**Introduction**

The ability to flexibly route information from sensory inputs to motor responses is key to the adaptability of human cognition. Consider, for illustrative purposes, a typical experimental condition in a task switching paradigm: on two successive trials a participant is presented with an alphanumeric target (e.g. ‘A4’) and needs to respond with a button press. The participant is instructed to either classify the letter (vowel/consonant) or the number (odd/even). On the first trial, the participant is required to classify the letter in the target, does so and responds with a left button press. On the second trial they need to classify the number in the target and respond with a right button push. In both trials the same stimuli is presented but there is clearly a need to route this identical information in different ways to perform the correct motor response. By employing cognitive control over the way information is routed, this can be achieved. The use of this control is complex: there is a need to inhibit processing irrelevant information (e.g. the number during the letter trial), shift between tasks, maintain the goals of the current task (e.g. classify the letter) and select and generate an appropriate response (e.g. press left button; Miyake et al., 2000). Cognitive control also has two distinct modus operandi: an anticipatory, proactive control mode utilised to prepare for an upcoming need to reroute information (i.e. prepare to classify the letter, ignore the number) and a reactive mode engaged to deal with information rerouting on a ‘as-needed’ basis (Braver, 2012; Braver, Burgess & Gray, 2007). The complexity and different operating modes that occur are the result of a need to reroute information in lines with an internal motivation, or goal. Whilst there has been great progress in understanding the anatomical connections of the brain that permit such goal-based information processing, the underlying neural mechanisms that give arise to this key feature of human cognition have yet to be fully elucidated.

Cognitive control is known to rely on a distributed frontoparietal network. The prefrontal cortex (PFC) facilitates goals-directed behaviour through interference resolution, top-down control and maintaining task-relevant features (Miller & Cohen, 2001), with the lateral PFC involved in anticipatory control processes (e.g. preparing for upcoming events (Ansari & Derakshan, 2011), inhibition (Banich et al., 2000; Fales et al., 2008; Swann et al., 2012), maintenance and changing between task sets (Braver, Reynolds & Donaldson, 2003; Kondo et al., 2004; Jamadar et al., 2010; Milham et al., 2003; Remijnse et al., 2005)) and the medial PFC involved in conflict monitoring and motivation/strategy adjustments (Bogacz et al., 2010; Botvinick et al., 2001; Critchley et al., 2001; D’Cruz et al., 2011; Erickson et al., 2004; Haup et al., 2009; Sheth et al., 2012; Volz et al., 2004; Zentgraf et al., 2005). Alternatively, the posterior parietal cortex (PPC) facilitates attention to relevant or salient features of the environment (Corbetta & Shulman, 2002; Posner & Petersen, 1990) and the generation of action plans (Andersen & Cui, 2009; Konen et al., 2004; Pellijeffe et al., 2006). Together, the frontoparietal network provides the architecture for the motivation of control to be assessed, relevant features to be attended to and an appropriate response to be selected (Dosenbach et al., 2007). Importantly, while lesion studies show that disruption to specific regions of this network result in specific deficits in control processes (see Alvarez & Emory, 2006), the microstructural organisation of the white matter pathways that form the anatomical connections of this network is also an important mediator of cognitive control abilities in individuals (Gold et al., 2010; Madden et al., 2008; Perry et al., 2009). As information can only be routed through existing anatomical connections, individuals with anatomy that promotes efficient information propagation are more likely to have flexibility in their cognition.

One plausible mechanism by which information can be selectively routed within the frontoparietal network is neural synchronisation. If two distinct populations of neurons are oscillating together they share a predictable excitability window which can be used to transfer information (Fries, 2005). As the peaks of a rhythmic wave (e.g. sinusoid) occur predictably, a sending population of neurons can encode information to arrive at the receiving population during their shared phase-locked excitability window. Such a pattern of communication would lead to efficient information transfer which can be adapted based on current needs. Studies in both animals (Engel, König, Kreiter & Singer, 1991; Fries et al., 2001; Fries, Womelsdorf, Oosterveld & Desimone, 2008; Khayat et al., 2010) and humans (Kahlbrock, Butz, May & Schnitzler, 2012; Kim, Grabowecky, Paller, Muthu & Suzuki, 2006; Rihs, Michel & Thut, 2007; Sauseng et al., 2005; Siegel et al., 2008; Vidal et al., 2006; Womelsdorf & Fries, 2007) have shown that increased neural synchronisation between brain regions is functionally relevant for integrative cognitive processes. For example, Kim et al (2006) reported increased visual evoked potentials on contralateral parietal electrodes when presented a grating to one visual hemisphere, which increased in strength with increasing attentional demands to the stimuli. Further, with increasing voluntary attention there was an increase in the amount of phase coherence that occurred across these sites. In a similar line of work, Kahlbrock and colleagues showed that during a cued divided attention task there was reduced gamma band synchronisation in primary visual cortices compared to a visually selective attention task. Importantly, Kahlbrock et al. found that these synchronisation differences occurred prior to target onset, with a cue that predicted a selectively visual task resulting in the strongest early visual area synchronisation, weaker synchronisation for a divided cue and the weakest synchronisation for an auditory attention cue. Further, during working memory tasks, increased theta band coherence across the human scalp has been shown during encoding and retention periods (Jensen & Tesche, 2002; Raghavachari et al., 2001; Stam, van Cappelen van Walsum & Micheloyannis, 2002) and increased alpha during retention and correct recall stages (Jensen, Gelfand, Kounios & Lisman, 2002; Sauseng, Klimesch & Doppelmayr, 2005; Tuladhar et al., 2007). Similarly, increased synchronisation has been seen during decision making (Donner, Siegel, Fries & Engel, 2009), planning (van der Werf, Jensen, Fries & Medendorp, 2010) and problem solving (Jung-Beeman et al., 2004). The frequency band utilised during these synchronisation periods likely reflects the underlying speed at which these cognitive integrations occur (von Stein & Sarnthein, 2000) – for example, given the importance of vision in humans, selectively attending to relevant features of the environment needs to occur quickly, which a high frequency gamma synchronisation would permit. Alternatively, slower integrative processes like inhibition and memory are typically associated with slower frequencies like alpha and theta (Klimesch, Sauseng & Hanslmayr, 2007; Klimesch, Schack & Sauseng, 2005; Palva & Palva, 2007; Sauseng et al., 2010). In sum, integrative cognitive processes rely on broad anatomical networks consisting of specialised hubs. By providing a periodically initiated phase-locked communication method, such regions may, when required, communicate to facilitate information integration.

As cognitive control relies on flexibly routing information it may also rely on efficient neural synchronisation for communication. To date, however, there have been few studies examining the role of neural synchronisation during goal-based information processing. Those which have, typically use a task switching paradigm, whereby switching between tasks results in a need to reroute information flexibly based on current task demands or goals. With this in mind, Gladwin, Lindsen & de Jong (2006) found increased neural synchronisation between frontal and parietal electrodes in the post-response interval prior to an upcoming switch trial, lateralised with respect to the upcoming response hand. Sauseng et al (2006) also reported an increase in frontoparietal theta coherence during trials where participants switched tasks in contrast to repeating a task. Further, Gladwin and de Jong (2005) found increased theta power over occipital and parietal sites when switching and increased occipital alpha power when repeating tasks, though they did not report coherence values. Similarly, Mansfield, Karayanidis and Cohen (2012) reported an increase in alpha power prior to a repeat trial in addition to an earlier switch-specific alpha increase prior after a cue (occurring in a similar time frame as previously seen switch-specific event-related electrophysiological features, Karayanidis et al., 2009; Nicholson et al., 2006) .

Unfortunately, given the inconsistencies in task structures and neural activity measures, clear insight into the particular role of neural synchronisation on cognitive control is difficult to establish. Clearly, switching between tasks, which requires rerouting of information, appears to rely on at least alpha and theta activity. However, whether this activity is related to oscillatory communication cannot be determined using simple power analyses (Gladwin & de Jong, 2005; Mansfield et al., 2012). While Gladwin et al (2006) and Sauseng et al (2006) both suggest that neural synchronisation is relevant for switching, Gladwin and colleagues used a response to target interval to suggest it was preparation for switching that relied to on synchronisation whereas Sauseng et al reported synchronisation during a switch trial. Without a cue, it is difficult to establish whether purely anticipatory switch-related processes are occurring during the response to target interval and as Gladwin et al used a variable response to target interval it is very likely that such anticipatory processes also reflected task carryover effects (de Baerne et al., 2011). Likewise, the increased theta synchronisation during switch trials reported by Sauseng et al probably involved additional target processing as the target carried the identity of the task that was additional to switch-specific processes. In both instances, switch trials were likely more difficult as they involved additional processes that cannot be disentangled and so whether increasing cognitive control demands per se or specifically proactive or reactive control require neural synchronisation has yet to be elucidated. As other integrative cognitive processes rely on neural synchronisation, it is plausible that cognitive control over the routing of information also requires neural synchronisation to facilitate communication.

The current study aims to further elucidate the relative role of neural synchronisation to facilitate flexible integration and routing of information during a cognitive control task. Specifically, we will systematically investigate how neural synchronisation in both theta and alpha frequencies are associated with proactive and reactive control processes. To do so, we will utilise a cued-trials task switching paradigm which allows examination of both anticipatory and target-driven processes that correspond with proactive and reactive control. Here we present evidence from two separate studies where we manipulate the relative importance of proactive, preparatory processes to highlight the specific functions of theta and alpha synchronisation in control.

In study one, we had participants perform a cued-task switching paradigm used previously (Karayanidis et al., 2009; Mansfield et al., 2012; Mansfield et al., 2011) and investigated the role of theta and alpha synchronisation during the cue to target interval. As anticipatory switch processes can occur given a sufficient cue to target interval we expected to see both theta and alpha synchronisation during the cue to target interval. Specifically, if theta synchronisation between frontal and parietal sites is indicative of increased involvement of proactive cognitive control, tasks which require increased flexible routing of information should be associated with increased theta synchrony. In particular, we expect switch trials to be associated with stronger frontoparietal theta synchronisation than repeat trials. Although, Sauseng showed increased frontoparietal theta synchronisation during switch trials, it is likely that if participants had sufficient time to prepare for a switch, this synchronisation may have occurred prior to target onset. Gladwin et al (2006)’s findings may have partially captured this during their response to target intervals. If theta is associated with anticipatory control processes, we should also see stronger theta synchronisation during cues that provide information about the identity of the upcoming task than those that do not. Alternatively, if alpha synchronisation is associated with inhibition processes, during switch and information related preparatory processes we expect to see increased alpha synchronisation, followed by decreased synchronisation prior to target onset and during the target as information processing is required.

In study two, we increased the requirement to utilise proactive control by providing an additional bivalent distractor during target presentation which inhibited participants from completing the task without preparing for the upcoming trial. Again, we expect the same relationships seen in study one with respect to theta and alpha synchronisation. However, we also predict that if theta is associated with proactive control processes, then we should see stronger theta synchronisation across the frontoparietal sites compared to study one.

Finally, as the organisation of the anatomical pathways that form the frontoparietal network has been related to cognitive control performance, we investigated whether intrinsic properties of the synchronisation that occurs during switching were apparent in a resting, task-free state. We then investigated whether the neural synchronisation at rest was predictive of individual performance during tasks. As these measures are derived in a task-free setting we did not expect differences between the relationships between rest and task performance across the studies.