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The role of the neural reward circuitry in self-referential optimistic belief updates

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A B S T R A C T

People are motivated to adopt the most favorable beliefs about their future because positive beliefs are experienced as rewarding. However, it is so far inconclusive whether brain regions known to represent reward values are involved in the generation of optimistically biased belief updates. To address this question, we investigated neural correlates of belief updates that result in relatively better future outlooks, and therefore imply a positive subjective value of the judgment outcome. Participants estimated the probability of experiencing different *adverse* future events. After being provided with population base rates of these events, they had the opportunity to update their initial estimates. Participants made judgments concerning *themselves* or a similar *other*, and were confronted with *desirable* or *undesirable* base rates (i.e., lower or higher than their initial estimates).

Belief updates were smaller following undesirable than desirable information, and this optimism bias was stronger for judgments regarding oneself than others. During updating, the positive value of *self-related updates* was reflected by neural activity in the subgenual ventromedial prefrontal cortex (vmPFC) that increased both with increasing sizes of favorable updates, and with decreasing sizes of unfavorable updates. During the processing of *self-related undesirable base rates*, increasing activity in a network including the dorsomedial PFC, hippocampus, thalamus and ventral striatum predicted decreasing update sizes.

Thus, key regions of the neural reward circuitry contributed to the generation of optimistically biased self-referential belief updates. While the vmPFC tracked subjective values of belief updates, a network including the ventral striatum was involved in neglecting information calling for unfavorable updates.

Introduction

Thinking about the future is part of a person's identity and supports action planning, decision-making and emotion regulation (Carver and Scheier, 2014; D'Argembeau et al., 2012, 2009). However, this highly influential prospective thinking does not provide us with the most realistic future outlook, but is instead prevalently optimistically biased. Cross-culturally and independent of gender and age, people tend to overestimate the likelihood of positive future outcomes, and to underestimate the likelihood of negative ones in various domains of daily life, including health-related issues, social relations, and professional success (Chowdhury et al., 2014; Leary, 2007; Sharot et al., 2012, 2011; Shepperd et al., 2002, 2013; Weinstein and Klein, 1996). The consequences of optimistically distorted judgments can be positive or negative: Overestimated chances of success may lead to positive feelings and an increase of effort with beneficial effects for the individual and its environment, but may also lead to miscalculations and failures.

It has been assumed that both motivational and cognitive factors contribute to the optimistic bias, and this reciprocal influence has also been more generally described as "motivated cognition" (Hughes and Zaki, 2015). Cognitive explanations focus on how people achieve desired end states of judgments, and refer to selective memory search and conclusions that are biased toward retrieving confirmatory information for rewarding beliefs (Shepperd et al., 2002). Motivational explanations, on the other hand, relate to the pleasure of having favorable beliefs regarding oneself and one's own future, and the resulting desire to adopt such optimistic beliefs (Shepperd et al., 2002). Accordingly, optimism bias has been described as "a motivation to adopt the most rewarding (or least aversive) perspective on future outcomes" (Sharot et al., 2011).

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However, a previous neuroimaging research on optimism bias reported solely the recruitment of brain regions related to complex cognitive processing, i.e., the inferior and dorsomedial prefrontal cortex (Sharot et al., 2011). Thus, there is still a lack of evidence for the motivational explanations, which would require a demonstration of recruitment of key structures of the neural reward circuit. While this complex network includes several cortical and subcortical regions, the most prominent structures involved in human value processing are the ventromedial prefrontal cortex (vmPFC) and the ventral striatum (vStr) (Bartra et al., 2013; Clithero and Rangel, 2014; Haber and Knutson, 2010; Kable and Glimcher, 2009; Peters and Buchel, 2010). The vmPFC, and particularly its subgenual part, has robustly been shown to play a critical role in representing the *positive* subjective value of rewards and emotional stimuli (Chase et al., 2015; Levy and Glimcher, 2012). While the vStr has traditionally been related to learning from errors in reward prediction, more recent research supports an integrative view involving both learning and motivational functions (Bartra et al., 2013; Hamid et al., 2016). More specifically, dopaminergic signaling in vStr has been shown to represent values of estimated future rewards, which influence decisions whether to invest effort in actions aiming at these reward states (Hamid et al., 2016).

The aim of the present study was to demonstrate that favorable beliefs recruit the same brain regions known to be associated with external rewards, to support the view that they have internal positive subjective values able to guide judgment and decision processes. We employed a revised version of an fMRI belief update paradigm. The paradigm assesses how people update their initial beliefs about risks of experiencing hazards when they are provided with base rates for these hazards that result in estimation errors (i.e., the difference between the subject's first risk estimation and the presented base rates). It could be shown that updating was optimistically biased because it was larger after *desirable* new information (lower risk than initially expected) than after *undesirable* information (higher risk than initially expected) (Sharot et al., 2011). These results contradict formal learning principles as these predict balanced updating in response to errors, independent of the desirability of the new information.

The first revision was to extend the study design in order to differentiate between judgments referring to oneself and others. Second, in order to increase the experimental control and precision, we systematically manipulated the presented base rates, and included both the first and the second estimations (before and after the presentation of the base rate) in one single trial. And third, we modified the analyses to allow the identification of neural regions that track fluctuations of *updates* on a trial-by-trial level (in contrast to tracking *estimation errors* as in Sharot et al., 2011), because belief updates represent the end state of the judgment process and are expected to have a specific subjective value for judging persons.

We hypothesized that the vmPFC would reflect the differential subjective value of varying update sizes that result in better or worse future outlooks relative to participants' initial beliefs, particularly for self-referential judgments. The larger an update toward an unexpectedly *low* average risk, the better is the subject's adjusted future outlook. Thus, *increasing updates* after *favorable* new information are expected to have *increasing positive value* and to be accompanied by an increasing vmPFC activity. In contrast, the greater an update toward an unexpectedly *high* average risk, the worse is the updated subject's future outlook, so that *decreasing updates* in this condition are expected to result in an *increasing positive value* and increasing vmPFC activity.

Furthermore, we explored in which brain regions the activity during the reception of the new information (base rates) predicted subsequent updates. The belief reconstruction initiated at this point may encompass cognitive processes such as memory retrieval or inferences, but may also be modulated by the motivation to adopt the most favorable conclusions (Shepperd et al., 2002), particularly when these are self-relevant and unfavorable (Sharot et al., 2011). Finally, we explored the relationships between the optimism bias in belief updating and trait optimism.

Material and methods

Participants

A total of 36 right-handed individuals with no reported history of neurological or psychiatric illness were recruited online within the Research Center Juelich, Germany, and participated in the fMRI study. Twelve persons were excluded from the analyses. Five persons had excessive head movements (outliers were selected by total movement greater than 3 mm or scan-to-scan motion greater than 1.5 mm, as assessed by ArtRepair Software; Mazaika et al., 2005), probably due to a relatively tight head coil used in the study; the logfiles of one person were overwritten; one person suspected that the base rates were not correct; two persons had insufficient German language skills as they did not know the meaning of a high number of stimulus events (18 and 24 events). The remaining three persons had a mean positive estimation error of less than 7, because of the frequent low fist estimates (see S.1). Thus, data from 24 participants were included in the analyses (mean age = 25.13 years, SD = 3.89, ranging from 19 to 38; 13 females). All the participants were naïve with respect to the specific purpose of the study, gave written informed consent and were paid for their participation. The study was approved by the local ethics committee of the Medical Faculty of the University of Cologne, Germany.

Stimulus material

We used 88 short German descriptions of adverse life events as stimuli and included a wide range of events relating to different life domains (e.g., dementia, arthritis, unemployment, or pest infestation in the home; see Kuzmanovic et al., 2015 for the complete list). The assignment of the stimuli to the experimental conditions and the order of trials were randomized anew for each participant. Note that by applying a random assignment of the stimuli to the experimental conditions, event characteristics that have been suggested to modulate the optimism bias (e.g., base rate, event valence, arousal, controllability, personal experience) (Rose et al., 2008; Sharot et al., 2007; Weinstein, 1980, 1987), or general stimulus characteristics (e.g., number of words or letters) were equally distributed across the experimental conditions, and thus do not constitute confounding variables (see also Kuzmanovic et al., 2015).

Design and procedure

In each trial of the update experiment, the participants first had to estimate the probability that different adverse events would occur at least once in a lifetime. Next, they were presented with a corresponding base rate for the general population, and were then given the opportunity to adjust their initial estimate (see Fig. 1 for illustration and durations of events). The intervals within the trial (“jitter 4 s” in Fig. 1) and between the trials randomly varied, resulting in mean durations of 4000 ms and 6000 ms, respectively (within-trial durations varied between 2875 ms and 5125 ms, between-trial durations between 4875 ms and 7125 ms). The successive arrangement of i) the first estimation, ii) the presentation of the base rate and iii) the second estimation (including the display of the initial estimate) within one trial represent a substantial modification of the original paradigm (Sharot et al., 2011) and served the purpose of minimizing confounding memory effects.

The factors that were expected to affect the update behavior within the task were the target person of the judgment (self, other), the valence of the new information (positive, negative), and the participants' trait optimism scoring (high, low). In contrast to the original paradigm that included self-related judgments only (Sharot et al.,