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The neural implementation of multi-attribute decision making: A parametric fMRI study with human subjects

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Decision making is not a unitary entity but involves rather a series of interdependent processes. Decisions entail a choice between two or more alternatives. Within the complex series of decisional processes, at least two levels can be differentiated: a first level of information integration (process level) and a second level of information interpretation (control level), leading to a subsequent motor response or cognitive process. The aim of this study was to investigate the neural network of these decisional processes. In a single trial fMRI study, we implemented a simple decision-making task, where subjects had to decide between two alternatives represented on five attributes. The similarity between the two alternatives was varied systematically in order to achieve a parametric variation of decisional effort. For easy trials, the two alternatives differed significantly in several attributes, whereas for difficult trials, the two alternatives differed only in small details. The results show a distributed neural network related to decisional effort. By means of time course analysis different subprocesses within this network could be differentiated: regions subserving the integration of the presented information (premotor areas and superior parietal lobe) and regions subserving the interpretation of this information (frontolateral and frontomedial cortex, anterior insula, and caudate) as well as a region in the inferior frontal junction updating task rules.

Keywords: Decision making; fMRI; Frontolateral cortex; Parametric modulation; Two-level model

Introduction

A decision arises when a person is consciously aware of two or more possible alternative behaviors (be it thoughts or actions), only one of which can or should be performed. This person (the decision maker) is thus forced to choose one option out of a set of alternatives. The process of making a decision is a sequence of subprocesses, e.g., evaluating specific aspects of each alternative, constructing a mental representation of the decision situation, or judging the involved uncertainty (Paulus et al., 2005). These subprocesses are at least to some degree interdependent. Most imaging studies investigating decision making have focused on subprocesses, like uncertain decision processes (Blackwood et al., 2004; Paulus et al., 2001; Volz et al., 2003), reward (Haruno et al., 2004; Rogers et al., 2004; Bush et al., 2002; Bechara et al., 1996, 1997, 2000), risk taking (Paulus et al., 2003a,b), ethical decision making (Heekeren et al., 2003), moral judgments (Heekeren et al., 2005; Moll et al., 2005), economic decisions (Sanfey et al., 2003), monetary gains (Gehring and Willoughby, 2002), or personal choice (Turk et al., 2004). An overview article by Krawczyk (2002) on the neural basis of human decision making shows that most research is done on the specific aspect of reward/punishment, emotion, and environmental adaptiveness. Very few functional imaging studies have investigated decision making as the process of relating several independent sources of variance, i.e., in the context of relational integration.

Functional magnetic resonance imaging (fMRI) studies have used mainly gambling situations as decision tasks. As recent research indicates, gambles omit relevant aspects of real-life decision making, such as active risk management (Huber, 2002). In order to get a better understanding of the complex neural network of human decisional processes, one should meet two goals: (i) the experimental situation ought to resemble real-life decision tasks (Ford et al., 1989); (ii) decision making should be stripped down to its bare essentials (Shadlen and Newsome, 1996).

The present study is a first attempt with a basic multi-attribute decision task, in which alternatives are evaluated according to several attributes. Uncertainty and risk could be introduced into a multi-attribute task, but in its basic version, these aspects are not involved. A typical example of such a multi-attribute task is the decision situation of a person who wants to rent an apartment. The

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decision maker may take into account the location, the quietness, the number of rooms, how luxurious the apartment is, the distance to the person's working place, whether there are shops and restaurants nearby, etc. Different attributes usually carry different importance or weight. If our decision maker is light sleeper, quietness of the apartment would get a high weight, if not, quietness may get only a small weight.

A multi-attribute decision situation can be represented by an Alternative by Attribute matrix, with alternatives as columns and attributes as rows. Table 1 shows the general scheme of such a multi-attribute task as used in our study. In making a decision, the decision maker usually combines her or his evaluations of the aspects and the weights of the attributes to an overall decision. Several theories have been developed to describe multi-attribute decisions, for example, the additive utility model (Slovic et al., 1977), simple heuristics (Payne et al., 1993; Rieskamp and Hoffrage, 1999; Svenson, 1979), or elementary information processing operators (Huber, 1989; Payne et al., 1993). In the present study, details of these theoretical approaches are not relevant.

We make the general assumption that the decision process consists of the application of one or more decision heuristics (e.g., Lexicographic heuristic, Weighted Pros, cf. e.g., Huber, 1989; Rieskamp and Hofrage, 1999; Svenson, 1979). A decision heuristic consists of a sequence of subprocedures that can be modeled as elementary cognitive operators. For example, the Lexicographic Heuristic consists of the following subprocedures (for a more detailed description in terms of elementary cognitive operators, see Huber, 1989): (i) weighting the attributes and selecting the most important one; (ii) evaluating and comparing the alternatives on this most important attribute; (iii) choosing the alternative that is better; and (iv) if no alternative is better, eliminating the most important attribute and restarting at item (i).

Cognitive process models of decision making, involving heuristics or elementary information processing operators, postulate at least two levels (or components) of the process: a process level and a control level. We regard the distinction of these two levels as being essential for the way decision making is reflected in the brain's activation pattern.

Process level

At this level, the subprocedures of the heuristic are performed, for example: evaluation of the alternatives features, the weighting of attributes, but also the concatenation of aspects (e.g., the amount of rent and the extras can be concatenated as 'costs') or the trade-off of aspects (e.g., the higher rent of apartment A is compensated for by its better location). At this level, information search is also performed (e.g., what is the size of apartment A).

Let us consider the involvement of the process level, when the decision maker gets information about both alternatives sequentially, for one attribute after the other. Thus, the decision maker would acquire first information concerning aspects A1 and B1 (see Table 1), next about aspects A2 and B2, and so on. The subprocedures on the process level have to be activated for every presented attribute, starting with the first two aspects till the whole information is displayed.

Control level

This level constitutes a meta-level for the decision process. It governs the activities on the process level. It selects a decision heuristic and coordinates the subprocedures on the process level when performing a heuristic. The selected heuristic determines how the evaluations on different attributes are integrated. In the Weighted-Pros heuristic, for example, the weights of the attributes are relevant in the integration. The integration of the weights of different attributes is performed by a subprocess within the heuristic. The control level decides whether the alternative favored at the moment is distinctly better than the others (e.g., Svenson, 1993) and thus whether the decision process can be terminated or has to be continued. For example, in a situation with several alternatives, first a heuristic is used that enables a fast reduction of the set of alternatives by inspecting only one or two attributes (e.g., lexicographic heuristic). When the set of alternatives has been reduced to a short list, these alternatives are inspected in more detail with the help, for example, of the 'Weighted-Pros' heuristic. There are different assumptions about the control level, which the present study will not dwell upon any further (Huber, 1989; Payne et al., 1993; Svenson, 1993).

With respect to the temporal dynamics, the processes on the control level should behave differently than the process level: in the first information acquisition step, the control process should only be activated weakly if at all because the decision maker knows that more information is coming and that a final decision would be premature. Furthermore, after inspecting the alternatives on the first dimension(s), it may not yet be clear what heuristic is best. For example, use of the 'Weighted Pros' Heuristic (e.g., alternative A is better on dimension 1 and 2, but B is better on dimension 3) cannot be considered until a preference conflict occurs. Furthermore, a trade-off between dimensions cannot occur if only one dimension has been inspected. Over time, with the presentation of additional information, activation of the control process should increase until a decision is finally reached.

Because of this, different temporal dynamics of the BOLD response are expected in relation to the underlying processes: areas related to the process level should show an early onset of the hemodynamic response, with the BOLD signal steadily increasing. On the other hand, areas related to the control level should show a delayed signal increase. Further, response-related areas should show signal changes only at the time the response is given.

We additionally hypothesize that the amount of neural activation of the process level and control level should be related to the difficulty of the decision task. Difficulty in the present study

Table 1
Examples of two multi-dimensional decision task as used in the present study

Attribute	Renting a flat	Easy task		Difficult task	
		Alt A	Alt B	Alt A′	Alt B′
1	Price square meter (Euro/m^2)	8	6.1	8	8.1
2	Size (in m^2)	59	90	72	69
3	Distance to City Center (minutes to walk)	30	11	20	21
4	Distance to public transport (m)	310	300	450	155
5	Distance to work (km)	5.1	1.0	2	1.9

In each task, two alternatives are described on five attributes. It is assumed that a lower price, the larger size, and the shorter distances are preferred. In the easy task, alternatives A and B are dissimilar, whereas in the difficult task, alternatives A′and B′are similar.