Task-switching Costs Have Distinct Phase-locked and Non-phase-locked EEG Power Effects

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Abstract

Event-related potentials (ERPs) and total time-frequency power analyses have shown that performance costs during task switching are related to differential preparation to switch tasks (switch cost) and repeat the same task (mixing cost) during both proactive control (cue-to-target interval; CTI) and reactive control (post-target). The time-frequency EEG signal is comprised of both phase-locked activity (associated with stimulus-specific processes) and non-phase-locked activity (represents processes thought to persist over longer timeframes and do not contribute to the average ERP). In the present study, we used a cued task-switching paradigm to examine whether phase-locked and non-phase-locked power are differentially modulated by switch and mixing effects in intervals associated with the need for proactive control (CTI) and reactive control (post-target interval). Phase-locked activity was observed in the theta and alpha bands, closely resembled that seen for total power, and was consistent with switch and mixing ERP positivities. Non-phase-locked analyses showed theta and alpha power effects for both switch and mixing effects early in the CTI and as well as more sustained alpha and beta activity around cue onset, and extending from mid-CTI into the post-target interval. Non-phase-locked activity in pre-target alpha and post-target theta power were both correlated with RT mixing cost. These findings provide novel insight into phase-locked and non-phase-locked activity associated with switch and mixing costs that are not evident with ERP or total time-frequency analyses.

1. Introduction

Cognitive control processes facilitate goal-directed adjustments of behavior, such as overriding automatic responses, flexibly switching between different task sets, and updating the contents of working memory (e.g. Gratton, Cooper, Fabiani, Carter, & Karayanidis, 2018; Miyake et al., 2000). The Dual Modes of Control (DMC) model postulates that cognitive control processes can be employed both proactively and reactively (Braver, 2012). Proactive control is typically conceptualized as involving anticipatory, relatively sustained, endogenous processes that support goal selection, maintenance and/or updating in order to facilitate goal completion. In contrast, reactive control refers to more transient, exogenous processes, such as conflict resolution, and goal adaptation. These processes support moment-by-moment adjustments of behavior in response to external cues that may interfere with goal completion or signal the need to change the current goal.

Within experimental settings, the task-switching paradigm is used to study cognitive control processes involved in switching between two or more goals or task-sets (see Karayanidis et al., 2010; Kiesel et al., 2010). In cued-trials task-switching paradigms, a cue signals which task to perform on the upcoming target. By manipulating the cue-target interval (CTI), these paradigms can temporally differentiate between proactive control processes (e.g., preparing to repeat the letter task or *switch* to the number task), and reactive control processes (e.g., resolving stimulus or response level conflict after target onset). Typically, performance is slower and less accurate on trials where participants are required to switch tasks as compared to repeat the same task, an effect known as the *switch* cost (e.g. Rogers & Monsell, 1995). The switch cost is partly attributed to the need for '*task-set reconfiguration*' – a term used to refer to the set of processes involved in updating and retrieving the relevant task-set and suppressing activation of the irrelevant task-sets. The switch cost reduces when the CTI provides sufficient opportunity to complete task-set reconfiguration before target onset, suggesting the engagement of proactive control processes. However, a significant residual switch cost remains, indicating that reactive control is also necessary to resolve target-

related interference (see Monsell, 2003). Performance is also slower and less accurate on repeat trials when they are intermixed with *switch* trials in a mixed-task block (*mixed-repeat* trials) as compared to repeat trials that occur in a single-task block (*all-repeat* trials). This *mixing cost* is thought to result from higher working memory demands on mixed-task blocks than single-task blocks, as participants need to actively maintain multiple task-sets throughout the block of trials and quickly update working memory when needed (see Los, 1996).

The excellent time resolution of event-related potential (ERP) and time-frequency analyses of electroencephalogram (EEG) data has provided insight into neural processes activated by *switch* and *mixed-repeat* trials. During the CTI, switch cues elicit a larger centroparietal positivity than *mixed-repeat* cues (Barcelo, Escera, Corral, & Perianez, 2006; Finke, Escera, & Barcelo, 2012; Jost, Mayr, & Rosler, 2008; Karayanidis, Coltheart, Michie, & Murphy, 2003; Karayanidis et al., 2009; Nicholson, Karayanidis, Poboka, Heathcote, & Michie, 2005), which in turn elicit a larger positivity than *all-repeat* cues (Jost et al., 2008; Karayanidis, Whitson, Heathcote, & Michie, 2011b; Manzi, Nessler, Czernochowski, & Friedman, 2011; Whitson et al., 2014). These effects are commonly referred to as the switch and the mixing positivities and have been mapped to processes involved in task-set reconfiguration and active maintenance of the repeated task-set, respectively (Karayanidis et al., 2010). After target onset, the N2 is larger and the P3 is smaller for *switch* compared to *repeat* trials (Astle, Jackson, & Swainson, 2006, 2008; Jamadar, Hughes, Fulham, Michie, & Karayanidis, 2010; Nicholson, Karayanidis, Bumak, Poboka, & Michie, 2006). The target P3 is also smaller for *mixed-repeat* compared to *all-repeat* trials (Goffaux, Phillips, Sinai, & Pushkar, 2006; Whitson et al., 2014). These post-target effects are likely to arise from increasing levels of stimulus and/or response level interference across *all-repeat*, *mixed-repeat* and *switch* trial types (Karayanidis & Jamadar, 2014).

Time-frequency analyses show similar switching and mixing effects during the CTI. Over frontal and parietal areas, EEG power is greater for *switch* compared to *repeat* trials across theta (~4

- 8 Hz Cooper, Wong, McKewen, Michie, & Karayanidis, 2017; Cunillera et al., 2012), alpha (8 - 13 Hz; Cooper, Darriba, Karayanidis, & Barcelo, 2016; Foxe, Murphy, & De Sanctis, 2014; Mansfield, Karayanidis, & Cohen, 2012), and delta (~0.5 - 4 Hz; Prada, Barcelo, Herrmann, & Escera, 2014) frequency bands. Theta power is also greater for *mixed-repeat* compared to *all-repeat* trials during the CTI (Cooper et al., 2017). After target onset, *switch* trials have higher theta (Enriquez-Geppert & Barcelo, 2018; Sauseng et al., 2006) and lower alpha power compared to repeat trials (Prada et al., 2014; Sauseng et al., 2006).

The switch and mixing effects in ERPs and time-frequency power occur over similar time intervals, have similar frontoparietal topography, and are often interpreted as reflecting similar processes (e.g. Cooper et al., 2017). Furthermore, both measures have been associated with task-switching performance: Faster RT is associated with a larger switch positivity (Jost et al., 2008; Karayanidis, Provost, Brown, Paton, & Heathcote, 2011a), larger mixing positivity (Karayanidis et al., 2011a), larger target-locked P3b (Provost, Jamadar, Heathcote, Brown, & Karayanidis, 2018), smaller target-locked N2 (Nieuwenhuis, Yeung, van den Wildenberg, & Ridderinkhof, 2003; Provost et al., 2018), and lower post-target mid-frontal theta power (Cooper et al., 2019). Moreover, higher theta power and lower theta phase variability during the CTI have been associated with low behavioural variability, suggesting more efficient performance (Cooper et al., 2017). Together, these findings suggest that ERP and time-frequency effects are associated with both proactive (CTI) and reactive (post-target) control processes which improve performance by reducing RT and RT costs of task-switching.

EEG epochs are temporally bound to an event (e.g., a cue) and represent time-locked activity across multiple frequency bands. This time-locked EEG signal may be decomposed into phase-locked and non-phase-locked activity (Cohen, 2014). The signal averaging process used to derive ERPs (i.e., averaging over multiple time-locked EEG epochs to increase signal to noise ratio) is intended to retain phase-locked activity (peaks and troughs time-locked and phase-locked to that event) and

remove non-phase-locked activity (i.e., activity that is time-locked but not phase-locked to that event) which is typically considered noise. Hence, by definition, the ERP (time domain signal) represents phase-locked EEG activity averaged across the frequency spectrum. In contrast, the time-frequency domain signal is derived by analyzing signal characteristics (e.g., power) at each frequency from these same EEG epochs, and therefore can retain contributions from both phase-locked and non-phase-locked activity. Thus, ERP analyses are unable to capture non-phase-locked activity, and total power does not distinguish between phase-locked and non-phase-locked power. As a result, there may be information in the non-phase-locked activity that ERP and total power analyses do not reveal. Recent studies have examined whether phase-locked and non-phase-locked activity make distinct contributions to total time-frequency power and ERPs extracted from the same EEG epochs. The non-phase-locked activity is derived by subtracting the average ERP (for a given trial type) from each single-trial EEG epoch that contributes to that average ERP waveform, and applying a time-frequency transformation to the resulting data (Cohen, 2014; Cohen & Donner, 2013; see Methods). The phase-locked activity is extracted by subtracting this non-phase-locked signal from the total time-frequency activity.

It has been suggested that non-phased-locked power may reflect relatively sustained cognitive processes that may impact stimulus or response processing, but are not phase-locked to the event itself, such as arousal, level of cautiousness in decision making, and sustained attention (Donner & Siegel, 2011; Siegel & Donner, 2010). Using a conflict paradigm, Luu, Tucker, and Makeig (2004) found that total theta power accounted for only 57% of the variance in the amplitude of the theta-filtered error-related negativity (ERN). Non-phase-locked theta activity showed a different scalp topology and was more sustained than the ERN, and differed between correct and incorrect responses. They concluded that ERN and non-phase-locked theta activity involve at least some distinct frontal EEG sources. In an oddball paradigm, N2 amplitude was positively correlated with phase-locked but only marginally with non-phase-locked theta power (Hajihosseini & Holroyd, 2013). Using a Simon task, Cohen and Donner (2013) found no significant relationship between N2

amplitude and non-phase-locked theta power. Both studies found that non-phase-locked theta power was a stronger contributor to total power than the phase-locked component (Cohen & Donner, 2013; Hajihosseini & Holroyd, 2013). Using single-trial comparisons, Cohen and Donner (2013) found that the non-phase-locked theta component was a better predictor of behaviour than the phase-locked theta. The only study to compare phase-locked and non-phase-locked activity in task-switching reported suppression of non-phase-locked gamma activity (30+ Hz) after repeat but not after *switch* trials, but no effects on phase-locked activity (Gruber, Giabbiconi, Trujillo-Barreto, & Muller, 2006). Taken together, these studies show that phase-locked and non-phase-locked signals extracted from the total time-frequency activity show different patterns of relationships with behavioral and/or ERP components, supporting the contention that they represent distinct underlying cognitive or neural processes.

Alternatively, however, it has been suggested that non-phase-locked activity may arise, at least partially, from trial-by-trial variability in the EEG (Cohen & Donner, 2013; Luu et al., 2004). The non-phase-locked signal is extracted by subtracting the participant's average ERP waveform from each EEG epoch that contributed to that waveform. So, trial-by-trial variability in different ERP components will remain in the single-trial EEG epoch and may contribute to the non-phase-locked signal. As a result, the non-phase-locked signal would be expected to include trial-by-trial variability that is present in the single-trial EEG epochs but has been averaged out of the average ERP waveform.

In this study, we examine whether phase-locked and non-phase-locked EEG signals are differentially modulated by proactive and reactive control processes during cued-trials task-switching. Specifically, we seek to examine whether the non-phase-locked signal provides insight into task-switching effects that are not evident in the ERP (i.e., only phase-locked EEG activity) or in total time-frequency power (i.e., both phase-locked and non-phase-locked activity). Based on our previous work with this paradigm, we hypothesize that time-frequency effects will be most

prominent in the theta band (Cooper et al., 2019; Cooper et al., 2015; Cooper et al., 2017). Phase-locked power is expected to show mixing and switch theta band effects that mirror cue-locked and target-locked ERP effects. In line with previous evidence of relationships between behavioral and ERP task-switching costs (Jost et al., 2008; Karayanidis et al., 2011a; Nieuwenhuis et al., 2003), RT switch cost and mixing cost are expected to be correlated with corresponding phase-locked power effects during the CTI and in the post-target interval.

It is more difficult to make specific hypotheses about non-phase locked effects. Previous studies derived non-phase-locked activity from target- or response-locked EEG, typically in conflict paradigms. Most studies found weak or no relationship with corresponding ERPs, and that non-phase-locked theta power more strongly resembled that shown in total time-frequency power than phase-locked power. On this basis, we expect that non-phase-locked power effects will be evident at least in the post-target interval, and will closely resemble total power effects. If non-phase-locked power effects represent relatively sustained processes (e.g., arousal, working memory load) that vary between easy single-task and more difficult mixed-task blocks, they are likely to be more prominent in mixing than switch cost comparisons.

2. Material and Method

2.1. Participants

Two hundred and fifteen participants aged 15 - 35 years were recruited from the community as part of the larger Age-ility Project (Karayanidis et al., 2016) and completed the task-switching paradigm with concurrent EEG (another 67 Age-ility participants did not complete this paradigm). The protocol complies with the Declaration of Helsinki and was approved by the University of Newcastle Human Research Ethics Committee (HREC: H-2012-0157). All participants provided written informed consent (participants under the age of 18 years also provided written parental consent) and were reimbursed $20 per hour. Participants were asked to abstain from caffeine and alcohol at least two hours prior to testing. Data from 18 participants were excluded from further

analyses: three had very fast RTs and very high error rates suggestive of premature responding; one had an EEG recording problem; 14 had noisy EEG recordings resulting in less than 50 trials for one or more condition/s (Cohen, 2014). This resulted in a final sample of 197 participants, 24 of whom were aged 15-17 years (see Table 1 for demographic information).

"INSERT TABLE 1 ABOUT HERE"

2.2. Stimuli and Task

A cued-trials task switching paradigm required a binary decision on one of three simple classification tasks: letter (vowel/consonant), number (odd/even) and color (hot/cold). A wheel was defined by a grey circle (5° visual angle) divided into six segments, with pairs of adjacent segments grouped by a thicker line that outlined the areas allocated to each of the three tasks (see Figure 1A). Each trial consisted of a cue-target sequence (Figure 1B). The wheel was continuously displayed and a trial commenced with a cue that highlighted two adjacent segments of the wheel for 1000 ms. The cue was replaced by a target that was presented in one of the two segments that the cue had highlighted. Targets were pairs of characters consisting of combinations of a letter, a digit or a non-alphanumeric symbol presented either in grey or color. Each target consisted of three dimensions: one from the currently relevant task (e.g., in Figure 1B, the letter A is mapped to a left hand response), one from either of the two currently irrelevant tasks and incongruently mapped with the task-relevant dimension (e.g., the number 4 is mapped to a right hand response) and one neutral dimension i.e., not mapped to any response (e.g., grey color). The neutral dimension was a non-alphanumeric character (#, $, %, &) for letter and number tasks or the color grey for the color task. The target was presented until a response was made or for 5000 ms. The response-cue interval was 400 ms and the CTI was 1000 ms. The same target could not appear on two consecutive trials.

Trial types were defined by the location of the cue on trial N relative to trial N-1 (Figure 1C) and were presented with equal probability in a pseudo-random sequence so that the same cue type was not repeated on more than four consecutive trials. *Repeat* cues highlighted the two segments

associated with the task that had been completed on the preceding trial, indicating that the same task would be repeated (e.g., letter task in Figure 1C). *Repeat* cues were identical for *all-repeat* trials in the single-task blocks and *mixed-repeat* trials in the mixed-task blocks. *Switch* cues highlighted both segments of one of the tasks not completed on the previous trial, indicating that the task would change and identifying which task would be required on the next target. The task included another two cue types: *switch-away* cues (that signaled the task would change but not task identity) and *noninformative* cues (that signaled the task may repeat or may change; see Cooper et al., 2017). As this study focusses on mixing and switch costs, we only report analyses on *all-repeat*, *mixed-repeat* and *switch* cues.

Participants were instructed to respond as quickly and accurately as possible. Stimulus-response mapping was counterbalanced across participants. Errors were followed by an auditory feedback tone. Mean RT and accuracy feedback was displayed after each block and participants were encouraged to use this feedback to improve performance. Participants were provided with brief (5 - 10 s) rests between blocks of trials and a longer rest was offered mid-way through testing to minimize fatigue. In order to form well-established cue-target and target-response associations, participants completed a total of 1320 practice trials over two training sessions scheduled no more than 14 days apart. Following the second training session, participants completed ten mixed-task blocks (77 trials/block) and three single-task blocks (53 trials/block) while EEG was recorded. Each block included five warm-up trials. The three single-task blocks always occurred consecutively, but were interspersed with the mixed-task blocks in pseudorandom order.

RT and EEG data analyses were performed on correct trials that i) had RT between 200 ms and three SD from the individual's mean RT, ii) did not follow an error trial, and iii) were not the initial five warm-up trials on each block. On average, 17.96% of trials ± 7.67 SD were excluded based on these criteria. Trials with high EEG noise levels (see below) were also excluded from RT and EEG analyses. Behavioral data were analyzed using two planned comparisons to target mixing cost (*all-*

repeat vs. *mixed-repeat*) and *switch* cost (*mixed-repeat* vs. *switch*) using JASP (Version 0.7.5.6) with a Bonferroni-corrected significance threshold of p <.025 (i.e. $\alpha = .05 / 2$).

"INSERT FIGURE 1 ABOUT HERE"

2.3. EEG Recording and Processing

EEG was recorded continuously using an ActiveTwo Biosemi EEG system (2048 Hz, bandpass filter of DC-400Hz) from 64 scalp electrodes according to the 10-20 international system plus bilateral mastoids, outer canthi, and both supraorbital and infraorbital ocular sites. Common mode sense (CMS) and driven right leg (DRL) electrodes for the Biosemi active electrode system were positioned inferior to P1 and P2 respectively. EEG data were recorded relative to an amplifier reference voltage, and then re-referenced offline to Cz to remove common-mode signals. EEG data were processed in MATLAB (Mathworks, Navick, MA) using a custom-built pipeline utilizing Fieldtrip (Oostenveld, Fries, Maris, & Schoffelen, 2011), EEGLab (Delorme & Makeig, 2004), CSD Toolbox (Kayser & Tenke, 2006) and in-house functions (written by authors AW and PC). Preprocessing was performed using Fieldtrip as follows. EEG data were re-referenced offline to electrode Cz, downsampled from 2048 Hz to 512 Hz using a zero-phase anti-aliasing filter with a low-pass cut off frequency of 245 Hz and then had high pass and notch filtering applied to remove line noise and low-frequency drift (high pass: 0.1 Hz, forward phase; 50 Hz notch: zero phase). Excessively noisy channels were identified by visual inspection and were excluded. The number of channels deemed bad ranged from 0 to 8, with an average of 0.76 (SD = 1.42).

Epochs for each trial type (*all-repeat*, *mixed-repeat*, switch) were extracted from 1000 ms before to 3500 ms after cue onset. To remove blink and vertical eye-movement artefact, independent components analysis (ICA) was performed using the fastica algorithm (Hyvarinen & Oja,

2000). The ICA produced a set of components equal to the number of available electrodes. From this, 1 to 6 components corresponding to ocular artefact were identified by visual inspection and deleted (mean components = 1.38 ± 0.76 SD). Data were then low pass filtered (30 Hz, zero-phase) to remove high frequency noise including muscular artefacts.

Trials that contained residual artefact larger than ±120 μV were deleted, resulting in an average of 112.19 (± 22.00 SD) *all-repeat*, 134.03 (± 25.16 SD) *mixed-repeat*, 128.73 (± 27.09 SD) *switch* for further analysis. Previously identified bad channels were reintroduced by interpolating data between neighboring electrodes. EEG data were then transformed using a surface Laplacian filter (smoothing = 10-5, number of iterations = 10, spherical spline order = 4) to reduce volume conduction effects (CSD Toolbox; Kayser & Tenke, 2006).

2.4. Time Frequency Analyses

Time-frequency analyses were performed on the surface Laplacian filtered data (c.f. Cooper et al., 2015) for each trial type (i.e., *all-repeat*, *mixed-repeat*, switch). Power was measured as normalized decibel values (Equation 1):

$$10 \times \log_{10}\left(\frac{TF_{power}}{TF_{baseline}}\right)$$

We differentiated between phase-locked and non-phase-locked power components by removing the phase-locked component from total time-frequency power (Cohen, 2014; Cohen & Donner, 2013; Donner & Siegel, 2011; Klimesch, Doppelmayr, Russegger, Pachinger, & Schwaiger, 1998; Pfurtscheller & Lopes da Silva, 1999; Siegel & Donner, 2010; Truccolo, Ding, Knuth, Nakamura, & Bressler, 2002)[1].

[1] The terms phase-locked and non-phase-locked are not consistently defined in the literature, so care needs to be taken when comparing findings across studies. For instance, some studies compute phase-locked power by applying a time-frequency transformation to an ERP (Bertrand & Tallon-Baudry, 2000; Busch, Schadow, Frund, & Herrmann, 2006; Tallon-Baudry & Bertrand, 1999) while others refer to total time-frequency power as non-phase-locked (Bertrand & Tallon-Baudry, 2000; Freunberger, Fellinger, Sauseng, Gruber, & Klimesch, 2009; Tallon-Baudry & Bertrand, 1999; Yuval-Greenberg, Tomer, Keren, Nelken, & Deouell, 2008)

First, we computed total time-frequency power, by extracting single-trial time-frequency representations via complex Morlet wavelet convolution (80 logarithmically spaced frequency bins, 2 - 30 Hz with logarithmically spaced tapers ranging from 3 - 14 cycles) for each trial type. Total power was calculated for each time point across the epoch as the ratio (in decibels, dB) of power at each time point relative to a 100 - 300 ms pre-cue baseline. To calculate non-phase-locked power, the ERP was computed for each participant, trial type and electrode from the surface Laplacian filtered EEG data (Cohen, 2014; Cohen & Donner, 2013). The ERP was subtracted from the corresponding single epochs of EEG data and a complex Morlet wavelet was applied as detailed above. The phase-locked power time-frequency signal was computed by subtracting the non-phase-locked power signal from the corresponding total power signal (Cohen, 2014; Cohen & Donner, 2013). It could be argued that this method may not result in a pure measure of non-phase-locked power as trial-by-trial latency jitter in the ERP may leave residual phase-locked activity in the non-phase-locked power. To determine whether there was significant and systematic latency jitter in the ERPs as a function of time on task, we conducted pairwise comparisons on the latency of the ERP for the first and last 10% of trials as well as the first and last 10% against the middle 10% of trials. There was no significant difference in ERP latency across these three intervals, suggesting that there was no systematic ERP contamination of non-phase-locked activity as a function of time on task. However, we cannot definitively conclude that there is no ERP contamination arising from other non-systematic sources of trial-by-trial variability.

ERPs and time-frequency data were plotted at six midline electrode sites: Fz, FCz, Cz, CPz, Pz, and POz. Based on visual inspection of the switch and mixing effects, two electrodes were selected: FCz and Pz for further analyses. These electrodes are in line with our previous work with this paradigm showing strongest effects at midline frontal to parietal sites (Cooper et al., 2019; Cooper et al., 2017; Wong et al., 2018). For each power type (i.e. total, phase-locked, and non-phase-locked), and for each electrode, switch cost was calculated by subtracting the average power for *mixed-repeat* from *switch* trials and mixing cost by subtracting the average power for *all-repeat*

trials from the *mixed-repeat* . At each electrode, one sample t-tests on mixing and switch costs were performed at each time*frequency pixel with False Discovery Rate (FDR) correction of level of significance at α = 0.001 (Benjamini, Krieger, & Yekutieli, 2006).

2.5. ERP Analyses

ERP waveforms for each trial type were derived from the same surface Laplacian filtered data, using a peri-cue baseline (i.e. -50 to 50 ms) consistent with our previous work (e.g. Wong et al., 2018), using the same electrodes as time-frequency analyses. Difference waveforms were calculated for the switch cost (*switch* – *mixed-repeat* trials) and mixing cost (*mixed-repeat* – *all-repeat* trials). Care needs to be taken when visually comparing ERPs and time-frequency figures as they are plotted using different baselines (i.e., -50 to 50 ms vs. -300 to -100 ms, respectively), and there is greater latency smearing for time-frequency analyses.

2.6. RT Correlations with Time-frequency Power and ERPs

We used proportion of RT costs to correct for individual differences in overall RT: *switch* cost ((*switch* - *mixed-repeat*)/*mixed-repeat*) and mixing cost ((*mixed-repeat* - *all-repeat*)/*all-repeat*)[2]. RT cost measures were used to examine Spearman correlations with switch cost and mixing cost for power at each ROI for each time*frequency pixel and for ERP waveforms (point-by-point) with FDR corrected level of significance at α = 0.001.

3. Results

3.1. Behavioral Results

Figure 2 shows the distribution of mean RT and percentage error rate for each trial type. Error rate showed a significant switch cost (t (196) = 9.99, p < .001, d = .71; 95% *CI* = 1.90, 2.84) but no mixing cost (t (196) = .54, p = .59; d = .04; 95% *CI* = -.23, .40). Proportion RT costs also produced

[2] Note: These cost proportions were not calculated for power as the power is already a proportion change from baseline. For consistency, the cost proportions were not calculated for ERPs either.

significant switch ($t(196) = 17.46$, $p < .001$; $d = 1.24$; 95% *CI* = .19, .23) and mixing effects ($t(196) = 16.68$, $p < .001$; $d = 1.19$; 95% *CI* = .17, .21, see Table 2).

"INSERT FIGURE 2 ABOUT HERE"

"INSERT TABLE 2 ABOUT HERE"

3.2. Time-Frequency Power and ERP Results

Given that we are primarily interested in the switch and mixing effects rather than the individual trial types, the results will focus on the cost plots making reference to the trial type plots as needed to assist interpretation.

3.2.1. *Switch* Cost

Figure 3 depicts time-frequency power plots for *mixed-repeat* and *switch* trials, as well as switch cost at FCz (A) and Pz (B) for each power measure (total, phase-locked, non-phase-locked). While the total and phase-locked power signal was very similar in strength, the non-phase-locked signal was much weaker and are plotted using a different scale.

"INSERT FIGURE 3 ABOUT HERE"

Total Power. Within the first half of the cue-target interval(Fig 3Ai), at FCz, both *mixed-repeat* and *switch* trials showed a brief burst of activity spanning across delta (~0.5 - 4 Hz) to alpha (~8 - 13 Hz) frequency ranges . The corresponding switch cost plot (right) shows three areas of differentiation: Over roughly 0 - 200 ms, theta (~4 - 8 Hz) total power was larger for *mixed-repeat* trials, whereas

shortly after power in theta/alpha[3] (~350 - 550 ms) and delta/theta (~350 - 600 ms) bands was larger for *switch* trials. At Pz (Figure 3Bi), over approximately 100 - 600 ms, switch trials had larger theta/alpha power than *mixed-repeat* trials. In the second half of the CTI, both *mixed-repeat* and *switch* trials showed a comparable decrease in total power relative to the level of pre-cue activity spreading from delta to beta (~13 - 30) frequency bands both mid-frontally and parietally. Similarly, after target onset, both trial types showed a comparable brief burst of theta/alpha total power at both FCz and Pz.

Phase-locked power. As shown in Figures 3Aii and 3Bii, phase-locked power analyses produced a pattern of findings that was almost identical to the total power effects. Specifically, in the first half of the CTI, compared to *mixed-repeat* trials, *switch* trials showed an early reduction in frontal theta power over the first 200ms, followed by brief bursts of increased power in theta/alpha and delta bands frontally, and a large burst of theta/alpha power parietally.

Although phase-locked power and ERP difference waveforms do not directly correspond in latency (given greater latency smearing for time-frequency analyses and use of different baselines), there was close temporal correspondence in switch effects during the first half of the CTI, particularly at Pz. The ERPs (Figure 4Aii) show a parietal switch positivity that spread across 300 - 700 ms and was temporally consistent with the phase-locked parietal theta switch effects. In the latter half of the CTI, the ERP difference waveform shows a frontocentral pre-target negativity that is larger for *switch* than *mixed-repeat* trials. This pre-target switch negativity was not reflected in the phase-locked frontal power. This slow effect occurs below the 2 Hz frequency limit used here. The parietal post-target switch negativity was also not reflected in the phase-locked parietal power.

Non-phase-locked power. Figures 3Aiii and 3Biii show that non-phase-locked power produced different effects than those seen in the total and phase-locked power plots. Although non-phase-

[3] Note: The slash character (/) is used here to denote an effect that extends across theta and alpha bands and not a ratio. This is also the case for other frequency bands e.g. delta/theta, alpha/beta.

locked effects were markedly weaker, they were highly significant. Time-frequency plots for both *switch* and *mixed-repeat* trials showed marked activity mid-frontally. This included a beta burst immediately post-cue, and a sustained alpha effect that spread across most of the CTI and extended into theta/delta bands after target onset. Difference plots show that, compared to *mixed-repeat* trials, *switch* trials produced larger non-phase-locked theta/alpha activity in the first half of the CTI, followed by lower theta/delta power (at times bleeding into alpha) from around 500ms after target onset. Parietally, (Figure 3Biii), there was again an increase in theta/alpha power for *switch* compared to *mixed-repeat* trials, extending into delta and beta bands. In the second half of the CTI, there was a sustained negative switch effect spanning alpha and beta bands. This effect was sustained beyond target onset where it becomes localized to the alpha band.

3.2.2. Mixing Cost

Figure 4 shows time-frequency plots for the mixing effects at FCz (A) and Pz (B). Note that the *mixed-repeat* trial type is the same as that shown in Figure 3, and that the mixing cost represents a comparison between trials that are physically identical, but presented in different blocks of trials, i.e., either interspersed amongst *switch* trials (*mixed-repeat*) or alone in a block (*all-repeat*).

"INSERT FIGURE 4 ABOUT HERE"

Total Power. At both FCz and Pz, all-repeat and mixed-repeat trials showed very similar activity, with the exception of larger activity early post-cue in the latter. This is most clearly evident in the difference plots: Across the first half of the CTI, there is large activity in theta/alpha bands and extending into delta band at FCz (see Figure 4Ai, 4Bi). The large parietally maximal theta/alpha burst seen after target onset did not differ between conditions.

Phase-locked Power. The phase-locked mixing effects were largely consistent with those seen in

total power: Increased power for *mixed-repeat* compared to *all-repeat* trials in delta/theta/alpha bands in the early CTI at both FCz (Figure 4Aii) and Pz (Figure 4Bii), and no significant differences in the post-target period. These phase-locked effects are broadly temporally consistent with effects seen in ERP difference waveforms (Figure 5Bi), particularly during the CTI, where the early frontal and parietal mixing positivities (100 - 300 ms) are seen.

Non-phase-locked power. Both repeat trial types showed a very similar pattern of widespread effects for non-phase-locked power plots (Figures 4Aiii and 4Biii). At both electrodes, non-phase-locked power in alpha/beta bands emerged before cue onset and extended to the middle of the CTI. This activity was weaker for *mixed-repeat* than *all-repeat* trials. Frontally, the difference waveform showed theta/delta activity over 200 - 700 ms, indicating relatively higher theta power for *mixed-repeat* compared to *all-repeat* trials – with a similar effect parietally (400-500ms). Difference plots showed a later alpha/beta mixing effect at both sites, spreading 700 - 1200 ms frontally and 700 - 1500 ms parietally. After target onset, *mixed-repeat* trials showed lower theta power at FCz (1100 - 1600 ms), larger theta power at Pz (1400 - 1600 ms) compared to *all-repeat* trials.

3.3 Relationship between time-frequency effects and RT

There were no significant correlations between RT switch cost and corresponding switching effects on any power type or ERPs (see Appendix A). Figure 6 depicts the correlation coefficients (r-value) of the association between RT mixing cost and the corresponding mixing effect for each power measure at each time*frequency pixel. There were no significant correlations between RT mixing cost and the mixing effect on either total or phase-locked power (Figure 6A and 6B). In contrast, RT mixing cost was correlated with three temporally and spatially distinct non-phase-locked mixing effects within the theta/alpha frequency bands (Figure 6C). Frontally, higher theta/alpha power for *mixed-repeat* than *all-repeat* trials over 1100 - 1600 ms after target onset was associated with smaller RT mixing cost. Parietally, higher alpha power for *mixed-repeat* than *all-repeat* trials just before target onset (800 - 1000ms) and in the peri-response interval (1600 - 2000

ms post-cue) were both associated with smaller RT mixing cost. These parietal peri-response effects are likely to result from differences in the timing of response selection and/or activation for *mixed-repeat* and *all-repeat* trials.

"INSERT FIGURE 5 ABOUT HERE"

4. Discussion

The present study examined whether phase-locked and non-phased-locked EEG power differentially contribute to mixing and switch effects during cued-trials task switching. Both phase-locked and non-phase-locked effects were expected to be most prominent in the theta band (e.g., Cooper, Wong et al., 2017; Cooper et al., 2015). Specifically, consistent with ERP effects, switch and mixing effects were expected to be evident in modulation of phase-locked theta power during periods of switch and/or task preparation (i.e., switch positivity, mixing positivity) and task implementation (i.e., N2), and to be associated with variability in RT switch and mixing cost (e.g., Jost, Mayr & Rösler, 2008; Karayanidis et al., 2011; Nieuwenhuis et al., 2003; Provost et al., 2018). Non-phase-locked power effects were expected to resemble effects seen in total power data, consistent with previous studies (Cohen & Donner, 2013; Hajihosseini & Holroyd, 2013; Luu et al., 2004). Non-phase-locked EEG power effects were also expected to be larger and more sustained for mixing than switch costs. The present study focused on effects observed at mid-frontal and parietal sites. It should be noted that phase-locked and non-phase-locked power may produce different switch and mixing effects at other sites.

Widespread effects of task-switching were evident in both phase-locked and non-phase-locked EEG power, although unexpectedly the signal was much weaker in the latter. Based on previous studies, we would have expected the non-phase-locked power to be larger than the phase-

locked power (Cohen & Donner, 2013; Hajihosseini & Holroyd, 2013). In the first half of the CTI, phase-locked and non-phase-locked power showed a similar pattern of effects in the theta/alpha range. These effects were evident for both mixing and switch costs. In addition, non-phase-locked activity showed more widespread effects that spanned across frequency bands (delta to high beta) and time (pre-cue to peri-response interval), and were uniquely correlated with behavioral mixing cost in peri-target and post-target intervals. These effects suggest that proactive control processes modulated both phase-locked and non-phase-locked theta activity, whereas non-phase-locked activity across a broader frequency range was modulated by both proactive and reactive control processes.

4.1 Theta/Alpha Activity in Proactive Control

During the early CTI, phase-locked theta/alpha power was modulated by both switch and mixing effects. These findings are highly consistent with those seen for total power during the preparation interval in this and previous studies (e.g. Cooper et al., 2017; Cunillera et al., 2012). Modulation of theta activity typically occurs in conditions that require cognitive control (Cavanagh, Zambrano-Vazquez, & Allen, 2012) and is conceptualized as a phase reset process. Following the onset of an event, ongoing activity becomes phase aligned, and this alignment is likely to underpin ERP components that are derived by averaging across multiple trials with similar phase-resets (see Bastiaansen, Mazaheri, & Jensen, 2011). Consistent with the notion of a phase reset, phase-locked theta/alpha activity emerged soon after cue onset (peaking ~ 250 - 350 ms) at both mid-frontal and parietal sites, and progressively increased in amplitude from *all-repeat* to *mixed-repeat* to *switch* trials. The timing and distribution of this theta/alpha effect is similar to the mixing and switch ERP positivities that are associated with selecting and maintaining the relevant task-set active in the face of high working memory load (Goffaux et al., 2006; Karayanidis et al., 2011b), and goal-resetting / task-set updating processes (Karayanidis et al., 2009), respectively. Alternatively, in line with the multiple demand system (Duncan, 2010), the progressive increase in phase-locked theta power may

represent the increasing demand for proactive control across the three type of cues (e.g., maintain currently active task-set representation, update the task-set, reload stimulus-response mapping). Over this same interval, non-phase-locked power effects were very similar to, albeit weaker than, the corresponding phase-locked power effects. This activity may arise from independent processes represented in the non-phase-locked signal and/or from trial-by-trial ERP variability that remains when subtracting the average ERP waveform from single-trial EEG epochs. We discuss these two interpretations of non-phase-locked power effects below (see 4.5).

4.2. Theta/Alpha Activity in Reactive Control

After target onset, all three trial types showed a large phase-locked theta/alpha effect that did not vary across trial types, suggesting a common target-driven process that occurs independently of task mixing or switching demands. As all target stimuli were incongruent (Figure 1, i.e., response hand for the relevant dimension was always incongruently mapped to the response for the irrelevant dimension), this theta/alpha effect is likely to arise from the need for interference control (i.e., to select the correct and suppress the incorrect response). This is consistent with previous studies showing that incongruence effects do not interact with task switching effects on either behavioral or ERP measures, and are represented in the ERP as a larger N2 for incongruent than congruent or neutral trials (e.g. Provost et al., 2018). However, the absence of any difference in the strength of this theta/alpha effect across trial types also suggests that, having prepared for a repeat or switch trial during the CTI, there remain no residual effects of mixing or switching tasks after target onset. This is inconsistent with both behavioral and ERP evidence of mixing and switch effects in these data as well as in previous studies. It is possible that the relatively slow mixing and switch ERP effects are below our low 2Hz frequency limit, and therefore are not evident in phase-locked power plots.

Non-phase-locked theta power effects were also evident in the post-target interval. At the mid-frontal site, theta power progressively reduced across trial type (i.e., *all-repeat, mixed-repeat, switch* trial type), whereas parietally it was greater for *mixed-repeat* compared to *all-repeat* trials. In

contrast, using a different cued-trials task-switching paradigm, Enriquez-Geppert and Barcelo (2018) found that total midfrontal theta was larger for *switch* than *repeat* trials. Similarly, in attention and conflict paradigms, non-phase-locked mid-frontal theta power was larger for target than standard trials in an oddball paradigm (Hajihosseini & Holroyd, 2013), for incongruent than congruent trials in a Simon task (Cohen & Donner, 2013), and on incorrect compared to correct trials in an emotional two-choice perception task (Luu et al., 2004). Thus, in these studies, consistent with the notion that mid-frontal theta power is a neural signature of cognitive control (Cavanagh & Frank, 2014; Cavanagh et al., 2012), non-phase-locked mid-frontal theta power was larger in conditions that require cognitive control, such as resolving conflict or adapting behaviour following an error. In contrast, the post-target mid-frontal theta effects observed here showed the opposite pattern: theta power *reduced* with increased need for control.

Our paradigm differs in many ways from the paradigms used in previous studies. Most other paradigms used a simple 2-choice decision task. Although Enriquez-Geppert and Barcelo (2018) also used a cued-trials task-switching paradigm, a pre-target baseline was used. In the present study, we used a pre-cue baseline to avoid contaminating our post-target effects with activity occurring in the preparatory period. Moreover, our participants were highly practiced on this very demanding cued-trials task-switching paradigm, having completed 1320 trials before EEG recording. Recall that, during the CTI, both phase-locked and non-phase-locked theta power progressively increased from the simplest all-repeat trial, to mixed-repeat and again to switch trials – resembling the pattern for post-target non-phase-locked theta power in studies that rely on reactive control. This is consistent with the interpretation that the cue-locked theta effects for both phase- and non-phase-locked theta tap into proactive cognitive control processes, and that having proactively completed task-set updating and maintenance changes the nature of processes completed after target onset.

4.3. Non-phase-locked Effect in Other Frequencies

In addition to substantial non-phase-locked switch and mixing effects in the theta band,

widespread effects were also found in other frequencies. Non-phase-locked activity first emerged before cue onset and was sustained until mid-CTI. Specifically, over this period, alpha/beta power was smaller for *mixed-repeat* than *all-repeat* at both sites. This may reflect increased arousal for *mixed-repeat* compared to *all-repeat* trials.

Switch and mixing post-target effects were also observed in the alpha/beta bands, where effects sustained from the mid-CTI to post-target period. Alpha/beta non-phase-locked power was larger for *mixed-repeat* compared to *all-repeat* trials both mid-frontally and parietally. A similar switch effect was observed mid-frontally. According to Engel and Fries (2010), total beta activity is greater for conditions that require maintenance of the current goals, i.e., the status quo. This is consistent with the beta effects seen here: Beta power was highest when the current task-set needed to be actively maintained (*mixed-repeat*), lower when there was a need to change task-set (*switch*), and remained unchanged when there was no need to for change or maintenance (*all-repeat*). Over this peri-target interval, *mixed-repeat* trials also showed larger sustained parietal alpha power relative to switch trials. Prada et al. (2014) have also shown alpha suppression for *switch* relative to *mixed-repeat* trials in a cued-trials task-switching paradigm.

4.4. Brain-behavior Correlations

Importantly, for the first time, we show significant correlations between non-phase-locked power and behavioral costs in a cued-trials task switching paradigm. A smaller RT mixing cost was associated with larger non-phase-locked power for *mixed-repeat* as compared to *all-repeat* trials in two distinct time periods and frequency bands. Specifically, a larger mixing effect in parietal alpha power just before target onset and frontal theta power around the timing of the behavioral response were both associated with reduced RT mixing cost. The fact that correlations between non-phase-locked power and behavior were evident for mixing but not switch effects, suggests that they represent mechanisms that vary across blocks (e.g., arousal, criterion setting, working memory load) rather than between trials in the same block (e.g., task-set updating; see Section 4.5). Total alpha

power is commonly associated with working memory (e.g. Sauseng et al., 2005). In fact, a memory-related increase in alpha power was associated with a source in the parieto-occipital sulcus (Tuladhar et al., 2007). Therefore, the correlation between behavioural and parietal alpha power mixing costs is consistent with increased working memory demands for *mixed-repeat* compared to an *all-repeat* trial. We also show a correlation between mid-frontal non-phase-locked theta power and mixing cost RT. Correlations between mid-frontal non-phase-locked theta power and RT have been observed previously (Cohen & Donner, 2013). For incongruent trial in the Simon task, larger non-phase-locked frontal theta power was positively correlated with RT, consistent with slower responding for trials that required greater reactive control. Here, we show that greater engagement of theta-related control processes during periods associated with response execution was associated with lower behavioral mixing cost.

Surprisingly however, we did not find expected relationships between RT mixing and switch costs and corresponding mixing and switch effects in either ERPs, phase-locked power or total power. While the reasons behind this are not clear, there are a few methodological differences with previous studies that may have contributed to this difference. In this paper, ERPs were derived using a Laplacian transformation procedure (see Wong et al., 2018 for comparison of montages), we estimated proportion rather than raw RT costs to control for individual variability in RT, and we used a conservative FDR correction procedure.

4.5. Source of Non-phase-locked Effects

In this study, we found widespread switching and mixing effects in non-phase-locked power, some of which occurred in the same time-frequency range as phase-locked effects (i.e., theta/alpha effects in early CTI), and others that showed distinct time-frequency patterns (i.e., peri-cue and peri-target effects in beta and alpha).

While a number of studies have reported distinct effects with phase-locked and non-phase-locked power, the origin of these differences remains unclear. Phase-locked and non-phase-locked

activity have previously been interpreted as representing distinct processes. For example, Siegel and Donner (2010; Donner & Siegel, 2011) argued that non-phase-locked power reflects sustained activity related to generic task-related processes. In the current context, this may involve differential demands between task blocks (e.g., arousal, attention, working memory demands, etc.) that are likely to impact mixing effects (i.e., differences in repeating the same task within a single-task vs. a mixed-task block), rather than between trials in the same block (e.g. changing task goal, updating task-set, implementing new task-set) that would impact switching effects.

One such process may be the adjustment of response criterion, which is a measure of how much information is required before making a decision (see Ratcliff, 2008). Like the non-phase-locked theta/alpha effects, response criterion increases for *all-repeat* to *mixed-repeat* trials, and for *mixed-repeat* to *switch* trials (Karayanidis et al., 2009; Karayanidis et al., 2011b). The non-phase-locked theta/alpha effects observed during the CTI may reflect changes in the response criterion in anticipation of a difficult *switch* trial and a less difficult *mixed-repeat* trial compared to the easy *all-repeat* trials. Additionally, the non-phase-locked mixing effect may also be a result of the sustained increase in working memory for *mixed-repeat* compared to *all-repeat* trials. Evidence for this is seen in the finding that as predicted, the non-phase-locked power mixing effects first emerged before cue onset, consistent with sustained task-related differences between mixed-task and single-task blocks. Furthermore, as discussed above, the non-phase-locked mixing effects were prominent in parietal alpha power, which has been previously been associated with working memory processes (e.g. Sauseng et al., 2005).

Alternatively, the non-phase-locked power signal may arise as an artefact of the process by which it is derived. Recall that non-phase-locked power is derived by a frequency transformation of the signal arising after subtracting the average ERP waveform from the single-trial EEG epochs. The phase-locked signal is then extracted by subtracting non-phase-locked from total power. The subtraction process used to derive the non-phase-locked signal may to leave behind two sources of

variability. The first is trial-by-trial ERP component variability (e.g., due to task practice, fatigue, attention lapses etc.; Kappenman & Luck, 2011) that the averaging process removes from the average ERP waveform. The other is variability from the ongoing EEG that is left behind when removing a low noise signal (i.e., in this case the ERP) from the noisy single-trial (EEG) signal. Therefore, the non-phase-locked power signal may contain at least some residual phase-locked power and more random noise than the phase-locked signal. The former source of variability would be expected to be time-locked to the eliciting event but more smeared across time and frequency than the corresponding phase-locked signal than the latter.

If non-phase-locked power arises as a result of variability in the single-trial EEG signal, we would expect that more variable EEG signal will result in strong non-phase-locked power contribution to the total power signal, in line with previous studies (Cohen & Donner, 2013; Hajihosseini & Holroyd, 2013). Previous studies comparing phase-locked and non-phase-locked signals typically include fewer participants, less task practice and fewer trials than the present study. Task practice improves performance and reduces single-trial ERP variability, as well as variability of the average ERP waveform. These methodological differences may partly explain the differences between the current and past studies in the relative magnitude of the power signal of phase-locked and non-phase-locked data. Given that participants in the present study are highly practiced and perform a large number of trials, it is possible that there is less variability in the single-trial EEG, and thus, the non-phase-locked power is of a smaller magnitude than the phase-locked power. Moreover, the non-phase-locked power was found to predict cost RT for the mixing cost. Even if non-phase-locked power simply reflects variance in the EEG, the fact that this measure of variability is predictive of RT mixing cost suggests that it is indicative of processes that contribute to behavior.

However, we argue that the variability in the single-trial EEG is unlikely to completely account for these and other non-phase-locked findings. Firstly, the ERP signal was very stable across mixed-task blocks (see section 2.4), possibly because participants were highly practiced on the task.

Secondly, non-phase-locked effects were evident across a much broader timeframe, consistent with more sustained nature of non-phase-locked activity. Furthermore, a high level of jitter between trials would lead to broader ERP components. This means that the ERP that is subtracted to calculate the non-phase-locked power would be in a slower frequency range than the single trial EEG. Therefore, if the non-phase-locked effects were caused by jitter in the EEG, the phase-locked and non-phase-locked effects would not be observed in the same frequency. However, many phase-locked and non-phase-locked power effects were in similar frequency bands (i.e. theta and alpha). Finally, only non-phase-locked activity correlated with performance costs, and did so mostly in timeframes that did not show phase-locked activity.

4.6. Conclusions

The present study has shown novel effects of switching and mixing tasks in phase-locked and non-phase-locked power. The switch and mixing effects in the phase-locked power were restricted to the proactive control period where they closely resembled the ERP effects, suggesting that they may reflect similar preparatory processes such as task-set reconfiguration. In contrast, the non-phase-locked effects were widespread across the epoch (i.e. in both proactive and reactive control periods). While it is not known what the non-phase-locked power represents, these effects may reflect more ongoing processes related to task-switching such as sustained working memory and adjustment of the response criterion. Furthermore, only the non-phase-locked power contrasts were predictive of performance cost and this was only the case for the mixing cost. These non-phase-locked effects are novel in task-switching literature which are not accessible in total time-frequency and/or ERP analyses.

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Figure legends

Figure 1. Cued trials task-switching paradigm. A) Structure of the task. Adjacent segments are mapped to the color, letter, or digit task. An example of stimulus-response mapping is also shown. B) Trial example. A cue highlights two adjacent segments (corresponding here to the letter task) for 1000 ms. After 1000 ms, the cue is replaced by a target that appears in one of the highlighted segments. Participants respond to the target and 400 ms after the response the next trial's cue appears. C) The subsequent trial (N) could be i) a repeat trial i.e., the same two segments will be highlighted and the same task will be performed, or ii) a *switch* trial i.e., the cue will highlight two segments associated with one of the other two tasks and validly indicates which of these tasks the participant will be required to perform on the target.

Figure 2. Behavioral task-switching results. Violin plots showing RT (left) and error rate (right) for each trial type. Plots display the distribution of each data series with a superimposed box and whisker plot. Notch center is the mean score, box edges = 1st and 3rd quartile, whisker ends = ± 1.5 interquartile range.

Figure 3. *Switch* cost power at FCz (A) and PZ (B). Power t-maps of *mixed-repeat* (left) and *switch* trials (middle) and the *switch* cost (*switch* – *mixed-repeat*; right) at electrodes FCz and Pz. i) Total power, ii) Phase-locked power, iii) Non-phase-locked power. White lines indicate significant clusters of time*frequency pixels ($p < .001$, FDR corrected). Note, cue onset occurs at 0 ms and target onset occurs at 1000 ms (black dashed lines).

Figure 4. ERPs. ERP waveforms for *switch* cost (A) and mixing cost (B) at FCz (i) and Pz (ii). The single conditions (i.e. *mixed-repeat* and *switch* (A) and *all-repeat* and *mixed-repeat* (B) are shown on the left. The difference waveforms (i.e. *switch* cost (A) and mixing cost (B) are shown on the right. Single condition and difference waveforms are shaded 95% confidence intervals calculated for a within-subjects design (c.f., Loftus and Masson, 1994). Significant intervals of *switch* or mix cost (FDR $a < 0.001$) are shown as thin pink or orange lines respectively.

Figure 5. Mixing cost power at FCz (A) and Pz (B). Power t-maps of *all-repeat* (left) and *mixed-repeat* trials (middle) and the mixing cost (*mixed-repeat* – *all-repeat*; right) at electrodes FCz and Pz. i) Total power, ii) Phase-locked power, iii) Non-phase-locked power. White lines indicate significant clusters of time*frequency pixels ($p < .001$, FDR corrected). Note, cue onset occurs at 0 ms and target onset occurs at 1000 ms (black dashed lines).

Figure 6. Mixing cost power and RT correlations. A-C, correlation plots of the mixing power (*mixed-repeat* – *all-repeat*) and mixing cost RT ((*mixed-repeat* – *all-repeat*)/*all-repeat*) at FCz (left) and Pz (right) for A) Total power, B) Phase-locked power, C) Non-phase-locked power. White lines indicate significant clusters of time*frequency pixels ($p < .001$, FDR corrected). Note, cue onset occurs at 0 ms and target onset occurs at 1000 ms (black dashed lines).

Appendix 1. *Switch* cost power and RT correlations. A-C, correlation plots of the mixing power (*switch* – *mixed-repeat*) and mixing cost RT ((*switch* – *mixed-repeat*)/*mixed-repeat*) at FCz (left) and Pz (right) for A) Total power, B) Phase-locked power, C) Non-phase-locked power. Note, cue onset occurs at 0 ms and target onset occurs at 1000 ms (black dashed lines).

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