation of value in the OFC adapts to the behavioral condition remains an important question for future work.

METHODS

Experimental design. One male (V, 9.5 kg) and one female (L, 6.3 kg) rhesus monkey participated in the experiments. Subjects, experimental setup, surgical procedures and recording procedures were the same as previously described[22]. The NIH Guide for the Care and Use of Laboratory Animals and the guidelines of the Harvard Medical School Standing Committee on Animals were strictly followed throughout the experiments.

Under general anesthesia, we implanted a head-restraining device and a recording chamber on the skull of the monkeys, and implanted a scleral eye coil[47]. We used large, oval, custom-made chambers (main axes 50 × 30 mm), centered on stereotaxic coordinates (A30, L0), with the longer axis parallel to a coronal plane. Following surgery, monkeys were given antibiotics (cefazolin, 20 mg per kg of body weight) and analgesics (buprenorphine, 0.005 mg per kg; flunixin, 1 mg per kg) for 3 d. During the experiments, monkeys sat in a monkey chair in a darkened room. The head was restrained and the eye position was monitored continuously using a scleral eye-coil system[47] (Riverbend Instruments). A computer monitor was placed 57 cm in front of the monkeys, and the behavioral task was controlled by custom-written software.

The trial structure is illustrated (**Fig. 1**). In each session, we pseudo-randomly interleaved trials with the three juice pairs. For any given offer type, the left and right positions were counterbalanced. Typically, 2–4 sessions, each consisting of 300–600 trials, were run each day. Across sessions, we used a variety of different juices, including high-sugar lemon Kool-Aid, grape juice, fruit punch (pure or diluted two-thirds with water), apple juice (diluted one-half with water), cranberry juice (diluted one-third with water), water,

peppermint tea, tea, low-sugar agua frescas Kool-Aid, low-sugar tamarind Kool-Aid and slightly salted water (0.60 g l^{−1} or 0.65 g l^{−1}). We used a total of 23 juice 'triplets'.

Juices were delivered through a three-line juice tube, with each juice line being controlled by a separate solenoid valve. We routinely calibrated the juice lines so that the valve-opening times corresponded to the desired multiple of juice quantum. We used quanta of 80 μl and 65 μl for monkeys V and L, respectively.

Neuronal recordings. Multi-electrode neuronal recordings were carried out in the same region examined in our previous study[22]. In monkey V, recordings were centered on stereotaxic coordinates A32.5 and L–9.0, and extended for 6 mm rostro-caudally and 5 mm medio-laterally. In monkey L, recordings were centered on stereotaxic coordinates A33.5 and L8.5, and extended for 6 mm rostro-caudally and 2 mm medio-laterally. Two structural MRI scans (1 mm sections) were made for each animal, before and after implanting the head post and recording chamber. For the second MRI, mineral oil–filled capillary tubes were placed at known locations in the chamber to aid in localizing electrode penetrations. We carried out two MRIs because the second MRI typically has some degree of metal artifact from the titanium plates and screws used to secure the chambers. Sulcal patterns from the two MRIs were superimposed to get a clearer image of the underlying anatomy. On the basis of this image and the patterns of gray and white matter encountered during penetrations, we tentatively identified the recording region as centered on area 13m (ref. 4).

Tungsten electrodes (125 μm diameter, 5 ± 1 MΩ initial impedance, Frederick Haer & Co.) were advanced with custom-built motorized microdrives (0.5 μm of depth resolution). Typically four electrodes were used each day. Electrodes were usually advanced by pairs (one motor for two electrodes), with the two electrodes being placed 1 mm apart. Electrical signals were amplified, band-pass filtered and recorded at 20 kHz (Power 1401, Cambridge Electronic Design). Action potentials were detected on-line by threshold crossing, and waveforms were saved to disk for subsequent analysis. Spike sorting was carried out off-line semi-manually (Spike 2, Cambridge Electronic Design). We routinely used multiple algorithms, including template matching, clustering on waveform measurements and principal component analysis. Only neurons that appeared well isolated throughout the recording session and that presented stable waveforms were included in the analysis.

Analysis of choice patterns. The method used to infer relative values is the same as the one that we previously employed for choices between two goods[22], generalized to the case of three goods offered pairwise. The approach is similar, but not identical, to a previous method[48]. We generally refer to 'relative' values because behavioral analyses allow measurement of quantities of different goods on a common value scale defined up to a scaling factor. In other words, values are always expressed in units of some arbitrarily designated good. Our measure of relative value rests on the assumption of linear indifference curves: if a monkey is repeatedly offered the choice between quantities q_A and q_B of juices A and B (offer q_BB:q_AA), the rate of B choices only depends on the ratio q_B/q_A (**Supplementary Results**).

In the analysis, choice patterns recorded for each pair of juices (for example, A:B) were expressed as a function of $\log(q_B/q_A)$, where q_A and q_B are the quantities of juices A and B offered to the monkey, respectively. We then fit the percentage of B choices with a normal sigmoid, which is a normal cumulative distribution function of the form $S(x) = \int_{-\infty}^{x} N(t, \mu, \sigma) \, dt$. We interpreted the underlying Gaussian (which has a mean of μ and a variance of σ^2) as a probability distribution for the log relative value. We thus computed the estimated relative value, $\hat{n} = \exp(\hat{\mu})$ (see **Fig. 2a**).

For each session, we thus obtained three probability distributions for the log relative values $u = \log(n_{A:B})$, $v = \log(n_{B:C})$ and $w = \log(n_{A:C})$. To test whether values satisfy transitivity, we tested whether the identity $u + v = w$ held statistically true. Because u, v and w are all normally distributed variables, transitivity violations can be identified with a z test. As illustrated (**Fig. 2b**), relative values measured in our experiments rarely violated transitivity.

Because measured values satisfied transitivity, we were able to express quantities of the three juices on a unique value scale. The estimated log relative values $\hat{u}$, $\hat{v}$ and $\hat{w}$ were computed by imposing the conditions $w = u + v$, $\partial P/\partial u = 0$ and $\partial P/\partial v = 0$ on the collective probability distribution $P(u,v,w)$.

The common value scale was defined up to a scaling factor, and we conventionally expressed values in units of $V(C)$. Except for the variable selection analysis (for which we used the relative values inferred from individual choice patterns), neuronal responses were always analyzed in relation to this common value scale.

Analysis of neuronal data. The 557 neurons analyzed here are an entirely new dataset (not previously published). Unless otherwise specified, the analysis was identical to the one previously described[22]. Behavioral and neuronal data were analyzed in Matlab (MathWorks). We divided trials into trial types on the basis of the offer type and the choice. For example, a monkey facing the offer type 3B:1A could choose either 1A or 3B, corresponding to the two trial types (3B:1A, 1A) and (3B:1A, 3B). In the analysis, we included only trial types with two or more trials. The number of trials per trial type thus ranged between 2 and 144 and was typically less than 30 (mean = 22.8, median = 20). For each trial type, we averaged the activity of each cell across trials separately in each time window. A response was defined as the activity of one neuron in one time window as a function of the trial type.

We previously showed that, for the limited quantity range explored in these experiments, the relationship between juice value and value-encoding neuronal responses is roughly linear[22]. Our analyses were thus based on linear regressions. The procedures and results for the variable selection analysis and for the analysis of classification conflicts are detailed in the **Supplementary Results**.

For the analysis of menu-dependent encoding, we defined seven variables as follows. In any given trial, *offer value A*, *offer value B* and *offer value C* were proportional to the quantity of juice A, B and C offered, respectively. The *chosen value* was always proportional to the value chosen by the monkeys, as expressed in the common value scale. Finally, *taste A* was proportional to a binary variable equal to 1 when monkeys chose and consumed juice A and equal to 0 otherwise. Variables *taste B* and *taste C* were defined analogously for juices B and C. Notably, the exact proportionality coefficients (the scale) were irrelevant because the analyses were based on linear regressions.

Note: Supplementary information is available on the Nature Neuroscience website.

AUTHOR CONTRIBUTIONS

C.P.-S. designed the experiment, collected and analyzed the data, and wrote the manuscript. J.A.A. assisted in the study and in manuscript preparation.

1. Fellows, L.K. The cognitive neuroscience of human decision making: a review and conceptual framework. *Behav. Cogn. Neurosci. Rev.* **3**, 159–172 (2004).
2. Glimcher, P.W., Dorris, M.C. & Bayer, H.M. Physiological utility theory and the neuro-economics of choice. *Games Econ. Behav.* **52**, 213–256 (2005).
3. Padoa-Schioppa, C., Jandolo, L. & Visalberghi, E. Multi-stage mental process for economic choice in capuchins. *Cognition* **99**, B1–B13 (2006).
4. Ongur, D. & Price, J.L. The organization of networks within the orbital and medial prefrontal cortex of rats, monkeys and humans. *Cereb. Cortex* **10**, 206–219 (2000).
5. Pasquier, F. & Petit, H. Frontotemporal dementia: its rediscovery. *Eur. Neurol.* **38**, 1–6 (1997).
6. Hodges, J.R. Frontotemporal dementia (Pick's disease): clinical features and assessment. *Neurology* **56**, S6–S10 (2001).
7. Izquierdo, A., Suda, R.K. & Murray, E.A. Bilateral orbital prefrontal cortex lesions in rhesus monkeys disrupt choices guided by both reward value and reward contingency. *J. Neurosci.* **24**, 7540–7548 (2004).
8. Fellows, L.K. & Farah, M.J. The role of ventromedial prefrontal cortex in decision making: judgment under uncertainty or judgment per se? *Cereb. Cortex* **17**, 2669–2674 (2007).
9. Everitt, B.J. & Robbins, T.W. Neural systems of reinforcement for drug addiction: from actions to habits to compulsion. *Nat. Neurosci.* **8**, 1481–1489 (2005).
10. Bechara, A., Tranel, D., Damasio, H. & Damasio, A.R. Failure to respond autonomically to anticipated future outcomes following damage to prefrontal cortex. *Cereb. Cortex* **6**, 215–225 (1996).
11. Rahman, S., Sahakian, B.J., Hodges, J.R., Rogers, R.D. & Robbins, T.W. Specific cognitive deficits in mild frontal variant of frontotemporal dementia. *Brain* **122**, 1469–1493 (1999).
12. Koenigs, M. & Tranel, D. Irrational economic decision-making after ventromedial prefrontal damage: evidence from the Ultimatum Game. *J. Neurosci.* **27**, 951–956 (2007).
13. Arana, F.S. *et al.* Dissociable contributions of the human amygdala and orbitofrontal cortex to incentive motivation and goal selection. *J. Neurosci.* **23**, 9632–9638 (2003).
14. Blair, K. *et al.* Choosing the lesser of two evils, the better of two goods: specifying the roles of ventromedial prefrontal cortex and dorsal anterior cingulate in object choice. *J. Neurosci.* **26**, 11379–11386 (2006).
15. O'Doherty, J.P. Reward representations and reward-related learning in the human brain: insights from neuroimaging. *Curr. Opin. Neurobiol.* **14**, 769–776 (2004).
16. Knutson, B., Taylor, J., Kaufman, M., Peterson, R. & Glover, G. Distributed neural representation of expected value. *J. Neurosci.* **25**, 4806–4812 (2005).
17. Pritchard, T.C. *et al.* Gustatory neural responses in the medial orbitofrontal cortex of the old world monkey. *J. Neurosci.* **25**, 6047–6056 (2005).
18. Wallis, J.D. & Miller, E.K. Neuronal activity in primate dorsolateral and orbital prefrontal cortex during performance of a reward preference task. *Eur. J. Neurosci.* **18**, 2069–2081 (2003).
19. Roesch, M.R. & Olson, C.R. Neuronal activity related to reward value and motivation in primate frontal cortex. *Science* **304**, 307–310 (2004).
20. Rolls, E.T., Sienkiewicz, Z.J. & Yaxley, S. Hunger modulates the responses to gustatory stimuli of single neurons in the caudolateral orbitofrontal cortex of the macaque monkey. *Eur. J. Neurosci.* **1**, 53–60 (1989).
21. Roesch, M.R. & Olson, C.R. Neuronal activity dependent on anticipated and elapsed delay in macaque prefrontal cortex, frontal and supplementary eye fields and premotor cortex. *J. Neurophysiol.* **94**, 1469–1497 (2005).
22. Padoa-Schioppa, C. & Assad, J.A. Neurons in orbitofrontal cortex encode economic value. *Nature* **441**, 223–226 (2006).
23. Montague, P.R. & Berns, G.S. Neural economics and the biological substrates of valuation. *Neuron* **36**, 265–284 (2002).
24. Tremblay, L. & Schultz, W. Relative reward preference in primate orbitofrontal cortex. *Nature* **398**, 704–708 (1999).
25. Kreps, D.M. *A Course in Microeconomic Theory*, 850 (Princeton University Press, Princeton, New Jersey, 1990).
26. Allingham, M. *Choice Theory: A Very Short Introduction*, 127 (Oxford University Press, Oxford, 2002).
27. Tobler, P.N., Fiorillo, C.D. & Schultz, W. Adaptive coding of reward value by dopamine neurons. *Science* **307**, 1642–1645 (2005).
28. Cromwell, H.C., Hassani, O.K. & Schultz, W. Relative reward processing in primate striatum. *Exp. Brain Res.* **162**, 520–525 (2005).
29. Hosokawa, T., Kato, K., Inoue, M. & Mikami, A. Neurons in the macaque orbitofrontal cortex code relative preference of both rewarding and aversive outcomes. *Neurosci. Res.* **57**, 434–445 (2007).
30. Logan, F.A. Decision-making by rats: delay versus amount of reward. *J. Comp. Physiol. Psychol.* **59**, 1–12 (1965).
31. Campione, J.C. Transitivity and choice behavior. *J. Exp. Child Psychol.* **7**, 387–399 (1969).
32. Mazur, J.E. & Coe, D. Tests of transitivity in choices between fixed and variable reinforcer delays. *J. Exp. Anal. Behav.* **47**, 287–297 (1987).
33. Choi, S., Fisman, R., Gale, D. & Kariv, S. Consistency and heterogeneity of individual behavior under uncertainty. *Am. Econ. Rev.* (in the press).
34. Tversky, A. The intransitivity of preferences. *Psychol. Rev.* **76**, 31–48 (1969).
35. Navarick, D.J. & Fantino, E. Transitivity as a property of choice. *J. Exp. Anal. Behav.* **18**, 389–401 (1972).
36. Shafir, S. Intransitivity of preferences in honey bees: support for 'comparative' evaluation of foraging options. *Anim. Behav.* **48**, 55–67 (1994).
37. Shafir, S. Context-dependent violations of rational choice in honeybees (*Apis mellifera*) and gray jays (*Perisoreus canadensis*). *Behav. Ecol. Sociobiol.* **51**, 180–187 (2002).
38. Tversky, A. & Simonson, I. Context-dependent preferences. *Manage. Sci.* **39**, 117–185 (1993).
39. Grace, R.C. Violations of transitivity: Implications for a theory of contextual choice. *J. Exp. Anal. Behav.* **60**, 185–201 (1993).
40. Price, J.L. Prefrontal cortical networks related to visceral function and mood. *Ann. NY Acad. Sci.* **877**, 383–396 (1999).
41. Sugrue, L.P., Corrado, G.S. & Newsome, W.T. Matching behavior and the representation of value in the parietal cortex. *Science* **304**, 1782–1787 (2004).
42. Padoa-Schioppa, C. Orbitofrontal cortex and the computation of economic value. *Ann. NY Acad. Sci.* published online 14 August 2007 (doi:10.1196/annals.1401.011).
43. LeDoux, J.E. Emotion circuits in the brain. *Annu. Rev. Neurosci.* **23**, 155–184 (2000).
44. Critchley, H.D. Neural mechanisms of autonomic, affective and cognitive integration. *J. Comp. Neurol.* **493**, 154–166 (2005).
45. Carmichael, S.T. & Price, J.L. Sensory and premotor connections of the orbital and medial prefrontal cortex of macaque monkeys. *J. Comp. Neurol.* **363**, 642–664 (1995).
46. Dorris, M.C. & Glimcher, P.W. Activity in posterior parietal cortex is correlated with the relative subjective desirability of action. *Neuron* **44**, 365–378 (2004).
47. Judge, S.J., Richmond, B.J. & Chu, F.C. Implantation of magnetic search coils for measurement of eye position: an improved method. *Vision Res.* **20**, 535–538 (1980).
48. Luce, R.D. *Individual Choice Behavior: A Theoretical Analysis* (Wiley, New York, 1959).