Decision-making and the frontal lobes

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Purpose of review

This article reviews the most significant advances concerning the neural correlates of decision-making with emphasis on those imaging studies investigating the neural implementation of evaluative judgment processes. This is done against the background of current concepts from the field of judgment and decision-making.

Recent findings

Actual neuroscientific findings suggest that subject to the extent of how deeply a decision-maker has to explore his/her value system in order to reach a decision, distinguishable orbital and medial prefrontal areas will be engaged. Decisions low in costs mapping the values onto the decision problem mainly rely on orbital and ventromedial prefrontal cortex, whereas decisions high in costs particularly draw on anterior–medial and dorsomedial prefrontal areas. This suggestion is related to the anatomic properties of the respective areas.

Summary

Combining neuroimaging data with concepts from research in judgment and decision-making may facilitate advances in our understanding of the contrast between normative theories and descriptive theories of decision-making. Incorporating findings from research on decision-making behavior in patients with specific prefrontal lesions may have much to offer for an understanding of both the areas' functions and cognitive theories on decision-making.

Keywords

decision-making, evaluative judgments, frontal lobes, orbital and medial prefrontal cortex, preference judgments

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Abbreviations

AMPFC	anterior–median prefrontal cortex
O/VMPFC	orbital and ventromedial prefrontal cortex
PFC	prefrontal cortex

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Introduction

When contemplating decisions, we usually think of significant ones such as which career to pursue, and whether to get married, or to have children. Yet, at the same time, decisions are a frequent phenomenon: every day we make numerous decisions that are mostly accomplished routinely. For example, throughout the day we decide what to wear to work, what to have for lunch, and what to do for leisure. As decision-making is such a common behavior, it is vital to understand its underlying cognitive processes in order to be able to anticipate what a person will do in a particular context. This is especially important as a contrast has been set up between normative theories of decision-making, that prescribe what people should do when making decisions, and descriptive or behavioral theories of decision-making, that describe the potentially flawed and simplistic things that people usually do [1–3]. To reach an answer to the question 'what do people actually do (in their minds) when they make decisions?' one should 'carve the mind at its joints', as Kosslyn and Koenig [4] framed it. Accordingly, psychological theorists strove to decompose the intellectual, social, or emotional competence underlying decision-making, into its constituent processes. To reliably determine the crucial processes, they relied on a combination of rational task analysis, computer simulations, self-reports, experimental set-ups, and findings from neuropsychology. In doing so, researchers in judgment and decision-making converged on the conclusion that people engage in four core processes when making decisions in a specific context: they set goals, that is, they generate an intention to act; they deliberate on one or more ways to accomplish these goals (information search included); they evaluate the options – whereby the goals set determine the value of the option at the time of decision – and select one of them; and they implement the option that seems ideal to proceed [5,6]. Thus, decision-making is the process of choosing between at least two alternatives, so that the option is chosen that maximizes subjective gains and minimizes subjective losses. Options can be objects, actions, longer term strategies, or decision rules. The outcome of a decision crucially biases the decision-maker's next encounter with a similar decision situation in terms of specific affective and action-guiding dispositions. The learning from the consequences is especially important for recurrent decisions and routine decisions.

In short, during decision-making people engage in goal-setting, option generation, option evaluation, and option selection. Yet, it has been shown that people do not always engage in all four processes when making a decision, especially not when they are presented with two options by someone else, nor do people usually accomplish all processes in a stepwise manner or in an analytic way [1,5]. The actual process of choosing an option, what we colloquially denote as decision, hence is only one part of the entire decision-making process.

Recently, cognitive neuroscience has begun to investigate the brain basis of decision-making, with a particular focus on the prefrontal cortex [7•]. This focus has primarily been motivated by clinical reports that frontal damage is associated with poor decision-making behavior despite preserved intellectual abilities otherwise [8,9]. In the available contribution, we will review a selection of recent imaging studies with regard to the neural implementation of decision-making and will discuss if, and if so how, these findings may contribute to a descriptive or behavioral conceptualization of decision-making. In doing so we will concentrate on those studies that investigated the neural correlates of the core processes of decision-making, that is, evaluation and selection processes. Due to the poor temporal response of the blood supply, which is the basis of functional magnetic resonance imaging, it is not possible to dissociate evaluation processes from selection processes, at least not when modeling realistic decision situations. Accordingly, we will discuss the two sorts of processes conjointly.

Defining evaluation/selection processes

The generic meaning of the term evaluation refers to the collection and processing of information and data in order to compare options or events to a set of normative criteria or goals [10]. The behavioral output of this scaling process is a judgment in the form of 'I like anchovies on my pizza' or 'I think San Diego is larger than San Antonio'.

At least two different kinds of judgments can be dissociated based on the content of the judgment: are people required to judge matters of fact, cases in which there are verifiably right answers, the behavioral output for which is referred to as non-evaluative judgments? Plain facts can be proven by logic or by experiment and, as Haidt and Kesebir [11] paraphrased it, would generally pass the 'alien test': 'If intelligent aliens were to visit Earth from another solar system, we would expect them to agree with us about things that are plain facts about the universe, independent of human perception of them' (p. 6). In contrast, we would neither expect intelligent aliens nor any arbitrary conspecific to necessarily agree with us regarding matters of value such as humor, taste or beauty. Judgments of this kind, which are referred to as evaluative judgments, go beyond the mere description of how the world is and rather express an attitude toward that world [5,6,12]. For example, whether John Irving is a better writer than Philip Roth or which of two paintings is more beautiful cannot be decided objectively. Thus, evaluative judgments can be described as assessing a stimulus on an internal scale that is related to the person's value system.

Present neuroimaging evidence consistently revealed evaluative judgment processes to draw on the orbital and median prefrontal cortex (PFC), whereas non-evaluative judgment processes, such as those operationalized in anagram problems, transfer problems, or insight problems, rather rely on the lateral PFC [13–16]. We will suggest different orbital and median PFC areas involved in distinctive decisions which in turn can be classified in terms of required information processing operations for mapping the decision-maker's values onto the decision problem [17].

Classification of evaluation/selection processes on the basis of the representation of the decision problem

Whether the choice of a specific option indeed results in the desired consequences depends on the states of the world, which defy control. Thus, in order to decide advantageously the decision-maker has to compare and evaluate the predicted consequences or reward values of the available options. This process is easy when the occurrence of the predicted consequences is certain (certain decisions) or can be assigned a specific probability (risky decisions). If the probability of occurrence of the consequences is unknown (uncertain decisions), the evaluation processes become more complex [2]. The quality of the predictions vary depending on the sampling rate and the variance of reward distribution: the more often one has encountered a specific decision problem, the more precisely one's predictions will be in terms of reward probability and reward variability. Thus, the classification of decision problems in terms of uncertainty is suggested to be correlated with the cognitive representation in terms of information processing for mapping the decision-maker's values onto the decision problem which in turn is affected by frequency. Depending on how deeply one has to explore his or her value system, four levels of decisions have been distinguished [2,17]. At the first level, the situation is recognized as being similar to a previous one and, hence, no explicit reference to the decision-maker's value system is needed. Processes such as similarity matching between actual options and options chosen in the past dominate first-level decisions. Due to frequent repetition, decisions are mainly reached automatically or routinely and therefore also termed recognition-primed decisions. Colloquially these are not looked on as decisions in a narrow sense. At the second level, the decision-maker feels that they make a decision with reference to his or her values. These sorts of decisions, termed stereotypical, are based on one or a few salient attributes favoring one option. Exemplary are consumer decisions such as 'shall I take the fruit salad or go for the creme brulée?' The selection for an option is suggested not to be reached by analytic, cognitive inferences but rather by holistic, intuitive processing including the application of non-compensatory decision strategies [18], heuristics. At the third level the decision-maker actively tries to relate his or her value system to the attributes by incorporating long-term information or contextual information. The processing implies access to values that can be regarded as meta-values or as more or less conscious justifications of the value system inherent in level 1 and 2 decisions. Reflective decisions, as this sort of decision is termed, often concern significant problems and hence are suggested to be open for affective or motivational influences. At level 4, the decision-maker is faced with novel or unprecedented decisions for which the options have yet to be elicited or created. Accordingly, the decision-maker has to go beyond the given problem in terms of both values and facts. Important to note, as a rule, lower level processes are included as sub-processes in higher level processing, behaviorally and in terms of brain activity. So far, most of the decision-making research has concerned level 2 and 3 decisions, whereas level 1 and 4 decisions have been less relevant as the former include processes other than comparisons of values and the latter are difficult to implement experimentally.

Considering the present neuroimaging data on decision-making, it seems as if level 2 and level 3 decisional processes can also be dissociated based on their neural correlates: level 2 decisional processes mainly elicit activation within the orbital and ventromedial PFC (O/VMPFC), whereas level 3 decisional processes mainly draw on anterior–medial and dorsomedial prefrontal areas. For instance, when participants have to judge the desirability or value of options or when participants have to evaluate the obtained outcome, activation foci within the O/VMPFC have consistently been reported [19,20•,21,22,23•,24–26]. Hence, O/VMPFC activation revealed when participants had either to passively view or to select between options that disposed of a reward history, whereas participants did not have to be aware of the reward history. (Although it might be important, at least from a theoretical point of view, to distinguish between the magnitude and the probability of reward, we will not concentrate on this distinction in terms of the underlying neural computations, as this understanding is as yet relatively weak [7•].) These findings are in accordance with previous studies in humans and primates that found reward value, expected reward value and other (hedonic) reinforcers to be represented in the O/VMPFC [27–32,33•]. Yet important to note are studies on reinforcer devaluation that suggest the O/VMPFC not only to represent the absolute reward value but the relative reward value and so to track changes in reward value [33•,34–36].

The finding of the O/VMPFC being involved in the representation of affective values of both primary and secondary reinforcers suggests this area to mainly respond to preference judgments. In accordance with the conceptualization of level 2 decisions, participants in the imaging studies evaluated and selected options based on an intuitive overall impression or on a few salient attributes; tradeoffs were either ingrained or in the case of unfamiliarly combined attributes were made up for simple rules such as non-compensatory decision rules. Recently, the O/VMPFC has also been reported for preference judgments based on an initial guess and feeling of knowing judgments [24,25,37•,38]. Exemplifying level 2 decisions were consumer decisions, which are distinguished by the decision-maker taking into account the current bodily needs. Although there are so far only a few imaging studies on food choices, specific O/VMPFC activation was reported [36,39]. Anatomic and physiological data from human and non-human primates suggest the O/VMPFC is dedicated to subserve functions crucial for level 2 decisions: the O/VMPFC has dual access to the entire sensory periphery by direct input from all sensory modalities and indirectly from the amygdala [40,41]. The indirect pathway through the amygdala was suggested to allow the O/VMPFC to extract the emotional significance of events. Furthermore, the O/VMPFC has relatively direct access to hypothalamic autonomic centers. These hypothalamic sites innervate neurochemically specific areas in the brainstem that broadcast to the cortex and spinal autonomic structures innervating peripheral organs that are crucial during emotional arousal. Accordingly, damage to the O/VMPFC disrupts PFC-autonomic circuits and thus may explain why patients with O/VMPFC lesions show inappropriate affect, lack emotional responsiveness, and make poor level 2 decisions. Opposite, an excessive O/VMPFC activation may lead to modified function and regularity of the autonomic structures so that disorders characterized by chronic anxiety may result. These considerations have much to offer for an understanding of depression and addictive behavior, as these pathologies have been associated with changes in O/VMPFC function and structure [42–46,47•,48,49]. In this context it may be auspicious to consider morphometric aspects, as the size of the O/VMPFC has been suggested to explain individual differences in fear extinction and its retention [50].

Level 3 decisions are exemplified in being asked to judge whether San Diego is larger than San Antonio or which of two presented abstract tableaus is more beautiful. In these cases one has to relate his or her value system to the attributes describing the decision alternatives: processing in example 1 implies access to meta-values and hence long-term information, whereas processing in example 2 implies access to such values that can be described as justifications of the value system inherent in level 1 and 2 decisions. Imaging studies investigating aesthetic judgments [51], mentalizing judgments [52,53, 54•,55], self-descriptive judgments [54•,56,57], first-person-perspective judgments [58], judgments about intentional moral transgressions [59], episodic retrieval [60,61] or valenced stimuli [62•] all elicited activation within anterior–median prefrontal cortex (AMPFC). Process-related, level 3 decisions have been distinguished by tradeoffs between the attractiveness of aspects of the attributes or by transforming the given attributes into new ones [17]. This assumption implies not only evaluative judgment processes to draw on AMPFC, as has been shown extensively, but also non-compensatory or heuristic processes to draw on this area. In fact, AMPFC activation has been reported for decisional processes based on the recognition heuristic [63].

From an anatomic point of view, AMPFC seems adapted for level 3 decisional processes. Cytoarchitectonic studies revealed as an important distinguishing feature of the AMPFC, even in comparison with other prefrontal areas, a high number of dendritic spines per cell, a low density of cell bodies, and a predominance for intra-frontal circuits [64,65]. These characteristics distinguish AMPFC to subserve computational properties by the integration of multidimensional input, such as the integration of stored meta-values and values inherent in level 1 and 2 decisions. In this way a coloring by motivational and affective aspects is feasible.

Level 3 decisions have often been found to mainly engage dorsomedial PFC (DMPFC), sometimes extending into AMPFC. This finding raises the question of whether level 3 decisions are to be further classified. Deducing an answer from neurobiology is inapplicable, as anatomic and physiological studies on DMPFC are very sparse. Thus, we suggest a distinction based on procedural aspects of the paradigms eliciting DMPFC activation [66–70]. The task of participants in many of the studies reporting DMPFC activation is to judge the consistency of events or stimuli, such as what another person may think or will do (generally referred to as mentalizing or 'theory of mind' processes) [71,72]. Being asked to judge how pleased the person in a photograph seems to be to have his or her photo taken, one does not have to map one's own values onto the decision problem, but those of someone else. That is, the decision cannot be inferred from our meta-values or values inherent in our level 1 and 2 decisions, but we may extrapolate from those by essentially incorporating given contextual, sequential, and temporal information. This processing is suggested to particularly imply abstract relational integration independent of domain [73]. Yet, in what way these social evaluative judgments relate to level 3 decisions both in terms of information processing operations and brain activity remains for future studies.

Conclusion

Significant decisions such as whether or whom to marry differ from everyday decisions such as what to have for lunch in frequency (at least most probably) resulting in different cognitive representations of the decision problems. Depending on the decision-maker's perception of the decision problem and on context variables, such as time pressure or framing of the problem, different decision processes will be implemented, which in turn are reflected by specific frontomedian activation. Thus, we suggest, knowing where in the brain processing takes place can tell us important potential correspondences between phenomenologically different decision strategies or whether phenomenologically similar strategies may draw on different, non-overlapping brain areas.

Over the lifetime, decision-making involves the acquisition of an increasing diverse array of decision strategies and heuristics. Accordingly, decision-making involves selection from an array of strategies which becomes increasingly complex with development [1,74]. For this reason we suppose that the investigation of decision-making processes in adolescents might be promising, especially in combination with neuroimaging. To investigate the neural underpinnings of different decision strategies, it may also be promising to investigate patients with specified PFC lesions in this respect. During multi-attribute decision-making, it has been shown that patients with VMPFC damage show a remarkable difference in their decision strategies from healthy controls and patients with lesions sparing VMPFC such that VMPFC lesioned patients favored an alternative-based information acquisition strategy whereas the other two groups pursued primarily attribute-based search strategies [75•]. This differentiation may in turn affect the quality of choice. In this context, it becomes important to investigate how specific genes affect cognitive processing during decision-making [76].

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