



## Theta frontoparietal connectivity associated with proactive and reactive cognitive control processes



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### ARTICLE INFO

#### Article history:

Accepted 10 December 2014

Available online 18 December 2014

#### Keywords:

Cognitive control

Coherence

Functional connectivity

Task switching

### ABSTRACT

Cognitive control involves both proactive and reactive processes. Paradigms that rely on reactive control have shown that frontoparietal oscillatory synchronization in the theta frequency band is associated with interference control. This study examines whether proactive control is also associated with connectivity in the same frontoparietal theta network or involves a distinct neural signature. A task-switching paradigm was used to differentiate between proactive and reactive control processes, involved in preparing to switch or repeat a task and resolving post-target interference, respectively. We confirm that reactive control is associated with frontoparietal theta connectivity. Importantly, we show that proactive control is also associated with theta band oscillatory synchronization but in a different frontoparietal network. These findings support the existence of distinct proactive and reactive cognitive control processes that activate different theta frontoparietal oscillatory networks.

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### Introduction

Cognitive control processes enable flexible adjustment of intentions and actions in order to guide goal-directed behavior. Imaging studies have shown that the implementation of these control processes relies on an extensive frontoparietal network (Corbetta and Shulman, 2002; Seeley et al., 2007; Vincent et al., 2008) that is well-suited to promoting flexible and rapid information propagation (Dosenbach et al., 2008). One mechanism by which information can be flexibly adjusted and rerouted in the frontoparietal network is oscillatory synchronization of electrical activity (Fries, 2005; Womelsdorf and Fries, 2006). Oscillatory synchronization allows neuronal assemblies to exchange information transiently by synchronizing or rhythmically oscillating their firing rate. This process both promotes efficient exchange of information within that assembly and protects against competing inputs from neighboring assemblies (Azouz and Gray, 2003; Engel et al., 2001).

Cognitive control and related top-down processes have often been linked to oscillatory synchronization in the slow wave, theta (4–7 Hz) frequency band. For example, top-down maintenance and manipulation of items in working memory is typically accompanied by synchronized theta activity (e.g. Klimesch et al., 2006; Jacobs et al., 2006; Jensen and Tesche, 2002; Onton et al., 2005; Raghavachari et al., 2006), and

successful encoding and recollection of items are linked to current theta wave phases (Rizzuto et al., 2006). Increased need for allocation of mental resources is also associated with greater interregional theta synchronization or coherence, particularly between distributed frontal and parietal sites (Mizuhara and Yamaguchi, 2007; Sauseng et al., 2005, 2006). Furthermore, increased theta synchronization has been associated with conflict-related processes, such as error detection and post-error correction (Cavanagh et al., 2009; Luu et al., 2004; Trujillo and Allen, 2007), goal conflict and response selection (Moore et al., 2006, 2012). This evidence supports a unique role of theta oscillations in gating neural assemblies in order to promote integration of information and enable goal-directed control processes (see Sauseng et al., 2010). Thus, low frequency EEG oscillations appear to be intimately tied to key cognitive control processes (e.g., information prioritization and transfer) that promote widespread integration across cortical regions.

Models of cognitive control differentiate between distinct modes of control. For instance, Braver (2012) differentiates between reactive control processes, that are required to resolve conflict and overcome interference, and proactive control processes, that are involved in pre-setting or preparing the system to be sensitive to future goal-relevant features of the environment. Reactive control is seen in moment-to-moment adjustment of neural activity. For example, in event-related potentials (ERPs), reactive control may be linked to adjustment of processing to deal with target-level conflict (e.g., the N2 component linked to conflict control, Folstein and Van Petten, 2008) or response feedback (e.g., the

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post-error negativity associated with response feedback, Gehring et al., 1993). Proactive or preparatory control is typically assumed to promote sustained attention towards upcoming goals, as indicated by sustained prefrontal activity in fMRI (Braver et al., 2009; Marklund and Persson, 2012), and pre-stimulus activity in ERPs (Bekker et al., 2004; Bickel et al., 2012). However, proactive control processes can also be transiently adjusted when using cues to selectively prepare in anticipation of target onset (Karayanidis et al., 2009; Mansfield et al., 2011). Despite converging evidence for a key role of theta oscillations in cognitive control (Cavanagh and Frank, 2014), the role of theta synchronization in proactive control has received little attention.

Task-switching paradigms that differentiate between proactive and reactive control processes can be used to define the nature of theta oscillations during cognitive control. In cued-trial paradigms, the cue provides valid information regarding the upcoming goal (e.g., to repeat or switch tasks). This allows temporal differentiation between proactive control processes activated during the cue–target interval (e.g., preparing to switch or repeat task) and reactive control processes activated after target onset (e.g., goal implementation and interference control). In cue-locked ERPs, proactive control processes are represented in an early, transient, positive component for *switch* vs. *repeat* cues (typically between 200 and 400 ms post-cue; e.g. Karayanidis et al., 2003; 2009; Miniussi et al., 2005; Nicholson et al., 2005; Periañez and Barceló, 2009) and a later, sustained negativity peaking prior to target onset (Aste et al., 2008; Karayanidis et al., 2009; Mueller et al., 2007). In addition, when the cue identifies the task to be performed, the early switch-positivity is followed by a second sustained switch-positivity and the pre-target negativity varies as a function of task information (e.g., Karayanidis et al., 2009). In target-locked ERPs, reactive control processes are represented in modulation of the N2 and P3 as a function of differential carry-over and target-driven interference for switch and repeat trials (e.g., Karayanidis et al., 2003; Nicholson et al., 2005; see for review Karayanidis et al., 2010 and Karayanidis and Jamadar, 2014).

The timing of ERP components linked to proactive and reactive control processes in task-switching may inform time windows where oscillatory networks would be expected to exhibit proactive and reactive control activity. Despite the utility of the task-switching paradigm, there are few studies examining the role of oscillatory activity during task-switching (Gladwin et al., 2006; Mansfield et al., 2012; Sauseng et al., 2006). For example, using a task-switching paradigm that did not differentiate between proactive and reactive control processes, Sauseng et al. (2006) reported that switching tasks was associated with a reduction in upper alpha (10–13 Hz) power as well as a large increase in theta, but not alpha, coherence across fronto-posterior networks. This is consistent with findings from other paradigms that rely primarily on reactive control processes. In a cued-Wisconsin Card Sorting task, cues associated with a rule switch led to sustained theta band activity across frontal and parietal sites, as well as a decrease in centro-parietal alpha band power (Cunillera et al., 2012). However, using a cued-trial paradigm, Mansfield et al., (2012) found differences in low-mid frequency oscillations between switch and repeat cues, relative to a non-informative cue baseline, over right frontal and bilateral parietal sites in time windows corresponding the early switch-positivity and pre-target negativity, respectively. In sum, these studies suggest a role for low frequency oscillations in task-switching, with differentiable effects at timelines consistent with proactive and reactive control.

The present study examines the role of theta band oscillations under proactive and reactive control conditions using a cued-trial task-switching paradigm. If proactive and reactive control processes both rely on theta synchronization, switch-related frontoparietal theta oscillation networks will be evident both in the cue–target interval, i.e., when preparing to switch or repeat tasks, and after target onset, i.e., when controlling interference. Given neuroimaging evidence that preparation to switch and implementation of a switch response involve distinct networks (for review see Ruge et al., 2013), theta oscillatory

synchronization for proactive and reactive control may be expected to involve distinct networks. Additionally, as previous work with this paradigm has shown increased alpha power when preparing to switch (Mansfield et al., 2012; see also Sauseng et al., 2006), we examine whether alpha oscillatory networks are also evident during switch preparation and/or implementation.

## Methods

### Participants

Twenty nine adults with no current neurological or psychiatric disorder (13 males, mean age  $25.69 \pm 5.64$  years, 27 right-handed) gave written, informed consent and were reimbursed \$20/h for participating in this study. Participants were asked to abstain from caffeine and alcohol at least 2 h prior to testing. The current protocol complies with the Declaration of Helsinki and was approved by the University of Newcastle Human Research Ethics Committee (HREC: H-2012-0157).

### Task and stimuli

Participants viewed a circle (5° of visual angle) divided into six wedges with pairs of adjacent wedges grouped by thicker lines demarcating three task sections: digit, letter, and color (see Fig. 1A; see Karayanidis et al., 2009). The target was a pair of characters consisting of combinations of a letter, a digit or a non-alphanumeric symbol and was presented either in gray or in color. Each target (e.g., gray A4) consisted of three dimensions: one relevant to the currently cued task (e.g., the letter A mapped to left hand response), one selected randomly from one of the two alternative tasks and incongruently mapped with the relevant task (e.g., the digit 4 mapped to right hand response) and one that was neutral (e.g., letter and digit presented in gray that was not mapped to any response). The target remained on the screen until a response was emitted or for 5000 ms. The same target could not appear on successive trials.

Each trial consisted of a cue–target sequence. Four cue types were defined by cue location and presented with equal probability in a pseudo-random sequence so that the same cue type was not repeated on more than four consecutive trials (Fig. 1B). The target always appeared in one of the two adjacent segments highlighted by the cue. *Repeat* cues highlighted the two segments associated with the task that was completed on the preceding trial, indicating that the same task would be repeated. *Switch-to* cues highlighted segments associated with one of the tasks not completed on the previous trial, both indicating that the task would change and identifying the new task. *Switch-away* cues highlighted one segment associated with each of the tasks not completed on the previous trial, indicating that the task would change, but not specifying which of the other two tasks would be relevant. Finally, *non-informative* cues highlighted one segment associated with the task completed on the preceding trial and another adjacent segment associated with one of the other two tasks, indicating that a switch or a repeat trial was equally likely. For both *switch-away* and *non-informative* cues, only the location of the target defined which task would be performed. *Non-informative* cues resulted equiprobably in a switch or a repeat trial. Thus, trials differed in whether the cues afforded the opportunity for proactive control and in the need for reactive control. Specifically, *switch-to* and *switch-away* cues validly predicted a task change, allowing participants to disengage the previously relevant task set. *Switch-to* cues also specified the relevant task, allowing uploading of the new task rules before target onset. In contrast, *non-informative* cues allowed no preparation, and like *switch-away* cues required task uploading after target onset. Participants used their left and right index fingers to respond and the hand assigned to each response was counterbalanced across participants. Participants were instructed to respond as quickly and as accurately as possible. Incorrect responses were followed by an auditory feedback tone. At the end of

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