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Research Report

Brain activations reflect individual discount rates in intertemporal choice

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ABSTRACT

Humans discount the value of future rewards following a hyperbolic function and thus may prefer a smaller immediate reward over a larger delayed reward. Marked interindividual differences in the steepness of this discounting function can be observed which can be quantified by the parameter *k* of the discount function. Here, we asked how differences in delay discounting behaviour are reflected by brain activation patterns. Sixteen healthy participants were studied in a slow event-related functional magnetic resonance imaging experiment at 3T. In each trial, participants had to decide between a smaller but immediately available monetary reward (ranging between 14 and 84 Euro) and a larger delayed reward (26 to 89 Euro; delay 5 to 169 days) by button press. Participants had the chance to receive the reward corresponding to one of their decisions at the end of the experiment. As expected, participants differed widely with respect to the steepness of their discount function. By contrasting decisions at or near the individual participant's indifference point (as determined by parameter *k*) with trials either well below or well above this point two different brain networks with opposing activation patterns were revealed: Trials below or above the indifference point were associated with activation in the ventral striatum and ventromedial prefrontal cortex, whereas decisions at the indifference point gave rise to activation in medial prefrontal cortex. The opposite effects in the two systems at individual indifference point were interpreted as a reflection of response conflict.

1. Introduction

Time affects the value of money, food and other rewarding commodities. In choosing between a (smaller) immediate and a (larger) delayed reward both, humans and animals ranging from great apes to pigeons often tend to prefer impulsive choices for the smaller but immediately available reward (Amiez et al., 2006; Kalenscher et al., 2005; Kalenscher and Pennartz, 2008). On the other hand, and crucial for human economic behaviour, we sometimes wait for the return on financial investments for years or even decades (Rosati et al., 2007).

Whereas standard normative economic theory (Strotz, 1956) predicts exponential discounting, empirical evidence in humans suggests that future gains are discounted in a hyperbolic or quasi-hyperbolic fashion (Frederick et al., 2003).

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For example, according to Mazur (1984) the value of a reward decreases over time following a hyperbolic function:

$$V = \frac{A}{1 + kD}$$

where V is the present value of the delayed reward A after a delay D, and k is the *delay discount rate*.

Patience is a virtue that is not shared by all humans, however. High individual values of k in the equation above indicate preference for immediate values (impulsive, impatient behaviour) and a steep discounting function, whereas lower values are associated with the patient willingness to wait for the larger delayed reward. Steeper discounting functions are found in heroin (Kirby and Petry, 2004; Kirby et al., 1999), cocaine (Kirby et al., 1999), tobacco (Reynolds, 2004; Reynolds et al., 2004) and alcohol addicts (Mitchell et al., 2005; Petry, 2001a) as well as pathological gamblers (Petry, 2001b), disorders characterized by impulsive behaviour. Discounting rate also presents a wide intersubject variability in the normal population (Chabris et al., 2008) and the individual k-rate seems to be related to the impulsivity personality trait (Reynolds, 2006).

A number of previous studies have investigated the neural systems involved in delay discounting (Bickel et al., 2009; Boettiger et al., 2007; Engelmann and Brooks, 2009; Hariri et al., 2006; Kable and Glimcher, 2007; Luhmann et al., 2008; McClure et al., 2004, 2007; Peters and Buchel, 2009; Pine et al., 2009; Weber and Huettel, 2008; Xu et al., 2009). Interestingly, Hariri et al. (2006) found that the interindividual variability of the delay discount rate determined off-line in a behavioural task was correlated to activation of the ventral striatum in a guessing-reward task. Kable and Glimcher (2007) recently showed how individual subjective value of delayed gains was reflected by the activity of reward related brain areas (ventral striatum, medial prefrontal cortex and posterior cingulate cortex). Peters and Buchel (2009) contrasted delay and probabilistic discounting conditions in a recent fMRI study. In their study delayed and probabilistic rewards were discounted behaviourally in a hyperbolic manner with discount rates varying greatly between participants. Functional imaging data suggested that ventral striatum and orbitofrontal cortex are involved in coding of subjective value irrespective of whether rewards were delayed or probabilistic. Fronto-polar, lateral parietal and posterior cingulate cortex only correlated with the value of delayed rewards, whereas other regions were driven by the value of probabilistic rewards. This led the authors to propose that coding of subjective value in the human brain is based on the combination of domain-general and domain-specific valuation networks.

Building on these previous results, we examined the neural correlates of interindividual differences in delay discounting focusing on choices at or near the individual indifference point. Each individual's delay discounting parameter k can be determined from their choices (see Fig. 1). From an individual's k we can deduce for which decisions this particular person will be indifferent (e.g., an individual k-value of 0.06 implies indifference for the choice: "What do you prefer, 55$ today or 75$ in 61 days?").

Previous work has shown that "difficult" decisions in delay discounting tasks lead to an engagement of the medial prefrontal cortex including the anterior cingulate cortex (McClure et al., 2004; Pine et al., 2009). What is a difficult decision and what is not, or, more precisely, which decisions lead to a conflict between the two possible options, should differ greatly between individuals as they also differ in the steepness of their discounting function. We therefore hypothesized that decisions at or near the individual indifference point, but not choices of either immediate or delayed rewards in trials far away from it, would engage the brain's conflict monitoring system located in the medial prefrontal cortex.

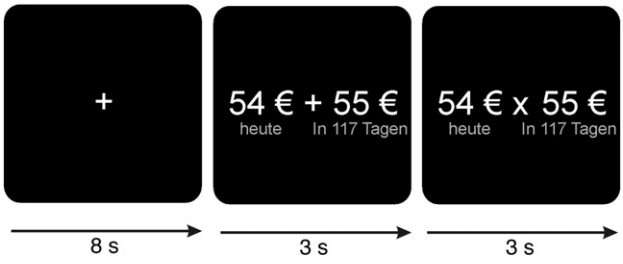

Fig. 1 – Experimental paradigm: First, a fixation '+' sign appeared in the screen. After 8 s, the two options were presented. After an additional 3 s the fixation turned to an 'x' and subjects had to decide between one of the two options.

2. Results

2.1. *Behavioural results*

The mean delay discount rate (k rank) was 5.3±1.2. Fig. 2A shows the distribution of discounting values of the different subjects. The consistency (percentage of participant's choices that were consistent with their assigned discount rate) was

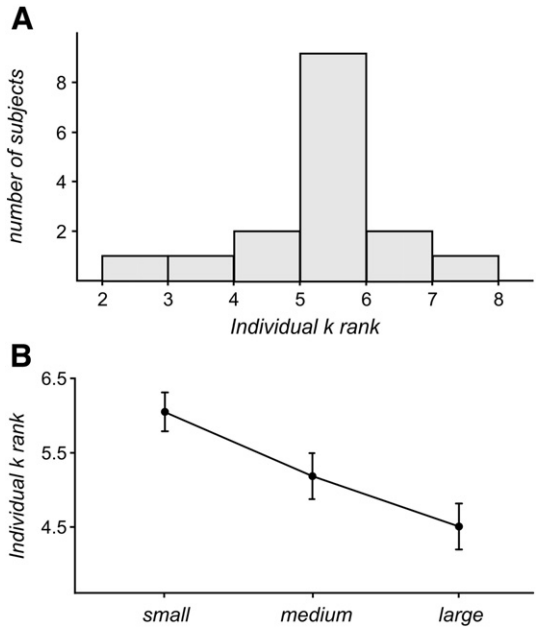

Fig. 2 – A. Histogram of the individual delay discount rates based on participants' responses. B. Delay discount rate according to magnitude of reward. Error bars indicate the standard error of the mean.