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Motivational effects on the processing of delayed intentions in the anterior prefrontal cortex

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ABSTRACT

Delaying intentions bears the risk of interference from distracting activities during the delay interval. Motivation can increase intention retrieval success but little is known about the underlying brain mechanisms. Here, we investigated whether motivational incentives (monetary reward) modulate the processing of delayed intentions in the anterior prefrontal cortex (aPFC), known to be crucial for intention processing. Using a mixed blocked and event-related functional Magnetic Resonance Imaging design, we specifically tested whether reward affects intention processing in the aPFC in a transient or in a sustained manner and whether this is related to individual differences in retrieval success.

We found a generalized effect of reward on both correct intention retrieval and ongoing task performance. Fronto-parietal regions including bilateral lateral aPFC showed sustained activity increases in rewarded compared to non-rewarded blocks as well as transient reward-related activity during the storage phase. Additionally, individual differences in reward-related performance benefits were related to the degree of transient signal increases in right lateral aPFC, specifically during intention encoding.

This suggests that the ability to integrate motivational relevance into the encoding of future intentions is crucial for successful intention retrieval in addition to general increases in processing effort. Bilateral aPFC is central to these motivation-cognition interactions.

Introduction

A common demand we have to meet in our everyday life is to hold a formed intention in mind, which cannot be performed immediately due to ongoing activities. At a future point in time, these stored intentions need to be remembered, when the circumstances permit or require to complete the intended action. This kind of memory for activities to be executed in the future (delayed intentions) is also referred to as prospective memory (Brandimonte et al., 1996; Meacham and Dumitru, 1976). Importantly, the retrieval of intentions and hence the achievement of the corresponding goals decisively relies on the degree to which an individual is motivated as has been shown in behavioral prospective memory studies (Brandimonte et al., 2010; Cook et al., 2015; Einstein et al., 2005; Kliegel et al., 2004; Meacham and Singer, 1977; Walter and Meier, 2014). Consequently, combining intentions with motivational significance enables individuals to create and realize plans based on their priorities and thus is essential for shaping the not so distant future (Penningroth and Scott, 2007).

The behavioral effects of motivation on intention retrieval increasingly attract attention (Penningroth and Scott, 2013; Walter and Meier, 2014), but little is known about the underlying brain mechanisms (but see Rea et al., 2011). Two major streams of research investigated the neurocognitive implementation of intention processing in general. On the one hand, research on volitional selection of intentions and the representation of their content indicates a crucial role of the dorsomedial prefrontal cortex for the processing of self-generated intentions (Brass

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et al., 2013; Brass and Haggard, 2007; Haynes et al., 2007; Momennejad and Haynes, 2013). On the other hand, prospective memory research consistently showed a crucial role of the lateral anterior prefrontal cortex (aPFC; Brodmann area [BA] 10) for the processing of instructed intentions to be retrieved based on a specific event or point in time (Burgess et al., 2001, 2011; Okuda et al., 1998). This lateral aPFC involvement has been further specified as being related to strategic monitoring for intention-relevant target events (Beck et al., 2014; McDaniel et al., 2013; Reynolds et al., 2009), processes related to the storage of the intention (Gilbert, 2011) and the establishment of an intention retrieval mode (Guynn, 2003). The study by Gilbert (2011) is of particular interest for the investigation of motivational modulations, as it is one of the rare studies using an event-related functional Magnetic Resonance Imaging (fMRI) paradigm to separate different phases of processing delayed intentions: (1) encoding of the intention into memory, (2) storage of the intention during a delay with an interfering ongoing task and (3) self-initiated retrieval of the intention based on a pre-defined event. The study showed that it is particularly the storage of intentions, which is selectively related to enhanced lateral aPFC activity compared to pure ongoing task performance. The novel options given by the Gilbert paradigm inspired the design of the present study, aiming at locating motivational effects on successful intention retrieval with regard to the different processing phases.

With respect to motivation-cognition interactions, recent evidence suggests that rewards strongly affect neurocognitive processing in various domains of cognition (Charron and Koechlin, 2010; Jimura et al., 2010; Krawczyk et al., 2007; Paschke et al., 2015; Soutschek et al., 2015; Wittmann et al., 2005). The available data widely support the view that reward enhances top-down processing in cognitive tasks, thereby recruiting control-related regions in the medial and lateral prefrontal cortex (PFC) as well as further task- and stimulus-related regions (Pessoa and Engelmann, 2010). Importantly, there is evidence that reward effects can be implemented via two different processing modes (Braver, 2012; Engelmann et al., 2009; Jimura et al., 2010). In a *sustained mode,* reward-related controlled processing is enhanced independent of the concrete occurrence of stimuli requiring controlled processing throughout a task block, indicating that proactive control mechanisms might be in play. In contrast, *transient* reward-related increases related to specific processing requirements of single stimuli provide a temporary, reactive mechanism to enhance specific information processing steps depending on the prospect of a reward. Hence, control mechanisms might be recruited to a higher degree when a reward is provided depending on the actual requirements at hand. In the case of intention processing, rewards might enhance the degree of goal relatedness assigned to the respective intentions (Penningroth and Scott, 2007). This, in turn can be assumed to enhance processing in brain regions associated with intention processing. Anterior regions of the lateral PFC have been repeatedly found to show a reward-related sustained activity increase in cognitive control tasks (Braver et al., 2003; Jimura et al., 2010; Locke and Braver, 2008). With respect to transient effects, the neuroanatomical location of reward effects seems to be more dependent on the specific task demands. For example, working memory studies showed effects of reward in stimulus-related regions specifically during the encoding of the stimuli (Krawczyk et al., 2007). Also, long-term memory studies using the subsequent-memory paradigm showed the crucial role of a reward-related modulation during encoding for later retrieval (Adcock et al., 2006; Wittmann et al., 2005), indicating that hippocampal and midbrain activity during the encoding of rewarded stimuli can predict retrieval success. Furthermore, transient activity increases related to interference processing in cognitive control tasks has been shown to be modulated by reward in stimulus-related regions but also in task-related regions in the left posterior lateral frontal cortex (Padmala and Pessoa, 2011; Paschke et al., 2015; Soutschek et al., 2015).

For intention processing, it is unclear whether motivation enhances intention retrieval via sustained processing increases in task-related regions in the lateral aPFC and/or by modulating intention processing in a transient manner by selectively enhancing specific processing phases, that is, the encoding, storage or retrieval of an intention. Here, we used fMRI to address this question, focusing on the association of reward-related processing increases in task-related regions with actual behavioral improvements in retrieving intentions depending on the expectation of a monetary reward. We expected reward to be associated with a sustained increase of activity in lateral aPFC regions. Additionally, based on the outlined working memory and long-term memory research, we expected that reward-related intention retrieval success would depend on transient activity changes in task-relevant regions in the lateral aPFC during the encoding of rewarded intentions.

To investigate this, we created a new version of the paradigm used in the study by Gilbert (2011), including a motivational manipulation by providing monetary incentives for correct intention retrievals in half of the blocks in a mixed blocked and event-related fMRI design. On a behavioral level, we hypothesized that increased motivation based on rewards would increase intention retrieval performance. Concerning the fMRI data, the current design enabled us to investigate not only (i) whether intention-related regions in the aPFC are affected by motivation in a sustained manner, but also (ii) whether transient reward-related modulations in the aPFC are present at specific processing stages (encoding, storage or retrieval) and finally (iii) whether sustained and/or transient motivational effects are related to behavioral improvements.

Materials and methods

Participants

A total of 24 healthy right-handed volunteers with no history of neurological or psychiatric disorders took part in this study. The datasets of two participants were excluded from the analysis due to scanner artifacts and an incidental finding of brain abnormalities, resulting in a final sample of 22 participants (12 female, mean age = 26.8 years, standard deviation = 3.7 years, range = 22–34 years). All participants were native German speakers with normal or corrected-to-normal vision. The experiment was approved by the Ethics Committee of the Department of Psychology, Humboldt University Berlin and participants provided written informed consent before taking part according to the Declaration of Helsinki. They received 10 Euro/hour and additionally performance-dependent monetary reward.

Experimental design

A new variant of the paradigm introduced by Gilbert (2011) was developed as a mixed blocked and event-related design (Fig. 1A and B). A trial consisted of a sequence of five to eight words. Participants performed an ongoing one-back task throughout the experiment, indicating on each stimulus whether a currently shown word matched the word presented as previous stimulus by pressing a left (for one-back non--targets) or right button (for one-back targets) with the index and middle fingers of their right hand, respectively. Note that we applied a one-back task instead of the two-back task used in Gilbert's study due to high error rates (ERs) observed during a two-back version in a pilot study conducted in our laboratory. The intention task was embedded within this one-back task. While stimuli in the ongoing task were surrounded by a grey frame, a green colored frame defined a word to be encoded as the target of the delayed intention ('intention encoding'). These intention-encoding stimuli were also part of the one-back task, but always one-back non-targets, so that participants had to press the non-target button with their right index finger. The delayed intention instruction was to press a third button with the right ring finger as soon as the word originally presented in the green frame was presented again in a grey frame in the stream of words ('intention retrieval'). Accordingly, they were then required to interrupt their ongoing performance of the one-back task in order to respond to the intention target word. Note that delayed intention target words were presented in a grey frame on their second appearance just