



Theta power as a marker for cognitive interference

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HIGHLIGHTS

- Increased theta activity in different types of cognitive conflict.
- Dynamic changes in theta activity accompany conflict resolution processes.
- Theta at different medial frontal cortex sites subserves performance monitoring.

ABSTRACT

Objective: The present study aimed at investigating whether theta activity within medio-frontal cortex (MFC) serves as a marker for increased cognitive control demands such as performance monitoring.

Methods: We confronted participants with at least two incompatible sources of information in a Simon task, a flanker task, and a NoGo task to assess whether changes in EEG theta activity correspond to executive control demands across different sources of cognitive interference.

Results: Overall, increases of theta power were to a different extent observed in all interference situations: (1) differences in theta power were largest between successful response inhibition in NoGo events compared to Go responses, (2) incongruent and congruent events in the flanker task differed to a lesser extent, and (3) differences in theta power were smallest comparing incompatible and compatible Simon events. Scalp-topographies and dipole modeling of theta activity pointed to different sources across interference conditions that encompassed various MFC areas within anterior cingulate cortex and (pre-) supplementary motor areas.

Conclusions: Our results indicate that theta power amplitude is sensitive to the recruitment of executive control in interference situations, whereas the MFC sources of theta power varied across different interference situations.

Significance: This study shows for the first time theta power enhancement related to the recruitment of cognitive control across different types of conflicts in the stream of information processing.

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1. Introduction

Executive control processes enable us to adapt our behavior according to environmental requirements. High demands on cognitive control are exerted to achieve monitoring for potential sources of risk when distracting information impedes goal directed behavior. The involvement of the medial frontal cortex (MFC) in conflict detection, performance monitoring, outcome evaluation and error commission has been widely investigated (Ridderinkhof et al., 2004a,b; Carter et al., 1998; Botvinick et al., 2004; Yeung et al., 2004b; Rushworth et al., 2004; Holroyd and Coles, 2002) and results in the postulation that the anterior cingulate cortex

(ACC) serves conflict control by monitoring (and detecting) all types of cognitive interference in the stream of information processing (Botvinick et al., 2004).

Classic interference paradigms are often employed to experimentally test how brain activity is changed by conflicts in perceptual processing or response preparation. The Simon paradigm requires spatial choice responses on the basis of a non-spatial stimulus feature. Although stimulus location is task-irrelevant responses are faster and less error-prone when stimulus and response location correspond than when they do not (Simon, 1969; see Simon, 1990, for overview), because the irrelevant location of the stimulus already primes the response location (Kornblum et al., 1990; Stürmer et al., 2002). In the flanker task (Eriksen and Eriksen, 1974) participants perform manual choice responses to a target stimulus that is compassed by stimuli that function as target stimuli in other trials of the task. On the one hand interference in this task is provoked between stimulus

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features of target and flanker stimuli. On the other hand, response conflicts are provoked in case target and flankers are mapped onto different responses. The flanker paradigm and the Simon paradigm are similar with respect to the requirement to inhibit primed but incorrect response activations. There are, however, substantial differences between both tasks, too. In the flanker task task-irrelevant and task-relevant stimulus features overlap whereas in the Simon task there is no overlap between the task-irrelevant stimulus location and task-relevant stimulus features. This difference might be crucial regarding the question at which processing stages interference is elicited and resolved. If only one mechanism would control several processing stages cognitive control should transfer between different types of conflict. According to the conflict monitoring account MFC activity occurs in case of competing response tendencies irrespective of its origin (Botvinick et al., 2004; Yeung et al., 2004a). Others suggest that conflicts at perceptual and response-related processing stages do not involve the same neuronal correlates (van Veen et al., 2001; van Veen and Carter, 2002). Such findings are in favor of multiple domain specific conflict-driven control mechanisms which can be activated separately depending on the processing demands of the task (Egner, 2008). A crucial question is, therefore, whether all types of cognitive interference share a common mechanism relating different substrates that show conflict monitoring related activation in function.

Apart from brain imaging techniques cognitive interference is studied by the help of event-related brain potentials (ERP). Prominent ERP components observed in interference tasks are negative-going potentials with a fronto-medial scalp distribution that are enlarged in interference situations requiring more cognitive control. One important ERP component in this domain is the so-called conflict-related N2, a negative difference potential at fronto-central electrode sites arising around 250–350 ms following stimulus onset which has consistently been observed in NoGo trials (Nieuwenhuis et al., 2003), incongruent trials in the Eriksen flanker task (Kopp et al., 1996; Heil et al., 2000) and in the Simon task (Leuthold, 2004).

Another fronto-centrally distributed negative ERP component generated in the MFC is the so-called error-related negativity (ERN; see for an overview Falkenstein et al. (2000)) that is consistently observed in error commission. The ERN shows up 60–100 ms after an erroneous response and is supposed to reflect response-locked error processing (Gehring et al., 1993).

It is argued that the conflict-related N2 and the ERN reflect the same process, hence, the ERN is just another case of conflict monitoring (Yeung et al., 2004b; for a different view see Masaki et al. (2007), Masaki and Segalowitz (2004), Carbonnell and Falkenstein (2006), and Burle et al. (2005, 2008)). In a recent review Folstein and van Petten (2008) pointed out that fronto-medial distributed ERP negativities should be subdivided into two subcomponents. One component is related to the detection of novelty or mismatch from a perceptual template when the eliciting stimuli are attended whereas a second component is related to cognitive control encompassing response inhibition, response conflict, and error monitoring.

This conflict-related N2 spans a wide time range and covers different components related to interference processing; that are the N2 in NoGo trials, the conflict N2 in incongruent flanker trials (which has been labeled N2c by several authors; Kopp et al., 1996), the N450 observed in Stroop tasks (West and Alain, 1999), as well as the ERN, and the feedback-related negativity. Especially the interpretations of N2 effects in NoGo paradigms have been difficult since overlapping movement-related potentials are a confounding variable in the comparison between Go and NoGo ERPs (Bruin and Wijers, 2002). Because the conflict-related N2 shows up in such a large variety of interference situations the question is raised whether this component reflects a single process or a mix-

ture of different processes located in the MFC and adjacent regions (Ullsperger and von Cramon, 2001; Falkenstein, 2006).

In addition to ERPs the analysis of EEG dynamics using spectral decomposition techniques is a useful tool to isolate specific components by their time–frequency characteristics. It was hypothesized that power changes in specific frequency bands indicate an increased firing rate and/or synchronization within cell populations reflecting in turn changes in cognitive processing (Klimesch, 1999; Makeig et al., 2004; Buzsaki, 2006; Basar, 1999).

The theta band (defined between 4 and 7 Hz in most studies) has been acknowledged for a wide span of cognitive functions such as focused attention (Ishii et al., 1999), encoding new information (Klimesch, 1999), increased memory-load (Jensen and Tesche, 2002), response-control via a distributed network (Basar et al., 2001). An inverse relationship between increased theta activity and decreased default mode network activity (Scheeringa et al., 2008) might account for higher theta power during attention-demanding tasks when the default mode pauses. Such an account for higher theta power would also apply to other top-down mechanisms that reduce default mode network activity. Furthermore, a pivotal role of theta phase characteristics is proposed for the integration of information coded in higher frequencies, such as nested gamma oscillations (Schack et al., 2002; Jensen, 2005; Jensen and Colgin, 2007; Canolty et al., 2006). Theta band activity is majorly generated in structures of the limbic system such as the hippocampus and the cingulate cortex but generators are also found in the prefrontal cortex (Miller, 1991; Raghavachari et al., 2006). Recently, time–frequency analyses have suggested that the theta band amplitude mirrors enhanced demands in cognitive control and performance monitoring (Luu et al., 2004; Trujillo and Allen, 2007; Cavanagh et al., 2009). Moreover, phase characteristics of theta related to the ERN can distinguish between differences in performance monitoring (Yordanova et al., 2004). Hanslmayr et al. (2008) found increased theta power in the ACC and sustained phase coupling with the lateral PFC during interference trials in a Stroop task. They assume that this finding reflects the engagement of higher-order control processes to resolve response conflict.

Cavanagh et al. (2009) analyzed the power and phase characteristics within the theta band during error commission and reported increased theta power at fronto-central electrode sites. Additionally, they showed enhanced theta phase synchrony between MFC and lateral prefrontal cortices that could predict behavioral adaptation in the upcoming trial. Data from intracranial recordings in a flanker task showed that oscillations in the theta range can be linked to scalp-ERP variance (Cohen et al., 2008). Here, the observed band-specific functional engagement of medial frontal subdivisions depended on the processing stage. Whereas dorsal regions exhibited pre-response beta suppression and little post-response theta enhancement, rostral regions exhibited post-response theta enhancement and little pre-response beta suppression. The authors, therefore, suggested that dorsal portions of the medial frontal cortex are functionally related to signaling or resolving pre-response conflict whereas rostral activity reflects post-response monitoring functions and might also signal the need for adjustments in upcoming trials to other structures.

Theta power changes related to performance monitoring have also been reported in NoGo paradigms (Yamanaka and Yamamoto, 2010), task switching paradigms (Sauseng et al., 2006), goal conflicts (Moore et al., 2006), and rule violation (Tzur and Berger, 2007). Furthermore, theta is related to attentional processes during memory encoding as well as maintenance and plays an integrative role in working memory, i.e., when cognitive control is needed to suppress task-irrelevant information (Klimesch, 1999; Jensen and Tesche, 2002; Raghavachari et al., 2001). Taken together these findings suggest that theta power increases are present during various control demanding situations and a network of brain areas related

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